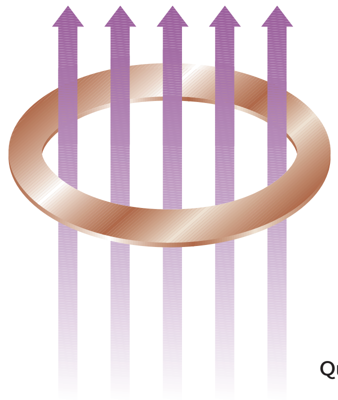
29. How is the unit of current defined?
30. How is the unit of charge defined?
31. One of Earth's magnetic poles is located in Antarctica. Is it a magnetic north pole or a magnetic south pole?
32. Why might it be more proper to call a north magnetic pole a "north-seeking" magnetic pole?
33. If you want to walk toward the geographic North Pole while in New York City, what compass heading would you follow?
34. How far does a compass in Portland, Oregon, point away from the geographic North Pole?
35. Why are there more cosmic rays in Antarctica than in Hawaii?
36. We can model Earth's magnetic field as due to a single large current-carrying loop that runs around the equator just below the surface. In this model, is the direction of the current east to west or west to east? Why?
37. If a charged particle travels in a straight line, can you say that there is no magnetic field in that region of space? Explain.
38. Can you accelerate a stationary charged particle with a magnetic field? An electric field? Explain.
39. A proton and an electron with the same velocity enter a bending magnet with a magnetic field perpendicular to their velocity. Compare the motions of the proton and electron.
40. A magnet produces a magnetic field that points vertically upward. In what direction does the force on a proton act if it enters this region with a horizontal velocity toward the east?
41. A conducting loop is lying flat on the ground. The north pole of a bar magnet is brought down toward the loop. As the magnet approaches the loop, will the magnetic field created by the induced current point up or down? What is the direction of the current in the loop? Explain.
42. The magnet in Question 41 is now lifted upward. Which, if either, of your answers will change? Explain.
43. Consider the case in which the north pole of a bar magnet is being moved toward a conducting copper ring. Do the field lines created by the induced current point toward the bar magnet or away? Will this induced field pull on the magnet or push against it? Explain.
44. Consider the case in which the north pole of a bar magnet is being moved away from a conducting copper ring. Do the field lines created by the induced current point toward the bar magnet or away? Will this induced field pull back on the magnet or push it away? Explain.
45. A copper ring is oriented perpendicular to a uniform magnetic field, as shown in the following figure. If the ring is suddenly moved in the direction opposite the field lines, will the magnitude of the net magnetic field in the center of the loop (the uniform field plus the induced field) be greater than, equal to, or less than the magnitude of the uniform field? Explain.



Questions 45 and 46.

46. A copper ring is oriented perpendicular to a uniform magnetic field, as shown in the preceding figure. The ring is quickly stretched such that its radius doubles over a short time. As the ring is being stretched, is the magnitude of the net magnetic field in the center of the loop (the uniform field plus the induced field) greater than, equal to, or less than the magnitude of the uniform field? Explain.
47. Quickly inserting the north pole of a bar magnet into a coil of wire causes the needle of a meter to deflect to the right. Describe two actions that will cause the needle to deflect to the left.
48. How could you produce a current in a solenoid by rotating a small magnet inside the coil?
49. When a transformer is plugged into a wall socket, it produces 9-volt alternating-current electricity for a portable tape player. Is the coil with the larger or smaller number of turns connected to the wall socket? Why?
50. If you had an old car that needed a 6-volt battery to drive the starter motor, could you use a 12-volt battery with a transformer to get the necessary output voltage? How?
51. What is the purpose of using a commutator in a motor?
52. What effect does a commutator have on the electrical output of a generator?
53. Describe an electromagnetic wave propagating through empty space.
54. How are electromagnetic waves generated?
55. Which of the following is *not* an electromagnetic wave: radio, television, blue light, infrared light, or sound?
56. Which of the following electromagnetic waves has the lowest frequency: radio, microwaves, visible light, ultraviolet light, or X rays? Which has the highest frequency?
57. What is the difference between X rays and gamma rays?
58. How fast do X rays travel through a vacuum?
59. How is sound encoded by an AM radio station?
60. How is sound transmitted by an FM radio station?
61. At what frequency does radio station FM 102.1 broadcast?
62. What does it mean when your local disc jockey says that you are "listening to radio 1380"?

Exercises

63. The record for a steady magnetic field is 45 T. What is this field expressed in gauss?

64. What is the magnetic field (expressed in gauss) of a refrigerator magnet with a magnetic field of 0.3 T?

65. The magnetic field at the equator of Jupiter has been measured to be 4.3 G. What is this field expressed in teslas?

66. The magnetic fields associated with sunspots are on the order of 1500 G. How many teslas is this?

67. An electron has a velocity of 5×10^6 m/s perpendicular to a magnetic field of 1.5 T. What force and acceleration does the electron experience?

68. What force and acceleration would a proton experience if it has a velocity of 5×10^6 m/s perpendicular to a magnetic field of 1.5 T?

69. A metal ball with a mass of 3 g, a charge of 1 μC, and a speed of 40 m/s enters a magnetic field of 20 T. What are the maximum force and acceleration of the ball?

70. A very small ball with a mass of 0.1 g has a charge of 10 μC. If it enters a magnetic field of 10 T with a speed of 30 m/s, what are the maximum force and acceleration the ball experiences?

71. If you wanted the maximum magnetic force on the ball in Exercise 69 to equal the gravitational force on the ball, what charge would you need to give it?

72. What speed would be needed in Exercise 70 for the maximum magnetic force to be equal to the gravitational force?

73. An ink drop with charge $q = 3 \times 10^{-9}$ C is moving in a region containing both an electric field and a magnetic field. The strength of the electric field is 3×10^5 N/C, and the strength of the magnetic field is 0.2 T. At what speed must the particle be moving perpendicular to the magnetic field so that the magnitudes of the electric and magnetic forces are equal?

74. How would your answer to Exercise 73 change if the charge on the ink drop were doubled?

75. A particle with charge $q = 5\ \mu$C and mass $m = 6 \times 10^{-5}$ kg is moving parallel to Earth's surface at a speed of 1000 m/s. What minimum strength of magnetic field would be required to balance the gravitational force on the particle?

76. What minimum strength of magnetic field is required to balance the gravitational force on a proton moving at speed 5×10^6 m/s?

77. A transformer is used to convert 120-V household electricity to 6 V for use in a portable CD player. If the primary coil connected to the outlet has 400 loops, how many loops does the secondary coil have?

78. The voltage in the lines that carry electric power to homes is typically 2000 V. What is the required ratio of the loops in the primary and secondary coils of the transformer to drop the voltage to 120 V?

79. A transformer is used to step down the voltage from 120 V to 6 V for use with an electric razor. If the razor draws a current of 0.5 A, what current is drawn from the 120-V lines? What is the ratio of the loops in the primary and secondary coils of the transformer?

80. Your 120-V outlet is protected by a 15-A circuit breaker. What is the maximum current that you can provide to an appliance using a transformer with one-tenth as many loops in the secondary as in the primary?

81. You are using a transformer with 800 loops in the primary and 80 loops in the secondary. If the 120-V input is supplying 2 A, what is the current in the appliance connected to the transformer?

82. You are using a transformer with 800 loops in the primary and 80 loops in the secondary. If the transformer is plugged into a 120-V outlet protected by a 15-A circuit breaker, what is the maximum power rating of an appliance that could be used with this transformer?

83. How long does it take a radio signal from Earth to reach the Moon when it is 384,000 km away?

84. The communications satellites that carry telephone messages between New York City and London have orbits above Earth's equator at an altitude of 13,500 km. Approximately how long does it take for each message to travel between these two cities via the satellite?

85. Many microwave ovens use microwaves with a frequency of 2.45×10^9 Hz. What is the wavelength of this radiation, and how does it compare with the size of a typical oven?

86. An X-ray machine used for radiation therapy produces X rays with a maximum frequency of 2.4×10^{20} Hz. What is the wavelength of these X rays?

87. The ultraviolet light that causes suntans (and sunburns!) has a typical wavelength of 300 nm. What is the frequency of these rays?

88. The radioactive isotope most commonly used in radiation therapy is cobalt-60. It gives off two gamma rays with wavelengths of 1.06×10^{-12} m and 9.33×10^{-13} m. What are the frequencies of these gamma rays?

Martin Dohrn/Science Photo Library/Photo Researchers, Inc.

89. What is the range of wavelengths for AM radio?

90. What is the range of wavelengths for FM radio?

91. What is the wavelength of the carrier wave for an AM radio station located at 1090 on the dial?

92. What is the longest wavelength used for TV broadcasts?

Blue-numbered answered in Appendix B = more challenging questions

The Big Picture

The Story of the Quantum


© Floyd Dean/Taxi/Getty Images

The shape of a snowflake is determined by the quantum-mechanical interactions of water molecules with each other.

In 1887 German physicist Heinrich Hertz generated sparks in an electrostatic machine and successfully caused a spark to jump across the gap of an isolated wire loop on the other side of his laboratory. Hertz had transmitted the first radio signal a distance of a few meters. Hertz was not interested in the societal implications of sending signals; he was testing James Clerk Maxwell's prediction of the existence of electromagnetic waves. Hertz also mentioned the curious fact that when ultraviolet light illuminated his loop, more sparks were produced.

The 19th century had been the age of steam engines and heat. It is no wonder that tremendous strides were made in the study of thermodynamics—the behavior of gases under different conditions of pressure and temperature. By the 1890s entirely new areas of confusing phenomena provided huge intellectual challenges to scientists. In 1895 Wilhelm Roentgen discovered a new form of radiation emanating from an electromagnetic device known as a cathode ray tube. The following year Henri Becquerel observed that a lump of uranium emitted some sort of energy that radiated through the wood of his desk and fogged his photographic plates. In 1900 Max Planck puzzled over unusual results when he calculated the spectrum of radiation from heated objects.

Some of the greatest minds of the 20th century grappled with these issues of radiation and matter, experimental fact and theory. They continually received information that was unbelievable. It was a crisis in the process of discovery itself, born in turmoil and confusion. What were they to believe? A philosopher of that era put it this way: "The senses do not lie. They just do not tell us the truth."

The only possible resolution was a revolution in the physics world view. Ideas that had been taken for granted were discarded, and the unbelievable became believable. The core of the revolution seemed innocent enough: Energy exists in "chunks," or quantum units. At first glance quantization may not seem that radical. The paintings of the French Impressionists look normal when viewed from afar, and our weight seems continuous even though it is really the sum of the weights of discrete atoms. But it is not just a matter of adding the many tiny components of this new discreteness to get the whole; it is the tiny components that control the character of the whole.

The quantum nature of energy was the first of three changes leading to this new physics. New insights into the nature of light and, finally, new insights into the nature of matter followed. Together these changes revealed the character of the universe, from the shape of snowflakes to the existence of neutron stars.

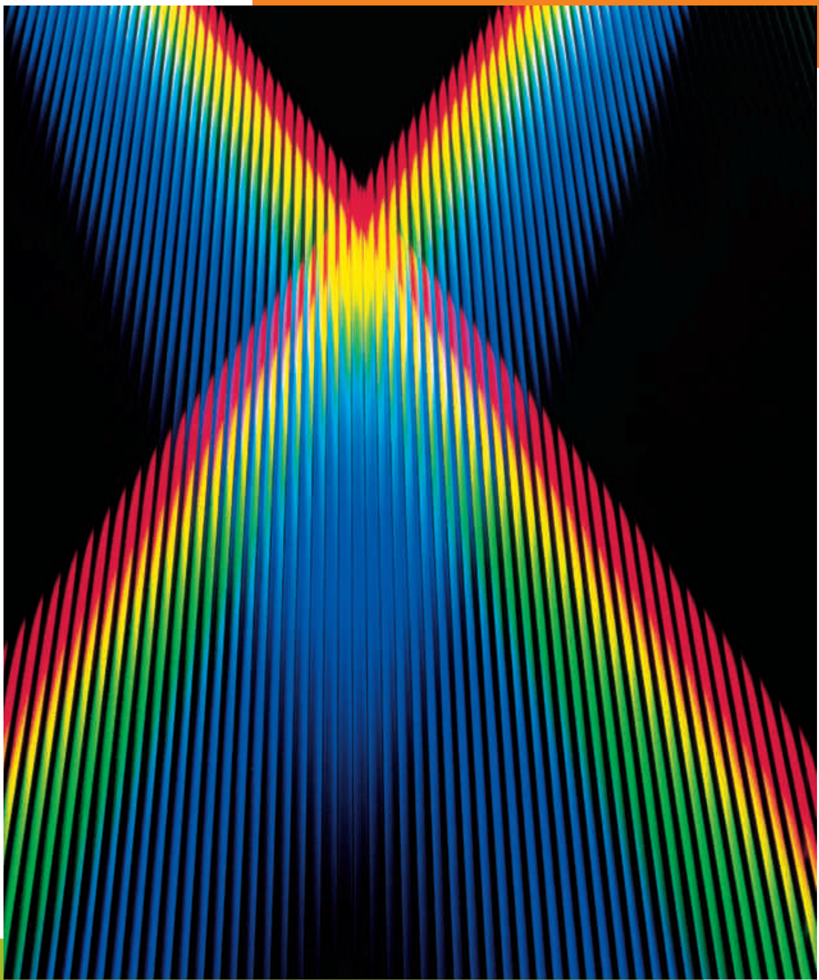
Heinrich Hertz

In the remaining chapters, we will follow the development of these ideas. Although it may seem easier to simply learn "the answers," they are unbelievable without knowing the experiments, the conflicts, the debates, and the eventual resolutions that led to them. As you track these developments, keep in mind Sir Hermann Bondi's comment: "We should be surprised that the gas molecules behave so much like billiard balls and not surprised that electrons don't."

23 The Early Atom

▶ We get much of our information about atoms from the light they emit. In fact, the pretty arrays of color emitted by atoms—known as atomic fingerprints—distinguish one type of atom from the others and hold many clues about atomic structure. What does the light tell us about atoms?

(See page 516 for the answer to this question.)



David Parker/SPL/Photo Researchers, Inc.

Diffraction gratings separate the different colors of light. These gratings can be used to probe the structure of atoms.

NEW world views don't emerge in full bloom—they start as seeds. Although a change may begin because of a single individual, it usually evolves from the collective efforts of many. Ideas are proposed. As they undergo the scrutiny of the scientific community, some are discarded and others survive, although almost always in a modified form. These survivors then become the beginnings of new ways of looking at the world.

During the early years of the last century, a number of phenomena were known or discovered that eventually led to several models for the atom. After exploring the phenomena, we will examine several atomic models that emerged in response to the experiments.

Periodic Properties

Figure 23-1 Mendeleev's arrangement of the elements.

Once the values of the atomic weights of the chemical elements were determined (Chapter 11), it was tempting to arrange them in numerical order. When this was done, a pattern emerged; the properties of one element corresponded closely to those of an element farther down the list and to another one even farther down the list. A periodicity of characteristics became apparent.

Russian chemist Dmitri Mendeleev wrote the symbols for the elements on cards and spent a great deal of time arranging and rearranging them. For some reason he omitted hydrogen, the lightest element, and began with the next lightest one known at that time, lithium (Li). He laid the cards in a row. When he reached the 8th element, sodium (Na), he noted that it had properties similar to lithium and therefore started a new row. As he progressed along this new row, each element had properties similar to the one directly above it. The 15th element, potassium (K), is similar to lithium and sodium, and so Mendeleev began a third row. His arrangement of the first 16 elements looked like Figure 23-1.

The next known element was titanium, but it did not have the same properties as boron (B) and aluminum (Al); it was similar to carbon (C) and silicon (Si). Mendeleev boldly claimed that there was an element that had not yet been discovered. He went on to predict two other elements, even predicting their properties from those of the elements in the same column. Later, these elements were discovered and had the properties that Mendeleev had predicted. Mendeleev's work was the beginning of the modern periodic table of the elements. At that time no theory could explain why the elements showed these periodic patterns. However, the existence of the periodicity was a clue to scientists that there might be an underlying structure to atoms.

Atomic Spectra

Another thing fascinated and confused scientists around the beginning of the 20th century. When an electric current passes through a gas, the gas gives off a characteristic color. A modern application of this phenomenon is the neon sign. Although each gas emits light of a particular color, it isn't necessarily unique. However, if you pass the light through a prism or a grating to spread out the colors, the light splits up into a pattern of discrete colored lines (Figure 23-2), which is always the same for a given gas but different from the patterns produced by other gases.

Q: If a particular gas glows with a yellow color when a current is passed through it, will its spectrum necessarily contain yellow light?

A: The spectrum will not necessarily contain yellow light because the yellow sensation could result from a combination of red and green spectral lines. In fact, red and green light from two different helium–neon lasers produces a beautiful yellow even though each laser has a narrow range of frequencies.

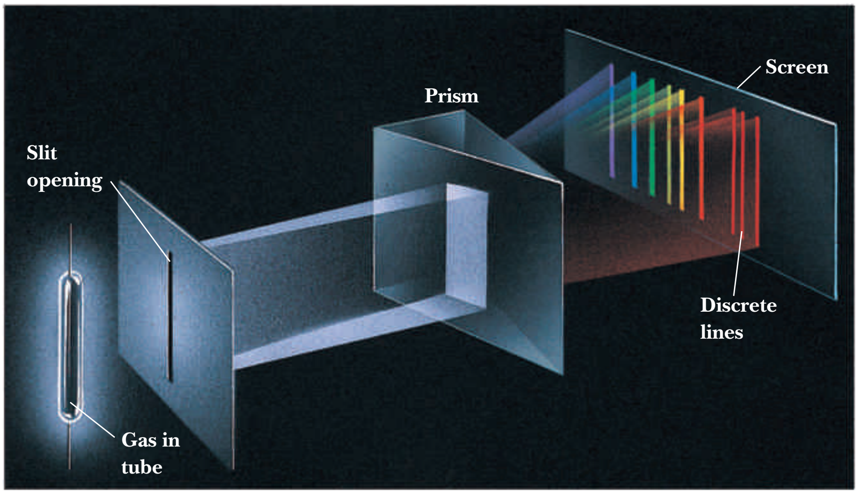


Figure 23-2 The emission spectrum of a gas consists of a small number of distinctly colored lines.

The various colors of light emitted by neon-type signs are due to different gases.

Each gas has its own particular set of spectral lines, collectively known as its **emission spectrum**. The emission spectra for a few gases are shown in the schematic drawings in Figure 23-3. Because these lines are unique—sort of an atomic fingerprint—they identify the gases even if they are in a mixture. Vaporized elements that are not normally gases also emit spectral lines, and these can be used to identify them.

Spectral lines also appear when white light passes through a cool gas (Figure 23-4). In this case, however, they do not appear as bright lines but as dark lines in the continuous rainbow spectrum of the white light; that is, light is missing in certain narrow lines. These particular wavelengths are absorbed or scattered by the gas to form this **absorption spectrum**.

All the lines in the absorption spectrum correspond to the lines in the emission spectrum for the same element. However, the emission spectrum has many lines that do not appear in the absorption spectrum, as illustrated in Figure 23-5.

Because the lines that appear in both spectra are the same, the absorption spectrum can also be used to identify elements. In fact, this is how helium was discovered. Spectral lines were seen in the absorption spectrum of sunlight that did not correspond to any known elements. These lines were attributed to

Figure 23-3 Schematic drawings of the emission spectra for sodium, mercury, helium, and hydrogen near the visible region.

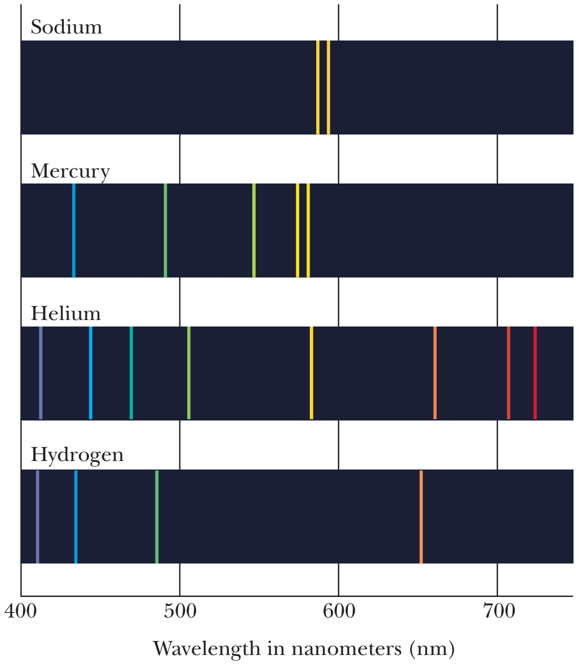


Figure 23-4 The absorption spectrum consists of a rainbow spectrum with a number of dark lines.

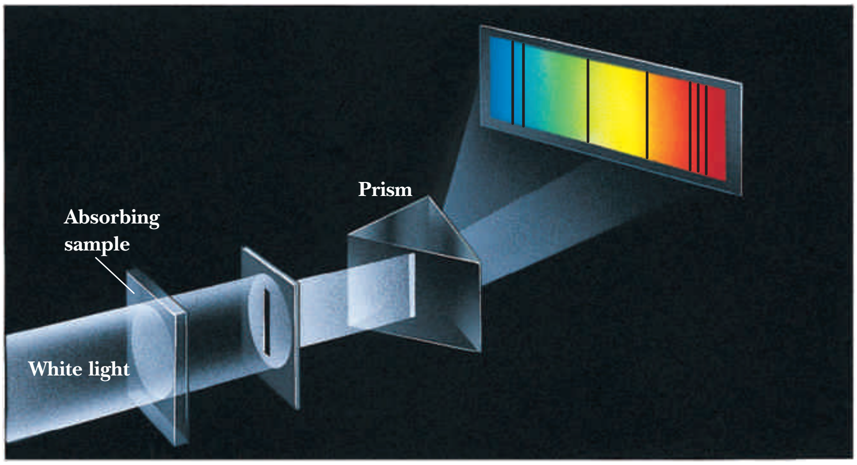
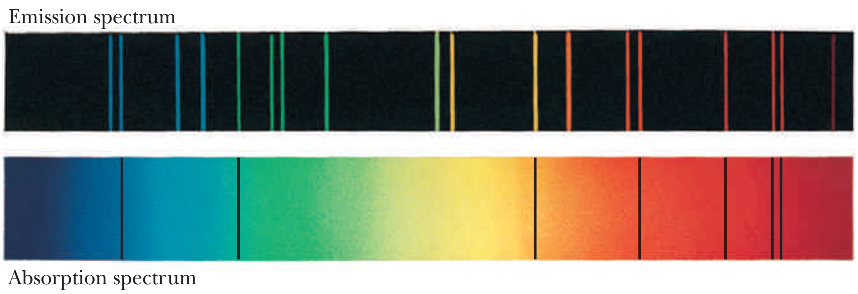


Figure 23-5 The absorption spectrum for an element has fewer lines than its emission spectrum.



a new element that was named *helium* after the Greek name for the Sun, *helios.* Helium was later discovered on Earth.

Spectral lines are a valuable tool for identifying elements. Although this is of great practical use, the scientific challenge was to understand the origin of the lines. Clearly, the lines carry fundamental information about the structure of atoms. The lines pose a number of questions. The most important question concerns their origin: what do spectral lines have to do with atoms? Also, why are certain lines in the emission spectra missing in the absorption spectra?

Cathode Rays

During the latter half of the 19th century, two new technologies contributed to the next advance in our understanding of atoms: vacuum pumps and high-voltage devices. It was soon discovered that a high voltage applied across two electrodes in a partially evacuated glass tube produces an electric current and light in the tube. Furthermore, the character of the phenomenon changes radically as more and more of the air is pumped from the tube. Initially, after a certain amount of the air is removed, sparks jump between the electrodes, followed by a glow throughout the tubes like that seen in modern neon signs. As more air is pumped out, the glow begins to break up and finally disappears. When almost all of the air has been removed, only a yellowish-green glow comes from one end of the glass tube.

These discoveries led to a flurry of activity. Experimenters made tubes with a variety of shapes and electrodes from a variety of materials. The glow always appeared on the end of the glass tube opposite the electrode connected to the negative terminal of the high-voltage supply. When the wires were exchanged, the glow appeared at the other end, showing that its location depended on which electrode was negative. A metal plate placed in a tube cast a shadow (Figure 23-6). These effects indicated that rays were coming from the negative electrode. Because this electrode was known as the *cathode* (the other electrode is the *anode*), the rays were given the name **cathode rays**.

The path of the cathode rays could be traced by placing a fluorescent screen along the length of the tube. The screen glowed wherever it was struck by the cathode rays. A magnet was used to see whether the rays were particles or waves. We saw in the previous chapter that a magnetic field exerts a force on a moving charged particle, but this does not occur for a beam of light. A magnet placed near the tube deflected the cathode rays, indicating that they were indeed charged particles.

Are You On the Bus?

Q: Based on the information given, would you expect the cathode rays to be positively or negatively charged?

A: Because they come from the cathode and the cathode is negatively charged, we expect the cathode rays to also have a negative charge. The directions of the magnetic deflections were also consistent with this expectation.

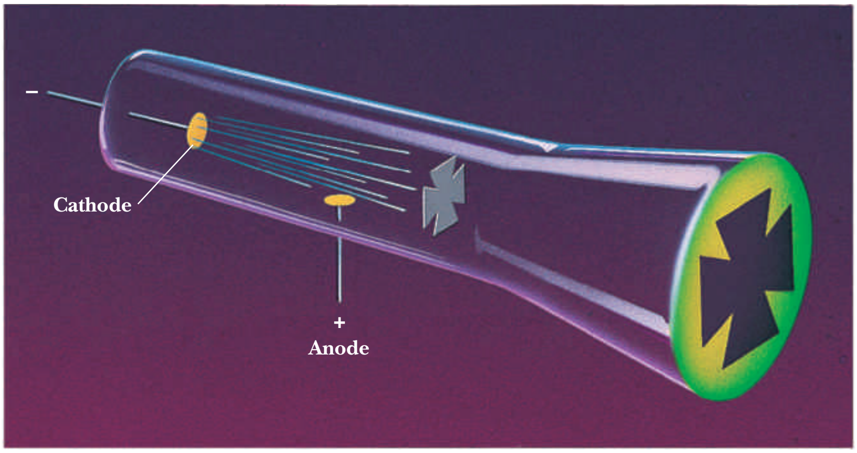
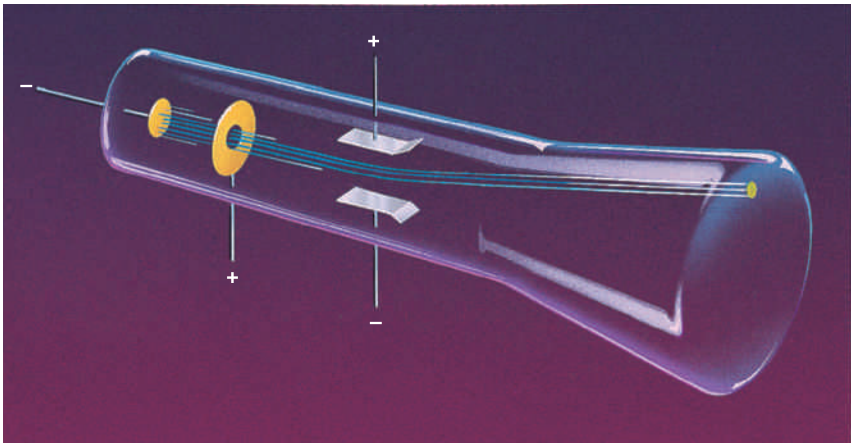


Figure 23-6 Cathode rays cast a shadow of the cross onto the end of the tube.

Figure 23-7 The cathode rays are deflected by an electric field.



This being the case, cathode rays should also be deflected by an electric field. Early experiments showed no observable effect until British scientist J. J. Thomson used the tube sketched in Figure 23-7. By placing the electric field plates inside the tube and by using a much better vacuum, he could observe electric deflection of the cathode rays. The direction of the deflection was that expected for negatively charged particles.

▶ Extended presentation available in the *Problem Solving* supplement

The Discovery of the Electron

Thomson went beyond these qualitative observations. He compared the amount of deflection using a known electric field with that of a known magnetic field. Using these values, he obtained a value for the ratio of the charge to the mass for the cathode particles. Furthermore, Thomson showed that the *charge-to-mass ratio* was always the same regardless of the gas in the tube or the cathode material. This was the first strong clue that these particles were universal to all matter and therefore an important part of the structure of matter.

J. J. Thomson

This ratio could be compared with known elements. The charge-to-mass ratio for positively charged hydrogen atoms (called hydrogen **ions**) had previously been determined; Thomson's number was about 1800 times as large. If Thomson assumed that the charges on the particles were all the same, the mass of the hydrogen ion was 1800 times that of the cathode particle. Conversely, if he assumed the masses to be the same, the charge on the cathode ray was 1800 times as large. (Of course, any combination in between was also possible.)

Thomson believed that the first option—assuming that all charges are equal—was the correct one. (Other data supported this assumption.) This assumption meant that the cathode particles had a much smaller mass than a hydrogen atom, the lightest atom. At this point, he realized that the atom had probably been split!

This was a special moment in the building of the physics world view. The discussion that had originated at least as far back as the early Greeks was centered on the question of the existence of atoms, never on their structure. It had always been assumed that these particles were indivisible. Thomson's work showed that the indivisible building blocks of matter are divisible; they have internal structures.

Around 1910 American experimentalist Robert Millikan devised a way of measuring the size of the electric charge, thus testing Thomson's assumption.

Millikan produced varying charges on droplets of oil between a pair of electrically charged plates (Figure 23-8). By measuring the motions of individual droplets in the electric field, he determined the charge on each droplet and confirmed the widely held belief that electric charge comes in identical chunks, or **quanta**. A particle may have one of these elemental units of charge, or two, or three, but never two and a half. This smallest unit of charge is 1.6 $\times 10^{-19}$ coulomb, an extremely small charge; a charged rod would have more than billions upon billions of these charges.

◀ elementary charge

The mass of the cathode particles could now be calculated from the value of the charge and the charge-to-mass ratio. The modern value for the mass of the cathode particle is 9.11×10^{-31} kilogram. This particle—a component part of all atoms with a mass $\frac{1}{1800}$ the size of the hydrogen atom and carrying the smallest unit of electric charge—is known as an **electron**. The electron is so small that it would take a trillion trillion of them in the palm of your hand before you would notice their mass.

◀ mass of the electron

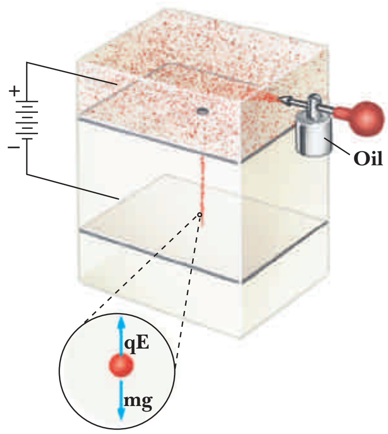


Figure 23-8 The Millikan oil-drop experiment showed that electric charges are quantized.

Thomson's Model

Thomson's work showing that atoms have structure was an exciting breakthrough. A natural question emerged immediately: what does an atom look like? One of its parts is the electron, but what about the rest? Thomson proposed a model for this structure, picturesquely known as the "plum-pudding" model, with the atom consisting of some sort of positively charged material with electrons stuck in it much like plums in a pudding (Figure 23-9). Because atoms were normally electrically neutral, he hypothesized that the amount of positive charge was equal to the negative charge and that atoms become charged ions by gaining or losing electrons.

Recall that gases were known to emit distinct spectral lines. Thomson suggested that forces disturbing the atom caused the electrons to jiggle in the positive material. These oscillating charges would then generate the electromagnetic waves observed in the emission spectrum. However, the model could not explain why the light was emitted only as definite spectral lines, nor why each element had its own unique set of lines.

Thomson also attempted to explain the repetitive characteristics in the periodic table. He suggested that each element in the periodic table had a different number of electrons. He hoped that with different numbers of electrons, different arrangements would occur that might show a periodicity and thus a clue to the periodicity shown by the elements. For example, three electrons might arrange themselves in a triangle, four in a pyramid, and so on. Perhaps there was a periodicity to the shapes. Patterns did occur in his model, but the periodicity did not match that of the elements.

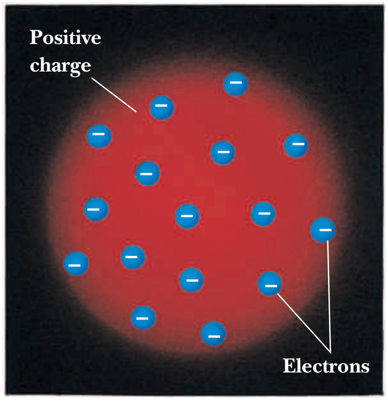


Figure 23-9 Thomson's model of the atom.

Rutherford's Model

Ernest Rutherford, a student of Thomson, did an experiment that radically changed his teacher's model of the atom. A key tool in Rutherford's work was the newly discovered radioactivity, the spontaneous emission of fast-moving atomic particles from certain elements. Rutherford had previously shown that one of these radioactive products is a helium atom without its electrons. These particles have two units of positive charge and are known as **alpha particles**.

Rutherford bombarded materials with alpha particles and observed how the alpha particles recoiled from collisions with the atoms in the material. This procedure was much like determining the shape of an object hidden under a table by rolling rubber balls at it (Figure 23-10). Rutherford used the alpha

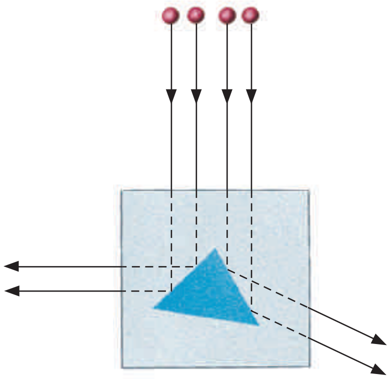


Figure 23-10 **The shape of a hidden object can be determined by rolling rubber balls and seeing how they are scattered.**

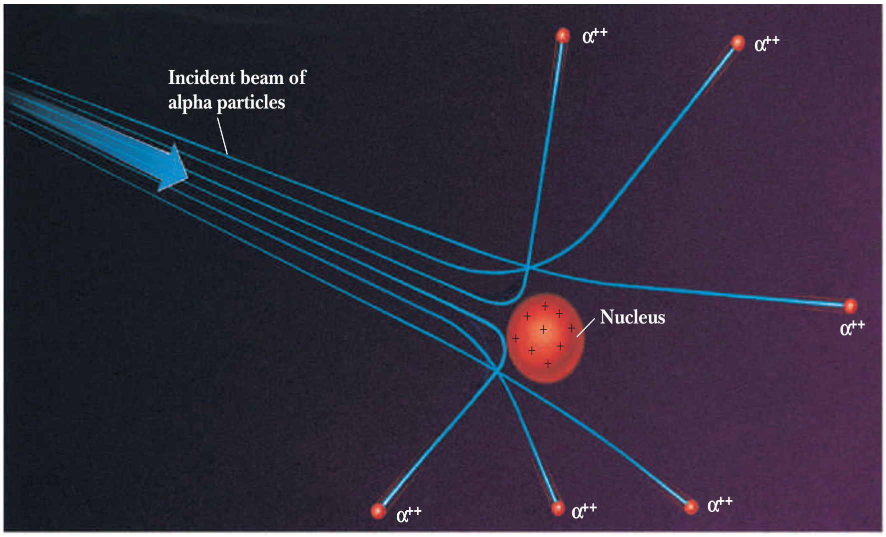


Figure 23-11 **The positively charged alpha particles are repelled by the positive charges in the nucleus.**

particles as his probe because they were known to be about the same size as atoms. (One doesn't probe the structure of snowflakes with a sledgehammer.) The target needed to be as thin as possible to keep the number of collisions by a single alpha particle as small as possible, ideally only one. Rutherford chose gold because it could be made into a thin foil.

The alpha particles are about 4 times the mass of hydrogen atoms and 7300 times the mass of electrons. Thomson's model predicted that the deflection of alpha particles by each atom (and hence by the foil) would be extremely small. The positive material of the atom was too spread out to be an effective scatterer. Consider the following analogy. Use 100 kilograms of newspapers to make a wall one sheet thick. Glue table-tennis balls on the wall to represent electrons. If you were to throw bowling balls at the wall, you would clearly expect them to go straight through with no noticeable deflection.

Initially, Rutherford's results matched Thomson's predictions. However, when Rutherford suggested that one of his students look for alpha particles in the backward direction, he was shocked with the results. A small number of the alpha particles were actually scattered in the backward direction! Rutherford later described his feelings by saying, "It was almost as incredible as if you fired a 19-inch shell at a piece of tissue paper and it came back and hit you!"

On the basis of his experiment, Rutherford proposed a new model in which the positive charge was not spread out but was concentrated in a very, very tiny spot at the center of the atom, which he called the **nucleus**. The scattering of alpha particles is shown in Figure 23-11. Returning to our analogy, imagine what would happen if all the newspapers were crushed into a small region of space: most of the bowling balls would miss the paper and pass straight through, but occasionally a ball would score a direct hit on the 100-kilogram ball of newspaper and recoil.

Rutherford determined the speed of the alpha particles by measuring their deflections in a known magnetic field. Knowing their speeds, he could calculate their kinetic energies. Because he knew the charges on the alpha particle and the nucleus of the gold atom, he could also calculate the electric potential energy between the two. These calculations allowed him to calculate the closest distance an alpha particle could approach the nucleus of the gold atom before its kinetic energy had been entirely converted to potential energy. These experiments gave him an upper limit on the size of the gold nucleus. The nucleus has a diameter approximately $\frac{1}{100,000}$ the size of its atom. This means that atoms are almost entirely empty space.

Are You On the Bus?

Q: If the nucleus were the size of a basketball, what would be the diameter of the atom?

A: Assuming that a basketball has a diameter of about 24 centimeters, the diameter of the atom would be (100,000)(0.24 meter) = 24 kilometers (15 miles) across.

Our work in electricity tells us that the negative electrons are attracted to the positive nucleus. Rutherford proposed that they don't crash together at the center of the atom because the electrons orbit the nucleus much as the planets in our solar system orbit the Sun (Figure 23-12). The force that holds the orbiting electrons to the nucleus is the electric force. (The gravitational force is negligible for most considerations at the atomic level.)

Are You On the Bus?

Q: If atoms are mostly empty space, why can't we simply pass through each other?

A: The atom's electrons in the outer regions keep us apart. When two atoms come near each other, the electrons repel each other strongly.

Rutherford's work led to a new explanation for the emission of light from atoms. The orbiting electrons are accelerating (Chapter 4), and accelerating charges radiate electromagnetic waves (Chapter 22). A calculation showed that the orbital frequencies of the electron correspond to the region of visible light. But there is a problem. If light is radiated, the energy of the electron must be reduced. This loss would cause the electron to spiral into the nucleus. In other words, this model predicts that the atom is not stable and should collapse. Calculations showed that this should occur in about a billionth of a second! Because we know that most atoms are stable for billions of years, there is an obvious defect in the model.

Rutherford's "solar system" model of the atom also failed to predict spectral lines and to account for the periodic properties of the elements. The resolution of these problems was accomplished by atomic models proposed during the two decades following Rutherford's work.

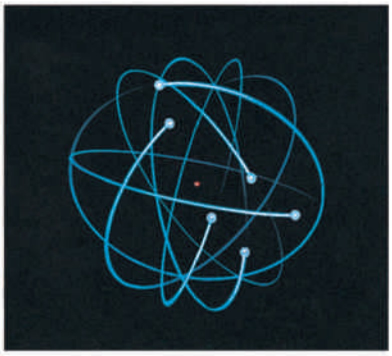


Figure 23-12 Rutherford's model of the atom. (The size of the nucleus is greatly exaggerated, and the electrons are known to be even smaller than the nucleus.)

Radiating Objects

The Thomson and Rutherford models of the atom could explain some of the experimental observations, but they had serious deficiencies. Clearly, a new model was needed. Interestingly, the germination of the next model began in yet another area of physics, one having to do with the properties of the radiation emitted by a hot object.

All objects glow. At normal temperatures the glow is invisible; our eyes are not sensitive to it. As an object gets warmer, we feel this glow—we call it heat. At even higher temperatures, we can see the glow. The element of an electric stove or a space heater, for example, has a red-orange glow. In all these cases, the object is emitting electromagnetic radiation. The frequencies, or colors, of the electromagnetic radiation are not equally bright, as can be seen in the photographs of Figure 23-13. Furthermore, the color spectrum shifts toward the blue as the temperature of the object increases.

All solid objects give off continuous spectra that are similar, but not identical. However, the radiation is the same for all materials at the same temperature if the radiation comes from a small hole in the side of a hollow block. Typical distributions of the brightness of the electromagnetic radiation versus wavelength are shown in the graph of Figure 23-14 for several temperatures. When the temperature changes, the position of the hump in the curve

Rutherford | *At the Crest of the Wave*

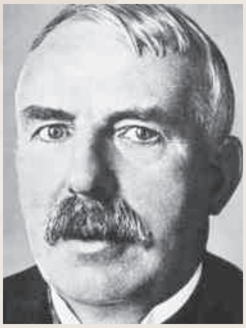
Well, I made the wave, didn't I?

—Ernest Rutherford, first Baron Rutherford of Nelson

Ernest Rutherford (1871–1937) grew up on a small farm near Nelson, New Zealand, at a time when that island nation was new and very much part of the expansive British Empire. He received a sound education in Nelson and won a scholarship to the University of New Zealand. His diligence and brilliance there earned him an imperial scholarship to Cambridge University, where J. J. Thomson, director of the Cavendish Laboratory, put him to work measuring electromagnetic waves. Teacher and student then moved on to analyze X-ray ionization in gases and aspects of the photoelectric effect. Henri Becquerel's discovery of radioactivity created a vast new arena for physicists to explore.

Rutherford had just begun to examine radium ionization because he had discovered that two types of radiation in this strange gas, alpha and beta, had different penetrating properties. The former was stopped by a thin layer of common air; the latter passed through a thin aluminum foil. Rutherford made a series of great discoveries involving alpha rays. He left England in 1898 and continued his work as a new professor at McGill University in Montreal, Quebec, Canada.

Rutherford's students and colleagues at McGill, the most notable of whom was Frederick Soddy, continued to work on explanatory mechanisms for radioactivity and published the first substantial study of that complex subject. In 1908 Rutherford received the Nobel Prize in chemistry. His address was a model of scientific reporting. He explained the importance of alpha radiations, their identity as helium atoms, and their use in analyzing atomic numbers. In 1909 Rutherford accepted a chair of physics at Manchester University, where he continued to work on the cutting edge of atomic energy questions and in 1912 attracted perhaps his most outstanding student, Niels Bohr. Another brilliant young physicist, Henry Moseley, arrived in 1913. Moseley's death on the Gallipoli battlefront in World War I led to Rutherford's futile request that scientists be exempted from frontline service. That piece of advice was taken by the United States in World War II. Rutherford also contributed to wartime research in a number of areas, most notably submarine detection.



U. K. Atomic Energy Authority, Courtesy AIP Emilio Segre Visual Archives

Lord Ernest Rutherford

The New Zealander was knighted in 1914 and returned to Cambridge in 1919 when Thomson retired. He was made a baron in 1931, which gave him a seat in the House of Lords. Rutherford, always gifted with a splendid clarity of vision and expression, lived out his life full of honors and continued scientific challenges. The most complex problem for him was a matter of resolving the key components into a simpler form so that they could be tackled. The great revolutions in physics—relativity, atomic physics, and quantum theory—all saw him at the center of ongoing work. His comment quoted previously was true: he had indeed been at the crest of the wave that swept over this heroic age of physics.

—Pierce C. Mullen, historian and author

Sources: David Wilson, *Rutherford: Simple Genius* (Cambridge, Mass.: MIT Press, 1983); Arthur S. Eve, *Rutherford* (New York: Macmillan, 1939).

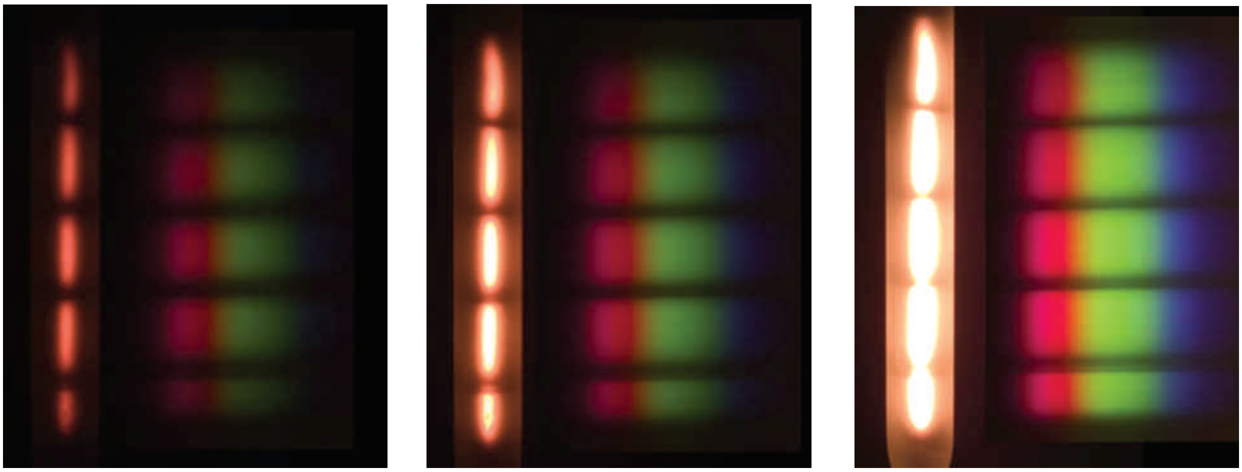


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Figure 23-13 The color of the hot filament and its continuous spectrum change as the temperature is increased.

changes; the wavelength with the maximum intensity varies inversely with the temperature—that is, as the temperature goes up, the highest point of the curve moves to smaller wavelengths.

Q: What happens to the frequency corresponding to the maximum intensity as the temperature increases?

A: Because the product of the frequency and the wavelength must equal the speed of light, the frequency must increase as the wavelength decreases. Therefore, the frequency increases as the temperature increases.

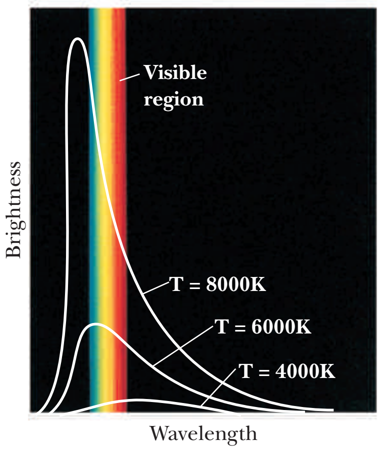


Figure 23-14 This graph shows the intensity of the light emitted by a hot object at various wavelengths for three different temperatures.

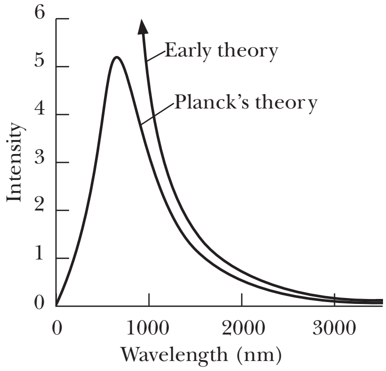


Figure 23-15 The theoretical ideas and the experimental data for the intensity of the light emitted by a hot body differed greatly in the low-wavelength (high-frequency) region.

The fact that the same distribution is obtained for cavities made in any material—gold, copper, salt, or whatever—puzzled and excited the experimenters. However, all attempts to develop a theory that would explain the shape of this curve failed. Most attempts assumed that the material contained some sort of charged atomic oscillators that generated light of the same frequency as their vibrations. Although the theories accounted for the shape of the large-wavelength end of the curve, none could account for the small contribution at the shorter wavelengths (Figure 23-15). Nobody knew why the atomic oscillators did not vibrate as well at the higher frequencies.

A solution was discovered in 1900 by Max Planck, a German physicist. He succeeded by borrowing a new technique from another area of physics. The technique called for temporarily pretending that a continuous property was discrete in order to make particular calculations. After finishing the calculation, the technique called for returning to the real situation—the continuous case—by letting the size of the discrete packets become infinitesimally small.

Planck was attempting to add up the contributions from the various atomic oscillators. Unable to get the right answer, he temporarily assumed that energy existed in tiny chunks. Planck discovered that if he didn't take the last step of letting the chunk size become very small, he got the right results! Planck announced his success in cautious tones—almost as if he were apologizing for using a trick on nature.

Planck's "incomplete calculation" was in effect an assumption that the atomic oscillators could vibrate only with certain discrete energies. Because the energy could have only certain discrete values, it would be radiated in little bundles, or quanta (singular, **quantum**). The energy E of each bundle was given by

$$E = hf$$

◀ energy quantum = Planck's constant × frequency

Planck's constant ▶

where h is a constant now known as *Planck's constant* and f is the frequency of the atomic oscillator. An oscillator could have an energy equal to 1, 2, 3, or more of these bundles, but not $1\frac{5}{8}$ or $2\frac{1}{2}$. The value of Planck's constant, 6.63 $\times 10^{-34}$ joule-second, was obtained by matching the theory to the radiation spectrum.

WORKING IT OUT *Energy of a Quantum*

We can get a feeling for the size of the energies of the atomic oscillators from our knowledge that red light has a frequency around 4.6×10^{14} Hz. Substituting these numbers into our relationship for the energy yields

$$E = hf = (6.63 \times 10^{-34}\,\mathrm{J \cdot s})(4.6 \times 10^{14}\,\mathrm{Hz}) = 3.05 \times 10^{-19}\,\mathrm{J}$$

Are You On the Bus?

Q: What is the size of the energy quantum for violet light with a frequency of 7×10^{14} Hz?

A: 4.64×10^{-19} J.

Planck's idea explained why the contribution of the shorter wavelengths was smaller than predicted by earlier theories. Shorter wavelengths mean higher frequencies and therefore more energetic quanta. Because there is only a certain amount of energy in the macroscopic object and this energy must be shared among the atomic oscillators, the high-energy quanta are less likely to occur.

This discreteness of energy was in stark disagreement with the universally held view that energy was a continuous quantity and any value was possible. At first thought you may want to challenge Planck's result. If this were true, it would seem that our everyday experiences would have demonstrated it. For example, the kinetic energy of a ball rolling down a hill appears to be continuous. As the ball gains kinetic energy, its speed appears to increase continuously rather than jerk from one allowed energy state to the next. There doesn't seem to be any restriction on the values of the kinetic energy.

We are, however, talking about very small packets of energy. A baseball falling off a table has energies in the neighborhood of 10^{19} times those of the quanta. These energy packets are so small that we don't notice their size in our everyday experiences. On our normal scale of events, energy seems continuous.

The Photoelectric Effect

Shortly before 1900, another phenomenon was discovered that connected electricity, light, and the structure of atoms. When light is shined on certain clean metallic objects, electrons are ejected from their surfaces (Figure 23-16). This effect is known as the **photoelectric effect**. The electrons come off with a range of energies up to a maximum energy, depending on the color of the light. If the light's intensity is changed, the rate of ejected electrons changes, but the maximum energy stays fixed.

Are You On the Bus?

Q: Does the name *photoelectric effect* make sense for this phenomenon?

A: Yes. The root *photo* is often associated with light; the most obvious example is photography. The *electric* root refers to the emitted electrons.

Planck | *Founder of Quantum Mechanics*

Max Planck personified science in the early 20th century. He fought a difficult battle against a technical problem in physics, and his victory ushered in a revolution that he neither wanted nor welcomed. He originated quantum mechanics; that is, he laid the foundation for modern physics and destroyed commonsense physical philosophy. He was awarded the Nobel Prize in physics, and his renown in the field was second only to that of Einstein.

Although he did not support Hitler, Planck stayed in Germany under the Hitler regime to provide an institutional basis for the rebirth of German science after the Third Reich. He lost a son in World War I, and a second was executed for plotting to assassinate Hitler. Late in the war, a bombing raid destroyed his priceless laboratory, correspondence, and manuscript collections. His was a noble and tragic life.

Planck's family background was filled with culture and learning. His father was a law professor at Kiel when Max, his sixth child, was born in 1858. He was gifted in many areas: mathematics, music, languages, history, and science. In his youth most friends would have predicted that he would become a humanist or a musician. He became a physicist because he wanted to solve problems that were intractable.

In his work with the radiation from heated bodies, he discovered that Maxwell's laws predicted a host of phenomena but not the equilibrium distribution Planck needed. His work in thermodynamics resulted in two constants (and constants are rare indeed in science), with h the most commonly encountered. As he expressed it in 1910, "The introduction of the quantum of action h into the theory should be done as conservatively as possible; that is, alterations should only be made that have shown themselves to be absolutely necessary."


Max Planck

AIP Niels Bohr Library, W. F. Meggers Collection

As the major figure in German physical science, Planck presided over great institutions and expenditures. He was a professor who led two dozen students through their doctorates. He served on an astounding 650 doctoral examination committees, and he championed, as only a powerful figure could, the careers of some great women and Jewish colleagues.

Max Planck lived long enough to see new science born from the ashes of the Third Reich. In 1946 the first institute to bear his name appeared in the British zone of occupation. At 89 he was the sole German to be invited to the 300th (belated) anniversary of Isaac Newton's birth. Planck died full of years, toil, pain, and honor in October 1947.

—Pierce C. Mullen, historian and author

Source: John L. Heilbron, *The Dilemmas of an Upright Man: Max Planck as Spokesman for German Science* (Berkeley: University of California Press, 1986).

The ideas about atoms and light prevalent at the end of the 19th century accounted for the possibility of such an effect. Because Planck's oscillators produced light, presumably light could jiggle the atoms. Light is energy, and when it is shined on a surface, some of this energy can be transferred to the electrons within the metal. If the electrons accumulate enough kinetic energy, some should be able to escape from the metal. But no theory could account for the details of the photoelectric process. For instance, if the light source is weak, the old theories predict that it should take an average of several hours before the first electron acquires enough energy to escape. On the other hand, experiments show that the average time is much less than 1 second.

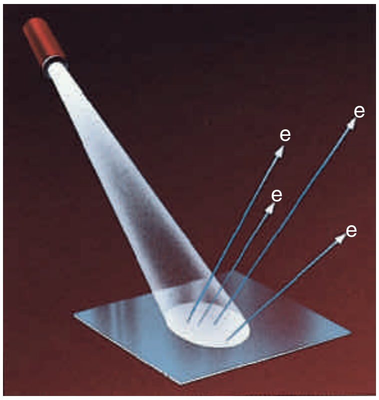


Figure 23-16 The photoelectric effect. Light shining on a clean metal surface causes electrons to be given off from the surface.

A range of kinetic energies made sense in the old theories—electrons bounced about within the metal accumulating energy until they approached the surface and escaped. There were bound to be differences in their energies. But a maximum value for the kinetic energy of the electrons was puzzling. The wave theory of light said that increasing the intensity of the light shining on the metal increases the kinetic energy of the electrons leaving the metal. However, experiments show that the intensity has no effect on the maximum kinetic energy. When the intensity is increased, the number of electrons leaving the metal increases, but their distribution of energy is unchanged.

One thing does change the maximum kinetic energy. If the frequency of the incident light increases, the maximum kinetic energy of the emitted electrons increases. This result was totally unexpected. If light is a wave, the amplitude of the wave should govern the amount of energy transferred to the electron. Frequency (color) should have no effect.

The established ideas about light were inadequate to explain the photoelectric effect. The conflict was resolved by Albert Einstein. In yet another outstanding paper written in 1905, he claimed that the photoelectric effect could be explained by extending the work of Planck. Einstein said that Planck didn't go far enough: not only are the atomic oscillators quantized, but the experimental results could be explained only if light itself is also quantized! Light exists as bundles of energy called **photons**. The energy of a photon is given by Planck's relationship:

energy of a photon ▶

$$E = hf$$

Although it was universally agreed that light was a wave phenomenon, Einstein said that photons acted like particles, little bundles of energy.

Einstein was able to explain all the observations of the photoelectric effect. The ejection of an electron occurs when a photon hits an electron. A photon gives up its *entire* energy to a single electron. The electrons that escape have different amounts of energy, depending on how much they lose in the material before reaching the surface. Also, the fact that the first photon to strike the surface can eject an electron easily accounts for the short time between turning on the light and the appearance of the first electron. A maximum kinetic energy for the ejected electrons is now easy to explain. A photon cannot give an electron any more energy than it has, and the chances of an electron getting hit twice before it leaves the metal are extremely small.

Are You On the Bus?

Q: How does this model explain the change in the maximum electron energy when the color of the light changes?

A: This change occurs because the photon's color and energy depend on the frequency: the higher the frequency, the more energy the photon can give to the electron.

Einstein's model suggests a different interpretation of intensity. Because all photons of a given frequency have the same energy, an increase in the intensity of the light is due to an increase in the number of photons, not the energy of each one. Therefore, the model correctly predicts that more electrons will be ejected by the increased number of photons but their maximum energy will be the same.

Einstein's success introduced a severe conflict into the physics world view. Diffraction and interference effects (Chapter 19) required that light behave as a wave; the photoelectric effect required that light behave as particles. How can light be both? These two ideas are mutually contradictory. This is not like saying that someone is fat and tall, but rather like saying that someone is short and tall. The two descriptions are incompatible. This conflict took some time to resolve. We will examine this important development in the next chapter.

Meanwhile, Einstein's work inspired a new, improved model of the atom.

Bohr's Model

The model of the atom proposed by Rutherford had several severe problems. It didn't account for the periodicity of the elements, it was unable to give any clue about the origins of the spectral lines, and it implied that atoms were extremely unstable. In 1913 Danish theoretician Niels Bohr proposed a new model incorporating Planck's discrete energies and Einstein's photon into Rutherford's model.

Scientists are always using models when attempting to understand nature. The trick is to understand the limitations of the models. Bohr challenged the Rutherford model, stating that it was a mistake to assume that the atom is just a scaled-down solar system with the same rules; electrons do not behave like miniature planets. Bohr proposed a new model for the hydrogen atom based on three assumptions, or postulates.

First, he proposed that the angular momentum of the electron is quantized. Only angular momenta L equal to whole-number multiples of a smallest angular momentum are allowed. This smallest angular momentum is equal to Planck's constant h divided by 2π. Bohr's first postulate can be written

◀ Bohr's first postulate

$$L_n = n\frac{h}{2\pi}$$

◀ allowed angular momenta

where n is a positive integer (whole number) known as a **quantum number**.

In classical physics the angular momentum L of a particle of mass m traveling at a speed v in a circular orbit of radius r is given by $L = mvr$ (Chapter 8). Therefore, the restriction on the possible values of the angular momentum puts restrictions on the possible radii and speeds. Bohr showed that this restriction on the electron's angular momentum means that the only possible orbits are those for which the radii obey the relationship

$$r_n = n^2 r_1$$

◀ allowed radii

where r_1 is the smallest radius and n is the same integer that appears in the first postulate. This means that the electrons cannot occupy orbits of arbitrary size but only a certain discrete set of allowable orbits, as illustrated in Figure 23-17. The numerical value of r_1 is 5.29×10^{-11} meter.

There is also a definite speed associated with each possible orbit. This means that the kinetic energies are also quantized. Because the value of the electric potential energy depends on distance, the quantized radii mean that the potential energy also has discrete values. Therefore, there is a discrete set of allowable energies for the electron.

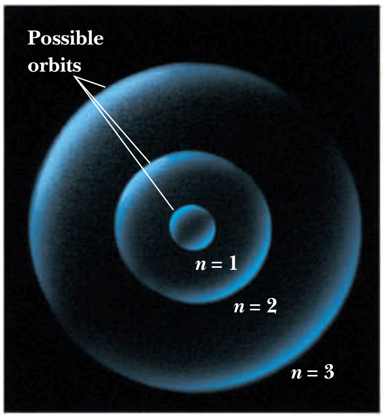


Figure 23-17 Electrons can only occupy certain orbits. These are designated by the quantum number n.

Q: Would you expect the energy of the electron to increase or decrease for larger orbits?

A: Because the electric force is analogous to the gravitational force, we can think about putting satellites into orbit around Earth. Higher orbits require bigger rockets and therefore more energy. Therefore, larger orbits should have more energy.

Bohr's second postulate states that an electron does not radiate when it is in one of the allowed orbits. This statement is contrary to the observation that accelerated charges radiate energy at a frequency equal to their frequency of vibration or revolution (Chapter 22). Bohr challenged the assumption that this property is also true in the atomic domain. Radically breaking away from what was accepted, Bohr said that an electron has a constant energy when it is in an allowed orbit.

◀ Bohr's second postulate

But atoms produce light. If orbiting electrons don't radiate light, how does an atom emit light? Bohr's third postulate answered this question: a single photon is emitted whenever an electron jumps down from one orbit to another. Energy conservation demands that the photon have an energy equal to the

◀ Bohr's third postulate

difference in the energies of the two levels. It further demands that jumps up to higher levels can occur only when photons are absorbed. The electron is normally in the smallest orbit, the one with the lowest energy. If the atom absorbs a photon, the energy of the photon goes into raising the electron into a higher orbit (Figure 23-18). Furthermore, it is not possible for the atom to absorb part of the energy of the photon. It is all or nothing.

The electron in the higher orbit is unstable and eventually returns to the innermost orbit, or ground state. If the electron returns to the ground state in a single jump, it emits a new photon with an energy equal to that of the original photon (Figure 23-19). Again, this is different from our common experience. When a ball loses its mechanical energy, its temperature rises—the energy is transferred to its internal structure. As far as we know, an electron has no internal structure. Therefore, it loses its energy by creating a photon.

Occasionally, the phrase "a quantum leap" is used to imply a big jump. But the jump needn't be big. There is nothing big about the quantum jumps we are discussing. A quantum leap simply refers to a change from one discrete value to another.

Ordinarily, an amount of energy is stated in joules, the standard energy unit. However, this unit is extremely large for work on the atomic level, and a smaller unit is customarily used. The **electron volt** (eV) is equal to the kinetic energy acquired by an electron falling through a potential difference of 1 volt. One electron volt is equal to 1.6×10^{-19} joule. It requires 13.6 electron volts to remove an electron from the ground state of the hydrogen atom.

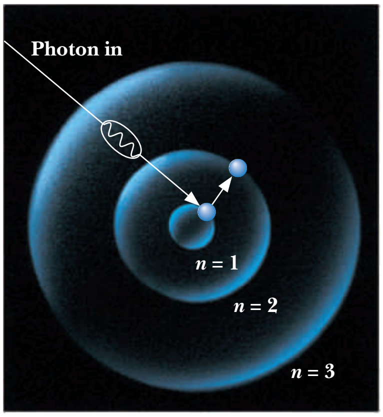


Figure 23-18 An electron can absorb a photon and jump to a higher-energy orbit.

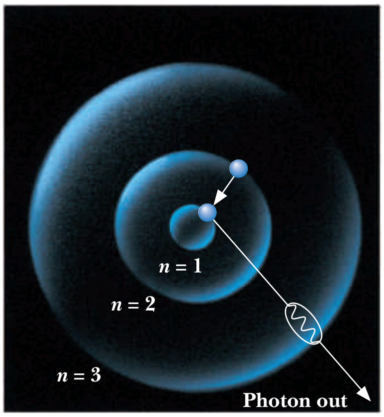


Figure 23-19 When an electron jumps to a lower-energy orbit, it emits a photon.

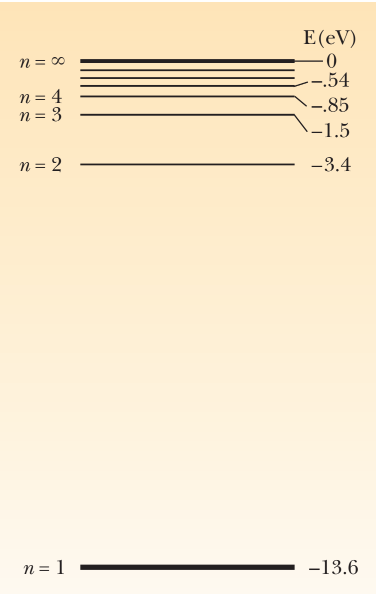


Figure 23-20 The energy-level diagram for the hydrogen atom.

Atomic Spectra Explained

Bohr's explanation accounted for the existence of spectral lines, and his numbers even agreed with the wavelengths observed in the hydrogen spectrum. To illustrate Bohr's model, we draw energy-level diagrams like the one in Figure 23-20. The ground state has the lowest energy and appears in the lowest position. Higher-energy states appear above the ground state and are spaced to indicate the relative energy differences between the states.

To see how Bohr's model gives the spectral lines, consider the energy-level diagram for the hypothetical atom shown in Figure 23-21(a). Suppose the electron has been excited into the $n = 4$ energy level. There are several ways that it can return to the ground state. If it jumps directly to the ground state, it emits the largest-energy photon. We will assume it appears in the blue part of the emission spectrum in Figure 23-21(b). This line is marked $4 \rightarrow 1$ on the spectrum, indicating that the jump was from the $n = 4$ level to the $n = 1$ level.

The electron could also return to the ground state by making a set of smaller jumps. It could go from the $n = 4$ level to the $n = 2$ level and then from the $n = 2$ level to the ground level. These spectral lines are marked $4 \rightarrow 2$ and $2 \rightarrow 1$. The energies of these photons are smaller, so their lines occur at the red end of the spectrum. The lines corresponding to the other possible jumps are also shown in Figure 23-21(b).

Are You On the Bus?

Q: How does the total energy of the photons that produce the $4 \rightarrow 2$ and $2 \rightarrow 1$ lines compare with the photon that produces the $4 \rightarrow 1$ line?

A: Conservation of energy requires that the two photons have the same total energy as the single photon.

A single photon is not energetic enough for us to see. In an actual situation, a gas contains a huge number of excited atoms. Each electron takes only

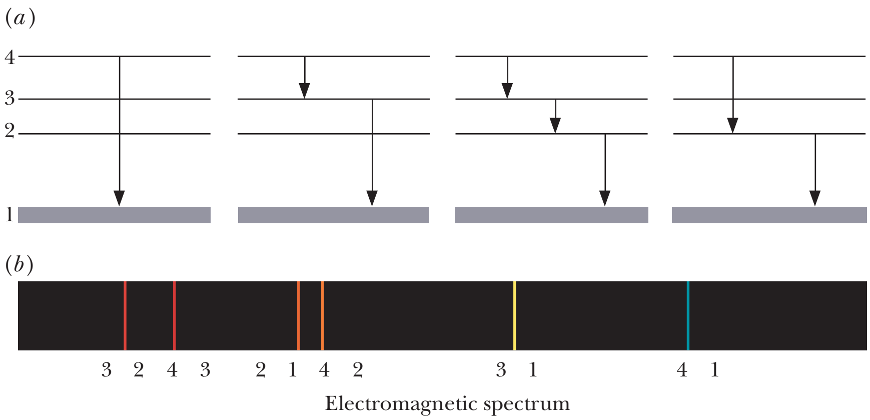


Figure 23-21 (a) Four possible ways for the electron in a hypothetical atom to drop from the $n = 4$ level to the $n = 1$ level. (b) The emission spectrum produced by these jumps.

one of the paths we have described in returning to the ground state. The total effect of all the individual jumps is the atomic emission spectrum we observe.

Bohr's scheme also explains the absorption spectrum. As we discussed earlier, the absorption spectrum is obtained when white light passes through a cool gas before a prism or a diffraction grating disperses it. In this case, selected photons from the beam of white light are absorbed and later reemitted. Because the reemitted photons are distributed in all directions, the intensities of these photons are reduced in the original direction of the beam. This removal of the photons from the beam leaves dark lines in the continuous spectrum.

The solution to the mystery of the missing lines in the absorption spectrum is easy using Bohr's model. For an absorption line to occur, there must be electrons in the lower level. Then they can be kicked up one or more levels by absorbing photons of the correct energy. Because almost all electrons in the atoms of the gas occupy the ground state, only the lines that correspond to jumps from this state show up in the spectrum. Jumps up from higher levels are extremely unlikely because electrons excited to a higher level typically remain there for less than a millionth of a second. Thus, there are fewer lines in the absorption spectrum (Figure 23-22) than in the emission spectrum, in agreement with the observations.

FLAWED REASONING

A large glass jar filled with helium gas is placed on the table and a hot, glowing chunk of steel is placed behind it. (*Caution:* This should only be done by professionals.) Joshua and Darcy are discussing what they would see if they looked through a diffraction grating at the light passing through the glass jar as the steel cools:

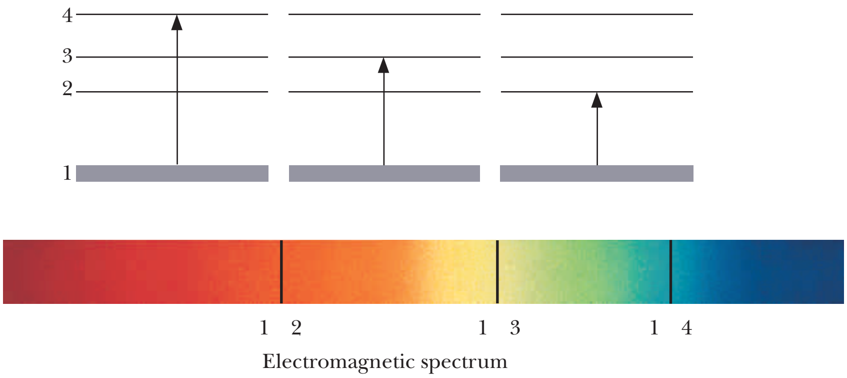
Joshua: "We should see the absorption spectrum for helium. The helium in the jar isn't changing, so the spectrum should remain constant as the steel cools."

Darcy: "But we learned that the spectrum for hot, glowing objects depends on temperature. As the steel cools, the entire spectrum, including the absorption lines, should move to longer wavelengths, a shift from blue toward red."

What will they see?

ANSWER There are two pieces to this puzzle. If they look directly at the piece of hot steel through the grating, they see a colorful rainbow spectrum. As the steel cools, the light will get dimmer, with the blue end of the spectrum fading the fastest. When the light passes through the jar of helium, certain wavelengths are removed by absorption, leaving dark lines in the rainbow pattern. The wavelengths that are absorbed by the helium do not change, so the absorption spectrum remains constant as the steel cools. However, the lines disappear as the colors dim because the photons of the required energy are no longer present in the light.

Figure 23-22 The absorption spectrum for the hypothetical atom in Figure 23-21.



The Periodic Table

"The Periodic Table"

Bohr's model helped unravel the mystery of the periodic properties of the chemical elements, a major unresolved problem for several decades. The table displaying the repeating chemical properties had grown considerably since Mendeleev's discovery and looked much like the modern one shown on the inside front cover of this text. About the time Bohr proposed his model, it became widely accepted that if the elements were numbered in the order of increasing atomic masses, their numbers would correspond to the number of electrons in the neutral atoms.

Bohr's theory gave a fairly complete picture of hydrogen (H): one electron orbiting a nucleus with one unit of positive charge (Figure 23-23). However, it could not explain the details of the spectrum of the next element, helium (He), because of the effects of the mutual repulsion of the two electrons. But the theory was successful for the helium atom with one electron removed (the He^+ ion). Bohr correctly assumed that the helium atom has two electrons in the lowest energy level. Because the electrons presumably have separate orbits, the collection of orbits of the same size was called a **shell**.

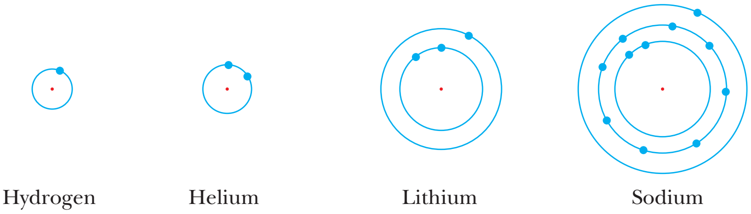
The next element, lithium (Li), has spectral lines similar to those of hydrogen. This similarity could be explained if lithium had one electron orbiting a nucleus with three units of positive charge and an inner shell of two electrons. The two inner electrons partially shield the nucleus from the outer electron, so the outer electron "sees" a net charge of approximately +1.

How many electrons can be in the second shell? The clue is found with the next element that has properties like lithium—sodium (Na), element 11. Sodium must have 1 electron outside two shells. Because the first shell holds 2, the second shell holds 8. The next lithium-like element is potassium (K), with 19 electrons. This time we have 1 electron orbiting 18 inner electrons: one shell of 2 and two shells of 8. And so on for succeeding elements.

Q: How many electrons are in the fourth shell?

A: The next lithium-like element is rubidium (Rb), with 37 electrons. Therefore, the 36 inner electrons must be arranged in shells with 2, 8, 8, and 18 electrons.

Figure 23-23 The electron shell structure for hydrogen, helium, lithium, and sodium.



Bohr | *Creating the Atomic World*

On January 16, 1939, the *Drottingholm* carried Niels Bohr into New York harbor. His arrival was eagerly awaited by a small group of physicists, among them several who had fled Hitler's spreading power. Bohr's hosts knew that he would bring the latest news from a Europe rapidly drifting toward war. Most important, he would relay the latest information on German science. He would tell them about work on the atom.

Niels Bohr is one of the best-known physicists of the 20th century. His pioneering work on atomic structure earned the Nobel Prize in 1922—the year after his friend Einstein received his. Bohr was comfortable with the commonsense violations of quantum physics and uncertainty. He believed in an underlying order, but it was a good deal messier than that which Einstein could accept. For Bohr, God could play dice because probability ruled the universe. Atomic physics, however, was no gamble. It was the future of humankind.

Niels Hendrik Bohr was born in the heart of Copenhagen in 1885. His father was a physiologist, and Bohr was reared in the embrace of a close professional family. He received his doctorate from the University of Copenhagen and then traveled to Cambridge to study with J. J. Thomson—the first Cavendish Professor. Bohr then moved on to the industrial city of Manchester to study with Ernest Rutherford, a pioneer in radiation studies. Armed with considerable laboratory and theoretical experience, Bohr returned to the University of Copenhagen as professor of physics. His work received a high honor when the Carlsberg Breweries foundation constructed a new building for theoretical physics (1921) and a House of Honor (1932) for the most distinguished Dane—Niels Bohr.

Bohr was naturally gregarious, and on his accession to the university professorship in Copenhagen he recognized that his small country would be a natural gathering place for scientists who had been so alienated from one another in World War I. Young American men and women of science also joined this cosmopolitan and vibrant society as American science came of age. But an old friend, a Jewish physicist of considerable talent named Lise Meitner, visited Bohr on her way to exile in Sweden and gave him the information on the Berlin experiments of Christmastide 1938: the uranium atom had released fission by-products. Great energy had been released. This was the portentous news Bohr brought to New York that cold January day in 1939.

Bohr remained in Copenhagen until it became too dangerous, and then he and his wife fled in September 1943 to Sweden, and a month later to England. British and American scientists of the highest rank wanted access to him and his knowledge of the German nuclear effort. Bohr worked assiduously, counseling British and American officials on postwar nuclear policy. He was convinced that there was no secret to nuclear energy and that developed industrial societies could acquire that capability if they desired. His efforts were recognized in the Ford Motor Company's Atoms for Peace Award—a part of President Eisenhower's policy on atomic energy.

Niels Bohr

Niels Bohr Archive, Courtesy of AIP Emilio Segre Visual Archives

Niels Bohr was first and foremost a scientist, but he was a committed and engaged human being. More clearly than most, he saw that science has consequences for society and that scientists should accept the task of educating their publics about those consequences. Neither President Franklin Roosevelt nor Prime Minister Winston Churchill could fathom Bohr's concern; later world leaders did recognize his prescience and his humanity.

Bohr continues to fascinate us. In 1998 British playwright and author Michael Frayn presented a popular and controversial drama, *Copenhagen*. In 2000 it was a hit on the New York stage. The title encapsulates a hypothetical meeting in Copenhagen between Bohr and his former student Werner Heisenberg in 1941. Bohr knew that an Allied program to develop atomic energy for military purposes was under way in Britain and the United States. Many leading scientists in that program were former associates and students. Bohr also recognized Heisenberg's leadership in the nascent Nazi bomb project. The two had been close, almost like father and son—certainly like mentor and pupil. Germany's destruction of European Jewry was also known. It was a meeting fraught with tension, memories, and cutting-edge science. The drama in *Copenhagen* takes place with these two protagonists and a third, more anti-German participant: Bohr's wife, Margrethe.

Did Heisenberg come to renew this old friendship with Bohr simply to spy on the Allied program? Did he come to assure his old friend that he would do his best as head of the atomic research program in Germany to ensure that the program would fail? Did he come simply to secure a blessing from the most civilized man in the world—the man whose word could confer moral comfort? In a series of flashbacks and references to scientific work in physics over the previous two decades, the actors build their characters and enlarge the audience's understanding of the colossal stakes in this nuclear game. "Bohr, I have to know! I'm the one who has to decide! If the Allies are building a bomb, what am I choosing for my country?" Does a physicist have a moral right to create a weapon of such vast destructive power? Neither man can answer sufficiently to satisfy the other. Margrethe passes the final judgment: "He is one of them." Scientists have become the creator and destroyer of worlds.

—Pierce C. Mullen, historian and author

Sources: Ruth Moore, *Niels Bohr* (New York: Knopf, 1966; MIT paperback edition, 1985); *Physics Today* (October 1985); R. Harre, *Scientific Thought 1900–1960: A Selective Survey* (Oxford: Oxford University Press, 1969); Michael Frayn, *Copenhagen* (New York: Random House–Anchor Books, 2000).

In this scheme the chemical properties of atoms are determined by the electrons in their outermost shells. This idea can be extended to other vertical columns in the periodic table. The outer shells of elements in the right-hand column (group 8) are completely filled. These elements do not react chemically with other elements and rarely form molecules with themselves. They are inert. They are also called the *noble elements* because they don't usually mix with the common elements. The properties of group-8 elements led to the idea that the most stable atoms are those with filled outer shells.

The elements in group 7 are missing one electron in the outer shell and, like the elements in group 1, are chemically very active. They become much more stable by gaining an electron to fill this shell. Therefore, they often appear as negative ions. On the other hand, the elements in group 1 are more stable if they give up the single electron in the outer shell to become positive ions. Therefore, group-1 atoms readily combine with group-7 atoms. The atom from group 1 gives up an electron to that from group 7, and these two charged ions attract each other. Common table salt—sodium chloride—is such a combination. As soon as the two atoms combine, their individual properties—reactive metal and poisonous gas—disappear because the outer structure has changed.

Q: What other salts besides sodium chloride would you expect to find in nature?

A: Most of the combinations of group-1 and group-7 elements should occur in nature. Therefore, we expect to find such salts as sodium fluoride, sodium bromide, potassium fluoride, potassium chloride, and rubidium chloride.

Atoms can also share electrons. Oxygen (O) is missing two electrons in the outer shell, and hydrogen (H) either is missing one or has an extra. They can both have "filled" outer shells if they share electrons. Two hydrogens combine with one oxygen to form the stable water molecule H_2O.

These ideas were a great accomplishment for the Bohr model of the atom. Finally, there was a simple scheme for explaining the large collection of properties of the elements. The model provided a *physical* theory for understanding the *chemical* properties of the elements.

X Rays

Burndy Library Collection, The Huntington Library, San Marino, California

X ray of a hand hit by pellets.

The cathode-ray experiments that we discussed earlier in this chapter led to another important discovery that had an impact on the new atomic theory. In 1895 German scientist Wilhelm Roentgen saw a glow coming from a piece of paper on a bench near a working cathode-ray tube. The paper had been coated with a fluorescent substance. Fluorescence was known to result from exposure to ultraviolet light, but no ultraviolet light was present. The glow persisted even when the paper was several meters from the tube, and the tube was covered with black paper!

Roentgen conducted numerous experiments demonstrating that although these new rays were associated with cathode rays, they were different. Cathode rays could penetrate no more than a few centimeters of air, but the new rays could penetrate several meters of air or even thin samples of wood, rubber, or metal. Using electric and magnetic fields, Roentgen could not deflect these rays, but he did find that if he deflected the cathode rays, the rays came from the new spot where the cathode rays struck the glass walls. The new rays were also shown to be emitted by many different materials. Roentgen named them **X rays** because of their unknown nature.

The discovery of X rays quickly created public excitement because people could see their bones and internal organs. This discovery was quickly put to use by the medical profession. In 1901 Roentgen received the first Nobel Prize in physics. We now know that X rays are high-frequency electromagnetic radiation created when the electrons in the cathode-ray tube are slowed down as they crash into the metal target inside the tube.

A typical X-ray spectrum (Figure 23-24) consists of two parts: a continuous spectrum produced by the rapid slowing of the bombarding electrons and a set of discrete spikes. These spikes are from X-ray photons emitted by the atoms that electrons are crashing into and therefore carry information about the element. They occur when a bombarding electron knocks an atomic electron from a lower energy level completely out of the atom. An electron in a higher energy level fills the vacancy. When this electron falls into the vacated level, an X-ray photon is emitted. The energies of these X rays can be used to calculate the energy differences of the atom's inner electron orbits, which are characteristic of the element.

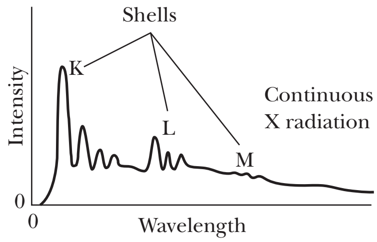


Figure 23-24 A typical X-ray spectrum contains a continuous background and characteristic lines from the inner atomic levels.

Shortly after Bohr proposed his model of the atom, Henry Moseley, a British physicist, used Bohr's model and X rays to resolve some discrepancies in the periodic table. In several cases, the order of the elements determined by their atomic masses disagreed with their order determined by their chemical properties. For instance, according to atomic masses, cobalt should come after nickel in the periodic table, yet its properties suggested that it should precede nickel.

Bohr's model predicted that the energies of these characteristic X rays would increase as the number of electrons in the atom increased. Moseley bombarded various elements with electrons and studied the X rays that were given off. His experimental results agreed with Bohr's theoretical prediction. In almost all cases, the results matched the order obtained from the atomic masses; however, they showed that cobalt should come before nickel. As a result of this work, we now know that the correct ordering of the elements is by **atomic number** (the number of electrons in a neutral atom) and not by atomic mass.

Summary

When an electric current passes through a gas, it gives off a characteristic emission spectrum. The absorption spectrum is obtained by passing white light through a cool gas, producing dark lines in the continuous, rainbow spectrum. The emission spectrum has all the lines in the absorption spectrum plus many additional ones.

Cathode rays are electrons with a charge-to-mass ratio about 1800 times that for hydrogen ions. Electrons have an electric charge of 1.6×10^{-19} coulomb and a mass of 9.11×10^{-31} kilogram. The cathode-ray experiments also led to the discovery of X rays, a form of high-frequency electromagnetic radiation.

Rutherford used alpha particles to show that the positive charge was concentrated in a nucleus with a diameter $\frac{1}{100{,}000}$ the size of the atom. Thus, Rutherford's "solar system" model of the atom is almost entirely empty space. His model failed to explain the chemical periodicity and details of the spectral lines.

All objects emit electromagnetic radiation. The spectrum of radiation emitted through a small hole in a heated, hollow block is the same for all materials at the same temperature. The frequencies are not equally bright, and the maximum of the spectrum shifts toward the blue as the temperature of the cavity increases. The spectrum drops to zero on both the high-frequency (small-wavelength) and low-frequency (long-wavelength) sides.

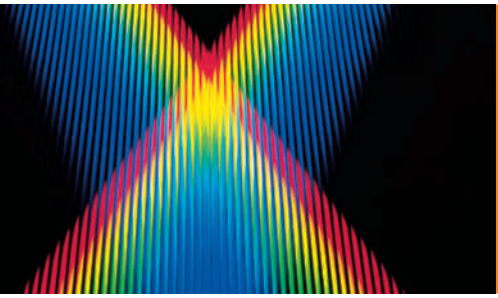
Planck's analysis of the electromagnetic spectrum emitted by hot cavities provided the first clues that phenomena on the atomic level are quantized.

The energy E of the quanta depends on Planck's constant h and the frequency f: $E = hf$.

Planck's idea was expanded to include the electromagnetic radiation by Einstein's efforts to explain the photoelectric effect. When light is shined on certain clean metallic surfaces, electrons are ejected with a range of kinetic energies up to a maximum energy, depending on the color of the light. If the light's intensity is changed, the rate of ejecting electrons changes, but the maximum kinetic energy stays fixed. This is explained by assuming that light is also quantized, existing as bundles of energy called photons. The energy of a photon is given by Planck's relationship, $E = hf$. A photon gives its entire energy to one electron in the metal.

Bohr's model for the hydrogen atom incorporated Planck's discrete energies and Einstein's photons into Rutherford's model. It was based on three postulates: (1) Allowed electron orbits are those in which the angular momentum is an integral multiple of a smallest possible value. (2) An electron in an allowed orbit does not radiate. (3) When an electron jumps from one orbit to another, it emits or absorbs a photon whose energy is equal to the difference in the energies of the two orbits.

The Bohr model was successful in accounting for many atomic observations, especially the emission and absorption spectra for hydrogen and the ordering of the chemical elements.



CHAPTER 23 *Revisited*

The light emitted by an atom is created when an atomic electron moves from one energy level to a lower one. The size of the jump determines the energy of the photon and—via Planck's relationship—the color of the emitted light. Therefore, the colors provide us with information about the energy levels of the atom's electronic structure.

Key Terms

absorption spectrum The collection of wavelengths missing from a continuous distribution of wavelength because of the absorption of certain wavelengths by the atoms or molecules in a gas.

alpha particle The nucleus of the helium atom.

atomic number The number of electrons in the neutral atom of an element. This number also gives the order of the elements in the periodic table.

cathode ray An electron emitted from the negative electrode in an evacuated tube.

electron The basic constituent of atoms that has a negative charge.

electron volt A unit of energy equal to the kinetic energy acquired by an electron or proton falling through an electric potential difference of 1 volt. The electron volt is equal to 1.6×10^{-19} joule.

emission spectrum The collection of discrete wavelengths emitted by atoms that have been excited by heating or electric currents.

ion An atom with missing or extra electrons.

nucleus The central part of an atom containing the positive charges.

photoelectric effect The ejection of electrons from metallic surfaces by illuminating light.

photon A particle of light. The energy of a photon is given by the relationship $E = hf$, where f is the frequency of the light and h is Planck's constant.

quantum (pl., *quanta*) The smallest unit of a discrete property. For instance, the quantum of charge is the charge on the proton.

quantum number A number giving the value of a quantized quantity. For instance, a quantum number specifies the angular momentum of an electron in an atom.

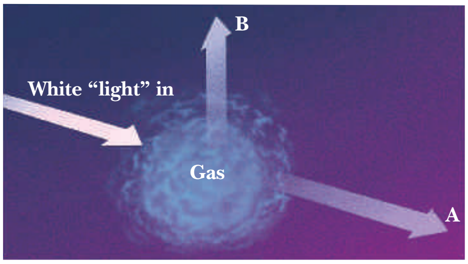
shell A collection of electrons in an atom that have approximately the same energy.

X ray A high-energy photon with a range of frequencies in the electromagnetic spectrum lying between the ultraviolet and the gamma rays.

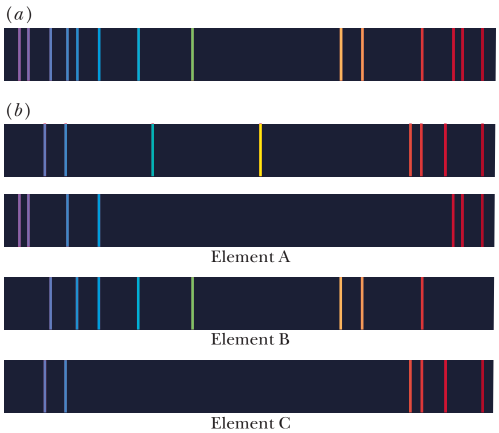
Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign **Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.**

Conceptual Questions

1. Today, we think of the periodic table as being arranged in order of increasing proton (or electron) number. Why did Mendeleev not use this approach?
2. If Mendeleev was ordering the elements according to their masses, why did he not produce a table with only one row?
3. What element in Mendeleev's periodic table is most similar to silicon (Si)?
4. What elements would you expect to have chemical properties similar to chlorine (Cl)?
5. Why are the spectral lines for elements sometimes called "atomic fingerprints"?
6. How could you determine whether there is oxygen in the Sun?
7. Would you obtain an emission or an absorption spectrum at location A in the setup shown in the following figure?

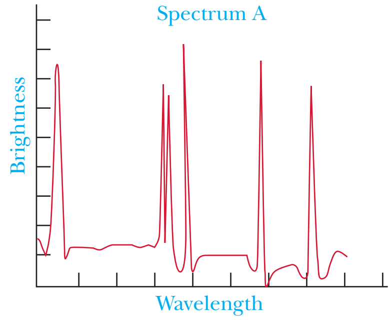


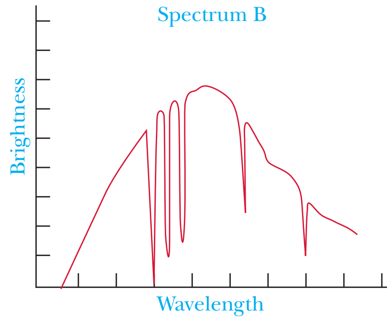
8. Would you obtain an emission or an absorption spectrum at location B in the setup shown in the preceding figure?
9. The emission spectra shown in the following figure were all obtained with the same apparatus. What elements can you identify in sample (a)? Are there any that you cannot identify?



Questions 9 and 10.

10. What element(s) can you identify in sample (b) of the preceding figure? Are there any that you cannot identify?
11. How does the number of lines in the absorption spectrum for an element compare with the number in the emission spectrum?
12. What are the differences between an emission spectrum and an absorption spectrum?
13. When your authors were students, their textbooks did not have color. Could the spectra in Figure 23-3 still be used to identify atoms if they were in black and white? Explain.
14. Two graphs of brightness versus wavelength are shown in the following figure. Identify which is an absorption spectrum and which is an emission spectrum.





15. To which of the brightness-versus-wavelength graphs in Question 14 does the line spectrum in the figure correspond?

16. Sketch the brightness-versus-wavelength graph for the hydrogen spectrum shown in Figure 23-3.
17. Suppose you were a 19th-century scientist who had just discovered a new phenomenon known as *zeta rays* (yes, we're making this up). What experiment could you

perform to determine whether zeta rays were charged particles or an electromagnetic wave? Could this experiment distinguish between neutral particles and an electromagnetic wave?

18. Imagine that you determined that the zeta rays from Question 17 were charged particles. How would you determine the sign of the charge?

19. In the Millikan oil-drop apparatus shown in Figure 23-8, an electric field provides a force that balances the gravitational force on charged oil drops. Millikan found that he needed the electric field to point down toward the floor. Was the net charge on the oil drops a result of an excess or a deficit of electrons?

20. Why was it not necessary for Millikan to use oil drops with an excess of only one electron to determine the charge of a single electron?

21. Millikan's oil-drop experiment was used to determine the charge on a single electron. Why should Millikan also get credit for determining the electron's mass?

22. What do we mean when we say that a physical quantity is quantized?

23. Why did Thomson feel that electrons were pieces of atoms rather than atoms of a new element?

24. How does Rutherford's model of an atom explain why most alpha particles pass right through a thin gold foil? How does it account for why some alpha particles are scattered backward?

25. Rutherford's model predicted that atoms should be unstable; the electrons should spiral into the nucleus in extremely short times. What caused this instability in Rutherford's model?

26. Rutherford's model provided an explanation for the emission of light from atoms. What was this mechanism and why was it unsatisfactory?

27. Why can the curves for the intensities of the colors emitted by hot solid objects not serve as "atomic fingerprints" of the materials?

28. If all objects emit radiation, why don't we see most of them in the dark?

29. As you move to the right along the horizontal axis of Figure 23-14, is the frequency increasing or decreasing? Explain your reasoning.

30. For an object at a temperature of 8000 K, use Figure 23-14 to determine whether the light intensity is greater for light in the ultraviolet or in the infrared.

31. You measure the brightness of two different hot objects, first with a blue filter and then with a red filter. You find that object A has a brightness of 25 in the blue and 20 in the red. Object B has a brightness of 12 in the blue and 3 in the red. The brightness units are arbitrary but the same for all measurements. Which is the hotter of the two objects?

32. The curves in Figure 23-14 show the intensities of the various wavelengths emitted by an object at three different temperatures. The region corresponding to visible light is indicated. How would the color of the object at 8000 K compare to the color of the object at 4000 K?

33. Why do astronomers often use the terms *color* and *temperature* interchangeably when referring to stars?

Questions 33 and 34.

34. Why are blue stars thought to be hotter than red stars?

35. What assumptions did Planck make that enabled him to obtain the correct curve for the spectrum of light emitted by a hot object?

36. What assumptions did Einstein make that enabled him to account for the experimental observations of the photoelectric effect?

37. What property of the emitted photoelectrons depends on the intensity of the incident light?

38. What property of the emitted photoelectrons depends on the frequency of the incident light?

39. If a metal surface is illuminated by light at a single frequency, why don't all the photoelectrons have the same kinetic energy when they leave the metal's surface?

40. How is it possible that ultraviolet light can cause sunburn but no amount of visible light will?

41. You find that if you shine ultraviolet light on a negatively charged electroscope, the electroscope discharges even if the intensity of the light is low. Red light, however, will not discharge the electroscope even at high intensities. How do you account for this?

42. You find that if you shine ultraviolet light on a negatively charged electroscope, the electroscope discharges. Can you discharge a positively charged electroscope the same way? Why or why not?

43. What are the three assumptions of Bohr's model of the atom?

44. Why did Bohr assume that the electrons do not radiate when they are in the allowed orbits?

45. An electron in the $n = 3$ energy level can drop to the ground state by emitting a single photon or a pair of photons. How does the total energy of the pair compare with the energy of the single photon?

46. If electrons in hydrogen atoms are excited to the fourth Bohr orbit, how many different frequencies of light may be emitted?

47. How can the spectrum of hydrogen contain so many spectral lines when the hydrogen atom only has one electron?

48. What determines the frequency of a photon emitted by an atom?

49. Why does the spectrum of lithium (element 3) resemble that of hydrogen?

50. How does Bohr's model explain that there are more lines in the emission spectrum than in the absorption spectrum?

51. How many electrons would you expect to find in each shell for chlorine (Cl)?

52. Radon (element 86) is a gas. Would you expect the molecules of radon to consist of a single atom or a pair of atoms? Why?

53. Sodium does not naturally occur as a free element. Why?

54. What effective charge do the outer electrons in aluminum "see"? (Aluminum is element 13.)

55. What type of electromagnetic wave has a wavelength about the size of an atom? (The electromagnetic spectrum is given in Figure 22-26.)

56. Are X rays deflected by electric or magnetic fields? Explain.

57. How does an X ray differ from a photon of visible light?

58. Why would you not expect an X-ray photon to be emitted every time an inner electron is removed from an atom?

Exercises

59. What is the charge-to-mass ratio for a cathode ray?

60. What is the charge-to-mass ratio for a hydrogen ion (an isolated proton)?

61. Given that the radius of a hydrogen atom is 5.29×10^{-11} m and that its mass is 1.682×10^{-27} kg, what is the average density of a hydrogen atom? How does it compare with the density of water?

62. What is the average density of the hydrogen ion (an isolated proton) given that its radius is 1.2×10^{-15} m and that its mass is 1.673×10^{-27} kg? It is interesting to note that such densities also occur in neutron stars.

63. If you were helping your younger brother build a scale model of an atom for a science fair and wanted it to fit in a box 1 m on each side, how big would the nucleus be?

64. A student decides to build a physical model of an atom. If the nucleus is a rubber ball with a diameter of 1 cm, how far away would the outer electrons be?

65. What is the energy of a photon of orange light with a frequency of 5.0×10^{14} Hz?

66. What is the energy of the most energetic photon of visible light?

67. A photon of green light has energy 3.6×10^{-19} J. What is its frequency?

68. An X-ray photon has energy 1.5×10^{-15} J. What is its frequency?

69. A microwave photon has an energy of 2×10^{-23} J. What is its wavelength?

70. A photon of yellow light has a wavelength of 6.0×10^{-7} m. What is its energy?

71. What is the angular momentum of an electron in the ground state of hydrogen?

72. What is the angular momentum of an electron in the $n = 4$ level of hydrogen?

73. What is the radius of the $n = 4$ level of hydrogen?

74. What is the quantum number of the orbit in the hydrogen atom that has 36 times the radius of the smallest orbit?

75. What is the frequency of a photon of energy 3 eV?

76. What is the energy, in electron volts, of a yellow photon of wavelength 6.0×10^{-7} m?

77. According to Figure 23-20, it requires a photon with an energy of 10.2 eV to excite an electron from the $n = 1$ energy level to the $n = 2$ energy level. What is the frequency of this photon? Does it lie in, above, or below the visible range?

78. When a proton captures an electron, a photon with an energy of 13.6 eV is emitted. What is the frequency of this photon? Does it lie in, above, or below the visible range?

79. What is the ratio of the volumes of the hydrogen atom in the $n = 1$ state compared with those in the $n = 2$ state?

80. The diameter of the hydrogen atom is 10^{-10} m. In Bohr's model this means that the electron travels a distance of about 3×10^{-10} m in orbiting the atom once. If the orbital frequency is 7×10^{15} Hz, what is the speed of the electron? How does this speed compare with that of light?

81. What difference in energy between two atomic levels is required to produce an X ray with a frequency of 2×10^{18} Hz?

82. What is the frequency of the X ray that is emitted when an electron drops down to the ground state from an excited state with 1000 eV more energy?

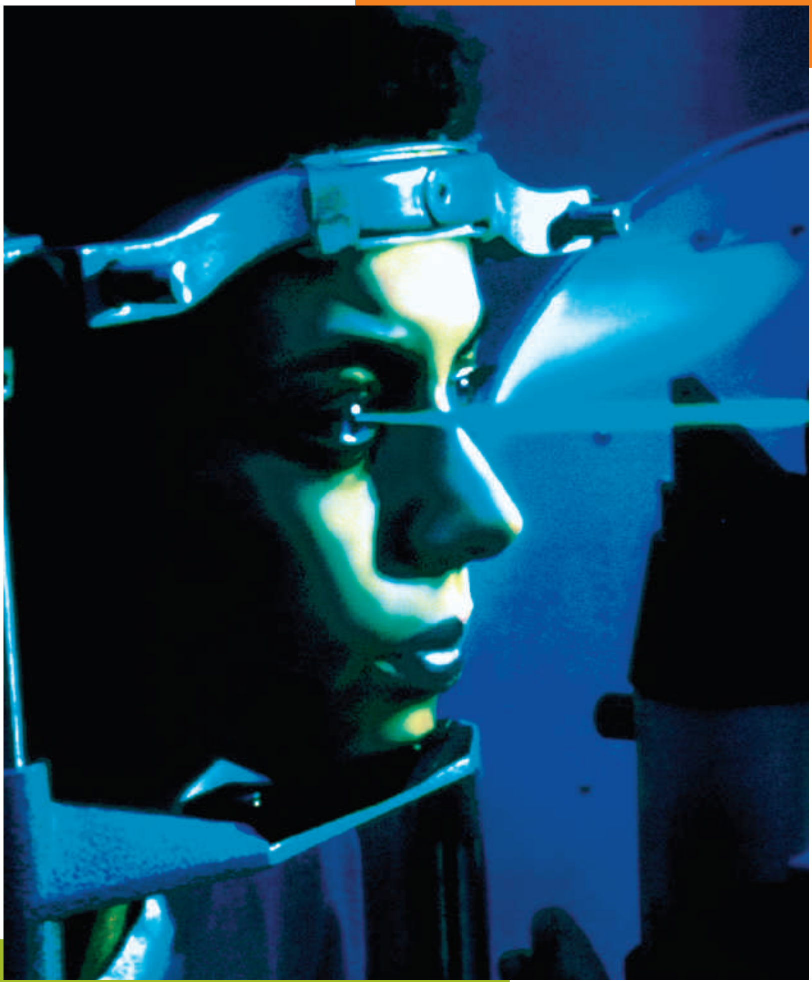
Blue-numbered answered in Appendix B = more challenging questions

24

The Modern Atom

▶Modern lasers have allowed us to take truly three-dimensional pictures (holography), perform surgery inside our bodies, weld retinas in our eyes, cut steel plates for industry and fabric for blue jeans, and perform myriad other amazing tasks. **What makes laser light so special?**

(See page 541 for the answer to this question.)



SuperStock

A laser being used to perform eye surgery.

BOHR'S model of the atom lacked "beauty"; the way the theory blended classical and quantum ideas together in a seemingly contrived way to account for the experimental results was troublesome. Bohr used the ideas of Newtonian mechanics and Maxwell's equations until he ran into trouble; then he abruptly switched to the quantum ideas of Planck and Einstein. For example, the electron orbits were like Newton's orbits for the planets. The force between the electron and the nucleus was the electrostatic force. According to Maxwell's equations, these electrons should have continuously radiated electromagnetic waves. Because this obviously didn't happen, Bohr postulated discrete orbits with photons being emitted only when an electron jumped from a higher orbit to a lower one. There was no satisfactory reason for the existence of the discrete orbits other than that they gave the correct spectral lines.

Bohr's model of the atom was remarkably successful in some areas, but it failed in others. Even though other models have replaced it, it was nevertheless important in advancing our understanding of matter at the atomic level.

Successes and Failures

Accounting for the stability of atoms by postulating orbits in which the electron did not radiate was a mild success of the Bohr theory. The problem was that nobody could give a fundamental reason for why this was so. Why *don't* the electrons radiate? They are accelerating, and according to the classical theory of electromagnetism, they should radiate.

The Bohr model successfully provided the numerical values for the wavelengths in the spectra of hydrogen and hydrogen-like ions. It provided qualitative agreement for the elements with a single electron orbiting a filled shell, but it could not predict the spectral lines when there was more than one electron in the outer shell.

But all along new data were being collected. Close examination of the spectral lines, especially when the atoms were in a magnetic field, revealed that the lines were split into two or more closely spaced lines. The Bohr theory could not account for this. Also, the different spectral lines for a particular element were not of the same brightness. Apparently, some jumps were more likely than others. The Bohr theory provided no clue to why this was so.

Although Bohr's model successfully described the general features of the periodic table, it could not explain why the shells had a certain capacity for electrons. Why did the first shell contain two electrons? Why not just one, or maybe three? And what's so special about the next level that it accepts eight electrons?

There were other loose ends. Einstein's theory of relativity was established, and it was generally accepted that the speeds of the electrons were fast enough and the measurements precise enough that relativistic effects should be included. But Bohr's model was nonrelativistic. Clearly, this was a transitional model.

De Broglie's Waves

Extended presentation available in the *Problem Solving* supplement

In 1923 a French graduate student proposed a revolutionary idea to explain the discrete orbits. Louis de Broglie's idea is easy to state but hard to accept: *electrons behave like waves*. De Broglie reasoned that if light could behave like particles, then particles should exhibit wave properties. He viewed all atomic objects as having this dualism; each exhibits wave properties *and* particle properties.

electrons behave like waves

AIP Niels Bohr Library, W. F. Meggers Collection

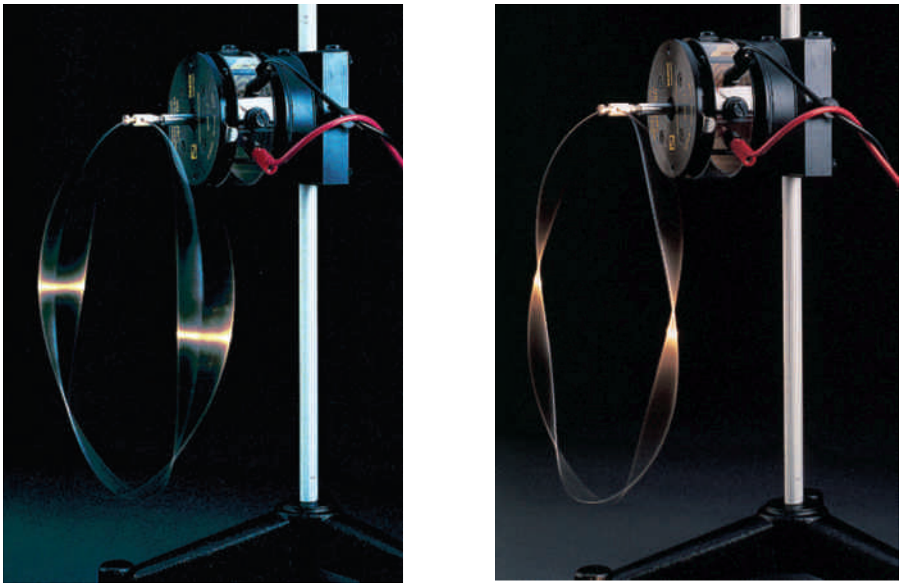
Louis de Broglie

De Broglie's view of the hydrogen atom had electrons forming standing-wave patterns about the nucleus like the standing-wave patterns on a guitar string (Chapter 16). Not every wavelength will form a standing wave on the string; only those that have certain relationships with the length of the string will do so.

Imagine forming a wire into a circle. The traveling waves travel around the wire in both directions and overlap. When a whole number of wavelengths fits along the circumference of the circle, a crest that travels around the circle arrives back at the starting place at the same time another crest is being generated. In this case the waves reinforce each other, creating a standing wave. This process is illustrated in Figure 24-1 for a wire and in Figure 24-2 for an atom.

De Broglie postulated that the wavelength λ of the electron is given by the expression

$$\lambda = \frac{h}{mv}$$



Courtesy of PASCO Scientific (both)

Figure 24-1 The shaft holding the wire executes simple harmonic motion that creates waves traveling around the circular wire in both directions. Standing waves form when the circumference is equal to a whole number of wavelengths.

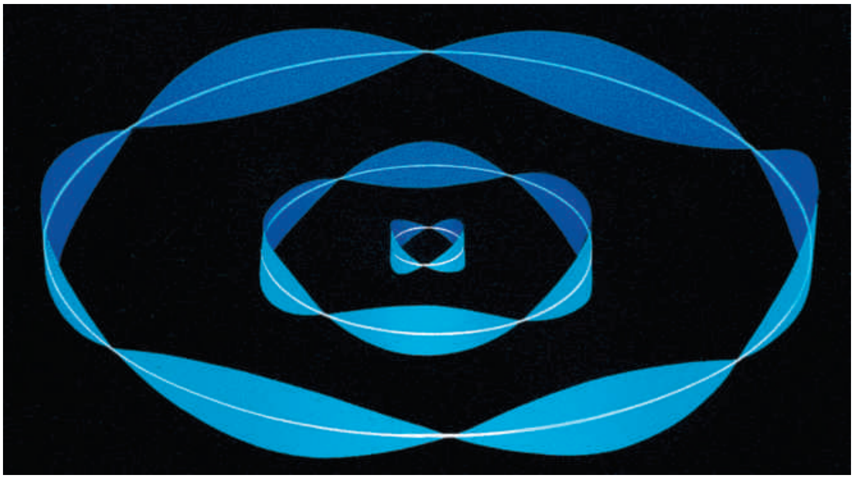


Figure 24-2 The electrons form standing waves about the nucleus.

where h is Planck's constant, m is the electron's mass, and v is the electron's speed. With this expression de Broglie could reproduce the numerical results for the orbits of hydrogen obtained by Bohr. The requirement that the waves form standing-wave patterns automatically restricted the possible wavelengths and therefore the possible energy levels.

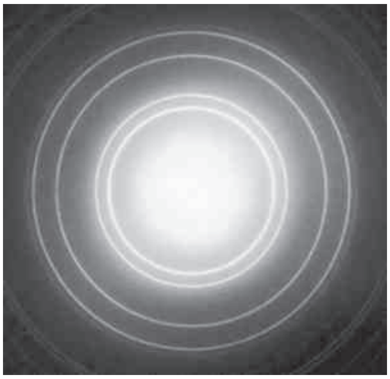
De Broglie's idea put the faculty at his university in an uncomfortable position. If his idea proved to have no merit, they would look foolish awarding a Ph.D. for a crazy idea. The work was very speculative. Although he could account for the energy levels in hydrogen, de Broglie had no other experimental evidence to support his hypothesis. To make matters worse, de Broglie's educational background was in the humanities. He had only recently converted to the study of physics and was working in an area of physics that was not well understood by the faculty. Further, de Broglie came from an influential noble family that had played a leading role in French history. He carried the title of prince. His thesis supervisor resolved the problem by showing the work to Einstein, who indicated that the idea was basically sound.

Although de Broglie's idea was appealing, it was still speculative. It was important to find experimental confirmation by observing some definitive wave behavior, such as interference effects, for electrons. An electron accelerated through a potential difference of 100 volts has a speed that yields a de Broglie wavelength comparable to the size of an atom. Therefore, to see interference effects produced by electrons, we need atom-sized slits. Because X rays have atom-sized wavelengths, they can be used to search for possible setups. Photographs of X rays scattered from randomly oriented crystals, such as the one shown in Figure 24-3, show that the regular alignment of the atoms in crystals can produce interference patterns, such as those produced by multiple slits. Therefore, we might look for the interference of electrons from crystals.

ZYGO Corporation

Figure 24-3 An interference pattern produced by light.

Experimental confirmation of de Broglie's idea came quickly. Two American scientists, C. J. Davisson and L. H. Germer, obtained confusing data from a seemingly unrelated experiment involving the scattering of low-energy electrons from nickel crystals. The scattered electrons had strange valleys and peaks in their distribution. While they were showing these data at a conference at Oxford, it was suggested to Davisson that this anomaly might be a diffraction effect. Further analysis of the data showed that electrons do exhibit wave behavior. The photograph in Figure 24-4 shows an interference pattern produced by electrons. De Broglie was the first of only two physicists to receive a Nobel Prize for their thesis work.



Courtesy of RCA/General Electric Corporate Research and Development

Figure 24-4 An interference pattern produced by electrons scattering from randomly oriented aluminum crystallites.

Nothing in de Broglie's idea suggests that it should apply only to electrons. This relationship for the wavelength should also apply to all material particles. Although it may not apply to macroscopic objects, assume for the moment that it does. A baseball (mass = 0.14 kilogram) thrown at 45 meters per second (100 mph) would have a wavelength of 10^{-34} meter! This is an incredibly small distance. It is 1 trillion-trillionth the size of a single atom. This wavelength is smaller when compared with an atom than an atom is when compared with the solar system. Even a mosquito flying at 1 meter per second would have a wavelength that is only 10^{-27} meter.

You shouldn't spend much time worrying that your automobile will diffract off the road the next time you drive through a tunnel. Ordinary-sized objects traveling at ordinary speeds have negligible wavelengths.

Are You On the Bus?

Q: Why would you not expect baseballs thrown through a porthole to produce a measurable diffraction pattern?

A: For diffraction to be appreciable, the wavelength must be about the same size as the opening.

WORKING IT OUT | *Electron Microscope*

Electron microscopes take advantage of the wave nature of particles. Electrons are accelerated to high speeds, giving them a very short de Broglie wavelength. Diffraction effects require that the wavelength of our probe be small compared to the size of the object being observed. How fast would electrons in our microscope need to be traveling to observe a gold atom that is 0.288 nm across?

To avoid diffraction effects, the wavelength of our electrons must be smaller than the size of the gold atom. Let's assume a wavelength that is smaller by one order of magnitude, or $\lambda = 0.0288$ nm $= 2.88 \times 10^{-11}$ m. The formula for the de Broglie wavelength

$$\lambda = \frac{h}{mv}$$

can then be rewritten to solve for the needed electron speed:

$$v = \frac{h}{m\lambda} = \frac{6.63 \times 10^{-34}\ \mathrm{J \cdot s}}{(9.11 \times 10^{-31}\ \mathrm{kg})(2.88 \times 10^{-11}\ \mathrm{m})} = 2.53 \times 10^{7}\ \mathrm{m/s}$$

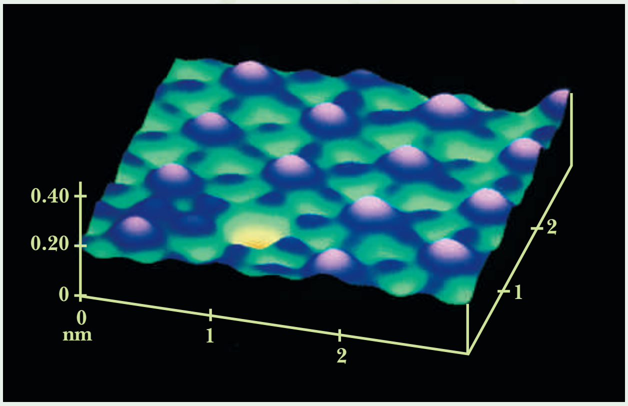
nearly 10% of the speed of light!

Everyday Physics | *Seeing Atoms*

Atoms are so small that they cannot be seen with the most powerful optical microscopes. This limitation is due to the wave properties of light that we discussed in Chapter 19. The relatively large wavelength of the light scatters from the atoms without yielding any information about the individual atoms. Although electron microscopes have much higher resolution (electrons can be accelerated to high speeds by electric fields, giving them wavelengths less than $\frac{1}{100}$ as long as wavelengths of visible light), even the most powerful electron microscope does not allow us to view individual atoms.

A new type of microscope, developed in the early 1980s, provides views of atomic surfaces with a resolution thousands of times greater than is possible with light. The developers of the *scanning tunneling microscope,* or STM, were awarded the Nobel Prize in 1986 (along with the inventor of the electron microscope).

The STM uses a sharp probe (several atoms across at the tip) placed close to the surface (about 1 ten-billionth of a meter) to "view" the surface under investigation. As the probe is moved back and forth over the surface, electrons are pulled from the atoms to the probe, creating a current that is monitored by a computer. The current is greatest when the probe is directly over an atom and quite small when the probe is between atoms. By carefully mapping the surface, the operator can plot the structure of the surface with a resolution smaller than the atomic dimensions. Computer displays like the one shown here clearly indicate the orderly arrangement of the atoms on the surface of the material. These measurements



Courtesy of VEECO Instruments and Purdue University

A scanning tunneling microscope image of iodine atoms absorbed on a platinum surface. Note the orderly arrangement of the atoms and that one of the atoms is missing.

can also show the location of individual atoms that are deposited onto the surface. Such studies are important in understanding the physics of surfaces as well as of the catalytic processes used in manufacturing.

1. What principle of physics limits the resolution of an optical microscope or an electron microscope?
2. Why is the STM not limited by the same resolution issues that apply to optical and electron microscopes?

Waves and Particles

Imagine the controversy de Broglie caused. Interference of light is believable because parts of the wave pass through each slit and interfere in the overlap region (Chapter 19). But electrons don't split in half. Every experiment designed to detect electrons has found complete electrons, not half an electron. So how can electrons produce interference patterns?

The following series of thought experiments was proposed by physicist Richard Feynman to summarize the many experiments that have been conducted to resolve the wave–particle dilemma. Although they are idealized, this sequence of experiments gets at crucial factors in the issue.

We will imagine passing various things through two slits and discuss the patterns that would be produced on a screen behind the slits. In each case there are three pieces of equipment: a source, two slits, and a detecting screen arranged as in Figure 24-5.

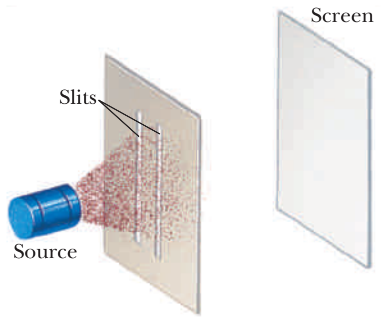


Figure 24-5 The experimental setup for the thought experiment concerning the wave–particle dilemma.

In the first situation, we shoot indestructible bullets at two narrow slits in a steel plate. Assume that the gun wobbles so that the bullets are fired randomly at the slits. Our detecting screen is a sandbox. We simply count the bullets in certain regions in the sandbox to determine the pattern.

Imagine that the experiment is conducted with the right-hand slit closed. After 1 hour we sift through the sand and make a graph of the distribution of bullets. This graph is shown in Figure 24-6(a). The curve is labeled N_L to indicate that the left-hand slit was open. Repeating the experiment with only the right-hand slit open yields the similar curve N_R shown in Figure 24-6(b).

Q: What curve would you expect with both slits open?

A: The curve with both slits open should be the sum of the first two curves.

When both slits are opened, the number of bullets hitting each region during 1 hour is just the sum of the numbers in the previous experiments—that is, $N_{LR} = N_L + N_R$.

◀ bullets add

This is just what we expect for bullets or any other particles. This graph is shown in Figure 24-6(c).

Now imagine repeating the experiment using water waves. The source is now an oscillating bar that generates straight waves. The detecting screen is a collection of devices that measure the energy (that is, the intensity) of the wave arriving at each region. Because these are waves, the detector does not detect the energy arriving in chunks but rather in a smooth, continuous manner. The graphs in Figure 24-7 show the average intensity of the waves at each position across the screen for the same three trials.

Once again, the three trials yield no surprises. We expect an interference pattern when both slits are open. We see that the intensity with two slits open is not equal to the sum of the two cases with only one slit open, $I_{LR} \neq I_L + I_R$, but this is what we expect for water waves or for any other waves.

◀ water waves interfere

Both sets of experiments make sense, in part, because we used materials from the macroscopic world—bullets and water waves. However, a new reality emerges when we repeat these experiments with particles from the atomic world.

This time we use electrons as our "bullets." An electron gun shoots electrons randomly toward two narrow slits. Our screen consists of an array of devices that can detect electrons. Initially, the results are similar to those obtained in the bullet experiment: electrons are detected as whole particles, not fractions of particles. The patterns produced with either slit open are the expected ones

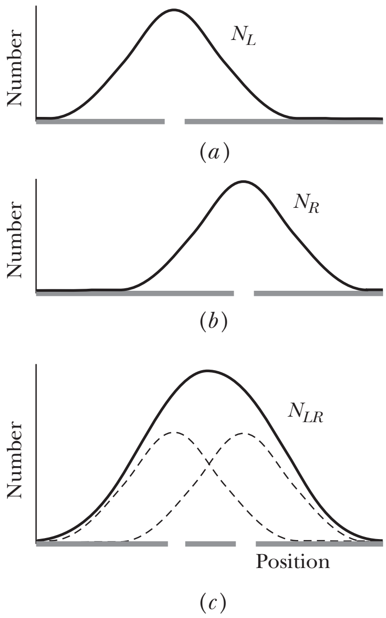


Figure 24-6 Distribution of bullets with (a) the left-hand slit open (N_L), (b) the right-hand slit open (N_R), and (c) both slits open (N_{LR}).

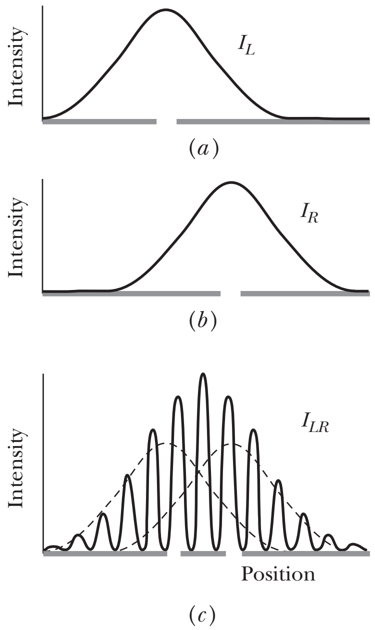


Figure 24-7 Intensity of water waves with (a) the left-hand slit open (I_L), (b) the right-hand slit open (I_R), and (c) both slits open (I_{RL}).

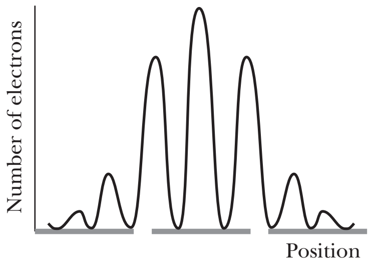


Figure 24-8 The distribution of electrons with two slits open.

and are the same as those in Figure 24-6(a) and (b). The surprise comes when we look at the pattern produced with both slits open: we get an interference pattern like the one for waves (Figure 24-8)!

electrons interfere ▶

Note what this means: if we look at a spot on the screen that has a minimum number of electrons and close one slit, we get an *increase* in the number of counts at that spot. Closing one slit yields more electrons! This is not the behavior expected of particles.

One possibility that was suggested to explain these results is that the electrons are somehow affecting each other. We can test this by lowering the rate at which the source emits electrons so that only one electron passes through the setup at a time. In this case we may expect the interference pattern to disappear. How can an electron possibly interfere with itself? Each individual electron should pass through one slit or the other. How can it even know that the other slit is open? But the interference pattern doesn't disappear. Even though there is only one electron in the apparatus at a time, the same interference effects are observed after a large number of electrons are measured.

The set of experiments can be repeated with photons. The results are the same. The detectors at the screen see complete photons, not half photons. But the two-slit pattern is an interference pattern. Photons behave like electrons. Photons and electrons exhibit a duality of particle and wave behavior. Table 24-1 summarizes the results of these experiments.

Table 24-1 *Summary of Experiments with Two Slits*

Source	Detection	Pattern
Bullets	Chunks	No interference
Water waves	Continuous	Interference
Electrons or photons	Chunks	Interference

FLAWED REASONING

Your friend argues: "The interference pattern for electrons passing through two slits isn't that mysterious. We know that two electrons interact via the electric force, and so an electron passing through one slit is going to affect the motion of an electron passing through the other slit."

What experimental evidence could you use to persuade your friend that the interference pattern is not caused by the interaction between electrons?

ANSWER Even if the beam is turned down so low that only one electron passes through the slits at a time, the same interference pattern is produced.

Probability Waves

Nature has an underlying rule governing this strange behavior. We need to unravel the mystery of why electrons (or photons, for that matter) are always detected as single particles and yet collectively they produce wavelike distributions. Something is adding together to give the interference patterns. To see this we once again look at water waves.

There is something about water waves that does add when the two slits are open—the displacements (or heights) of the individual waves at any instant of time. Their sum gives the displacement at all points of the interference pattern—that is, $h_{12} = h_1 + h_2$. The maximum displacement at each point is the amplitude of the resultant wave at that point.

With light and sound waves we observe the intensities of the waves, not their amplitudes. Intensity is proportional to the square of the amplitude. It is important to note that the resultant, or total, intensity is *not* the sum of the individual intensities. The total intensity is calculated by adding the individual displacements to obtain the resulting amplitude of the combined waves and then squaring this amplitude. Thus, the intensity depends on the amplitude of each wave *and* the relative phase of the waves. As you can see in Figure 24-9, the intensity of the combined waves is larger than the sum of the individual intensities when the displacements are in the same direction and smaller when they are in opposite directions.

There is an analogous situation with electrons. The definition for a **matter–wave amplitude** (called a *wave function*) is analogous to that for water waves.

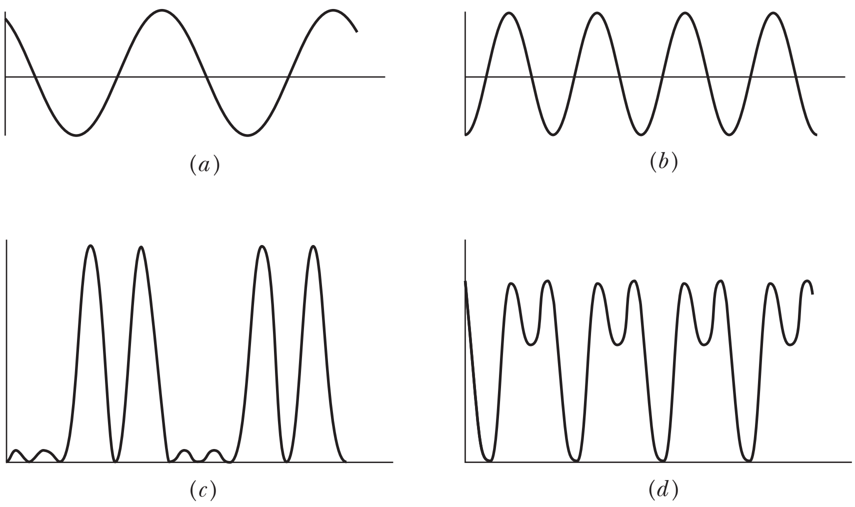


Figure 24-9 The two individual waves (a and b) are combined (c) by adding the displacements before squaring. Note the difference when the individual displacements are squared before adding (d).

(This matter–wave amplitude is usually represented by the Greek letter ψ, and pronounced "sigh".) The square of the matter–wave amplitude is analogous to the intensity of a wave. In this case, however, the "intensity" represents the likelihood, or probability, of finding an electron at that location and time. There is one important difference between the two cases. We can physically measure the amplitude of an ordinary mechanical wave, but there is *no* way to measure the amplitude of a matter wave. We can only measure the value of this amplitude squared.

These ideas led to the development of a new view of physics known as **quantum mechanics,** which are the rules for the behavior of particles at the atomic and subatomic levels. These rules replace Newton's and Maxwell's rules. A quantum-mechanical equation, called *Schrödinger's equation* after Austrian physicist Erwin Schrödinger, is a wave equation that provides all possible information about atomic particles.

A Particle in a Box

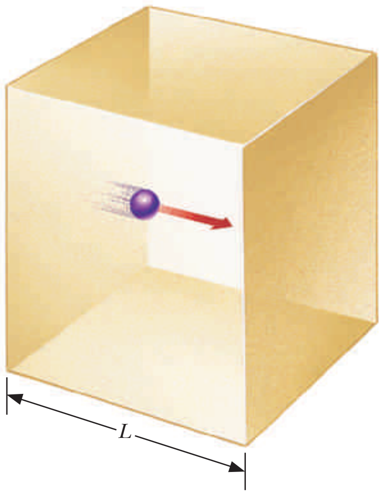


Figure 24-10 A particle in a box has quantized values for its de Broglie wavelength.

It is instructive to look at another simple, though somewhat artificial, situation. Imagine you have an atomic particle that is confined to a box. Further imagine that the box has perfectly hard walls so that no energy is lost in collisions with the walls and that the particle moves in only one dimension, as shown in Figure 24-10.

From a Newtonian point of view, there are no restrictions on the motion of the particle; it could be at rest or bouncing back and forth with any speed. Because we assume that the walls are perfectly hard, the sizes of the particle's momentum and kinetic energy remain constant. In this classical situation, things happen much as we would expect from our commonsense world view. The particle is like an ideal Super Ball in zero gravity. It follows a definite path; we can predict when and where it will be at any time in the future.

Until the early 1900s, it was assumed that an electron would behave the same way. We now know that atomic particles have a matter–wave character and their properties—position, momentum, and kinetic energy—are governed by Schrödinger's equation. When these particles are confined, their wave nature guarantees that their properties are quantized. For example, the solutions of Schrödinger's equation for the particle in a box are a set of standing waves. In fact, the solutions are identical to those for the guitar string that we examined in Chapter 16. There is a discrete set of wavelengths that fits the conditions of confinement.

Q: How would you expect the wavelength of the fundamental standing wave to compare with the length of the box?

A: As with the guitar string analogy, we would expect the wavelength to be twice the length of the box.

The fundamental standing wave corresponds to the lowest energy state (the ground state), and one-half of a wavelength fits into the box, as shown in Figure 24-11(a). The probability of finding the particle at some location depends on the square of this wave amplitude. These probability values [Figure 24-11(b)] help locate the particle. You can see that the most likely place for finding the atomic particle is near the middle of the box because ψ^2 is large there. The probability of finding it near either end is quite small.

A bizarre situation arises with the higher energy levels. The wave amplitude and its square for the next higher energy level are shown in Figure 24-12. Now the most likely places to find the particle are midway between the center and

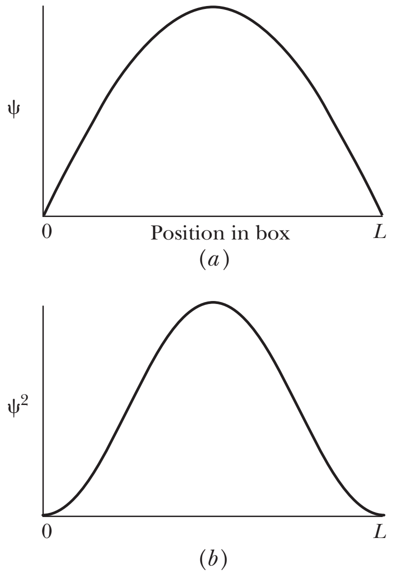


Figure 24-11 The (a) wave amplitude and (b) probability distribution for the lowest energy state for a particle in a box.

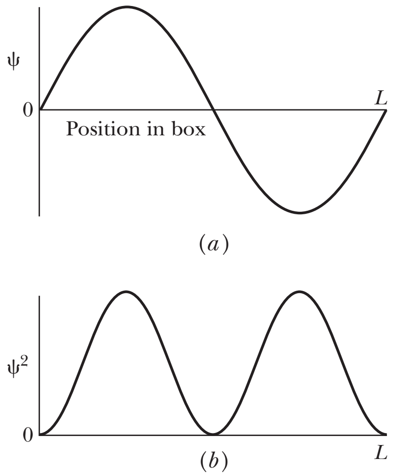


Figure 24-12 The (a) wave amplitude and (b) probability distribution for the first excited state for a particle in a box.

either end of the box. The least likely places are near an end or near the center. It is tempting to ask how the atomic particle gets from one region of high probability to the other. How does it cross the center where the probability of locating it is zero? This type of question, however, does not make sense in quantum mechanics. Particles do not have well-defined paths; they have only probabilities of existing throughout the space in question.

Q: Where are the most likely places to find the particle in the third energy level?

A: The square of the third standing wave will have maxima at the center and between the center and each side of the box (see Figure 16-6).

Suppose you try to find the particle. You would find it in one place, not spread out over the length of the box. However, you cannot predict where it will be. All you can do is predict the probability of finding it in a particular region. In addition, even if you know where it is at one time, you still cannot predict where it will be at a later time. Atomic particles do not follow well-defined paths as classical objects do.

The existence of quantized wavelengths means that other quantities are also quantized. Because de Broglie's relationship tells us that the momentum is inversely proportional to the wavelength, momentum is quantized. The kinetic energy is proportional to the square of the momentum. Therefore, kinetic energy must also be quantized. Thus, the particle in a box has quantized energy levels that can be labeled with a quantum number to distinguish one level from another as we did for the Bohr atom.

The Quantum-Mechanical Atom

The properties of the atom are calculated from the Schrödinger equation just as those for the particle in a box. Quantum mechanics works; it not only accounts for all the properties of the Bohr model but also corrects most of the deficiencies of that earlier attempt.

But this success has come at a price. We no longer have an atom that is easily visualized; we can no longer imagine the electron as being a little billiard ball moving in a well-defined orbit. It is meaningless to ask "particle" questions such as how the electron gets from one place to another or how fast it will be going after 2 minutes. The electron orbits are replaced by standing waves that represent probability distributions. The best we can do is visualize the atom as an electron cloud surrounding the nucleus. This is no ordinary cloud; the density of the cloud gives the probability of locating an electron at a given point in space. The probability is highest where the cloud is the most dense and lowest where it is the least dense. An artist's version of these three-dimensional clouds is shown in Figure 24-13. (Although each drawing is

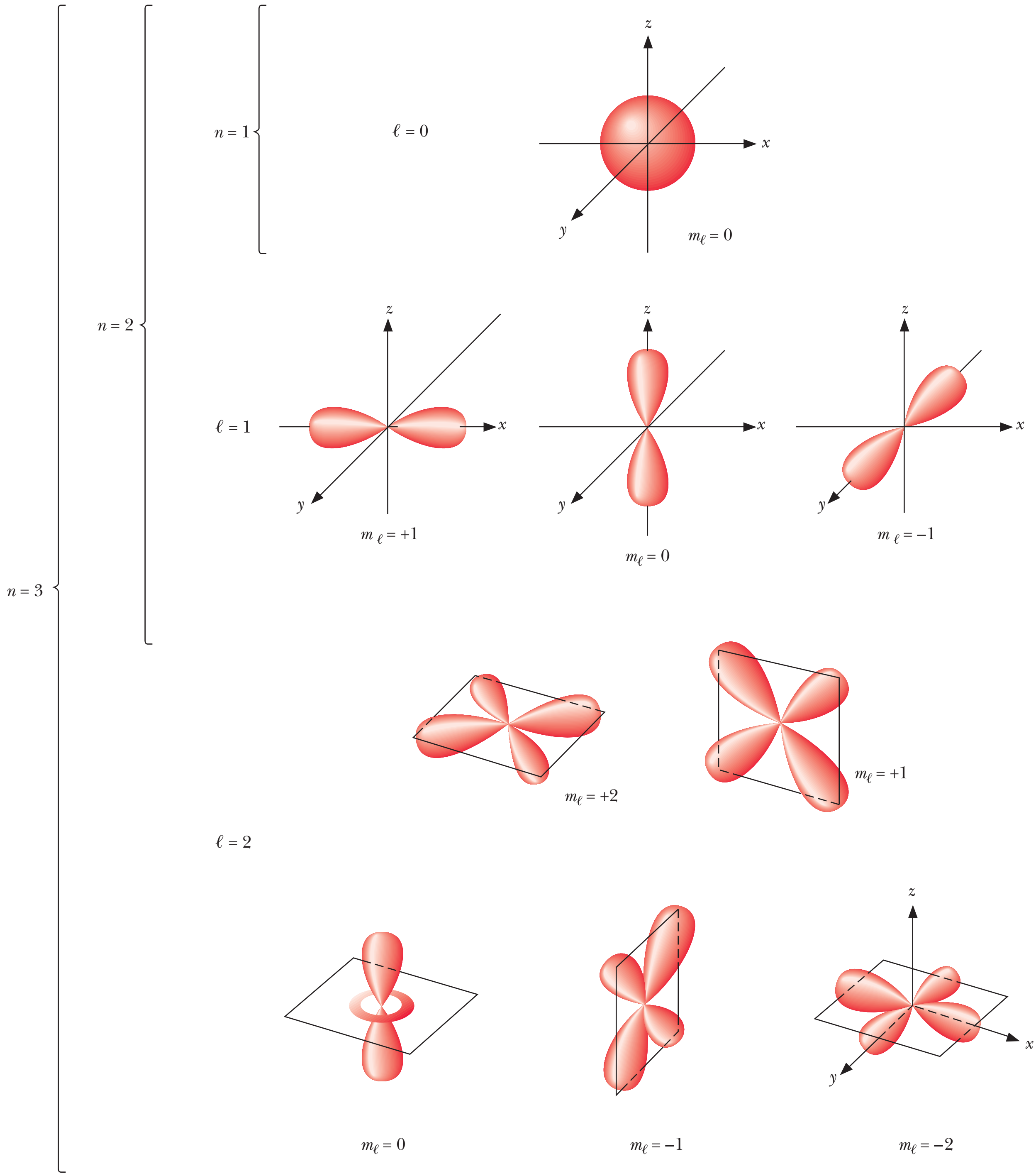


Figure 24-13 Probability clouds for a variety of electron states. See the following pages for a discussion of the quantum numbers n, ℓ, and m_ℓ.

Everyday Physics | *Psychedelic Colors*

In Chapter 17 we discussed why objects have colors. The object's color depends on the colors reflected from the illuminating light, but there is an exception to this. When certain materials are illuminated with ultraviolet (UV) light, they glow brightly in a variety of colors. This process is called *fluorescence* and is responsible for the colors seen on the "psychedelic" posters that were popular in the 1960s.

The "black lights" used to illuminate these posters radiate mostly in the UV region, which is invisible to our eyes. Although the light gives off a little purple, there are certainly no reds, yellows, or greens present. And yet these bright colors appear in the posters. The atomic model explains their presence. UV photons are very energetic and can kick electrons to higher energy levels. If the electron returns by several jumps as shown in Figure A, it gives off several photons, each of which has a lower energy. When one or more of these photons lie in the visible region of the electromagnetic spectrum, the material fluoresces.

A laundry detergent manufacturer once claimed that its soap could make clothes "whiter than white" by pointing out that the soap contained fluorescent material. This makes sense scientifically because some of the UV light is converted to visible light, making the shirt give off more light in the visible region. You may wish to observe various types of clothing and laundry soap under UV light to see whether they fluoresce. Do not look directly at the black light because UV light is dangerous to your eyes.

This process is also at work in fluorescent lights. The gas atoms inside the tube are excited by an electric discharge and emit UV photons. These photons cause atoms in the coating on the inside of the tube to fluoresce, giving off visible photons (Figure B).

A related phenomenon, *phosphorescence,* occurs with some materials. These materials continue to glow after the ultraviolet light is turned off. Some luminous watch dials are phosphorescent. In these materials the excited electrons remain much longer in upper energy states. In effect, phosphorescence is really a delayed fluorescence.

1. If the excited electron returns to its original state in a single jump, no fluorescence occurs. Why?
2. What is the difference between phosphorescence and fluorescence?

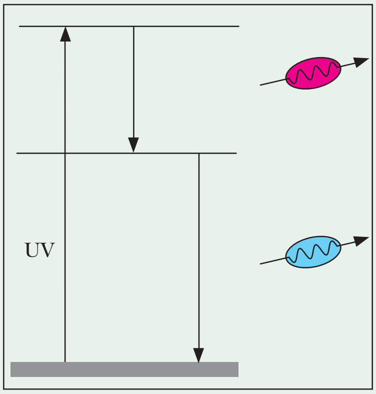
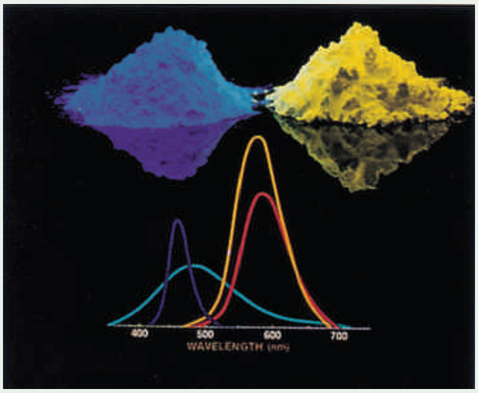


Figure A Fluorescence may occur when an electron makes several jumps in returning to its original state.

(a)


(b)


General Electric Company (both)

Figure B In a fluorescent lamp, a gas discharge produces ultraviolet light that is converted into visible light by a phosphor coating on the inside of the tube. (a) The two-component phosphor of praseodymium and yttrium fluorides produces the visible soft violet-pink light flooding the face of the researcher (b).

confined to a finite space, the probability cloud extends to infinity, getting rapidly thinner the farther away you go from the center.)

The loss of orbiting electrons also means, however, the loss of the idea of an accelerating charge continuously radiating energy. The theory agrees with nature: atoms are stable.

As with the particle in a box, the simple act of confining the electron to the volume of the atom results in the quantization of its properties. If we allow the particle in the box to move in all three dimensions, we have standing waves in three dimensions and therefore three independent quantum numbers, one for each dimension. Similarly, the three-dimensionality of the atom yields three quantum numbers.

The particular form that these numbers take depends on the symmetry of the forces involved. In the case of atoms, the force is spherically symmetric, and the three quantum numbers are associated with the energy n, the size ℓ of the angular momentum, and its direction m_ℓ. However, these three quantum numbers were not adequate to explain all the features of the atomic spectra. The additional features could be explained by assuming that the electron spins on its axis. A fourth quantum number m_s was added that gave the orientation of the electron spin. There are only two possible spin orientations, usually called "spin up" and "spin down." Although the classical idea of the electron spinning like a toy top does not carry over into quantum mechanics, the effects analogous to those of a spinning electron are accounted for with this additional quantum number. The quantum number is retained, and, for convenience, we use the Newtonian language of electron spin.

Oesper Collection in the History of Chem/Univ of Cincinnati

Wolfgang Pauli

The most recent model of the atom combines relativity and the quantum mechanics of electrons and photons in a theory known as *quantum electrodynamics* (QED), which is even more abstract than the quantum-mechanical model. In this theory, however, the concept of electron spin is no longer just an add-on but is a natural result of the combination of quantum mechanics and relativity.

The Exclusion Principle and the Periodic Table

Let's return to the periodicity of the chemical elements that we discussed in Chapter 23. The periodicity required that we think of electrons existing in shells, but the theory did not tell us how many electrons could occupy each shell. The introduction of the quantum numbers said that electrons could exist only in certain discrete states and that these states formed shells, but it did not say how many electrons could exist in each state.

exclusion principle ▶

In 1924 Wolfgang Pauli suggested that no two electrons can be in the same state; that is, no two electrons can have the same set of quantum numbers. This statement is now known as the Pauli **exclusion principle.** When this principle is applied to the quantum numbers obtained from Schrödinger's equation and the electron spin, the periodicity of the elements is explained, as we will demonstrate.

Table 24-2 gives the first two quantum numbers for the first 30 elements. The values of the angular momentum quantum number ℓ are restricted by Schrödinger's equation to be integers in the range from 0 up to $n - 1$, and the values for the direction of the angular momentum m_ℓ are all integers from $-\ell$ to $+\ell$. Unlike the Bohr model, the angular momentum of the lowest energy state is zero, further supporting the notion that we cannot expect these atomic particles to act classically. For each value of n, ℓ, and m_ℓ, two spin states are available: spin up and spin down.

The good news is that the relationships between the quantum numbers explain why the orbital shells have different capacities, and this in turn explains the properties of the elements in the periodic table shown on the inside front cover of this

Table 24-2 *Ground State Quantum Numbers for the First 30 Elements*

Atomic Number	Element	$n = 1$, $\ell = 0$	2, 0	2, 1	3, 0	3, 1	3, 2	4, 0
1	hydrogen (H)	1						
2	helium (He)	2						
3	lithium (Li)	2	1					
4	beryllium (Be)	2	2					
5	boron (B)	2	2	1				
6	carbon (C)	2	2	2				
7	nitrogen (N)	2	2	3				
8	oxygen (O)	2	2	4				
9	fluorine (F)	2	2	5				
10	neon (Ne)	2	2	6				
11	sodium (Na)	2	2	6	1			
12	magnesium (Mg)	2	2	6	2			
13	aluminum (Al)	2	2	6	2	1		
14	silicon (Si)	2	2	6	2	2		
15	phosphorus (P)	2	2	6	2	3		
16	sulfur (S)	2	2	6	2	4		
17	chlorine (Cl)	2	2	6	2	5		
18	argon (Ar)	2	2	6	2	6		
19	potassium (K)	2	2	6	2	6	0	1
20	calcium (Ca)	2	2	6	2	6	0	2
21	scandium (Sc)	2	2	6	2	6	1	2
22	titanium (Ti)	2	2	6	2	6	2	2
23	vanadium (V)	2	2	6	2	6	3	2
24	chromium (Cr)	2	2	6	2	6	5	1
25	manganese (Mn)	2	2	6	2	6	5	2
26	iron (Fe)	2	2	6	2	6	6	2
27	cobalt (Co)	2	2	6	2	6	7	2
28	nickel (Ni)	2	2	6	2	6	8	2
29	copper (Cu)	2	2	6	2	6	10	1
30	zinc (Zn)	2	2	6	2	6	10	2

text. The $n = 1$ state has only one angular momentum state and two spin states, so its maximum capacity is two electrons, both with $n = 1$ and $\ell = 0$, but with different spins. The first element, hydrogen, has one electron in the lowest energy state, whereas helium, the second element, has both of these states occupied. Because there are no more $n = 1$ states available and the Pauli exclusion principle does not allow two electrons to fill any one state, this completes the first shell.

The next two electrons go into the states with $n = 2$ and $\ell = 0$ because these states are slightly lower in energy than the $n = 2$ and $\ell = 1$ states. This takes care of lithium (element 3) and beryllium (4). There are six states with $n = 2$ and $\ell = 1$ because m_ℓ can take on three values (–1, 0, 1), and each of these can be occupied by two electrons, one with spin up and the other with spin down. These six states correspond to the next six elements in the periodic table, ending with neon (element 10). This completes the second shell, and the completed shell accounts for neon being a noble gas.

The electrons in the next eight elements occupy the states with $n = 3$ and $\ell = 0$ or $\ell = 1$. This completes the third shell, ending with the noble gas argon (18). The two states with $n = 4$ and $\ell = 0$ are lower in energy than the rest of the $n = 3$ states and are filled next. These correspond to potassium (19) and calcium (20). Then the remaining 10 states corresponding to $n = 3$ and $\ell = 2$ are filled, yielding the transition elements scandium (21) through zinc (30). Thus, the quantum-mechanical picture of the atom accounts for the observed periodicity of the elements.

Are You On the Bus?

Q: There are 18 states with $n = 3$. How many are there with $n = 4$?

A: With $n = 4$ we can now have $\ell = 3$ in addition to the other values possible for $n = 3$. This gives us seven values of m_ℓ ranging from -3 to $+3$. Because each of these has two spin states, there are 14 additional states for a total of 32.

The Uncertainty Principle

Werner Heisenberg

The interpretation that atomic particles are governed by probability left many scientists dissatisfied and hoping for some ingenious thinker to rescue them from this foolish predicament. German physicist Werner Heisenberg showed that there was no rescue. He argued that there is a fundamental limit to our knowledge of the atomic world.

Heisenberg's idea—that there is an indeterminacy of knowledge—is often misinterpreted. The uncertainty is not due to a lack of familiarity with the topic, nor is it due to an inability to collect the required data, such as the data needed to predict the outcome of a throw of dice or the Kentucky Derby. Heisenberg was proposing a more fundamental uncertainty—one that results from the wave–particle duality.

Imagine the following thought experiment. Suppose you try to locate an electron in a room void of other particles. To locate the electron, you need something to carry information from the electron to your eyes. Suppose you use photons from a dim lightbulb. Because this is a thought experiment, we can also assume that you have a microscope so sensitive that you will see a single photon that bounces off the electron and enters the microscope (Figure 24-14).

You begin by using a bulb that emits low-energy photons. These have low frequencies and long wavelengths. The low energy means that the photon will not disturb the electron much when it bounces off it. However, the long wavelength means that there will be lots of diffraction when the photon scatters from the electron (Chapter 19). Therefore, you won't be able to determine the location of the electron precisely.

To improve your ability to locate the electron, you now choose a bulb that emits more energetic photons. The shorter wavelength allows you to determine the electron's position relatively well. But the photon kicks the electron so hard that you don't know where the electron is going next. The smaller the wavelength, the better you can locate the electron but the more the photon alters the electron's path.

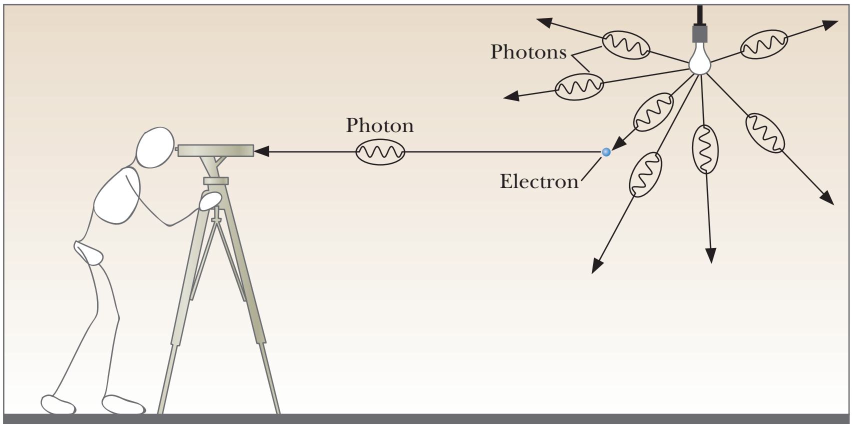


Figure 24-14 Heisenberg's thought experiment to determine the location of an electron.

Heisenberg argued that we cannot make any measurements on a system of atomic entities without affecting the system in this way. The more precise our measurements, the more we disturb the system. Furthermore, he argued, the measured and disturbed quantities come in pairs. The more precisely we determine one half of the pair, the more we disturb the other. In other words, the more *certain* we are about the value of one, the more *uncertain* we are about the value of the other. This is the essence of the uncertainty principle.

Two of these paired quantities are the position and momentum along a given direction. (Recall from Chapter 6 that the momentum for a particle is equal to its mass multiplied by its velocity.) As we saw in the thought experiment just described, the more certain your knowledge of the position, the more uncertain your knowledge of the momentum. The converse is also true.

This idea is now known as Heisenberg's **uncertainty principle.** Mathematically, it says that the product of the uncertainties of these pairs has a lower limit equal to Planck's constant. For example, the uncertainty of the position along the vertical direction Δy multiplied by the uncertainty of the component of the momentum along the vertical direction Δp_y must always be greater than Planck's constant h:

$$\Delta p_y \Delta y > h$$

◀ **uncertainty principle**

This principle holds for the position and component of momentum along the same direction. It does not place any restrictions on simultaneous knowledge of the vertical position and a horizontal component of momentum.

Another pair of variables that is connected by the uncertainty principle is energy and time, $\Delta E\, \Delta t > h$. This mathematical statement tells us that the longer the time we take to determine the energy of a given state, the better we can know its value. If we must make a quick measurement, we cannot determine the energy with arbitrarily small uncertainty. Stated in another way, the energy of a stable state that lasts for a long time is well determined. However, if the state is unstable and exists for only a short time, its energy must have some range of possible values given by the uncertainty principle.

WORKING IT OUT *Uncertainty*

The speed of a proton is measured to be 5.00×10^4 m/s $\pm$ 0.003%. What is the minimum uncertainty in the position of the proton along the direction of its velocity?

We begin by finding the uncertainty in the proton's momentum. The momentum of the proton is:

$$p = mv = (1.67 \times 10^{-27}\ \text{kg})(5.00 \times 10^4\ \text{m/s}) = 8.35 \times 10^{-23}\ \text{kg} \cdot \text{m/s}$$

Because the uncertainty is 0.003% of this value, we have

$$\Delta p = 0.00003p = 2.51 \times 10^{-27}\ \text{kg} \cdot \text{m/s}$$

We can now use Heisenberg's uncertainty principle to find the minimum uncertainty in the proton's position:

$$\Delta x > \frac{h}{\Delta p} = \frac{6.63 \times 10^{-34}\ \text{J} \cdot \text{s}}{2.51 \times 10^{-27}\ \text{kg} \cdot \text{m/s}} = 2.64 \times 10^{-7}\ \text{m}$$

FLAWED REASONING

Two students are discussing the interpretation of Heisenberg's uncertainty principle:

Kristjana: "A particle cannot have a well-defined position and a well-defined momentum at the same time, which really goes against our common sense."

Matthew: "There's nothing really strange about the uncertainty principle—we learn in lab that all measurements have some degree of uncertainty."

Which of these students really understands the uncertainty principle?

ANSWER Matthew is mistakenly thinking of the uncertainty principle as putting a limit on our ability to measure properties that, at least in principle, have well-defined values. Kristjana understands that it is more fundamental than that and really does challenge our common sense.

Are You On the Bus?

Q: What does the uncertainty principle say about the energy of the photons emitted when electrons in the $n = 2$ state of hydrogen atoms drop down to the ground state?

A: Because the electrons spend a finite time in the $n = 2$ state, the energy of that state must have a spread in energy. Therefore, the photons have a spread in energy that shows up as a nonzero width of the spectral line.

The Complementarity Principle

Frustrating questions emerged as physicists built a world view of nature on the atomic scale. Is there *any* underlying order? How can one contemplate things that have mutually contradictory attributes? Can we understand the dual nature of electrons and light, which sometimes behave as particles and other times as waves?

There was no known way out. Physicists had to learn to live with this wave–particle duality. A complete description of an electron or a photon requires both aspects. This idea was first stated by Bohr and is known as the **complementarity principle.**

complementarity principle ▶

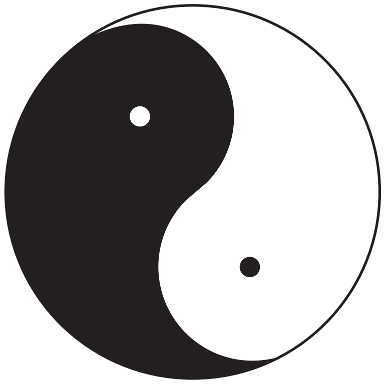
The complementarity principle is closely related to the uncertainty principle. As a consequence of the uncertainty principle, we discover that being completely certain about particle aspects means that we have no knowledge about the wave aspects. For example, if we are completely certain about the position and time for a particle, the wave aspects (wavelength and frequency) have infinite uncertainties. Therefore, wave and particle aspects do not occur at the same time.

Are You On the Bus?

Q: If you could determine which slit the electron goes through, would this have any effect on the two-slit interference pattern?

A: It would destroy the interference pattern. Knowledge of the particle properties (that is, the path of the electron) precludes the wave properties.

The idea that opposites are components of a whole is not new. The ancient Eastern cultures incorporated this notion as part of their world view. The most common example is the yin-yang symbol of tai chi tu. Later in life, Bohr was so attracted to this idea that he wrote many essays on the existence of complementarity in many modes of life. In 1947, when he was knighted for his work in physics, he chose the yin-yang symbol for his coat of arms.



The yin-yang symbol reflects the complementarity of many things.

Determinism

Classical Newtonian mechanics and the newer quantum mechanics have been sources of much debate about the role of cause and effect in the natural world. With Newton's laws of motion came the idea that specifying the position and momentum of a particle and the forces acting on it allowed the calculation of its future motion. Everything was determined. It was as if the universe was an enormous machine. This idea was known as the *mechanistic view*. In the 17th century, René Descartes stated, "I do not recognize any difference between the machines that artisans make and the different bodies that nature alone composes."

These ideas were so successful in explaining the motions in nature that they were extended into other areas. Because the universe is made of particles whose futures are predetermined, it was suggested that the motion of the entire universe must be predetermined. This notion was even extended to living organisms. Although the flight of a bumblebee seems random, its choices of which flowers to visit are determined by the motion of the particles that make up the bee. These generalizations caused severe problems with the idea of free will—that humans had something to say about the future course of events.

Is the flight of the bumblebee predetermined or a result of free will?

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There were, however, some practical problems with actually predicting the future in classical physics. Because measurements could not be made with absolute precision, the position and momentum of an object could not be known exactly. The uncertainties in these measurements would lead to uncertainties about the calculations of future motions. However, at least in principle, certainty was possible. It was also impossible to measure the positions and momenta of all atomic particles in a small sample of gas, let alone all those in the universe. However, the motion of each atom was predetermined, and therefore the properties of gases were predetermined. Even though humans could not determine the paths, nature knew them. The future was predetermined.

With the advent of quantum mechanics, the future became a statistical issue. The uncertainty principle stated that it was impossible *even in principle* to measure simultaneously the position and momentum of a particle. The mechanistic laws of motion were replaced by an equation for calculating the matter waves of a system that gave only *probabilities* about future events. Even if we know the state of a system at some time, the laws of quantum mechanics do not permit the calculation of a future, only the probabilities for each of many possible futures. The future is no longer considered to be predetermined but is left to chance.

One of the main opponents of this probabilistic interpretation was Albert Einstein. His objections did not arise out of a lack of understanding. He understood quantum mechanics very well and even contributed to its interpretation. He believed that the path of an electron was governed by some (hidden) deterministic set of rules (like an atomic version of Newton's laws), not by some unmeasurable probability wave. The new physics didn't fit into his philosophy of the natural world. Einstein's famous rebellious quote is, "I, at any rate, am convinced that [God] is not playing at dice."

But nobody has ever found those hidden rules, and quantum mechanics continues to work better than anything else that has been proposed. The point is that hoping doesn't change the physics world view. Einstein spent a lot of time trying to disprove the very theory that he helped begin. He did not succeed. New work has shown that quantum mechanics is a complete theory, proving that there are no hidden variables.

Lasers

The understanding of the quantized energy levels in atoms and the realization that transitions between these levels involved the absorption and emission of photons led to the development of a new device that produced a special beam of light. Assume that we have a gas of excited atoms. Further assume that an electron drops from the $n = 3$ to the $n = 2$ level in the energy diagram in Figure 24-15(a). A photon is emitted in some random direction. It could escape the gas, or it could interact with another atom with an electron in one of two ways. It could be absorbed by an atom with an electron in the $n = 2$ level, exciting the electron to the $n = 3$ level. This excited atom would then emit another photon at a random time in a random direction. On the other hand, the original photon could stimulate an electron in the $n = 3$ level to drop to the $n = 2$ level, causing the emission of another photon [Figure 24-15(c)]. This latter process is known as **stimulated emission.** Moreover, this new photon does not come out randomly. It has the same energy, the same direction, and the same phase as the incident photon; that is, the two photons are coherent. These photons can then stimulate the emission of further photons, producing a coherent beam of light.

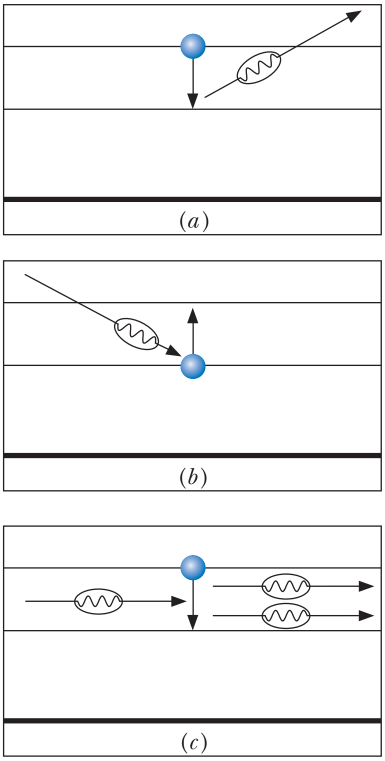


Figure 24-15 (a) Spontaneous emission. (b) Absorption. (c) Stimulated emission.

The device that produces coherent beams of light is called a **laser,** which is the acronym derived from *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation. A laser produces a beam of light that is very different from that emitted

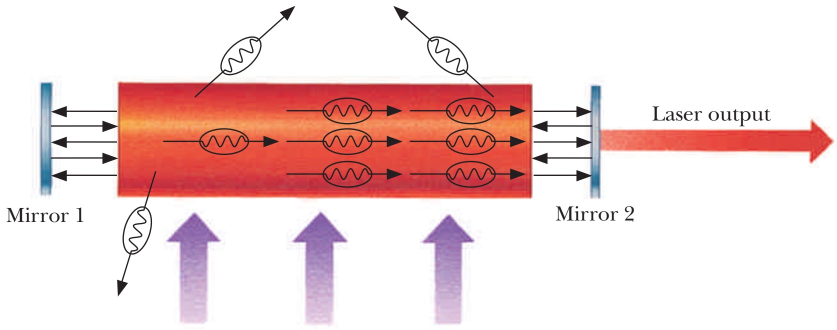


Figure 24-16 A schematic of a simple laser.

by an ordinary light source such as a flashlight. The laser beam has a very narrow range of wavelengths, is highly directional, and can be quite powerful. The laser beam is a single color because all the photons have the same energy. For instance, the helium–neon laser usually has a wavelength of 632.8 nanometers. The beam is highly directional because the stimulated photons move in the same direction as those doing the stimulating. The fact that all the photons have the same phase means that the amplitude of the resulting electromagnetic wave is very large. The intensity of a collection of coherent photons is obtained by adding the amplitudes and then squaring the sum. The intensity of a collection of incoherent photons is obtained by squaring the amplitudes and then adding these squares. The difference can be illustrated by considering a collection of five photons. In the laser beam, we have $(2 + 2 + 2 + 2 + 2)^2 = 100$, whereas in the ordinary light beam we have $(2^2 + 2^2 + 2^2 + 2^2 + 2^2) = 20$. The effect is even more drastic for the large number of photons in a laser beam. These factors combine to allow us to clearly see a 1-milliwatt laser beam shining on the surface of a 100-watt lightbulb.

Making a working laser was more complicated than the preceding description implies. A method had to be found for "building" a beam of many photons. This was done by putting mirrors at each end of the laser tube to amplify the beam by passing it back and forth through the gas of excited atoms. One of the mirrors was only partially silvered, so that a small part of the beam was allowed to escape (Figure 24-16).

The construction of a laser was difficult because a photon is just as likely to be absorbed by an atom with an electron in the lower level as it is to cause stimulated emission of an electron in an excited level. Usually, most of the atoms are in the lower energy state, so most of the photons are absorbed and only a few cause stimulated emission. Therefore, building a laser depends on developing a *population inversion,* a situation in which there are many more electrons in the excited state than in the lower energy state. This is usually done by exciting the atom's electrons into a *metastable state* that decays into an unpopulated energy state. A metastable state is one in which the electrons remain for a long time. The electrons can be excited by using a flash of light, an electric discharge, or collisions with other atoms.

Lasers have a wide range of uses, including surveying and surgery. In surveying, the light beam defines a straight line, and by pulsing the beam, surveyors can use the time for a round-trip to measure distances. This same method is used on a gigantic scale to determine the distance to the Moon to an accuracy of a few centimeters. A very short pulse (less than 1 nanosecond long) of laser light is sent through a telescope toward the Moon's surface. The beam is so well collimated that it spreads out over an area only a few kilometers in diameter. The Apollo astronauts left a panel of retroreflectors (Chapter 17) on the surface that reflects the light back to the telescope, allowing the round-trip

Rick Poley/Visuals Unlimited

A laser-surveying instrument used to ensure proper placement of underground sewer pipes.

time to be measured. These measurements serve as a test of the validity of the general theory of relativity because the theory predicts the detailed orbit of the Moon.

Laser "knives" are used in optometry and surgery. Two leading causes of blindness are glaucoma and diabetes. In treating glaucoma, a laser beam "drills" a small hole to relieve the high pressure that builds up in the eye. One of the complications of diabetes is the weakening of the walls of blood vessels in the eye to the point where they leak. The laser can be shined into the eye to cause coagulation to stop the bleeding. The energy in laser beams can also be used to weld detached retinas to the back of the eye. In laser surgery, the beam coagulates the blood as it slices through the tissue, greatly reducing bleeding. Laser beams can also be directed by fiber optics through tiny incisions to locations that would otherwise require major incisions and long healing times.


Alexander Tsiaras/Science Source/ Photo Researchers, Inc.

Light from an argon laser is carried by a fiber-optic cable to perform surgery deep within an ear.

Lasers also have widespread use in the marketplace. Laser beams read the audio and video information stored in the pits on CDs and DVDs. Likewise, the lasers at store checkout counters read the bar codes on the product identification labels, allowing the computer to print out a short description of the object and its current price. This has greatly reduced billing errors as well as the time required to check out.

Lasers have made practical holography possible (Chapter 19) and opened up a whole new research tool in holographic measurements.

Summary

The Bohr model was successful in accounting for many atomic observations, especially the emission and absorption spectra for hydrogen and the ordering of the chemical elements. However, it failed to explain the details of some processes and could not give quantitative results for multielectron atoms. It described the general features of the periodic table but could not provide the details of the shells, nor explain how many electrons could occupy each shell. Primary among the Bohr model's failures was the lack of intuitive reasons for its postulates. Finally, it was nonrelativistic.

The replacement of Bohr's model of the atom began with de Broglie's revolutionary idea that electrons behave like waves. The de Broglie wavelength of the electron is inversely proportional to its momentum. The primary consequence of this wave behavior is that confined atomic particles form standing-wave patterns that quantize their properties.

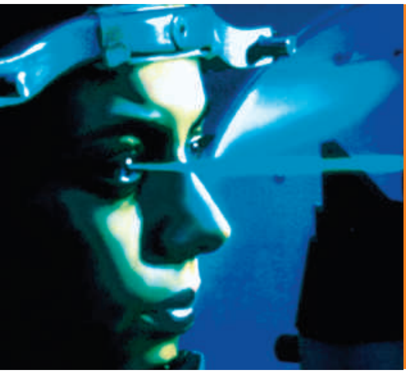
Although successful, this new understanding led to a wave–particle dilemma for electrons and other atomic particles: they are always detected as single particles, and yet collectively they produce wavelike distributions. The behavior of these particles is governed by a quantum-mechanical wave equation that provides all possible information about the particles. For example, the probability of finding the particle at a given location is determined by the square of its matter–wave amplitude. As a consequence, atomic particles do not follow well-defined paths as classical particles do. This quantum-mechanical view of physics replaced the classical world view containing Newton's laws and Maxwell's equations.

Four quantum numbers are associated with an electron bound in an atom: the energy n, the size ℓ and direction m_ℓ of the angular momentum, and the orientation m_s of the spin. The periodicity of the chemical elements is explained by the existence of shells of varying capacity determined by the constraints of quantum mechanics and the Pauli exclusion principle. This principle states that no two electrons can have the same set of quantum numbers.

According to the complementarity principle, all atomic entities require both wave and particle aspects for a complete description, but these cannot

appear at the same time. These ideas also led to Heisenberg's uncertainty principle, a statement that there is an indeterminacy of knowledge that results from the wave–particle duality. Mathematically, the product of the uncertainties of paired quantities has a lower limit equal to Planck's constant.

The understanding of the quantified energy levels in atoms led to the development of lasers, which produce coherent beams of light through the stimulated emission of radiation by electrons in excited, metastable states.



CHAPTER 24 *Revisited*

Laser light is special for a number of reasons. In many of the applications mentioned in the opening question, the laser light's key attribute is that it is (nearly) unidirectional, allowing for a very concentrated beam. With proper optical focusing, this beam can be concentrated to a very small spot, drastically increasing the intensity—the amount of energy per unit area—striking a surface. In holography the most important attribute is its coherence, allowing a beam of light to be split and recombined while preserving the phase information.

Key Terms

complementarity principle A complete description of an atomic entity such as an electron or a photon requires both a particle description and a wave description, but not at the same time.

exclusion principle No two electrons can have the same set of quantum numbers.

laser A device that uses stimulated emission to produce a coherent beam of electromagnetic radiation. *Laser* is the acronym from *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation.

matter–wave amplitude The wave solution to Schrödinger's equation for atomic and subatomic particles. The square of the matter–wave amplitude gives the probability of finding the particle at a particular location.

quantum mechanics The rules for the behavior of particles at the atomic and subatomic levels.

stimulated emission The emission of a photon from an atom because of the presence of an incident photon. The emitted photon has the same energy, direction, and phase as the incident photon.

uncertainty principle The product of the uncertainty in the position of a particle along a certain direction and the uncertainty in the momentum along this same direction must be greater than Planck's constant: $\Delta p_y \Delta y > h$. A similar relationship applies to the uncertainties in energy and time.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. Make a list summarizing the successes and failures of the Bohr theory.
2. The theory of special relativity requires that time, distance, and energy be treated in a new way as a particle approaches the speed of light. Because these corrections were understood at the time that Bohr developed his model of the hydrogen atom, could he have included them and achieved better agreement with experimental results? Why or why not?
3. You find that the lowest frequency at which you can set up a standing wave in a wire loop, as shown in Figure 24-1, is 10 hertz. When you increase the driving frequency slightly above 10 hertz, the resonance goes away. What is

the next frequency at which resonance will again appear? Explain.

4. A 48-centimeter-long wire loop is used to demonstrate standing waves, as shown in Figure 24-1. What are the three longest wavelengths that will produce standing waves?

5. One may be tempted to interpret the de Broglie wave of an electron as a modified orbital path around the nucleus in which the electron deviates up and down from a circular path as it orbits. Does this model overcome the difficulties of Bohr's model? Explain.

6. For standing waves on a guitar string, adjacent antinodes are always moving in opposite directions. Use this principle to explain why a standing-wave pattern with three antinodes cannot exist on a wire loop.

7. Your friend claims that light is a wave. What experimental evidence could you cite to demonstrate that light behaves like a particle?

8. Your friend claims that electrons are particles. What experimental evidence could you cite to demonstrate that electrons behave like waves?

9. In Chapter 10 we found that an infinite amount of energy is required to accelerate a massive particle to the speed of light. What does this imply about the mass of a photon?

10. De Broglie argued that his relationship between wavelength and momentum should apply to photons as well as to electrons. For massless particles, the relationship takes the form $p = h/\lambda$. Which has more momentum, a red photon or a blue photon? Explain.

11. When applied to photons, the de Broglie relationship $p = h/\lambda$ shows that mass is not required for a particle to have momentum, which disagrees with our classical definition for particles. What other quantity that classically depends on mass can also be attributed to a photon?

12. Which of the following technical terms can be used to describe both an electron and a photon: wavelength, velocity, mass, energy, or momentum? Explain.

13. Why is it not correct to say that an electron is a particle that sometimes behaves like a wave and light is a wave that sometimes acts like a particle?

14. Why do you think that the particle nature of the electron was discovered before its wave nature?

15. The wavelength of red light is 600 nanometers. An electron with a speed of 1.2 kilometers per second has the same wavelength. Will the electron look red? Explain.

16. An electron and a proton have the same speeds. Which has the longer wavelength? Why?

17. Bohr could never really explain why an electron was limited to certain orbits. How did de Broglie explain this?

18. What do standing waves have to do with atoms?

19. Why is the wave behavior of bowling balls not observed?

20. Why doesn't a sports car diffract off the road when it is driven through a tunnel?

21. When we perform the two-slit experiment with electrons, do the electrons behave like particles, waves, or both? What if we perform the experiment with photons?

22. Two students are discussing what happens when you turn down the rate at which electrons are fired at two slits. Tyson claims, "Because you still get an interference pattern even with only one electron at a time, each electron must interfere with itself. As weird as it sounds, each electron must be going through both slits." Ulricht counters, "That's crazy. I can't be at class and on the ski slope at the same time. Each electron must pass through only one slit." Which student is correct? Explain.

23. What are the differences between an electron and a photon?

24. What are the similarities between an electron and a photon?

25. If the two-slit experiment is performed with a beam of electrons so weak that only one electron passes through the apparatus at a time, what kind of pattern would you expect to obtain on the detecting screen?

26. In the two-slit experiment with photons, what type of pattern do you expect to obtain if you turn the light source down so low that only one photon is in the apparatus at a time?

27. Two lightbulbs shine on a distant wall. To obtain the brightness of the light, do we add the displacements or the intensities? Explain.

28. Two coherent sources of light shine on a distant screen. If we want to calculate the intensity of the light at positions on the screen, do we add the displacements of the two waves and then square the result, or do we square the displacements and then add them? Explain.

29. What meaning do we give to the square of the matter–wave amplitude?

30. The waves that we studied in Chapters 15 and 16 could be classified as either longitudinal or transverse. Why does this classification scheme have no meaning when applied to de Broglie's matter waves?

31. Where would you most likely find an electron in the lowest energy state for a one-dimensional box, as shown in Figure 24-11?

32. Where would you most likely find an electron in the first excited state for a one-dimensional box, as shown in Figure 24-12?

33. In discussing the first excited state of a particle in a one-dimensional box, your classmate claims, "The electron has to get from one region of high probability to the other without spending much time in between. It must be accelerating, so it must radiate energy." What is wrong with this reasoning?

34. Why doesn't the quantum-mechanical model of the atom have the problem of accelerating charges emitting electromagnetic radiation?

35. Where would you most likely find the electron if it is in a quantum state with $n = 2$, $\ell = 1$, and $m_\ell = -1$, as shown in Figure 24-13?

36. Where would you most likely find the electron if it is in a quantum state with $n = 3$, $\ell = 2$, and $m_\ell = -2$, as shown in Figure 24-13?

37. How many electrons can have the quantum numbers $n = 5$ and $\ell = 1$?

38. How many electrons can have the quantum numbers $n = 5$ and $\ell = 4$?

39. Make a list showing the quantum numbers for each of the four electrons in the beryllium atom when it is in its lowest energy state.

40. Make a list showing the quantum numbers for each of the 10 electrons in the neon atom when it is in its lowest energy state.

41. Your friend argues: "The Heisenberg uncertainty principle shows that we can never be certain about anything. If this is true, we shouldn't believe anything that science teaches." How do you respond?

42. Like light, electrons exhibit diffraction when passed through a single slit. Use the Heisenberg uncertainty principle to explain why narrowing the slit (that is, improving the knowledge of the electron's position in a direction perpendicular to the beam) causes the diffraction pattern to get wider.

43. Explain why the Heisenberg uncertainty principle does not put any restrictions on our simultaneous knowledge of a particle's momentum and its energy.

44. According to the uncertainty principle, why does a tennis ball appear to have a definite position and velocity but an electron does not?

45. De Broglie's relationship gives the wavelength for an electron of given momentum. If we have some idea where the electron is, what does the uncertainty principle tell us about the electron's wavelength?

46. In principle you can balance a pencil with its center of mass directly above its point, even if this point is perfectly sharp. Explain why the uncertainty principle makes this feat impossible.

47. Explain why Bohr's model of the atom is not compatible with the uncertainty principle.

48. What does the uncertainty principle say about the energy of an excited state of hydrogen that exists only for a short time? How will this affect the emission spectrum?

49. Einstein once complained, "The quantum mechanics is very imposing. But an inner voice tells me that it is still not the final truth. The theory yields much, but it hardly brings us nearer to the secret of the Old One. In any case, I am convinced that He does not throw dice." What about quantum mechanics was troubling him?

50. If the Bohr model of the atom has been replaced by the newer quantum-mechanical models, why do we still teach the Bohr model?

51. What quantum-mechanical variable is complementary to time?

52. What quantum-mechanical variable is complementary to position?

53. If we are certain about the energy of a particle, what does the Heisenberg uncertainty principle say about the uncertainty in its frequency?

54. If we are certain about the position of a particle, what does the Heisenberg uncertainty principle say about the uncertainty in its wavelength?

55. Why do some minerals glow when they are illuminated with ultraviolet light?

56. When ultraviolet light from a "black light" shines on crayons, visible light is emitted. How can you account for this?

Aaron Haupt/Photo Researchers, Inc.

57. Phosphorescent materials continue to glow after the lights are turned off. How can you use the model of the atom to explain this?

58. Can infrared rays cause fluorescence? Why or why not?

59. What is stimulated emission?

60. How does light from a laser differ from light emitted by an ordinary lightbulb?

Blue-numbered answered in Appendix B = more challenging questions

Exercises

61. What is the de Broglie wavelength of a Volkswagen (mass = 1000 kg) traveling at 30 m/s (67 mph)?

62. A bullet for a .30-06 rifle has a mass of 10 g and a muzzle velocity of 900 m/s. What is its wavelength?

63. Nitrogen molecules (mass = 4.6×10^{-26} kg) in room-temperature air have an average speed of about 500 m/s. What is a typical wavelength for these nitrogen molecules?

64. What is the de Broglie wavelength for an electron traveling at 50 m/s?

65. What is the wavelength for a photon with energy 2 eV?

66. What is the wavelength for an electron with energy 2 eV?

67. What speed would an electron need to have a wavelength equal to the diameter of a hydrogen atom (10^{-10} m)?

68. What is the speed of a proton with a wavelength of 2 nm?

69. What is the size of the momentum for an electron that is in the lowest energy state for a one-dimensional box whose length is 2 nm?

70. What is the size of the momentum for an electron that is in the first excited energy state for a one-dimensional box whose length is 2 nm?

71. A child runs straight through a door with a width of 0.75 m. What is the uncertainty in the momentum of the child perpendicular to the child's path?

72. A Honda Civic passes through a tunnel with a width of 10 m. What uncertainty is introduced in the Civic's momentum perpendicular to the highway?

73. A proton passes through a slit that has a width of 10^{-10} m. What uncertainty does this introduce in the momentum of the proton at right angles to the slit?

74. Repeat Exercise 73 for an electron.

75. What is the minimum uncertainty in the position along the highway of a Ford Escort (mass = 1000 kg) traveling at 20 m/s (45 mph)? Assume that the uncertainty in the momentum is equal to 1% of the momentum.

76. What is the uncertainty in the momentum of an Acura NSX with a mass of 1200 kg parked by the curb? Assume that you know the location of the car with an uncertainty of 1 cm.

Image not available due to copyright restrictions

77. What is the uncertainty in the location of a proton along its path when it has a speed equal to 0.1% the speed of light? Assume that the uncertainty in the momentum is 1% of the momentum.

78. What is the uncertainty in each component of the momentum of an electron confined to a box approximately the size of a hydrogen atom, say, 0.1 nm on a side?

79. Consider an electron confined to a diameter of 0.1 nm, about the size of a hydrogen atom. If the electron's speed is on the order of the uncertainty in its speed, approximately how fast is it traveling? Assuming that the electron can still be treated without making relativistic corrections, find its kinetic energy (in electron volts).

80. Repeat Exercise 79 for a proton confined to a diameter of 10^{-14} m, about the size of a nucleus.

81. Electrons in an excited state decay to the ground state with the release of a photon. The uncertainty in the time that an electron spends in the excited state can be estimated by the average time electrons spend in that state. What is the spread in energy, in electron volts, of the photons from a state with a lifetime of 2×10^{-8} s?

82. The lifetime of an excited nuclear state is 5×10^{-12} s. What will be the spread in energy, in electron volts, of the photons from this state?

83. If the photons from an excited atomic state show a spread in energy of 2×10^{-4} eV, what is the lifetime (see Exercise 81) of the state?

84. The uncertainty principle allows for "violation" of conservation of energy for times less than the associated uncertainty. For how long could an electron increase its energy by 10 eV without violating conservation of energy?

The Big Picture

The Subatomic World

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The quantum-mechanical model of the atom has been very successful. From a large collection of seemingly unrelated phenomena has come a rather complete picture of the atom. This development has created a very profound change in our physics world view.

Our study of the physical world now goes one "layer" deeper, to that of the atomic nucleus. The search for the structure of the nucleus led to the discovery of new forces in nature, forces much more complicated than those of gravity and electromagnetism. It is not possible to write simple expressions for the nuclear forces like the one we wrote for gravity; the nuclear forces depend on much more than distance and mass. This discovery radically changed our basic concepts about forces. The models for the interactions between particles that began with Newton's action at a distance and progressed to the field concept in Maxwell's time now involve the exchange of fundamental particles.

Because the nuclear force is so strong, the energy associated with it is very large. The power of nuclear energy became evident with the explosion of nuclear bombs over Japan in World War II. The release of this energy in the form of bombs or nuclear power plants poses serious questions not only for scientists and engineers but also for our entire society.

In our search for the ultimate structure of all matter, we have discovered that atoms are not the most basic building blocks in nature. They are composed of electrons and very small, very dense nuclei. The nuclei are in turn composed of particles. These were originally believed to be electrons and protons. This notion was appealing because it required only three elemental building blocks: the electron, the proton, and the photon. Later, the neutron replaced the electron in the nucleus, but the overall picture for the fundamental structure was still appealing.

But as scientists delved deeper and deeper into the subatomic world, new particles emerged. The number of "elementary" particles grew to more than 300! In current theories, most of these are composed of a small number of more basic particles called quarks.

The search for the elusive elementary particles is analogous to a child playing with a set of nested eggs. Each egg is opened only to reveal another egg. However, the child eventually reaches the end of the eggs. In one version the smallest egg contains a bunny. Is there an end to the search for the elementary particles? Do quarks represent the bunny?

Gerald F. Wheeler

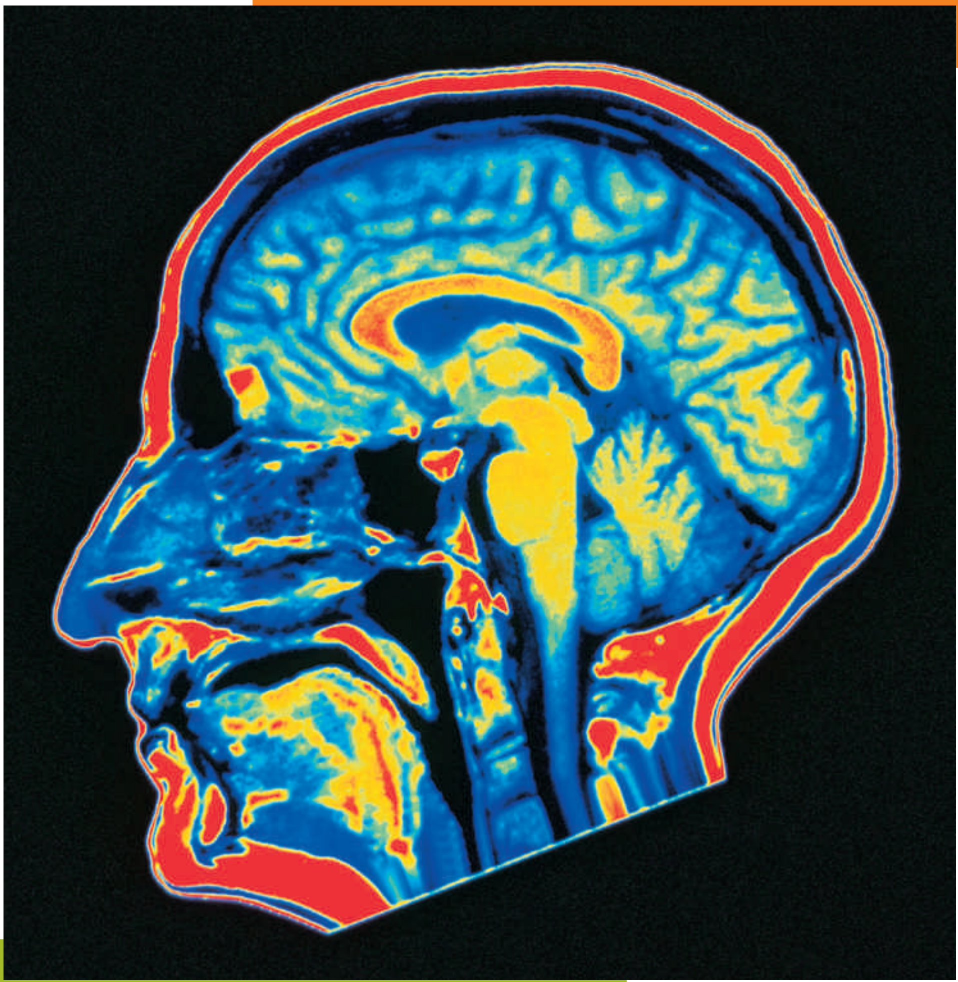
Are the layers of matter like the nested dolls, or is there a final set of elementary particles?

25

The Nucleus

▶As our knowledge of nuclei has grown, whole new technologies have been developed to make use of this new knowledge. The new technologies are as varied as obtaining medical images of our internal organs and determining the age of mummies or artifacts. How can nuclear techniques be used to determine the age of an artifact?

(See page 570 for the answer to this question.)



Scott Camazine/Photo Researchers, Inc.

Magnetic resonance image of a normal human brain.

THE **nucleus** of an atom is unbelievably small. If you could line up a trillion (10^{12}) of them, they would stretch only a distance equal to the size of the period at the end of this sentence. Another way of visualizing these sizes is to imagine expanding things to more human sizes and then comparing relative sizes. If we imagine a baseball as big as Earth, the baseball's atoms would be approximately the size of grapes. Even at this scale, the nucleus would be invisible! To "see" the nucleus, we need to expand one of these grape-sized atoms until it is as big as the Superdome in New Orleans. The nucleus would be in the middle and would be about the size of a grape.

These analogies are a little risky because the quantum-mechanical view does not consider atomic entities to be classical particles. The images do, however, demonstrate the enormous amount of ingenuity required to study this submicroscopic realm of the universe. You don't just pick up a nucleus and take it apart.

We learn about the nucleus by examining what pieces come out—through either naturally occurring radioactivity or artificially induced nuclear reactions. Studying the nucleus is more difficult than studying the atom because we already understood the electric force that held the atom together. There, the task was to find a set of rules that governs the behavior of the atom. These rules were provided by quantum mechanics. In nuclear physics the situation was turned around; quantum mechanics provided the rules, but at first there wasn't a good understanding of the forces.

The Discovery of Radioactivity

Discoveries in science are often not anticipated. Radioactivity is such a case. Radioactivity is a nuclear effect that was discovered 15 years before the discovery of the nucleus itself. Although the production of X rays is not a nuclear effect, their study led to the discovery of radioactivity. Four months after Roentgen's discovery of X rays (Chapter 23), a French scientist, Henri Becquerel, was looking for a possible symmetry in the X-ray phenomenon. Roentgen's experiment had shown that X rays striking certain salts produced visible light. Becquerel wondered whether the phenomenon might be symmetric—whether visible light shining on these fluorescing salts might produce X rays.

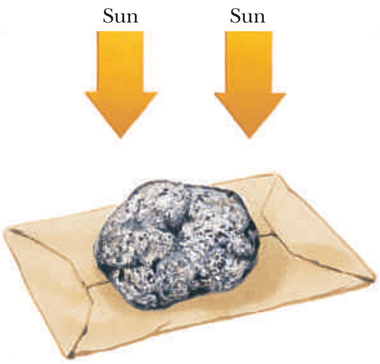


Figure 25-1 Becquerel's experimental setup to test whether X rays would penetrate the paper and expose the photographic plate.

His experiment was simple. He completely covered a photographic plate with paper so that no visible light could expose it. Then he placed a fluorescing mineral on this package and took the arrangement outside into the sunlight (Figure 25-1). He reasoned that the sunlight might activate the atoms and cause them to emit X rays. The X rays would easily penetrate the paper and expose the photographic plate.

The initial results were encouraging; his plates were exposed as expected. However, during one trial, the sky was clouded over for several days. Convinced that his photographic plate would be slightly exposed, he decided to start over. But, being meticulous, he developed the plate anyway. Much to his surprise, he found that it was completely exposed. The fluorescing material—a uranium salt—apparently exposed the photographic plate without the aid of sunlight. Becquerel soon discovered that all uranium salts exposed the plates—even those that did not fluoresce with X rays.

Q: What hypothesis does Becquerel's observation suggest about the origin of the radiation?

A: Because the radiation came from all uranium salts, it is likely that the phenomenon is a property of uranium and not of the particular salt.

This new phenomenon appeared to be a special case of Roentgen's X rays. They penetrated materials, exposed photographic plates, and ionized air molecules; but unlike X rays, the new rays occurred naturally. There was no need for a cathode-ray tube, a high voltage, or even the Sun!

Becquerel did a series of experiments that showed that the strength of the radiation depended only on the amount of uranium present—either in pure form or combined with other elements to form uranium salts. Later it was realized that this was the first clue that radioactivity was a nuclear effect rather than an atomic one. Atomic properties change when elements undergo chemical reactions; this new phenomenon did not. The nuclear origin of this radiation was further supported by observations that the exposure of the photographic plates did not depend on outside physical conditions such as strong electric and magnetic fields or extreme pressures and temperatures.

Pierre Curie, a colleague of Becquerel, and Marie Sklodowska Curie developed a way of quantitatively measuring the amount of radioactivity in a sample of material. Marie Curie then discovered that the element thorium was also radioactive. As with uranium, the amount of radiation depended on the amount of thorium and not on the particular thorium compound. It was also not affected by external physical conditions.

The Curies found that the amount of radioactivity present in pitchblende, an ore containing a large percentage of uranium oxide, was much larger than expected from the amount of uranium present in the ore. They then attempted to isolate the source of this intense radiation, a task that turned out to be difficult and time-consuming. Although they were initially unable to isolate the new substance, they did obtain a sample that was highly concentrated. The new element was named polonium after Marie Curie's native Poland. Further work led to the discovery of another highly radioactive element, radium. A gram of radium emits more than a million times the radiation of a gram of uranium. A sample of radium generates energy at a rate that keeps it hotter than its surroundings. This mysterious energy source momentarily created doubt about the validity of the law of conservation of energy.

FLAWED REASONING

A question on the midterm exam asks: "If radium (which is radioactive) and chlorine (which is not radioactive) combine to form radium chloride, is the compound radioactive?"

Shannon gives the following answer: "Not necessarily. We found that the reactive metal sodium combines with the poisonous gas chlorine to form common table salt. A compound can have very different properties than the elements that form it."

Shannon's answer sounds reasonable, but she is missing an important concept. **What is it?**

ANSWER The *chemical* properties of elements are governed by the structure of their outer electron shells. These properties can change when compounds are formed because the outer shell structure is changed. Radioactivity, on the other hand, is independent of conditions outside the nucleus. Radium chloride is radioactive because it contains radium nuclei.

Types of Radiation

These radioactive elements were emitting two types of radiation. One type could not even penetrate a piece of paper; it was called **alpha (α) radiation** after the first letter in the Greek alphabet. The second type could travel through a meter of air or even thin metal foils; it was named **beta (β) radiation** after the second letter in the Greek alphabet.

Curie | *Eight Tons of Ore*

Nothing in life is to be feared. It is only to be understood.

—Marie Sklodowska Curie

Maria Sklodowska (1867–1934) was born in Warsaw, the daughter of a rather rigid and demanding father and a brilliant, artistic mother. She was well tutored at home, so it was natural for her to want a university education. Warsaw was under Russian rule, and higher education for women was impossible in Poland. Her sister Bronya shared her thirst for learning, and the two made a pact. Maria would work to support her older sister in the pursuit of a medical degree in Paris. With her new economic security, Bronya would then support Maria, who had long dreamed of studying at the Sorbonne.

Maria taught briefly in a Warsaw school and served as a governess in eastern Poland. When she was 24, she eagerly accepted her sister and new brother-in-law's invitation to come and live with them in Paris. Because their apartment was two hours away from the Sorbonne and to save tram fare, Marie—the French version of her name—took an attic room in an ancient and unheated building. She endured bitter cold but rejoiced in her freedom to learn and to work: "It was like a new world to me, the world of science." In 1893 she took her first university degrees, receiving a first in physics and a runner-up in mathematics. Her intention was to obtain a teaching diploma and return to Poland. Fate intervened and she met a charming, shy, and handsome young professor, Pierre Curie; they were married in 1896. Pierre had no sooner finished his final degree than he persuaded his new wife to pursue the same high goal.

She began research under the supervision of a distinguished committee—two of whom would be awarded Nobel Prizes. She sought to explore thoroughly the most critical aspects of the new phenomenon of radioactivity that was discovered by Henri Becquerel. After an exhaustive analysis of radiation intensity and the elements and compounds that produced it, Marie came to a brilliant conclusion: this strange energy came from the interior of the atoms.

With Pierre's assistance she began to assay possible sources of radioactive materials. They located a considerable amount of ore in an old and well-known mine at Joachimstal in Bohemia. The Curies had tons of the ore shipped to Paris, where they dug, boiled, and refined this material in order to isolate one-tenth of a gram of the most intense radiation source—a radium salt. When she presented her thesis research in 1903, her committee noted that this was the most significant work ever submitted by a student at the Sorbonne. Later that year Henri Becquerel and Pierre and Marie Curie shared the Nobel Prize in physics for their work with radioactivity—a word she was the first to use scientifically.

Marie Curie

AIP Niels Bohr Library, W.F. Meggers Collection

The Nobel Prize, the new and mysterious subject of radiation, and the love story of the two young scientists combined to promote the importance of the Nobel Prizes and to focus an intense journalistic attention on the Curies. From that time onward, Marie—Pierre died tragically in 1906 when he was struck by a heavy, horse-drawn freight wagon—was the subject of popular interest to an extent unknown to scientists previously. Marie concentrated her incredible work ethic on rearing her two young daughters and discovering the ultimate element from which the intense radiation in pitchblende emanated. Her reclusive and reticent style later made Albert Einstein a better subject for story-hungry writers.

Despite taboos against women, Marie Curie's outstanding record secured her a position as the first female professor at the Sorbonne. She raised her two young daughters, Irene and Eve, in a circle of elite children of similar age. They were to be instructed only by close friends and university professors, and the standards of their scientific training were extraordinary. Irene Joliot-Curie won the Nobel Prize in chemistry in 1935—and her husband was also a Nobel laureate. Marie was the first of three scientists to win a second Nobel Prize—this time in chemistry for her isolation of pure radium and polonium. Curium, element 96, was named in honor of Marie and Pierre Curie.

World War I shattered the European scientific community. Marie took her tremendous drive and dedication to the trenches. She set up mobile X-ray units and trained a generation of radiologists. Like Florence Nightingale a generation earlier, she took on any military authority who stood in the way of medical treatment.

She did not live quite long enough to see her daughter and son-in-law receive their Nobel Prizes. She died of leukemia on July 4, 1934. She was eventually interred in the great Pantheon. Poland produced her, France nourished her, and the world inherits her great work.

—Pierce C. Mullen, historian and author

Sources: Rosalynd Pflaum, *Grand Obsession: Marie Curie and Her Work* (New York: Doubleday, 1989); Susan Quinn, *Marie Curie: A Life* (New York: Simon & Schuster, 1995); Eve Curie, *Madame Curie* (New York: Doubleday, 1938).

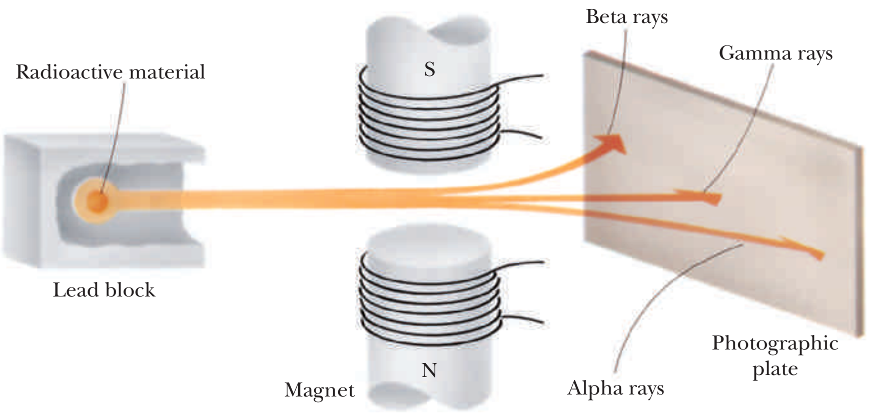


Figure 25-2 Alpha, beta, and gamma radiation behave differently in a magnetic field.

By 1900 several experimentalists had shown that beta radiation could be deflected by a magnetic field, demonstrating that it was a charged particle. These particles had negative charges and the same charge-to-mass ratio as the newly discovered electrons. Later it was concluded that these **beta particles** were in fact electrons that were emitted by nuclei.

In 1903 Rutherford showed that alpha radiation could also be deflected by magnetic fields and that these particles had a charge of +2. (The unit of charge is assumed to be the elementary charge—that is, the magnitude of the charge on the electron or proton.) Because they had a larger charge than electrons and yet were much more difficult to deflect, it was concluded that they were much more massive than electrons. Six years later Rutherford showed that **alpha particles** are the nuclei of helium atoms.

The third type of radiation was discovered in 1900. Naturally, it was named after the third letter of the Greek alphabet and is known as **gamma (γ) radiation.** This radiation has the highest penetrating power; it can travel through many meters of air or even through thick walls. Unlike the other two types of radiation, gamma radiation was unaffected by electric and magnetic fields (Figure 25-2). Gamma rays, like X rays, are now known to be very high-energy photons. Although the energy ranges associated with these labels overlap, gamma-ray photons usually have more energy than X-ray photons, which in turn have more energy than photons of visible light.

The Nucleus

The recognition that radioactivity is a nuclear phenomenon indicated that nuclei have an internal structure. Because nuclei emitted particles, it was natural to assume that nuclei were composed of particles. It was hoped there would be only a small number of different kinds of particles and that all nuclei would be combinations of these.

Rutherford's early work with alpha particles showed that he could change certain elements into others. While bombarding nitrogen with alpha particles, Rutherford discovered that his sample contained oxygen. Repeated experimentation convinced him that the oxygen was being *created* during the experiment. In addition to heralding the beginning of artificially induced transmutations of elements, this experiment led to the discovery of the proton.

Rutherford noticed that occasionally a fast-moving particle emerged from the nitrogen. These particles were much lighter than the bombarding alpha particles and were identified as **protons.** Rutherford and James Chadwick bombarded many of the light elements with alpha particles and found 10 cases in which protons were emitted. By 1919 they realized that the proton was a fundamental particle of nuclei.

The hydrogen atom has the simplest and lightest nucleus, consisting of a single proton. The next lightest element is helium. Its nucleus has approximately four times the mass of hydrogen. Because helium has two electrons, it must have two units of positive charge in its nucleus. If we assume that the helium nucleus contains two protons, we obtain the correct charge but the wrong mass—it would only be twice that of hydrogen. What accounts for the other two atomic mass units? One possibility is that the nucleus also contains two electron–proton pairs. Each pair would be neutral in charge and contribute 1 atomic mass unit. Thus, the helium nucleus might consist of four protons and two electrons.

This scheme had some appeal. It accounted for the electrons emitted from nuclei, and it could be used to "build" nuclei. However, it had several serious defects that caused it eventually to be discarded. For example, the spins of the electron and proton cause each of them to act as miniature magnets, and therefore the magnetic properties of a nucleus should be a combination of those of its protons and electrons. These magnetic values did not agree with the experimental results. The existence of electrons in the nucleus was also incompatible with the uncertainty principle (Chapter 24). If the location of the electron were known well enough to say that it was definitely in the nucleus, its momentum would be large enough to easily escape the nucleus. This left the "extra" mass unexplained.

The Discovery of Neutrons

By 1924 Rutherford and Chadwick began to suspect there was another nuclear particle. The **neutron** would have a mass about the same as the proton's but no electric charge. Chadwick received a Nobel Prize (1935) for the experimental verification of the neutron's existence in 1932. The "extra" mass in nuclei was now explained. Nuclei are combinations of protons and neutrons, as illustrated in Figure 25-3. Helium nuclei are made of 2 protons and 2 neutrons, oxygen nuclei have 8 protons and 8 neutrons, gold nuclei have 79 protons and 118 neutrons, and so on.

When it is not necessary to distinguish between neutrons and protons, they are often called **nucleons.** The number of nucleons in the nucleus essentially determines the atomic mass of the atom because the electrons' contribution to the mass is negligible. The scale of relative atomic masses has been chosen so that the atomic mass of a single atom in atomic mass units is nearly equal to the number of nucleons in the nucleus. This equivalence is attained by setting the mass of the neutral carbon atom with 12 nucleons equal to 12.0000 atomic mass units (Chapter 11). The masses of the electron, proton, and neutron are

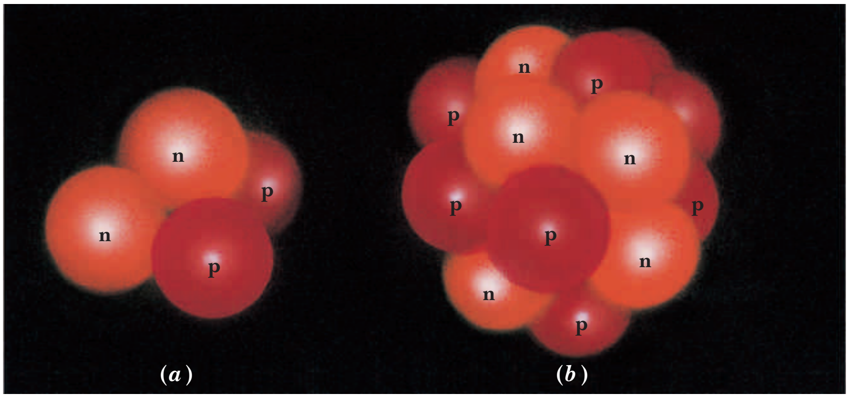


Figure 25-3 The helium nucleus (a) consists of two protons and two neutrons, and the oxygen nucleus (b) has eight protons and eight neutrons.

Table 25-1 *Masses of Electrons, Protons, and Neutrons in Kilograms, Atomic Mass Units, and Units in Which the Mass of the Electron = 1*

Particle	kg	amu	$m_e 1$
Electron	9.109×10^{-31}	0.000 549	1
Proton	1.6726×10^{-27}	1.007 276	1836
Neutron	1.6750×10^{-27}	1.008 665	1839

given in Table 25-1 for several different mass units. The masses of nuclei vary from 1 to about 260 atomic mass units and the corresponding radii vary from 1.2 to 7.7×10^{-15} meter.

Isotopes

While studying the electric and magnetic deflection of ionized atoms, J. J. Thomson discovered that the nuclei of neon atoms are not all the same. The neon atoms did not all bend by the same amount. Because each ion had the same charge, some neon atoms must be more massive than others. It was shown that the lighter ones had masses of about 20 atomic mass units, whereas the heavier ones had masses of about 22 atomic mass units. This discovery destroyed the concept that all atoms of a given element were identical, an idea that had been accepted for centuries. We now know that all elements have nuclei that have different masses. These different nuclei are known as **isotopes** of the given element. Isotopes have the same number of protons but differ in the number of neutrons.

Q: Given that neon is the 10th element, how many neutrons and protons would each of its isotopes have?

A: Because each nucleon contributes about 1 atomic mass unit and neon must have 10 protons, the lighter isotope with 20 atomic mass units must have 10 neutrons and the heavier one with 22 atomic mass units must have 12 neutrons.

Although each isotope of an element has its own nuclear properties, the chemical characteristics of isotopes do not differ. Adding a neutron to a nucleus does not change the electric charge; therefore, the atom's electronic structure is essentially unchanged. Because the electrons govern the chemical behavior of elements, the chemistry of all isotopes of a particular element is virtually the same. Some differences, however, can be detected. There are slight changes in the electronic energy levels that show up in the atomic spectra. The extra mass of the heavier isotopes also slows the rates at which chemical and physical reactions occur.

Hydrogen has three isotopes (Figure 25-4). The most common one contains a single proton. The next most common has one proton and one

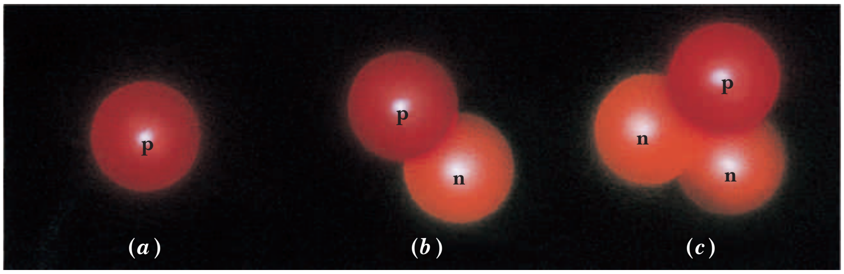


Figure 25-4 Hydrogen has three isotopes: (a) hydrogen, (b) deuterium, and (c) tritium.

neutron; it has about twice the mass of ordinary hydrogen. This "heavy" hydrogen, known as *deuterium,* is stable and occurs naturally as 1 atom out of approximately every 6000 hydrogen atoms. The third isotope has one proton and two neutrons. This "heavy, heavy" hydrogen, known as *tritium,* is radioactive.

Isotopes of other elements do not have separate names. The symbolic way of distinguishing between isotopes is to write the chemical symbol for the element with two added numbers to the left of the symbol. A subscript gives the number of protons, and a superscript gives the number of nucleons—that is, the total number of neutrons and protons. The most common isotope of carbon has six protons and six neutrons and is written ${}^{12}_{6}C$. Because there is some redundancy here (the number of protons is already specified by the chemical symbol), the isotope is sometimes written ${}^{12}C$ and read "carbon-12."

The Alchemists' Dream

The discovery of radioactivity changed another long-held belief about atoms. If the particle emitted during radioactive decay is charged, the resulting nucleus (commonly called the **daughter nucleus**) does not have the same charge as the original (the **parent nucleus**). The parent and daughter are not the same element because the charge on the nucleus determines the number of electrons in the neutral atom, and this number determines the atom's chemical properties. The belief that atoms are permanent was wrong; they can change into other elements. We see that nature has succeeded where the alchemists failed.

Although we can't control the process of nuclear transformation, we can bombard materials as Rutherford did and change one element into another. But what kinds of reactions are possible? Can we, perhaps, change lead into gold? As scientists examined various processes that might change nuclei, they observed that the conservation laws are obeyed. These laws include the conservation of mass–energy, linear momentum, angular momentum, and charge, which we studied earlier. In addition, a new conservation law was discovered, the conservation of nucleons. Although the nucleons may be rearranged or a neutron changed into a proton, the total number of nucleons after the process is the same as before.

conservation of nucleons ▶

The reaction in which Rutherford produced oxygen (O) and a proton (p) by bombarding nitrogen (N) with alpha particles (α) can be written in the form

$$ {}^{4}_{2}\alpha + {}^{14}_{7}N \rightarrow {}^{17}_{8}O + {}^{1}_{1}p $$

where the arrow separates the initial nuclei on the left from the final nuclei on the right. Notice that the conservation of charge is obeyed; there are $2 + 7 = 9$ protons on the left-hand side of the arrow and $8 + 1 = 9$ protons on the right-hand side. The number of nucleons must also be conserved. There are $4 + 14 = 18$ nucleons on the left and $17 + 1 = 18$ nucleons on the right.

Neutrons are effective at producing nuclear transformations because they do not have a positive charge and can penetrate to the nuclei, even with low energies. An example that occurs naturally in the atmosphere is the conversion of nitrogen to carbon via neutron (n) bombardment:

$$ {}^{1}_{0}n + {}^{14}_{7}N \rightarrow {}^{14}_{6}C + {}^{1}_{1}p $$

Let's now look at changes in the nucleus that occur naturally. For example, when a nucleus emits an alpha particle, it loses two neutrons and two protons. Therefore, the parent nucleus changes into a nucleus that is two elements lower in the periodic chart. This daughter nucleus has a nucleon number that is four less. For instance, when $^{226}_{88}\text{Ra}$ decays by alpha decay, the daughter nucleus has $88 - 2 = 86$ protons and $226 - 4 = 222$ nucleons. The periodic table printed on the inside front cover of this text tells us that the element with 86 protons is radon, which has the symbol Rn. Therefore, the daughter nucleus is $^{222}_{86}\text{Rn}$. This process can be written in symbolic form as

$$^{226}_{88}\text{Ra} \rightarrow {}^{222}_{86}\text{Rn} + {}^{4}_{2}\alpha$$

◀ alpha decay

Are You On the Bus?

Q: What daughter results from the alpha decay of $^{232}_{90}\text{Th}$?

A: The daughter will have $232 - 4 = 228$ nucleons and $90 - 2 = 88$ protons, so it must be $^{228}_{88}\text{Ra}$.

FLAWED REASONING

Two students are discussing alpha decay:

Brielle: "Our teacher claims that the alchemists were right; atoms can be changed from one element to another. She said that radium becomes radon when it emits an alpha particle, but that doesn't make sense. When radium gives up two protons and two neutrons, it still has the same number of electrons. Therefore, it should still react chemically like radium."

Hyrum: "Well, maybe the radium atom loses two electrons after the alpha decay, so it becomes electrically neutral. I think the atom is still radium until the electrons leave."

What important principle are these students misunderstanding?

ANSWER It is the number of protons, not electrons, in an atom that defines its chemical identity. A chlorine atom with an extra electron is a chlorine ion, not an argon atom. As soon as the alpha particle is ejected from the nucleus of the radium atom, the energy levels change to those of the radon atom.

The electron that is emitted in beta (β) decay is not one of those around the nucleus, nor is it one that already existed in the nucleus. The electron is ejected from the nucleus when a neutron decays into a proton. (We will study the details of this process in Chapter 27.) A new element is produced because the number of protons increases by one. The number of neutrons decreases by one, but it is the change in the proton number that causes the change in element. The daughter nucleus is one element higher in the periodic chart and has the same number of nucleons. For example,

$$^{24}_{11}\text{Na} \rightarrow {}^{24}_{12}\text{Mg} + {}^{\;\,0}_{-1}\beta^{-}$$

◀ beta minus decay

Are You On the Bus?

Q: What is the daughter of $^{228}_{89}\text{Ac}$ if it undergoes beta decay?

A: The daughter must have the same number of nucleons and one more proton. Therefore, it is $^{228}_{90}\text{Th}$.

An inverse beta-decay process has also been observed. In this process an atomic electron (e) in an inner shell is captured by one of the protons in the nucleus to become a neutron. This **electron capture** decreases the number of protons by one and increases the number of neutrons by one. Therefore, the daughter nucleus belongs to the element that is one lower in the periodic table and has the same number of nucleons as the parent. For example,

electron capture ▶

$$^{7}_{4}\text{Be} + {}^{0}_{-1}\text{e} \rightarrow {}^{7}_{3}\text{Li}$$

This process is detected by observing the atomic X rays given off when the outer electrons drop down to fill the energy level vacated by the captured electron. The evidence for this transformation is very convincing; the spectral lines are characteristic of the daughter nucleus and not the parent nucleus.

Are You On the Bus?

Q: What daughter is produced when $^{234}_{93}\text{Np}$ undergoes electron capture?

A: Once again, the number of nucleons does not change, only this time the number of protons decreases by one to yield $^{234}_{92}\text{U}$.

A third type of beta decay was observed in 1932. In this case the emitted particle has one unit of positive charge and a mass equal to that of an electron. This positive electron (**positron**) is the antiparticle of the electron, a concept that will be described further in Chapter 27. The emission of a positron results from the decay of a proton into a neutron. This process is called *beta plus decay* to distinguish it from *beta minus decay,* the process that produces a negative electron. Like electron capture, this decreases the number of protons by one and increases the number of neutrons by one. For example,

beta plus decay ▶

$$^{15}_{8}\text{O} \rightarrow {}^{15}_{7}\text{N} + {}^{0}_{1}\beta^{+}$$

Are You On the Bus?

Q: What is the result of $^{11}_{6}\text{C}$ decaying via beta plus decay?

A: Because a proton turns into a neutron, we have $^{11}_{5}\text{B}$.

Nuclei that emit gamma rays do not change their identities, because gamma rays are high-energy photons and do not carry charge. The nucleus has discrete energy levels analogous to those in the atom. If the nucleus is not in the ground state, it may change to a lower energy state with the emission of the gamma ray. This process often happens after a nucleus has undergone one of the other types of decay to become an excited state of the daughter nucleus. Table 25-2 summarizes the changes produced by each type of decay.

▶ Extended presentation available in the *Problem Solving* supplement

Radioactive Decay

Equal amounts of different radioactive materials do not give off radiation at the same rate. For example, 1 gram of radium emits 20 million times as much

Table 25-2 *Changes in the Number of Protons, Neutrons, and Nucleons for Each Type of Radioactive Decay*

	Changes in the Number of		
Decay	**Protons**	**Neutrons**	**Nucleons**
α	−2	−2	−4
β^{-}	+1	−1	0
Electron capture	−1	+1	0
$\beta+$	−1	+1	0
γ	0	0	0

radiation per unit time as 1 gram of uranium. The **activity** of a radioactive sample is a measure of the number of decays that take place in a certain time. The unit of activity is named the **curie** (Ci) after Marie Curie and has a value of 3.7×10^{10} decays per second, which is the approximate activity of 1 gram of radium.

◀ curie

Two factors determine the activity of a sample of material. First, the activity is directly proportional to the number of radioactive atoms in the sample. Two grams of radium will have twice the activity of 1 gram. Second, the activity varies with the type of nucleus. Some nuclei are quite stable, whereas others decay in a matter of seconds and still others in millionths of a second.

Both factors can be illustrated with an analogy that emphasizes the random nature of radioactive decay. Imagine that you have 36 dice. Throwing the dice can simulate the radioactive decay process. Each throw represents a certain elapsed time. Assume that any die whose number 1 is face up represents an atom that has decayed during the last period.

On the average, 6 of the 36 dice will have 1s up.

Let's look at the "activity" of the sample of dice. How many dice would you expect to have 1s up after the first throw? Because each die has six faces that are equally likely to appear as the top face, there is a 1-in-6 chance of having 1s up. Because there are 36 dice in the sample, we expect that, on the average, 6 (that is, $\frac{1}{6}$ of 36) will "decay" on the first throw. This number represents the activity of the sample.

If you double the number of dice in your sample, how many of the 72 dice should show 1s up after the first throw? On average, 12 ($\frac{1}{6}$ of 72) will have 1s up. From this analogy we see that the level of radioactivity is directly proportional to the number of radioactive atoms in a sample.

In a sample of radioactive material, the number of nuclei of the original isotope continually decreases, which decreases its activity. To illustrate this, imagine that we once again have 36 dice in our sample. After each throw of the dice, we remove the dice with 1s up. They are no longer part of the sample because they have changed to a new element. After the first throw there will be, on the average, 6 dice that decay. Removing them reduces the sample size to 30.

Q: On average, how many of these 30 dice do you expect to have 1s up on the next throw?

A: The number of 1s up will probably be $\frac{1}{6} \times 30 = 5$.

Removing the 5 dice that are expected to have 1s up on the second throw leaves a sample size of 25. Each successive throw of the dice yields a smaller sample size and consequently a lower level of activity on the next throw. The same is true of the radioactive sample. As with the dice, when a nucleus decays, it is no longer part of the sample. The activity of the radioactive sample decreases with time.

This change in the activity with time has a simple behavior, due to the probabilistic nature of radioactivity. The graph in Figure 25-5 shows this behavior. Notice that the time it takes the activity to drop to one-half its value is constant throughout the decay process. This time is called the **half-life** of the sample. In one half-life the activity of the sample decreases by a factor of 2. During the next half-life, it decreases by another factor of 2, to $\frac{1}{4}$ of its initial value. After each additional half-life, the activity would be $\frac{1}{8}$, $\frac{1}{16}$, $\frac{1}{32}$, . . . , that of the original value. It does not matter when you begin counting. If you wait 1 half-life, your counting rate drops by one-half.

Q: If a sample of material has an activity of 20 millicuries, what activity do you expect after waiting 2 half-lives?

A: After waiting 1 half-life, the activity will be half as much, namely, 10 millicuries. After waiting the other half-life, the activity will drop to half of this value. Therefore, the activity will be 5 millicuries.

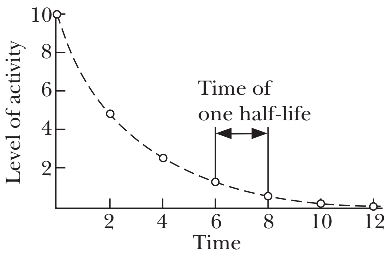


Figure 25-5 A graph of the activity of a radioactive material versus time. Notice that the time needed for the activity to decrease by a factor of 2 is always the same.

Twelve-sided Arabian dice have a smaller probability for a given number to be on top.

This decay law also applies to the number of radioactive nuclei remaining in the sample. The time it takes to reduce the population of radioactive nuclei by a factor of 2 is also equal to the half-life. The important point is that you do not get rid of the radioactive material in 2 half-lives. Let's say that you initially have 1 kilogram of a radioactive element. One half-life later you will have $\frac{1}{2}$ kilogram. After 2 half-lives, you will have $\frac{1}{4}$ kilogram, and so on. In other words, one-half of the remaining radioactive nuclei decays during the next half-life.

The second factor that determines the activity of a sample depends on the character of the nuclei. As we saw in the previous chapter, quantum mechanics determines the probability that something will occur. Therefore, the dice analogy is especially appropriate for nuclear decays. The probability in our dice analogy depends on the number of faces on each die. Six faces means there is a probability of 1 in 6 that a given face will be up on each throw of the dice. Imagine that instead of using 6-sided dice, we use Arabian dice, which have 12 sides. In this case there are more alternatives, and the probability of 1s up is lower. Each die has a 1-in-12 chance of decaying. On the first throw of 36 dice, we would expect an average of 3 dice with 1s up. The half-life of the Arabian dice is twice as long. This variation also occurs with radioactive nuclei, but with a much larger range of probabilities. Nuclear half-lives range from microseconds to trillions of years.

This process is all based on the probability of random events. With dice it is the randomness of the throwing process; with radioactive nuclei it is the quantum-mechanical randomness of the behavior of the nucleons within the nucleus. As with all probabilities, any prediction is based on the mathematics of statistics. Each time we throw 36 dice, we should not expect exactly 6 dice to have 1s up. Sometimes there will be only 5; other times there may be 7 or 8. In fact, the number can vary from 0 to 36! However, statistics tells us that as the total number of dice increases, our ability to predict also increases. Because there are more than 10^{15} nuclei in even a small sample of radioactive material, our predictions of the number of nuclei that will decay in a half-life are very reliable.

Although our predictions get better with large numbers, we must remember the probabilistic nature of dice and radioactive nuclei; we cannot predict the behavior of an individual nucleus. One particular nucleus may last a million years, whereas an "identical" one may last only a millionth of a second.

Radioactive Clocks

The decay rate of a radioactive sample is unaffected by physical and chemical conditions ordinarily found on Earth (excluding the extreme conditions found in nuclear reactors or bombs). Normal conditions involve energies that can rearrange electrons around atoms but cannot cause changes in nuclei. The nucleus is protected by its electron cloud and the large energies required to change the nuclear structure, which means that radioactive samples are good time probes into our history. Knowing the half-life of a particular isotope and the products into which it decays, we can determine the relative amount of parent and daughter atoms and calculate how long the isotope has been decaying. In effect, we have a radioactive "clock" for dating events in the past.

One of the first such clocks gave us the age of Earth. Before this, many different estimates were made by different groups. A 17th-century Irish bishop traced the family histories in the Old Testament and obtained a figure of 6000 years. Another estimate was obtained by calculating the length of time required for all the rivers of the world to bring initially freshwater oceans up to their present salinity. Another value was obtained by assuming that the Sun's energy output was due to its slow collapse under the influence of the gravitational force. These latter two methods yielded estimates on the order of 100,000 years. Charles Darwin suggested that Earth was much older, as his theory of evolution indicated that more time was required to produce the observed biodiversity.

This is one of the rocks brought back from the Moon by the Apollo astronauts.

The best value was obtained through the radioactivity of uranium. Uranium and the other heavy elements are formed only during supernova explosions that occur near the end of some stars' lives. Therefore, any uranium found on Earth was present in the gas and dust from which the solar system formed. Uranium-238 decays with a half-life of 4.5 billion years into a stable isotope of lead ($^{206}_{82}Pb$) through a long chain of decays. Suppose we find a piece of igneous rock and determine that one-half of the uranium-238 has decayed into lead-206. We then know that the rock was formed at a time in the past equal to 1 half-life. The oldest rocks are found in Greenland and have a ratio of lead-206 to uranium-238 of a little less than 1, meaning that a little less than one-half of the original uranium-238 has decayed. This indicates that the rocks are about 4 billion years old. Incidentally, the rocks brought back from the Moon have similar ratios, establishing that Earth and Moon were formed about the same time.

Another radioactive clock is used to date organic materials. Living organisms contain carbon, which has two isotopes of interest—the stable isotope $^{12}_{6}C$ and the radioactive isotope $^{14}_{6}C$, which has a half-life of 5700 years. Cosmic rays bombarding our atmosphere continually produce carbon-14 to replace those that decay. Because of this replacement, the ratio of carbon-12 to carbon-14 in the atmosphere is relatively constant. While the plant or animal is living, it continually exchanges carbon with its environment and therefore maintains the same ratio of the two isotopes in the tissues that exists in the atmosphere. As soon as it dies, however, the exchange ceases and the amount of carbon-14 decreases because of the radioactive decay. By examining the ratio of the amount of carbon-14 to that of carbon-12 in the plant or animal, we can learn how long ago death occurred.

WORKING IT OUT *Radioactive Dating*

As an example of radioactive dating, suppose a piece of charred wood is found in a primitive campsite. To find out how long ago the campsite was occupied, one examines the ratio of carbon-14 to carbon-12 in the wood. Suppose that the ratio is only one-eighth of the atmospheric value. Roughly how long has it been since the piece of wood was put into the fire?

As long as the piece of wood was part of a living tree, the ratio of carbon-14 to carbon-12 in the wood is the same as the ratio in the atmosphere. Once the wood is cut from the tree, carbon-14 in the wood begins to decay and is not replenished from the atmosphere. Because $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$, the wood was removed from the living tree 3 half-lives ago. This gives an approximate age for the campsite of 3×5700 years $= 17{,}100$ years.


Paul Hanny/Eyedea Presse

Radiocarbon dating of this skeleton found in the Tyrolean Alps has helped estimate that the man lived around 5000 years ago.

Because the Dead Sea Scrolls were written on parchment, their age was determined by this technique. Similar studies indicate that the first human beings may have appeared on the North American continent about 27,000 years ago.

Radioactive dating with carbon-14 is not useful beyond 40,000 years (seven half-lives), as the amount of carbon-14 becomes very small. Other radioactive clocks can be used to go beyond this limit. These clocks indicate that humans, or at least prehumans, may have been around for more than 3.5 million years, mammals about 200 million years, and life for 3–4 billion years.

Radiation and Matter

How would you know if a chunk of material was radioactive? Radiation is usually invisible. However, if the material is extremely radioactive, like radium, the enormous amount of energy being deposited in the material by the radiation can make it hotter than its surroundings. In extreme cases it may even glow. A less radioactive sample may leave evidence of its presence over a longer time. Pierre Curie developed a radioactive burn on his side because of his habit of carrying a piece of radium in his vest pocket.

We learn about the various types of radiation through their interactions with matter. In most cases, these interactions are outside the range of direct human observation. One exception is light. Although we don't see photons flying across the room, we do see the interaction of these photons with our retinas. Our eyes are especially tuned to a small range of photon energy. Other radiations are detected by extending our senses with instruments. For exam-

Everyday Physics | *Smoke Detectors*

Many of the uses of radioactive isotopes are not often apparent to most of us. For example, some smoke detectors (Figure A) commonly found in our homes use radioactive americium to detect the smoke particles. As shown in the schematic diagram of Figure B, the weak radioactive source ionizes the air, allowing a small current to flow between the electrodes. When smoke enters the detector, the ions are attracted by the smoke particles and stick to them. The larger mass of the smoke particles causes them to move slower than the ions, reducing the current in the circuit and setting off the alarm.

Americium-241 is an alpha emitter with a half-life of 433 years, so the level of ionization does not decrease significantly over the lifetime of the detector. This isotope is obtained as a by-product of the processing of fuel rods from nuclear reactors.

1. Explain how the air near a radioactive source may become ionized.
2. Explain how the smoke detector uses the ionized air to detect smoke particles.


© Radius Images RF/Jupiterimages

Figure A A household smoke detector.

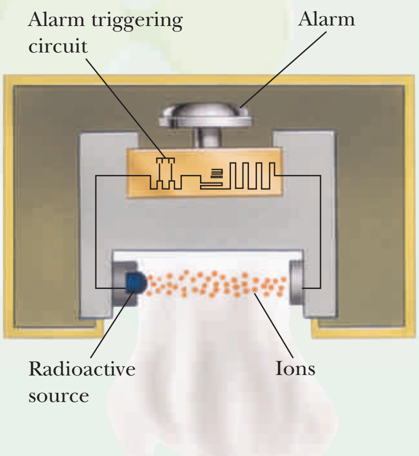


Figure B Diagram of a smoke detector.

ple, the electromagnetic radiation from radio and television stations is not detected by our bodies but interacts with the electrons in antennas.

We also observe nuclear radiations through their interactions with matter. Alpha and beta particles interact with matter through their electric charge. For example, in Becquerel's discovery, the charged particles interacted with the photographic chemicals to expose the film. For the most part, these charged particles interact with the electrons in the material. As we saw in Rutherford's scattering experiment, they rarely collide with nuclei. As the alpha and beta particles pass through matter, they interact with atomic electrons, causing them to jump to higher atomic levels or to leave the atom entirely. This latter process is called **ionization.**

The relatively large mass of alpha particles compared with electrons means that the alpha particles travel through the material in essentially straight lines. This is like a battleship passing through a flotilla of canoes. Because beta particles are electrons, they are more like canoes hitting canoes and have paths that are more ragged. In both cases the colliding particles deposit energy in the material in a more or less continuous fashion. Therefore, the distance they travel in a material is a measure of their initial energy. We can determine this energy experimentally by measuring the distance the particle travels—that is, its range. Some sample ranges are given in Table 25-3.

The interaction of gamma rays with matter is quite different. Gamma rays do not lose their energy in bits and pieces. (There is no such thing as half a photon.) Whenever a photon interacts with matter, it is completely annihilated in one of three possible ways. The photon's energy can ionize an atom, be transferred to a free electron with the creation of a new photon, or be converted into a pair of particles according to Einstein's famous equation $E = mc^2$. If we count the number of gamma rays surviving at various distances in a material and make a graph, we would obtain a curve like the one in Figure 25-6. This curve has the same shape as the one for radioactive decay in Figure 25-5, which means that gamma rays do not have a definite range but are removed from the beam with a characteristic half-distance. That is, one-half of the original gamma rays are removed in a certain length, half of the remaining are removed in the next region of this length, and so on. From Table 25-4 you can see that gamma rays are much more penetrating than alpha or beta particles of the same energy.

The electromagnetic radiation from the local radio station is not detected by our bodies, but interacts with the radio's antenna.

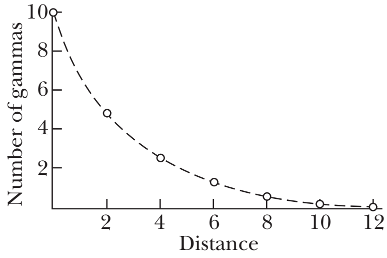


Figure 25-6 A graph of the number of gamma rays surviving at various distances through a material. Notice the similarity with the graph of the radioactivity in Figure 25-5.

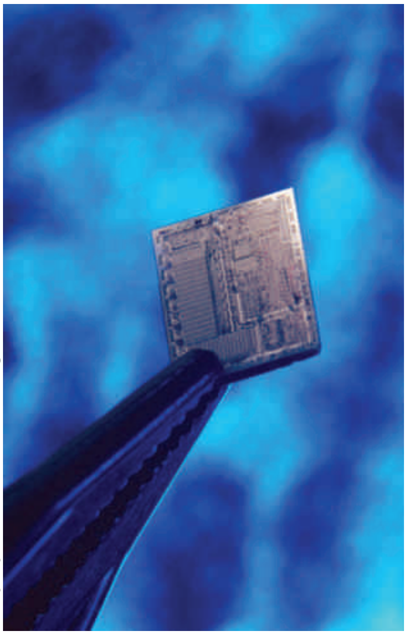
Q: How far must a beam of 10-million-electron-volt gamma rays travel in aluminum before it is all gone?

A: Theoretically, this never happens; some of the gamma rays will travel very large distances. However, by the time the beam has traveled 7 half-distances, less than 1% of the gamma rays remain.

Table 25-3 *Ranges of Alpha Particles, Protons, and Electrons in Air and Aluminum*

	Range in Air (cm)			Range in Aluminum (cm)		
Energy (MeV)*	α	p	e^-	α	p	e^-
1	0.5	2.3	314	0.0003	0.0014	0.15
5	3.5	34	2000	0.0025	0.019	0.96
10	10.7	117	4100	0.0064	0.063	1.96

*MeV (million electron volts) is an energy unit equal to 1.6×10^{-13} joule.



The 200,000 individual electronic components in this small crystalline chip are especially sensitive to radiation damage.

Table 25-4 *Half-Distances for the Absorption of Gamma Rays by Aluminum*

Energy (MeV)*	Half-Distance (cm)
1	4.2
5	9.1
10	11.1

* MeV (million electron volts) is an energy unit equal to 1.6×10^{-13} joule.

Any radiation passing through matter deposits energy along its path, resulting in temperature increases, atomic excitations, and ionization. The ionization caused by radiation can damage a substance if its properties depend strongly on the detailed molecular or atomic structure. For example, radiation can damage the complex molecules in living tissues and cause cancer or genetic defects. Damage can also occur in nonliving objects, such as transistors and integrated circuits. These modern electronic devices are made of crystals in which the atoms have definite geometric arrangements. Integrated circuits, such as those found in pocket calculators and computers, contain thousands of individual electronic components in small crystalline chips. A disruption of these atomic structures can change the electronic properties of these components. If the radiation damage is severe, the device could fail. This hazard is obviously serious if the device is a control component for a nuclear reactor or part of the guidance system for a missile. However, there is not enough radiation around the university computer for you to expect all of your grades to change into A's.

WORKING IT OUT *Gamma Ray Shield*

Gamma rays are highly penetrating and produce serious damage when absorbed by living tissues. Consequently, those working near such dangerous radiation must be protected by a shield of absorbing materials. If you are working near a source of 5-MeV gamma rays, and you are protected by an aluminum wall that is 27.3 cm thick, what fraction of the gamma rays are getting past your shield?

Using Table 25-4, we see that the half-distance for 5-MeV gamma rays is 9.1 cm of aluminum. Only half of the original gamma rays survive after passing through the first 9.1 cm of the wall. Because the aluminum wall is three times as thick as this half-distance, we find that $\frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} = \frac{1}{8}$ of the gamma rays are getting through the shield and reaching you. Perhaps you should have built the shield wall thicker, or used a more absorbing material, such as lead.

Biological Effects of Radiation

The ionization caused by radiation passing through living tissue can destroy organic molecules if the electrons are involved in molecular binding. If too many molecules are destroyed in this fashion or if DNA molecules are destroyed, cells may die or become cancerous.

The effects of radiation on our health depend on the amount of radiation absorbed by living tissue and the biological effects associated with this absorption. A **rad** (the acronym from *r*adiation *a*bsorbed *d*ose) is the unit used to designate the amount of energy deposited in a material. One rad of radiation deposits 0.01 joule per kilogram of material. Another unit, the **rem** (*r*oentgen *e*quivalent in *m*ammals), was developed to reflect the biological effects caused by the radiation. Different radiations have different effects on our bodies.

Alpha particles, for example, deposit more energy per centimeter of path than electrons with the same energy; therefore, the alpha particles cause more biological damage. One rad of beta particles can result in 1–1.7 rem of exposure, 1 rad of fast neutrons or protons may result in 10 rem, and 1 rad of alpha particles produces between 10 and 20 rem. The rad and the rem are nearly equal for photons. Because most human exposure involves photons and electrons, the two units are roughly interchangeable when talking about typical doses.

Knowing the amount of energy deposited or even the potential damage to cells from exposure to radiation is still not a prediction of the future health of an individual. The biological effects vary considerably among individuals depending on their age, health, the length of time over which the exposure occurs, and the parts of the body exposed. Large doses, such as those resulting from the nuclear bombs exploded over Japan or the accident at the nuclear reactor at Chernobyl in the former Soviet Union (Figure 25-7), cause radiation sickness, which can result in vomiting, diarrhea, internal bleeding, loss of hair, and even death. It is virtually impossible to survive a dose of more than 600 rem to the whole body over a period of days. An exposure of 100 rem in the same period causes radiation sickness, but most people recover. For comparison, the maximum recommended occupational dose is 5 rem per year, the maximum rate recommended for the general public by the U.S. Environmental Protection Agency is 0.5 rem per year, and the natural background radiation is about 0.3 rem per year.

Sovfoto/Eastfoto

Figure 25-7 One of the world's major nuclear reactor accidents happened in April 1986 at Chernobyl in the former Soviet Union. This photograph shows the structure built to contain the leaking radiation.

Obtaining data on the health effects of exposures to low levels of radiation is difficult, primarily because the effects are masked by effects not related to radiation and the effects do not show up for a long time. Although cancers such as leukemia may show up in two to four years, the more prevalent tumorous cancers take much longer. Imagine conducting a free-fall experiment with an apple in which the apple doesn't begin to move noticeably for three years. Even after you spot its motion, you are compelled to ask whether it occurred because of your actions or something else. When cause and effect are so widely separated in time, making connections is difficult. For example, because there is already a high incidence of cancer, it is hard to determine whether any increase is due to an increase in radiation or to some other factor. On the other hand, large doses of radiation do cause significant increases in the incidence of cancer. Marie Curie died of leukemia, most likely the result of her long-term exposure to radiation.

Genetic effects due to low-level radiation are also difficult to determine. These effects can be passed on to future generations through mutation of the reproductive cells. Although mutations are important in the evolution of species, most of them are recessive. It is generally agreed that an increase in the rate of mutations is detrimental.

© Royalty-free/Corbis

Air travelers implicitly accept the risk of the increased radiation for the benefits of quicker travel.

Any additional nuclear radiation hitting our bodies is detrimental. However, we live in a virtual sea of radiation during our entire lives. Exposure to some of this radiation is beyond our control, but other exposure is within our control. Indeed, many of the "nuclear age" debates center on this issue of assessing the effects of *additional* radiation on the health of the population and evaluating its risks and benefits. As an example, the increased radiation exposure during air travel due to the reduced shielding of the atmosphere is about 0.5 millirem per hour. This increase is not much for an occasional traveler, but may result in an additional 0.5 rem per year for an airplane pilot, which equals the maximum recommended dose.

The average dosage rates for a variety of sources are given in Table 25-5. A word of caution is appropriate here. Although the concept of averaging helps make some comparisons, in some situations the value of the average is quite meaningless. Consider, for example, the amount of radiation our population receives from the nuclear power industry. The bulk of this radiation exposure

Table 25-5 *Average Annual Radiation Doses**

Source	Dose (mrem/yr)
Cosmic rays	30
Surroundings	30
Internal	40
Radon	200
Naturally occurring	300
Medical	50
Consumer products	5
Nuclear power	5
Human-made	60
Total	360

*Frank E. Gallagher III, California Campus Radiation Safety Officers Conference, September 1993.

occurs for the workers in the industry. Most of the rest of us get very little radiation from this source. This situation is similar to putting one foot in ice water, the other foot in boiling water, and claiming that on the average you are doing fine.

Radiation around Us

It is impossible to get away from all radiation. The radiation that is beyond our control comes from the cosmic rays arriving from outer space, from reactions in our atmosphere initiated by these cosmic rays, from naturally occurring radioactive decays in the material around us, and from the decay of radioactive isotopes (mostly potassium-40) within our bodies. In fact, even table salts that substitute potassium for sodium are radioactive. Radiation is part of the world in which we live. The radiations within our control include testing of nuclear weapons, nuclear power stations, and medical radiation used for diagnosing and treating diseases.

Medical sources of radiation *on average* contribute less to our yearly dose than the background radiation. The risks of diagnostic X rays have decreased over the years with new improvements in technology. Modern machines and more sensitive photographic films have greatly reduced the exposure necessary to get the needed information. The exposure from a typical chest X ray is 0.01 rem.

We saw in Chapter 23 that X rays can be used to examine internal organs and other structures for abnormalities. During this process, however, some cells are damaged or killed. We need to ask, is the possible damage worth the benefits of a better treatment based on the information gained? In most cases the answer is yes. In other cases the answer ranges from a vague response to a definite no. If your physician suspects that your ankle is broken, the benefits of having an X ray are definitely worth the risks. On the other hand, having an X ray of your lungs as part of an annual physical exam is not felt to be worth the risks. However, if there is good reason to suspect lesions or a tumor, the odds are in favor of having the X ray.

The largest doses of medically oriented radiation occur during radiation treatment of cancer. In these cases radiation is used to deliberately kill some cells to benefit the patient. Because a beam of radiation causes damage along its entire path, the beam is rotated around the body to minimize damage to normal cells. This procedure is shown in Figure 25-8. Only the cells in the overlap region (the cancerous tumor) get the maximum dosage. Alternative techniques use beams of charged particles. Because charged particles deposit energy at the highest rate near the end of their range, the damage to normal cells along the entrance path is minimized.

Sometimes radioactive materials are ingested for diagnostic or treatment purposes. Our bodies do not have the ability to differentiate between various isotopes of a particular chemical element. If a tumor or organ is known to accumulate a certain chemical element, a radioactive isotope of that element can be put into the body to treat the tumor or to produce a picture of the tumor or organ. For instance, because iodine collects in the thyroid gland, iodine-131, a beta emitter, can be used to kill cells in the thyroid with little effect on more distant cells.

With each source of radiation the debate returns to the question of risk versus benefit: does the potential benefit of the exposure exceed the potential risk?

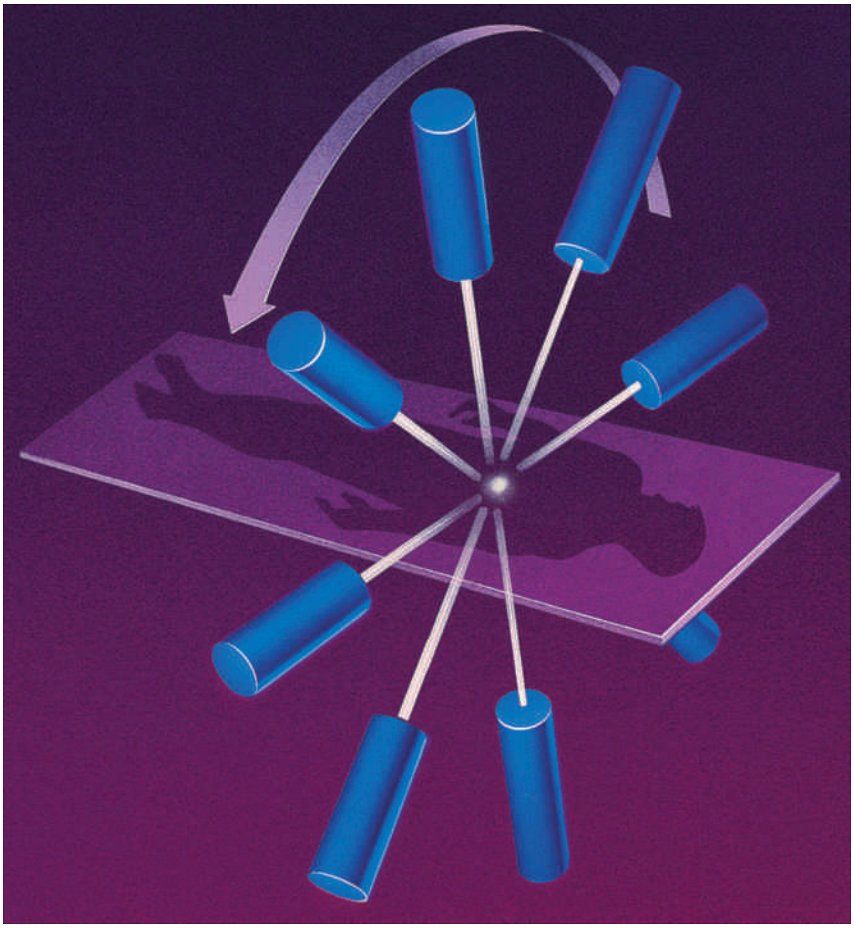


Figure 25-8 During cancer treatment, the direction of the radiation beam is changed to minimize the damage to normal cells surrounding a tumor.

Radiation Detectors

Many devices have been developed to detect nuclear radiation. The earliest was the fluorescent screen Rutherford used in his alpha-particle experiments. Alpha particles striking the screen ionized some of the atoms on the screen. When these atomic electrons returned to their ground states, visible photons were emitted. Rutherford and his students used a microscope to count the individual flashes.

The fluorescent screen is just one example of a *scintillation detector,* a detector that emits visible light on being struck by radiation. The most familiar device of this type is the television screen. Scintillation detectors can be combined with electronic circuitry to automatically count the radiation. When a photon enters the device, it strikes a photosensitive surface and ejects an electron via the photoelectric effect (Chapter 23). A voltage then accelerates this electron so that it strikes a surface with sufficient energy to free two or more electrons. These electrons are accelerated and release additional electrons when they strike the next electrode. A typical photomultiplier, like the one in Figure 25-9, may have 10 stages, with a million electrons released at the last stage. This signal can then be counted electronically. Furthermore, the signal is proportional to the energy deposited in the scintillation material, and hence it gives the energy of the incident radiation.

Everyday Physics | *Radon*

A source of radiation that is partly under our control is the radioactive gas radon. Much attention has been focused by the media on the presence of indoor radon, especially in the air of some household basements. This awareness came about in part because of energy conservation efforts. In attempts to reduce heating bills, many homeowners improved their insulation and sealed many air leaks. This resulted in less air circulation within homes and allowed the concentration of radon in the air to increase.

Radioactive Decay

${}^{238}_{92}\text{U} \rightarrow$	${}^{234}_{90}\text{Th}$	$+\ \alpha$	$(9.5 \times 10^9$ years)
	$\downarrow$		
	${}^{234}_{91}\text{Pa}$	$+\ \beta^-$	(24 days)
	$\downarrow$		
	${}^{234}_{92}\text{U}$	$+\ \beta^-$	(6.7 hours)
	$\downarrow$		
	${}^{230}_{90}\text{Th}$	$+\ \alpha$	$(2.5 \times 10^5$ years)
	$\downarrow$		
	${}^{226}_{88}\text{Ra}$	$+\ \alpha$	$(7.5 \times 10^4$ years)
	$\downarrow$		
	${}^{222}_{86}\text{Rn}$	$+\ \alpha$	(1622 years)
	$\downarrow$		
	${}^{218}_{84}\text{Po}$	$+\ \alpha$	(3.85 days)
	$\downarrow$		
	${}^{214}_{82}\text{Pb}$	$+\ \alpha$	(3 minutes)
	$\downarrow$		
	${}^{214}_{83}\text{Bi}$	$+\ \beta^-$	(27 minutes)
	$\downarrow$		
	${}^{214}_{84}\text{Po}$	$+\ \beta^-$	(19.7 minutes)
	$\downarrow$		
	${}^{210}_{82}\text{Pb}$	$+\ \alpha$	$(10^{-4}$ seconds)
	$\downarrow$		
	${}^{210}_{83}\text{Bi}$	$+\ \beta^-$	(19 years)
	$\downarrow$		
	${}^{210}_{84}\text{Po}$	$+\ \beta^-$	(5 days)
	$\downarrow$		
	${}^{206}_{82}\text{Pb}$	$+\ \alpha$	(138 days)

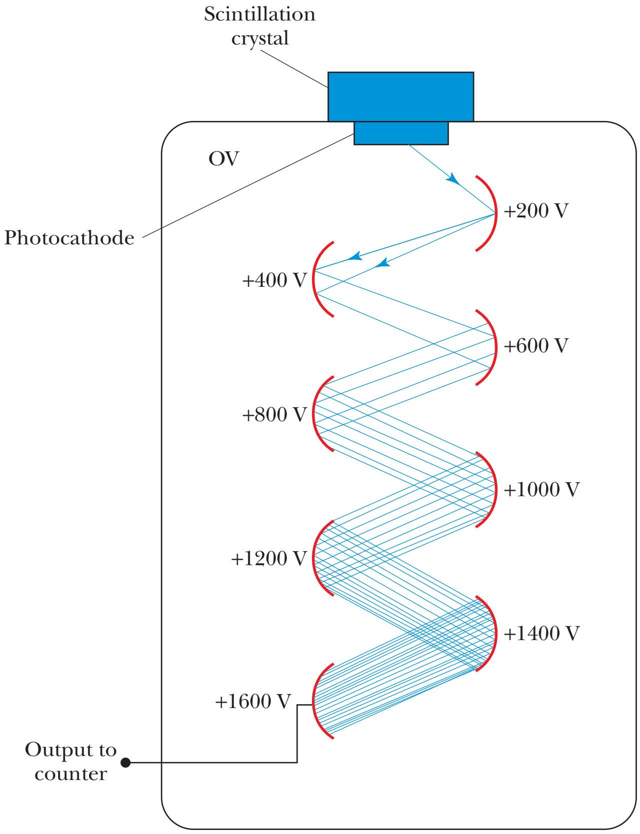
A commercially available kit for testing radon gas levels in homes.

The source of the radon is uranium ore that exists in the ground; the ore's quantities vary geographically. Through a long chain of decays shown in the table, the uranium eventually becomes a stable isotope of lead. All the radioactive daughters are solids except one, the noble gas radon (Rn). This gas can travel through the ground and enter basements of homes through small (or large) cracks in the basement floors or walls. Because radon is an inert gas, it doesn't deposit on walls and leave the air. Thus, it can be inhaled into a person's lungs and become trapped there. In this case, each of the eight subsequent decays causes the lungs to experience additional radiation and possible damage. The maximum "safe" level of radon has been established by the Environmental Protection Agency at 4×10^{-12} curie per liter. Kits to test for excessive concentrations are available through retail outlets. If high levels are found, the homeowner can take measures to ventilate the radon and to block its entry into the house by sealing cracks around the foundation and in the basement.

1. What is the source of radon gas found in the basements of some houses?
2. What measures should you take to protect your family from possible radiation poisoning from radon gas?

The Geiger counter, popularized in old-time movies about prospecting for uranium, uses the ionization of a gas to detect radiation. The essential parts of a Geiger counter are shown in Figure 25-10. The cylinder contains a gas and has a wire running along its length. As the radiation interacts with the gas, it ionizes gas atoms. The electrons gain kinetic energy from the electric field in the cylinder, which they then lose in collisions with other gas atoms. These collisions release more electrons, and the process continues. This quickly results in an avalanche of electrons that produces a short electric current pulse that is detected by the electronics in the Geiger counter. In the movies the counter

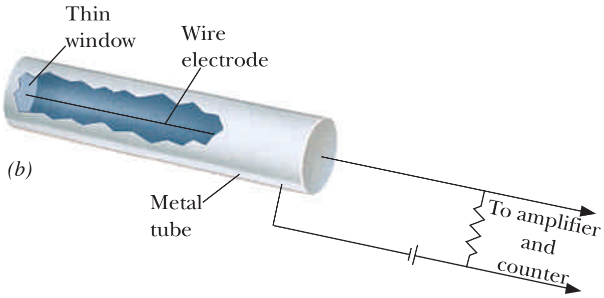
(a)



(b)

Figure 25-9 (a) Photograph and (b) schematic drawing of a photomultiplier tube used to detect radiation striking a scintillation counter.

(a)



(b)

Figure 25-10 (a) A civil defense Geiger counter. (b) Schematic drawing of a Geiger counter.

produces audible clicks. Many clicks per second means that the count rate is high and our hero is close to fame and fortune.

Another type of detector produces continuous tracks showing the paths of charged particles. These tracks are like those left by wild animals in snow. The big difference, however, is that although we may eventually see a deer, we cannot ever hope to see the charged particles. One track chamber is a bubble chamber in which a liquid is pressurized so that its temperature is just below the boiling point. When the pressure is suddenly released, boiling does not begin unless there is some disturbance in the liquid. When the disturbance is caused by the ionization of a charged particle, tiny bubbles form along its path. These bubbles are allowed to grow so that they can be photographed, and then the liquid is compressed to remove them and get ready for the next picture.

The paths of the charged particles are bent by placing the bubble chamber in a magnetic field; positively charged particles bend one way, and negatively charged particles bend the other way. Examination and measurement of the tracks in bubble chamber photographs, such as the one in Figure 25-11, yield information about the charged particles and their interactions.

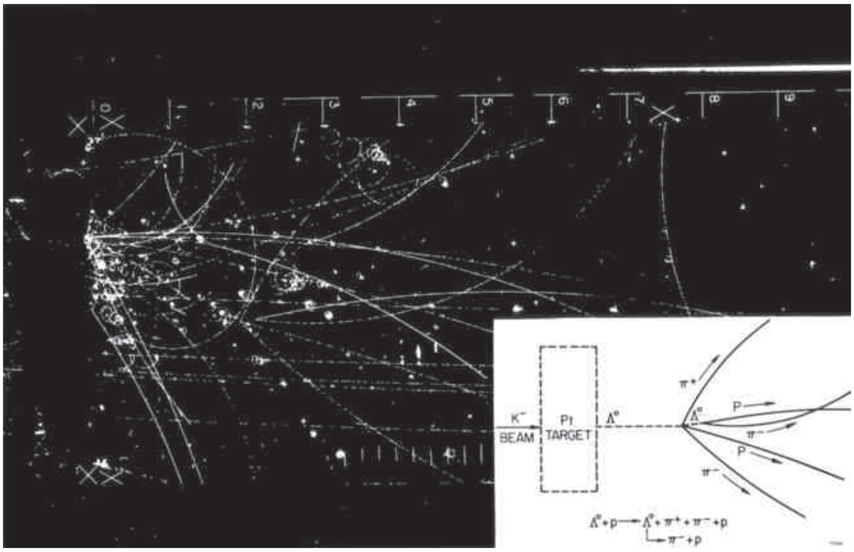
Modern particle detectors come in a variety of forms and sizes. In many of these, the particles cannot be seen; their locations and identities are all determined by large arrays of electronics connected to large computers like the one shown in Figure 25-12.

Summary

Radioactivity is a nuclear effect rather than an atomic one. It is virtually unaffected by outside physical conditions, such as strong electric and magnetic fields or extreme pressures and temperatures. Three types of radiation can occur: alpha (α) particles, or helium nuclei; beta (β) particles, which are electrons; and high-energy photons, or gamma (γ) rays. These different radiations have different penetrating properties, ranging from the gamma ray that can travel through many meters of air or even through thick walls to the alpha ray that won't penetrate a piece of paper.

Nuclei are composed of protons and neutrons. Nuclei of the same element have the same number of protons, but isotopes of this element have different numbers of neutrons. Isotopes of a particular element have their own nuclear properties but nearly identical chemical characteristics, because adding a neutron to a nucleus does not change the atom's electronic structure appreciably.

Radioactive decays are spontaneous, obey the known conservation laws (mass–energy, linear momentum, angular momentum, electric charge, and nucleon number), and most often change the chemical nature of their atoms. There are five main naturally occurring nuclear processes: a nucleus (1) emits an alpha particle, producing a nucleus two elements lower in the periodic chart; (2) beta decays, emitting an electron and producing the next higher



Fermi National Accelerator Laboratory

Figure 25-11 Photograph of tracks in a hydrogen bubble chamber shows the production of some strange particles that we will discuss in Chapter 27. The spiral track near the top of the photograph was produced by an electron.

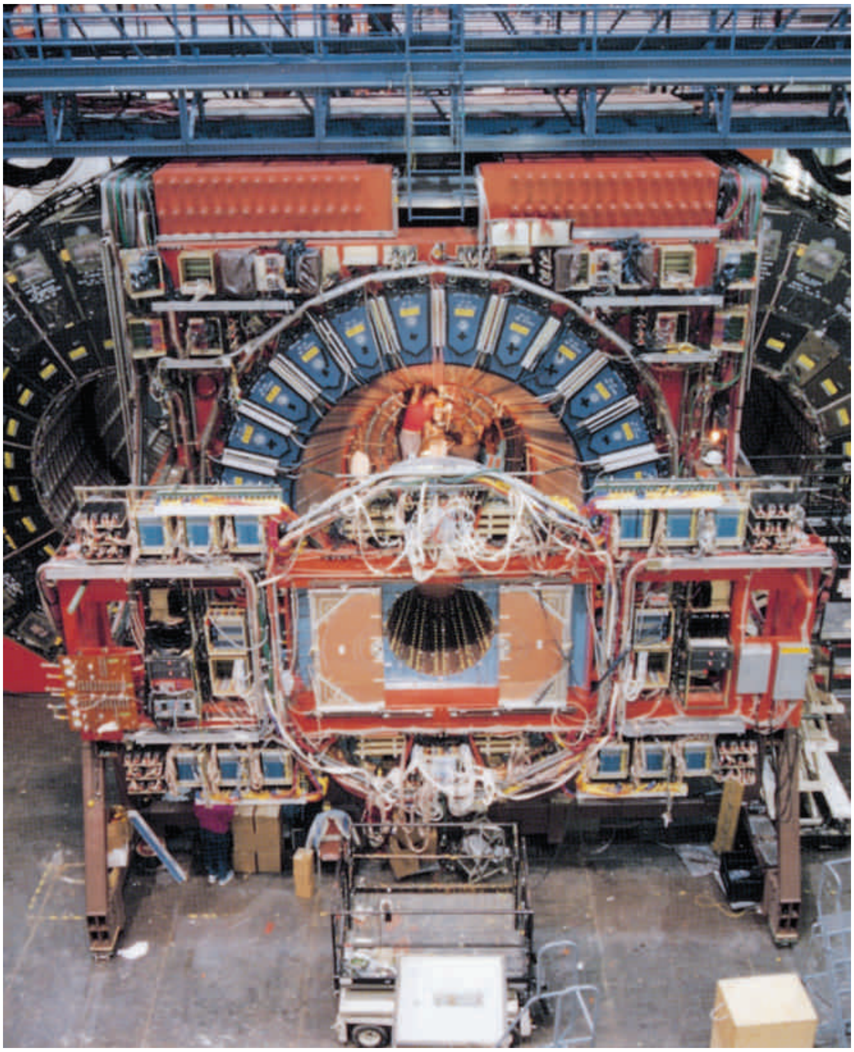


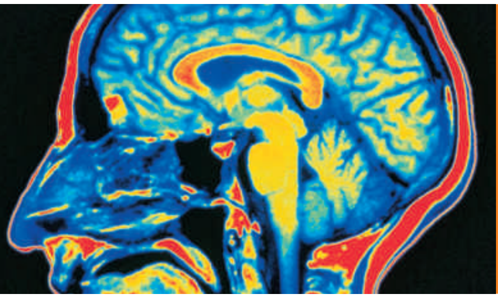
Figure 25-12 This very large particle detector is used at the Fermi National Accelerator Laboratory to study collisions of particles at very high energies.

Fermi National Accelerator Laboratory

element; (3) inverse beta decays via electron capture, producing a daughter nucleus one lower in the periodic table; (4) beta decays with a positron, an antiparticle of the electron, decreasing the number of protons by one and increasing the number of neutrons by one; or (5) emits gamma rays, leaving its identity unchanged.

Equal amounts of different radioactive materials do not give off radiation at the same rate. The unit of activity, a curie, has a value of 3.7×10^{10} decays per second. Two factors determine the activity of a sample of material—the number of radioactive atoms in the sample and the characteristic half-life of the isotope. The quantum-mechanical nature of nucleons results in a wide range of decay rates and prohibits us from predicting the behavior of individual nuclei. Radioactive samples are good clocks for dating events in the past.

Radiation interacts with matter, often outside the range of direct human observation. Alpha and beta particles interact with matter through their electric charge, whereas gamma rays ionize atoms or convert into a pair of particles. All radiation interactions with matter deposit energy, resulting in temperature increases, atomic excitations, and ionization. The ionization caused by radiation passing through living tissue can kill or damage cells. It is impossible to get completely away from radiation.



CHAPTER 25 Revisited

If the artifact is made from material that was once living, its organic material had the same ratio of carbon-14 to carbon-12 as the atmosphere at the time the artifact was made. Over time, the ratio of these carbon isotopes decreases because the carbon-14 is radioactive while the carbon-12 is stable. The change in this isotopic ratio serves as a clock, dating the artifact.

Key Terms

activity The number of radioactive decays that take place in a unit of time. Activity is measured in curies.

alpha particle The nucleus of helium, consisting of two protons and two neutrons.

alpha (α) radiation The type of radioactive decay in which nuclei emit alpha particles (helium nuclei).

beta particle An electron emitted by a radioactive nucleus.

beta (β) radiation The type of radioactive decay in which nuclei emit electrons or positrons (antielectrons).

curie A unit of radioactivity; 3.7×10^{10} decays per second.

daughter nucleus The nucleus resulting from the radioactive decay of a parent nucleus.

electron capture A decay process in which an inner atomic electron is captured by the nucleus. The daughter nucleus has the same number of nucleons as the parent but one less proton.

gamma (γ) radiation The type of radioactive decay in which nuclei emit high-energy photons. The daughter nucleus is the same as the parent.

half-life The time during which one-half of a sample of a radioactive substance decays.

ionization The removal of one or more electrons from an atom.

isotope An element containing a specific number of neutrons in its nuclei. Examples are $^{12}_{6}C$ and $^{14}_{6}C$, carbon atoms with six and eight neutrons, respectively.

neutron The neutral nucleon; one of the constituents of nuclei.

nucleon Either a proton or a neutron.

nucleus The central part of an atom that contains the protons and neutrons.

parent nucleus A nucleus that decays into a daughter nucleus.

positron The antiparticle of the electron.

proton The positively charged nucleon; one of the constituents of nuclei.

rad The acronym for *r*adiation *a*bsorbed *d*ose; a rad of radiation deposits 0.01 joule per kilogram of material.

rem The acronym for *r*oentgen *e*quivalent in *m*ammals, a measure of the biological effects caused by radiation.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. What was the biggest difference between Becquerel's radiation and Roentgen's X rays?
2. What makes modeling the behavior of neutrons and protons inside the atomic nucleus more difficult than modeling the behavior of electrons in an atom?
3. Why can't we use visible light to look at nuclei?
4. What first led scientists to conclude that radioactivity is a nuclear phenomenon?
5. Which of the three types of radiation will interact with an electric field?
6. Why do beta rays and alpha rays deflect in opposite directions when moving through a magnetic field?
7. Which of the following names do *not* refer to the same thing: beta particles, cathode rays, alpha particles, and electrons? Explain.
8. Why are X rays not a fourth category of radiation?
9. Is the chemical identity of an atom determined by the number of neutrons, protons, or nucleons in its nucleus? Why?
10. How would the activity of 1 gram of uranium oxide compare with that of 1 gram of pure uranium?
11. What is a nucleon?
12. What observation told scientists that nuclei had to contain more than just protons?

13. What is the name of the element represented by the X in each of the following?
    a. ${}^{89}_{39}\mathrm{X}$
    b. ${}^{140}_{58}\mathrm{X}$
    c. ${}^{81}_{35}\mathrm{X}$
14. What is the name of the element represented by the X in each of the following?
    a. ${}^{197}_{79}\mathrm{X}$
    b. ${}^{34}_{16}\mathrm{X}$
    c. ${}^{118}_{50}\mathrm{X}$
15. How many neutrons, protons, and electrons are in each of the following atoms?
    a. ${}^{24}_{12}\mathrm{Mg}$
    b. ${}^{59}_{27}\mathrm{Co}$
    c. ${}^{208}_{82}\mathrm{Pb}$
16. How many neutrons, protons, and electrons are in each of the following atoms?
    a. ${}^{19}_{9}\mathrm{F}$
    b. ${}^{63}_{29}\mathrm{Cu}$
    c. ${}^{221}_{88}\mathrm{Ra}$
17. What is the approximate mass of ${}^{90}_{40}\mathrm{Zr}$ in atomic mass units?
18. What is the approximate mass of ${}^{69}_{31}\mathrm{Ga}$ in atomic mass units?
19. The three naturally occurring isotopes of neon are ${}^{20}_{10}\mathrm{Ne}$, ${}^{21}_{10}\mathrm{Ne}$, and ${}^{22}_{10}\mathrm{Ne}$. Given that the atomic mass of natural neon is 20.18 atomic mass units, which of these three isotopes must be the most common?
20. The two naturally occurring isotopes of chlorine are ${}^{35}_{17}\mathrm{Cl}$ and ${}^{37}_{17}\mathrm{Cl}$. Which of these isotopes must be the most common?
21. What happens to the charge of the nucleus when it decays via electron capture?
22. What happens to the charge of the nucleus when it decays via beta plus decay?
23. Each of the following isotopes decays by alpha decay. What is the daughter isotope in each case?
    a. ${}^{224}_{92}\mathrm{U}$
    b. ${}^{197}_{83}\mathrm{Bi}$
24. Each of the following isotopes can be produced by alpha decay. What is the parent isotope in each case?
    a. ${}^{238}_{96}\mathrm{Cm}$
    b. ${}^{240}_{94}\mathrm{Pu}$
25. What daughter is formed when each of the following undergoes beta minus decay?
    a. ${}^{18}_{7}\mathrm{N}$
    b. ${}^{90}_{38}\mathrm{Sr}$
26. Each of the following isotopes can be produced by beta minus decay. What is the parent isotope in each case?
    a. ${}^{47}_{18}\mathrm{Ar}$
    b. ${}^{128}_{49}\mathrm{In}$
27. Each of the following isotopes decays by electron capture. What is the daughter isotope in each case?
    a. ${}^{181}_{77}\mathrm{Ir}$
    b. ${}^{237}_{94}\mathrm{Pu}$
28. Each of the following isotopes can be produced by electron capture. What is the parent isotope in each case?
    a. ${}^{65}_{29}\mathrm{Cu}$
    b. ${}^{253}_{99}\mathrm{Es}$
29. Each of the following isotopes decays by beta plus decay. What is the daughter isotope in each case?
    a. ${}^{28}_{15}\mathrm{P}$
    b. ${}^{22}_{11}\mathrm{Na}$
30. Each of the following isotopes can be produced by beta plus decay. What is the parent isotope in each case?
    a. ${}^{50}_{24}\mathrm{Cr}$
    b. ${}^{52}_{25}\mathrm{Mn}$
31. The isotope ${}^{40}_{15}\mathrm{P}$ can beta decay to the isotope ${}^{39}_{16}\mathrm{S}$. What else must have happened during this reaction?
32. Beta plus decay and electron capture both result in one additional neutron and one less proton in the nucleus. Why does beta minus decay not have a “mirror” reaction that produces the same change in the nucleus?
33. The isotope ${}^{64}_{29}\mathrm{Cu}$ can decay via beta plus and via beta minus decay. What are the daughters in each case?
34. The isotope ${}^{153}_{66}\mathrm{Dy}$ decays by alpha decay or by electron capture. What are the daughters in each case?
35. What type of decay process is involved in each of the following?
    a. ${}^{228}_{92}\mathrm{U} \rightarrow {}^{228}_{91}\mathrm{Pa} + (?)$
    b. ${}^{254}_{100}\mathrm{Fm} \rightarrow {}^{250}_{98}\mathrm{Cf} + (?)$
36. What does the (?) stand for in each of the following decays?
    a. ${}^{233}_{90}\mathrm{Th} \rightarrow {}^{233}_{91}\mathrm{Pa} + (?)$
    b. ${}^{18}_{9}\mathrm{F} \rightarrow {}^{17}_{8}\mathrm{O} + (?)$
37. Uranium-238 decays to a stable isotope of lead through a series of alpha and beta minus decays. Which of the following is a possible daughter of ${}^{238}\mathrm{U}$: ${}^{206}\mathrm{Pb}$, ${}^{207}\mathrm{Pb}$, ${}^{208}\mathrm{Pb}$, or ${}^{209}\mathrm{Pb}$?
38. What isotopes of lead (element 82) could be the decay products of ${}^{234}_{90}\mathrm{Th}$ if the decays are all alpha and beta minus decays?
39. A proton strikes a nucleus of ${}^{20}_{10}\mathrm{Ne}$. Assuming an alpha particle comes out, what isotope is produced?
40. What isotope is produced when a neutron strikes a nucleus of ${}^{10}_{5}\mathrm{B}$ and an alpha particle is emitted?
41. What changes in the numbers of neutrons and protons occur when a nucleus is bombarded with a deuteron (the nucleus of deuterium containing one neutron and one proton) and an alpha particle is emitted?
42. A nucleus of ${}^{238}_{92}\mathrm{U}$ captures a neutron to form an unstable nucleus that undergoes two successive beta minus decays. What is the resulting nucleus?
43. You place a chunk of radioactive material on a scale and find that it has a mass of 4 kilograms. The half-life of the material is 10 days. What will the scale read after 10 days?
44. You place a chunk of radioactive material on a scale and find that it has a mass of 10 kilograms. The half-life of the material is 20 days. How long will you have to wait for the scale to read 5 kg?

45. A radioactive material has a half-life of 50 days. How long would you have to watch a particular nucleus before you would see it decay?

46. The isotope $^{239}_{93}$Np has a half-life of about $2\frac{1}{2}$ days. Is it possible for a nucleus of this isotope to last for more than one year? Explain.

47. How do radioactive clocks determine the age of things that were once living?

48. Assume that the atmospheric ratio of ^{14}C to ^{12}C has been increasing by a small amount every 1000 years. Would determinations of age by radiocarbon dating be too short or too long? Why?

49. Can carbon-14 dating be used to date the stone pillars at Stonehenge? Why?

50. Why can carbon-14 dating not be used to determine the age of old-growth forests?

51. In decreasing order, rank the following in terms of range: a 10-million-electron-volt alpha particle, a 10-million-electron-volt electron, and a 10-million-electron-volt gamma ray.

52. A beam containing electrons, protons, and neutrons is aimed at a concrete wall. If all particles have the same kinetic energy, which particle will penetrate the wall the least?

53. Why do we often not worry about the distinction between rads and rems?

54. Which of the following causes the most biological damage if they all have the same energy: photons, electrons, neutrons, protons, or alpha particles?

55. Which of the following sources of radiation contributes the least to the average yearly dose received by humans: surroundings, medical, internal, cosmic rays, or nuclear power?

56. Which external source would most likely cause the most damage to internal organs, X rays or alpha particles? Why?

57. Why is it difficult to determine the biological effects of low levels of exposure to radiation?

58. What are the methods for using radiation to treat cancerous tumors?

59. Why are radioactive substances that emit alpha particles more dangerous inside the body than outside? Explain.

60. Would you expect more radiation damage to occur with a rad of X rays or a rad of alpha particles? Explain.

Exercises

61. Your younger brother plans to build a model of the gold atom for his science fair project. He plans to use a baseball (radius = 6 cm) for the nucleus. How far away should he put his outermost electrons?

62. The radius of the Sun is 7×10^8 m, and the average distance to Pluto is 6×10^{12} m. Are these proportions approximately correct for a scaled-up model of an atom?

63. What is the mass of the neutral carbon-12 atom in kilograms?

64. The atomic mass of neutral nickel-60 is 59.93 amu. What is its mass in kilograms?

65. The neutral atoms of an unknown sample have an average atomic mass of 3.19×10^{-25} kg. What is the element?

66. What element has an average atomic mass of 4.48×10^{-26} kg?

67. A hydrogen atom consists of a proton and an electron. What is the atomic mass of the hydrogen atom?

68. A deuterium atom consists of a single electron orbiting a nucleus consisting of a proton and a neutron bound together. Compare the sum of the masses of three constituents of the deuterium atom to its measured atomic mass of 2.014 101 8 amu. How do you account for any difference?

69. The activity of a radioactive sample is initially 32 μCi (microcuries). What will the activity be after 4 half-lives have elapsed?

70. If the activity of a particular radioactive sample is 60 Ci and its half-life is 200 years, what would you expect for its activity after 800 years?

71. A radioactive material has a half-life of 10 min. If you begin with 512 trillion radioactive atoms, approximately how many would you expect to have after 30 min?

72. You have a sample of material whose activity is 64 Ci. After 60 minutes the material's activity has decreased to 4 Ci. What is the material's half-life?

73. If the ratio of carbon-14 to carbon-12 in a piece of bone is only one-quarter of the atmospheric ratio, how old is the bone?

74. If the ratio of carbon-14 to carbon-12 in a piece of parchment is only one-sixteenth of the atmospheric ratio, how old is the parchment?

75. A beam of 1-MeV (million electron volts) gamma rays is incident on a block of aluminum that is 12.6 cm thick. What fraction of the gamma rays penetrates the block?

76. How thick an aluminum plate would be required to reduce the intensity of a 5-MeV beam of gamma rays by a factor of 4?

77. How many chest X rays are required to equal the maximum recommended radiation dose for the general public?

78. Cosmic rays result in an average annual radiation dose of 41 mrem at sea level and 160 mrem in Leadville, Colorado (elevation 10,500 ft). How many chest X rays would a person living at sea level have to have each year to make up for this difference in natural exposure?

26

Nuclear Energy

▶Our world and its economy run on energy. Without an abundant supply of energy, people in third-world countries will not be able to obtain the standard of living of industrialized nations. With the depletion of fossil fuels—coal, oil, and natural gas—the need arises to explore alternatives. What options are available for using nuclear energy, and what are the primary issues in extracting this nuclear energy?

(See page 593 for the answer to this question.)

In a nuclear power plant, heavy nuclei are split, releasing energy that is used to generate electricity.

Don Collins, Montana State University

The chemical energy released by the burning of the forests in Yellowstone National Park was a result of the electromagnetic forces between atoms.

U.S. Army, White Sands Missile Range

The nuclear energy released in the explosion of a nuclear bomb is a result of the strong force between nucleons.

ALTHOUGH radioactivity indicates that nuclei are unstable and raises questions about why they are unstable, the more fundamental question is just the opposite: why do nuclei stay together? The electromagnetic and gravitational forces do not provide the answer. The gravitational force is attractive and tries to hold the nucleus together, but it is extremely weak compared with the repulsive electric force pushing the protons apart. Nuclei should fly apart. The stability of most known nuclei, however, is a fact of nature. There must be another force—a force never imagined before the 20th century—that is strong enough to hold the nucleons together.

The existence of this force also means that there is a new source of energy to be harnessed. We have seen in previous chapters that an energy is associated with each force. For example, an object has gravitational potential energy because of the gravitational force. Hanging weights can run a clock, and falling water can turn a grinding wheel. The electromagnetic force shows up in household electric energy and in chemical reactions such as burning. When wood burns, the carbon atoms combine with oxygen atoms from the air to form carbon dioxide molecules. These molecules have less energy than the atoms from which they are made. The excess energy is given off as heat and light when the wood burns.

Similarly, the rearrangement of nucleons results in different energy states. If the energy of the final arrangement is less than that in the initial one, energy is given off, usually in the form of fast-moving particles and electromagnetic radiation. To understand the nuclear force, the possible types of nuclear reactions, and the potential new energy source, early experimenters needed to take a closer look at the subatomic world. This was accomplished with nuclear probes.

Nuclear Probes

Information about nuclei initially came from the particles ejected during radioactive decays. This information is limited by the available radioactive nuclei. How can we study stable nuclei? Clearly, we can't just pick one up and examine it. Nuclei are $\frac{1}{100,000}$ the size of their host atoms.

The situation is much more difficult than the study of atomic structure. Although the size of atoms is also beyond our sensory range, we can gain clues about atoms from the macroscopic world because it is governed by atomic characteristics. That is, the chemical and physical properties of matter depend on the atomic properties, and some of the atomic properties can be deduced from these everyday properties. On the other hand, no everyday phenomenon reflects the character of stable nuclei.

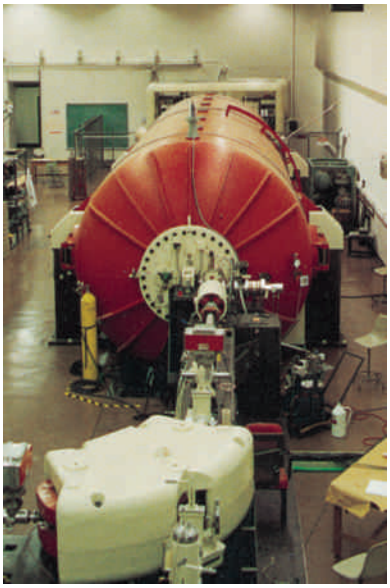
The initial information about the structure of stable nuclei came from experiments using particles from radioactive decays as probes. These probes—initially limited to alpha and beta particles—failed to penetrate the nucleus. The relatively light beta particle is quickly deflected by the atom's electron cloud. As the Rutherford experiments showed, alpha particles could penetrate the electron cloud, but they were repelled by the positive charge on the nucleus. Higher-energy alpha particles had enough energy to penetrate the smaller nuclei, but they could not penetrate the larger ones. Even when penetration was possible, the matter–wave aspect of the alpha particles hindered the exploration. In Chapter 24 we learned that the wavelength of a particle gets larger as its momentum gets smaller. Typical alpha particles from radioactive processes have low momenta, which places a limit on the details that can be observed because diffraction effects hide nuclear structures that are smaller than the alpha particle's wavelength.

Accelerators

This limit was lowered by constructing machines to produce beams of charged particles with much higher momenta and, consequently, much smaller wavelengths. **Particle accelerators**, such as the Van de Graaff generator shown in Figure 26-1, use electric fields to accelerate charged particles to very high velocities. In the process the charged particle acquires a kinetic energy equal to the product of its charge and the potential difference through which it moves (Chapter 20). The paths of the charged particles are controlled by magnetic fields.

There are two main types of particle accelerators: those in which the particles travel in straight lines and those in which they travel in circles. The simplest linear accelerator consists of a region in which there is a strong electric field and a way of injecting charged particles into this region. The maximum energy that can be given to a particle is limited by the maximum voltage that can be maintained in the accelerating region without electric discharges. The largest of these linear machines can produce beams of particles with energies up to 10 million electron volts (10 MeV), where 1 electron volt is equal to 1.6×10^{-19} joule (Chapter 25). This energy is somewhat larger than the fastest alpha particles obtainable from radioactive decay.

Passing the charged particles through several consecutive accelerating regions can increase the maximum energy. The largest linear accelerator is the Stanford Linear Accelerator, shown in Figure 26-2. This machine is about 3 kilometers (2 miles) long and produces a beam of electrons with energies of 50 billion electron volts (that is, 50 GeV, in which the G stands for "giga-," a prefix that means 10^9). Electrons with this energy have wavelengths approximately one-hundredth the size of the carbon nucleus, greatly reducing the diffraction effects.



Courtesy of Gene Sprouse, SUNY-Stony Brook

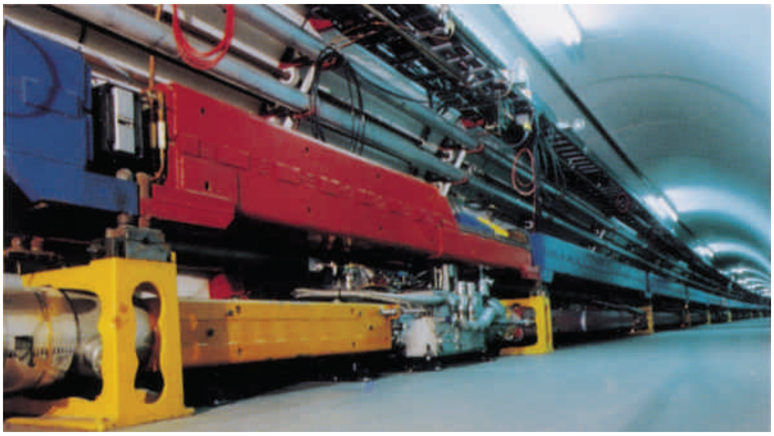
Figure 26-1 This Van de Graaff generator is used to accelerate protons to high velocities to probe the structure of nuclei.

© SLAC National Accelerator Laboratory

Figure 26-2 An aerial view of the Stanford Linear Accelerator Center in California.

Fermi National Accelerator Laboratory (both)

(a)



(b)

Figure 26-3 (a) An aerial view of the Fermi National Accelerator Laboratory. (b) This interior view shows magnets surrounding the two vacuum tubes in the main tunnel. The conventional magnets around the upper tube are red and blue, whereas the newer superconducting magnets are yellow.

An alternative technology, the circular accelerator, allows the particles to pass through a single accelerating region many times. The maximum energy of these machines is limited by the overall size (and cost), the strengths of the magnets required to bend the particles along the circular path, and the resulting radiation losses. Because particles traveling in circles are continuously being accelerated, they give off some of their energy as electromagnetic radiation. These radiation losses are more severe for particles with smaller masses, so circular accelerators are not as suitable for electrons. The most energetic accelerator of this type is at the Fermi National Accelerator Laboratory outside of Chicago, shown in Figure 26-3. It has a diameter of 2 kilometers and can accelerate a beam of protons to energies of nearly 1 trillion electron volts (1 TeV, where T stands for "tera-," a prefix that means 10^{15}) with a corresponding wavelength smaller than nuclei by a factor of several thousand.

The Nuclear Glue

Experiments with particle accelerators provide a great deal of information about the structure of nuclei and the forces that hold them together. The nuclear force between protons is studied by shooting protons at protons and analyzing the angles at which they emerge after the collisions. Because it is not possible to make a target of bare protons, experimenters use the next closest thing: a hydrogen target. They also use energies that are high enough that the deflections due to the atomic electrons can be neglected.

At low energies the incident protons are repelled in the fashion expected by the electric charge on the proton in the nucleus. As the incident protons are given more and more kinetic energy, some of them pass closer and closer to the nuclear protons. When an incident proton gets within a certain distance of the target proton, it feels the nuclear force in addition to the electric force. This nuclear force changes the scattering. Some of the details of this new force can be deduced by comparing the scattering data with the known effects of the electrical interaction.

We know that the nuclear force has a very short range; it has no effect beyond a distance of about 3×10^{-15} meter (3 fermis). Inside this distance it is strongly attractive, approximately 100 times stronger than the electrical repulsion. At even closer distances, the force becomes repulsive, which means that the protons cannot overlap but act like billiard balls when they get this close. The nuclear force is not a simple force that can be described by giving its strength as a function of the distance between the two protons. The force depends on the orientation of the two protons and on some purely quantum-mechanical effects.

The nuclear force also acts between a neutron and a proton (the n–p force) and between two neutrons (the n–n force). The n–p force can be studied by scattering neutrons from hydrogen. The force between two neutrons, however, cannot be studied directly because there is no nucleus composed entirely of neutrons. Instead, this force is studied by indirect means—for example, by scattering neutrons from deuterons (the hydrogen nucleus that has one proton and one neutron) and subtracting the effects of the n–p scattering. These experiments indicate that when the effects of the proton's charge are ignored, the n–n, n–p, and p–p forces are nearly the same. Therefore, the nuclear force is independent of charge.

Are You On the Bus?

Q: Because neutrons are neutral, they cannot be accelerated in the same manner as protons. How might one produce a beam of fast neutrons?

A: A beam of fast neutrons can be produced by accelerating protons and letting them collide with a foil. Head-on collisions of these protons with neutrons produce fast neutrons. The extra protons can be bent out of the way by a magnet.

There is another force in the nucleus. Investigations into the beta-decay process led to the discovery of a fourth force. This nuclear force is also short ranged but very weak. Although it is not nearly as weak as the gravitational force at the nuclear level, it is only about one-billionth the strength of the other nuclear force. The force involved in beta decay is thus called the **weak force**, and the force between nucleons is called the **strong force**. We concentrate on the strong force in this chapter because this force is involved in the release of nuclear energy.

Nuclear Binding Energy

Extended presentation available in the *Problem Solving* supplement

Because nucleons are attracted to each other, a force is needed to pull them apart. This force acts through a distance and does work on the nucleons. Because work is required to take a stable nucleus apart, the nucleus must have a lower energy than its separated nucleons. Therefore, we would expect energy to be released when we allow nucleons to combine to form one of these stable nuclei. This phenomenon is observed: a 2.2-million-electron-volt gamma ray is emitted when a neutron and a proton combine to form a deuteron (Figure 26-4).

Are You On the Bus?

Q: How much energy would be required to separate the neutron and proton in a deuteron?

A: Conservation of energy requires that the same amount of energy be supplied to separate them as was released when they combined—in this case, 2.2 million electron volts.

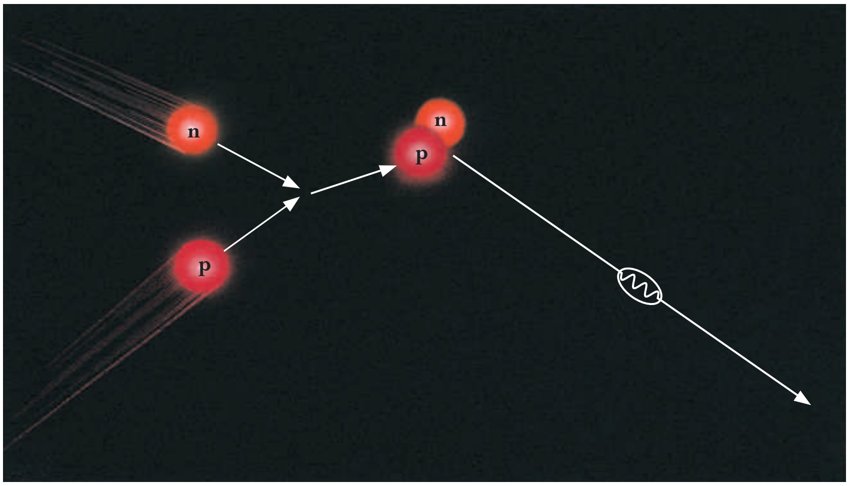


Figure 26-4 A 2.2-million-electron-volt gamma ray is emitted when a neutron and a proton combine to form a deuteron, indicating that the deuteron has a lower mass than the sum of the individual proton and neutron masses.

As an analogy, imagine baseballs falling into a hole. The balls lose gravitational potential energy while falling. This energy is given off in various forms such as heat, light, and sound. To remove a ball from the hole, we must supply energy equal to the change in gravitational potential energy that occurred when the ball fell in. The same occurs with nucleons. In fact, it is common for nuclear scientists to talk of nucleons falling into a "hole"—a nuclear potential well.

If we add the energies necessary to remove all the baseballs, we obtain the **binding energy** of the collection. This binding energy is a simple addition of the energy required to remove the individual balls because the removal of one ball has no measurable effect on the removal of the others. In the nuclear case, however, each removal is different because the removal of previous nucleons changes the attracting force. In any event, we can define a meaningful quantity called the *average binding energy per nucleon*, which is equal to the total amount of energy required to completely disassemble a nucleus divided by the number of nucleons.

We don't have to actually disassemble the nucleus to obtain this number. The energy difference between two nuclear combinations is large enough to be detected as a mass difference. The assembled nucleus has less mass than the sum of the masses of its individual nucleons. The difference in mass is related to the energy difference by Einstein's famous mass–energy equation, $E = mc^2$. Therefore, we can determine the binding energy of a particular nucleus by comparing the mass of the nucleus to the total mass of its parts.

Figure 26-5 shows a graph of the average binding energy per nucleon for the stable nuclei. The graph is a result of experimental work; it is simply a reflection of a pattern in nature. The graph shows that some nuclei are more tightly bound together than others.

Are You On the Bus?

Q: Which nuclei are the most tightly bound?

A: According to the graph in Figure 26-5, the most tightly bound nuclei have about 60 nucleons.

WORKING IT OUT *Nuclear Binding Energies*

As an example, we calculate the total binding energy and the average binding energy per nucleon for the helium nucleus. We add the masses of the component parts and subtract the mass of the helium nucleus:

2 protons = 2 × 1.007 28 amu	=	2.014 56 amu
2 neutrons = 2 × 1.008 67 amu	=	+2.071 34 amu
mass of parts		4.031 90 amu
1 helium nucleus	=	−4.001 50 amu
mass difference		0.030 40 amu

Therefore, the helium nucleus has a mass that is 0.030 40 amu less than its parts. Using Einstein's relationship, we can calculate the energy equivalent of this mass. A useful conversion factor is that 1 amu is equivalent to 931 MeV. Therefore, the total binding energy is

$$(0.030\,4 \text{ amu})\left(\frac{931 \text{ MeV}}{1 \text{ amu}}\right) = 28.3 \text{ MeV}$$

Dividing by 4, the number of nucleons, yields 7.08 MeV per nucleon.

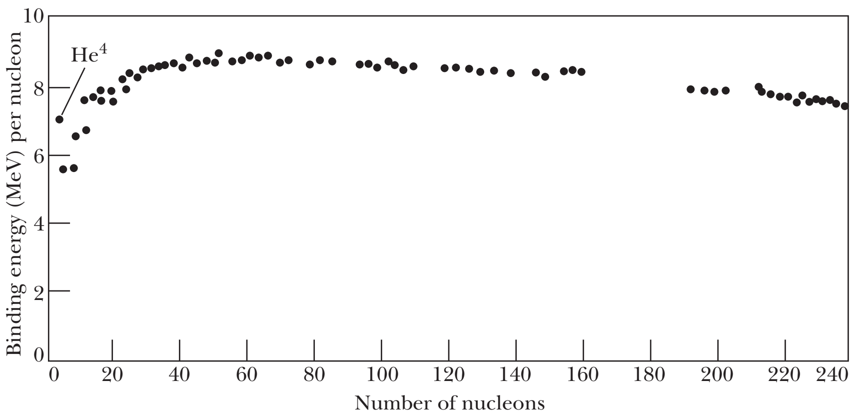


Figure 26-5 A graph of the average binding energy per nucleon versus nucleon number. Notice that the graph peaks in the range of 50 to 80 nucleons.

These differences mean that energy can be released if we can find a way to rearrange nucleons. For example, combining light nuclei or splitting heavier nuclei would release energy. But all of these nuclei are stable. To either split or join them we need to know more about their stability and the likelihood of various reactions.

Stability

Not all nuclei are stable. As we saw in the previous chapter, some are radioactive, whereas others seemingly last forever. A look at the stable nuclei shows a definite pattern concerning the relative numbers of protons and neutrons. Figure 26-6 is a graph of the stable isotopes plotted according to their

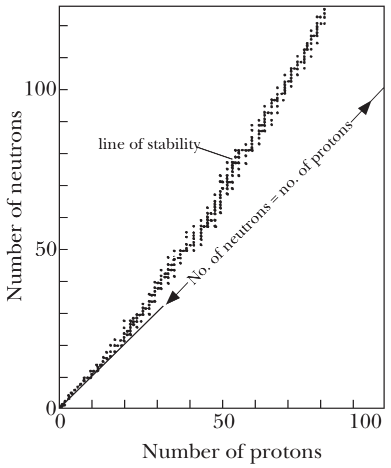


Figure 26-6 A graph of the number of neutrons versus the number of protons for the stable nuclei.

FLAWED REASONING

Two students are discussing the conservation of mass:

Russell: "I have always been taught that mass is conserved, but if we put a chunk of radioactive material in a sealed bottle, half of it will be gone in one half-life."

Heidi: "*Gone* is the wrong word to use. Half of the radioactive material will have changed into something else, but the mass of the bottle will remain the same."

Heidi has cleared up a misconception held by Russell, but **is Heidi's claim entirely correct?**

ANSWER Einstein taught us that mass can be converted to energy and energy to mass through his relationship $E = mc^2$. When a nucleus decays, the products will always have less mass than the parent. The missing mass is converted to energy. If some of the energy leaves the bottle (for example, as heat, light, or gamma rays), a careful measurement will show that the mass of the bottle does not remain the same. Of course, if the bottle is open and some of the daughters are gases, the change in mass will be easily observed.

numbers of neutrons and protons. The curve, or **line of stability** as it is sometimes called, shows that the light nuclei have equal, or nearly equal, numbers of protons and neutrons. As we follow this line into the region of heavier nuclei, it bends upward, meaning that these nuclei have more neutrons than protons.

To explain this pattern we try to "build" the nuclear collection that exists naturally in nature. That is, assuming we have a particular light nucleus, can we decide which particle—a proton or neutron—is the best choice for the next nucleon? Of course, the best choice is the one that occurs in nature.

Looking at the line of stability tells us that in the heavier nuclei, adding a proton is not usually as stable an option as adding a neutron. Why is this so? Consider the characteristics of the two strongest forces involved. (We assume that gravity and the weak force play no role.) If you add a proton to a nucleus, it feels two forces—the electrical repulsion of the other protons and the strong nuclear attraction of the nearby nucleons. Although the electrical repulsion is weaker than the nuclear attraction, it has a longer range. The new proton feels a repulsion from *each* of the other protons in the nucleus but feels a nuclear attraction only from its nearest neighbors. With even heavier nuclei, the situation gets worse; the nuclear attraction stays roughly constant—there are only so many nearest neighbors it can have—but the total repulsion grows with the number of protons.

An equally valid way of explaining the upward curve in the line of stability is to recall that quantum mechanics is valid in the nuclear realm. Imagine the nuclear potential-energy well described in the previous section. Quantum mechanics tells us that the well contains a number of *discrete* energy levels for the nucleons. The Pauli exclusion principle that governs the maximum number of electrons in an atomic shell (Chapter 24) has the same effect here, but there is a slight difference. Because we have two different types of particles, there are two discrete sets of levels. Each level can only contain two neutrons or two protons.

In the absence of electric charge, the neutron and proton levels would be side by side (Figure 26-7) because the strong force is nearly independent of the type of nucleon. If this were true—that is, if level 4 for neutrons were the same height above the ground state as level 4 for protons—we would predict that there would be no preferential treatment when adding a nucleon. We would simply fill the proton level with two protons and the neutron level with two neutrons and then move to the next pair of levels. It would be unstable

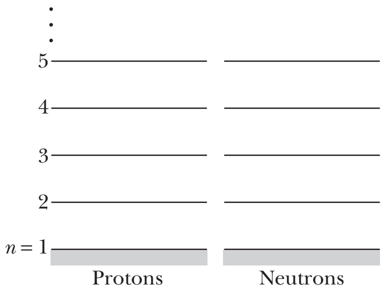


Figure 26-7 The proton and neutron energy levels in a hypothetical nucleus without electric charge occur at the same values.

to fill proton level 5 without filling neutron level 4 because the nucleus could reach a lower energy state by turning one of its protons in level 5 into a neutron in level 4.

However, the electrical interaction between protons means that the separations of the energy levels are not identical for protons and neutrons. The additional force means that proton levels will be higher (the protons are less bound) than the neutron levels, as shown schematically in Figure 26-8. This structure indicates that at some point it becomes energetically more favorable to add neutrons rather than protons. Thus, the number of neutrons would exceed the number of protons for the heavier nuclei. Of course, too many neutrons will also result in an unstable situation.

Understanding the line of stability adds to our understanding of instability as well. We can now make predictions about the kinds of radioactive decay that should occur for various nuclei. If the nucleus in question is above the line of stability, it has extra neutrons. It would be more stable with fewer neutrons. In rare cases the neutron is expelled from the nucleus, but usually a neutron decays into a proton and an electron via beta minus decay. If the isotope is below the line of stability, we expect alpha or beta plus decay or electron capture to take place to increase the number of neutrons relative to the number of protons. In practice, alpha decay is rare for nucleon numbers less than 140, and beta plus decay is rare for nucleon numbers greater than 200.

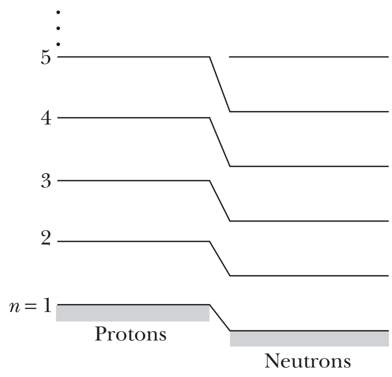


Figure 26-8 The proton energy levels in the hypothetical nucleus are raised because of the mutual repulsion of their positive charges.

Goeppert-Mayer | *Magic Numbers*

Like Marie Curie, Maria Goeppert-Mayer (1906–1972) was born in Poland but of a German family. When she was 4 years old, her pediatrician father moved the family to Göttingen, where she enrolled as a university student in mathematics in 1924. Excitement in the new field of quantum mechanics led her to physics, and in 1930 she earned her doctorate under Max Born, James Franck, and Adolf Windaus, world-renowned leaders in the field. While a graduate student, she met, fell in love with, and married a postdoctoral fellow from America, Joseph E. Mayer, who was working in physical chemistry.

Maria Goeppert-Mayer

Courtesy of Louise Barker/AIP Niels Bohr Library

Goeppert-Mayer accompanied her husband to the United States, where he taught at Johns Hopkins University in Baltimore. They coauthored an important book on statistical mechanics in 1940. In 1939 they relocated to Columbia University in New York City. She taught there, as she had at Johns Hopkins, only as a "volunteer" because of the nepotism clauses in her husband's contract. She joined Harold Urey in the early work on the separation of uranium isotopes that led to the use of atomic energy.

After the war, Goeppert-Mayer accepted a position at the University of Chicago, which had been the home base for so many refugees from Hitler's Europe. Her correspondence is a gold mine of fascinating information concerning these colleagues. Her work on the structure of nuclei was conducted at the Argonne National Laboratory in the Chicago area.

"For a long time I have considered even the craziest ideas about the atomic nucleus, and suddenly I discovered the truth," she said. She was trying to find a way of arranging the neutrons and protons into shells within nuclei to explain why nuclei with so-called magic numbers of neutrons and protons were particularly stable. One day, her old friend Enrico Fermi asked her whether there was evidence of spin coupling. "When he said that, it all fell into place. In ten minutes I knew." The magic numbers made sense.

J. Hans Daniel Jensen independently arrived at the same theory, and they collaborated on the important book on nuclear shell structure that was published in 1955. In 1963 Goeppert-Mayer and Jensen were awarded the Nobel Prize for their work in nuclear structure. One hundred and seventy-five Nobel Prizes have been awarded in physics, but only two have gone to women. It is easy to see how women in science faced an uphill battle until many obstacles were removed so that they could participate more fully in the great work of the new academy.

—Pierce C. Mullen, historian and author

Sources: Sharon Bertsch McGrayne, *Nobel Prize Women in Science: Their Lives, Struggles and Momentous Discoveries*, rev. ed. (New York: Carol, 1998); J. Dash, *Maria Goeppert-Mayer: A Life of One's Own* (New York: Paragon, 1973).

When the nuclei get too large, there is no stable arrangement. None of the elements beyond uranium (element 92) occur naturally on Earth. Some of them existed on Earth much earlier but have long since decayed. They can be artificially produced by bombarding lighter elements with a variety of nuclei. The list of elements (and isotopes) continues to grow through the use of this technique.

Are You On the Bus?

Q: What kind of decay would you expect to occur for $^{214}_{82}Pb$?

A: Because this isotope is above the line of stability, it should undergo beta minus decay.

Nuclear Fission

The discovery of the neutron added a new probe for studying nuclei and initiating new nuclear reactions. Enrico Fermi, an Italian physicist, quickly realized that neutrons made excellent nuclear probes. Neutrons, being uncharged, have a better chance of probing deep into the nucleus. Working in Rome in the mid-1930s, Fermi produced new isotopes by bombarding uranium with neutrons. These new isotopes were later shown to be heavier than uranium. Although this discovery is exciting, it perhaps isn't surprising; it seems reasonable that adding a nucleon to a nucleus results in a heavier nucleus.

The real surprise came later when scientists found that their samples contained nuclei that were much less massive than uranium. Were these nuclei products of a nuclear reaction with uranium, or were they contaminants in the sample? It seemed unbelievable that they could be products. Fermi, for example, didn't even think about the possibility that a slow-moving neutron could split a big uranium nucleus. But that was what was happening.

The details of this process are now known. The capture of a low-energy neutron by uranium-235 results in another uranium isotope, uranium-236. This nucleus is unstable and can decay in several possible ways. It may give up the excitation energy by emitting one or more gamma rays, it may beta decay, or it may split into two smaller nuclei. This last alternative is called **fission**. The fissioning of uranium-235 is shown in Figure 26-9. A typical fission reaction is

$$\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow {}^{236}_{92}\mathrm{U} \rightarrow {}^{142}_{56}\mathrm{Ba} + {}^{91}_{36}\mathrm{Kr} + 3\mathrm{n}$$

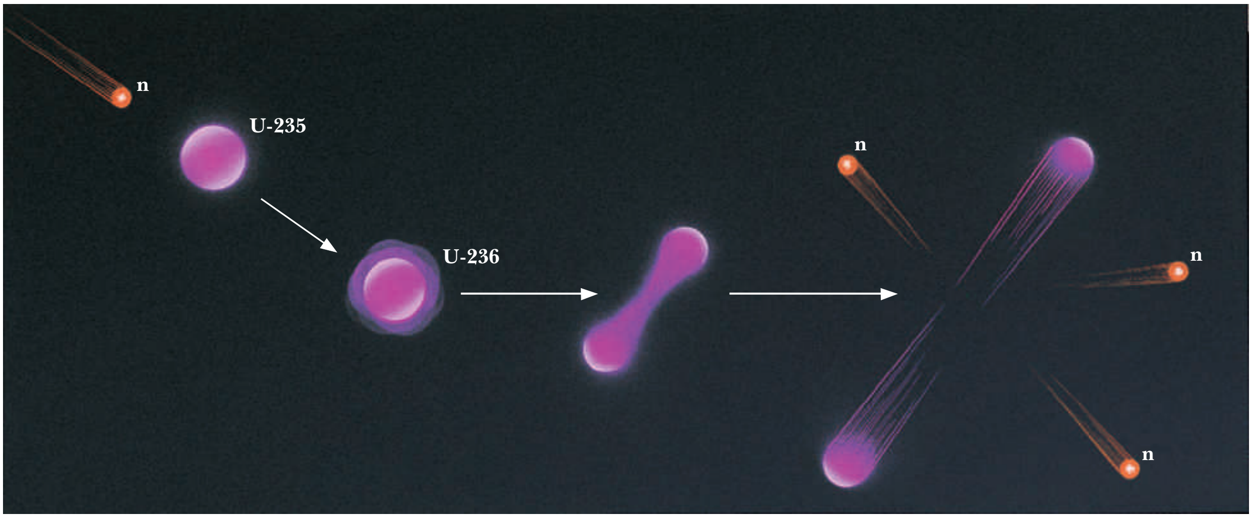


Figure 26-9 The fissioning of a uranium-235 nucleus caused by the capture of a neutron results in two intermediate mass nuclei, two or more neutrons, and some energy as gamma rays and kinetic energy.

The fission process releases a large amount of energy. This energy comes from the fact that the product nuclei have larger binding energies than the uranium nucleus. As the nucleons fall deeper into the nuclear potential wells, energy is released. The approximate amount of energy released can be seen from the graph in Figure 26-5. A nucleus with 236 nucleons has an average binding energy of 7.6 million electron volts per nucleon. Assume for simplicity that the nucleus splits into two nuclei of equal masses. A nucleus with 118 nucleons has an average binding energy of 8.5 million electron volts per nucleon. Therefore, each nucleon is more tightly bound by about 0.9 million electron volts, and the 236 nucleons must release about 210 million electron volts. This is a *tremendously* large energy for a single reaction. Typical energies from chemical reactions are only a few electron volts per atom, a hundred-millionth as large.

Q: How many joules are there in 210 million electron volts?

A: $(2.1 \times 10^8$ electron volts$)(1.6 \times 10^{-19}$ joule per electron volt$) = 3.36 \times 10^{-11}$ joule. Although this is indeed a small amount of energy, it is huge relative to other single-reaction energies.

Even though these energies are much larger than chemical energies, they are small on an absolute scale. The energy released by a single nuclear reaction as heat or light would not be large enough for us to detect without instruments. Knowledge of this led Rutherford to announce in the late 1930s that it was idle foolishness to even contemplate that the newly found process could be put to any practical use.

Chain Reactions

Rutherford's cynicism about the practicality of nuclear power seems silly in hindsight. But he was right about the amount of energy released from a single reaction. If you were holding a piece of uranium ore in your hand, you would not notice anything unusual; it would look and feel like ordinary rock. And yet nuclei are continuously fissioning.

What is the difference between the ore in your hand and a nuclear power plant? The key to releasing nuclear energy on a large scale is the realization that a single reaction has the potential to start additional reactions. The accumulation of energy from many such reactions gets to levels that not only are detectable but can become tremendous. This occurs because the fission fragments have too many neutrons to be stable. The line of stability in Figure 26-6 shows that the ratio of protons to neutrons for nuclei in the 100-nucleon range is different from that of uranium-235. These fragments must get rid of the extra neutrons. In practice they usually emit two or three neutrons within 10^{-14} second. Even then the resulting nuclei are neutron-rich and need to become more stable by emitting beta particles.

The release of two or three neutrons in the fissioning of uranium-235 means that the fissioning of one nucleus could trigger the fissioning of others; these could trigger the fissioning of still others, and so on. Because a single reaction can cause a chain of events as illustrated in Figure 26-10, this sequence is called a **chain reaction.**

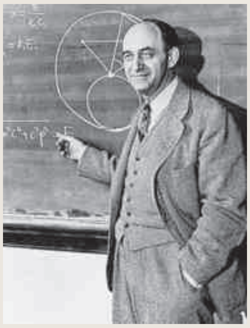
Q: How many neutrons must be emitted when $^{236}_{92}U$ fissions to become $^{141}_{55}Cs$ and $^{92}_{37}Rb$?

A: Because the total number of nucleons remains the same, we expect to have $236 - 141 - 92 = 3$ neutrons emitted.

Fermi | *A Man for All Seasons*

The Italian Navigator has landed in the New World.
—Enrico Fermi

On the bitterly cold afternoon of December 2, 1942, Italian American physicist Enrico Fermi (1901–1954) and his team removed neutron-absorbing control rods from a massive ellipsoidal stack of graphite blocks and uranium oxide to achieve the first sustained nuclear chain reaction. The United States was fighting World War II at that time, and this nuclear experiment led to the development of weapons that ended the world conflict. A coded message informing American scientific authorities of this magnificent success began with the quote that opens this feature. It was a new world and a new age, and the Italian Navigator illuminated it with beams of neutrons.


AIP Emilio Segre Visual Archives

Enrico Fermi

Fermi was the son of an Italian railroad communications inspector and a mother who also had achieved a good education. The young Fermi was intellectually quick and curious. His application for a full scholarship to the selective Scuola Normale Superiore at the University of Pisa was a highly advanced study of sound characteristics. Gifted with mathematical ability, Fermi used differential equations and Fourier transforms to analyze sound vibrations. He began his studies at a level beyond most of the faculty, and when he graduated, he was an acknowledged authority on relativity and quantum mechanics—the hot new areas in physics.

At age 26, Fermi was appointed professor of theoretical physics at the University of Rome. He moved easily into the mainstream of European science and was recognized as one of an outstanding crop of brilliant movers and shakers in science. Early in his career, he became interested in the newly discovered neutron. Through a series of serendipitous discoveries, Fermi and his team noticed that neutrons that were slowed in passing through paraffin blocks were better at producing artificially radioactive isotopes. The Rome group produced a plethora of such isotopes, and the biomedical uses of some of these were important and highly publicized.

Going outside regular channels, Bohr told Fermi that he would receive the 1938 Nobel Prize in physics. This warning allowed Fermi to plan for his escape from Mussolini's increasingly anti-Semitic Italy—his wife, Laura, was Jewish. He accepted the prize in Stockholm, came directly to New York, and ultimately went to Chicago. At the University of Chicago, Fermi worked on many problems associated with nuclear fission and weapons. Although he was adamantly opposed to the construction of thermonuclear weapons, his work led to the development of the plutonium bomb that devastated Nagasaki in August 1945.

He died in 1954 of stomach cancer. He had lived vigorously, in harmony with his peers and family, and displayed a wonderful balance of good humor and serious thinking. Element 100, fermium, is named in his honor. He may well have been the last physicist who could comprehend both experimental and theoretical physics. He was a man for all seasons.

—Pierce C. Mullen, historian and author

Sources: Laura Fermi, *Atoms in the Family* (Chicago: University of Chicago Press, 1954); Emilio Segrè, *Enrico Fermi: Physicist* (Chicago: University of Chicago Press, 1970); Daniel J. Kevles, *The Physicists: The History of a Scientific Community in Modern America* (New York: Knopf, 1978).


Argonne National Laboratory and the U.S. Department of Energy

The world's first nuclear reactor was assembled in Chicago in 1942. No photographs were taken of this reactor because of wartime secrecy.

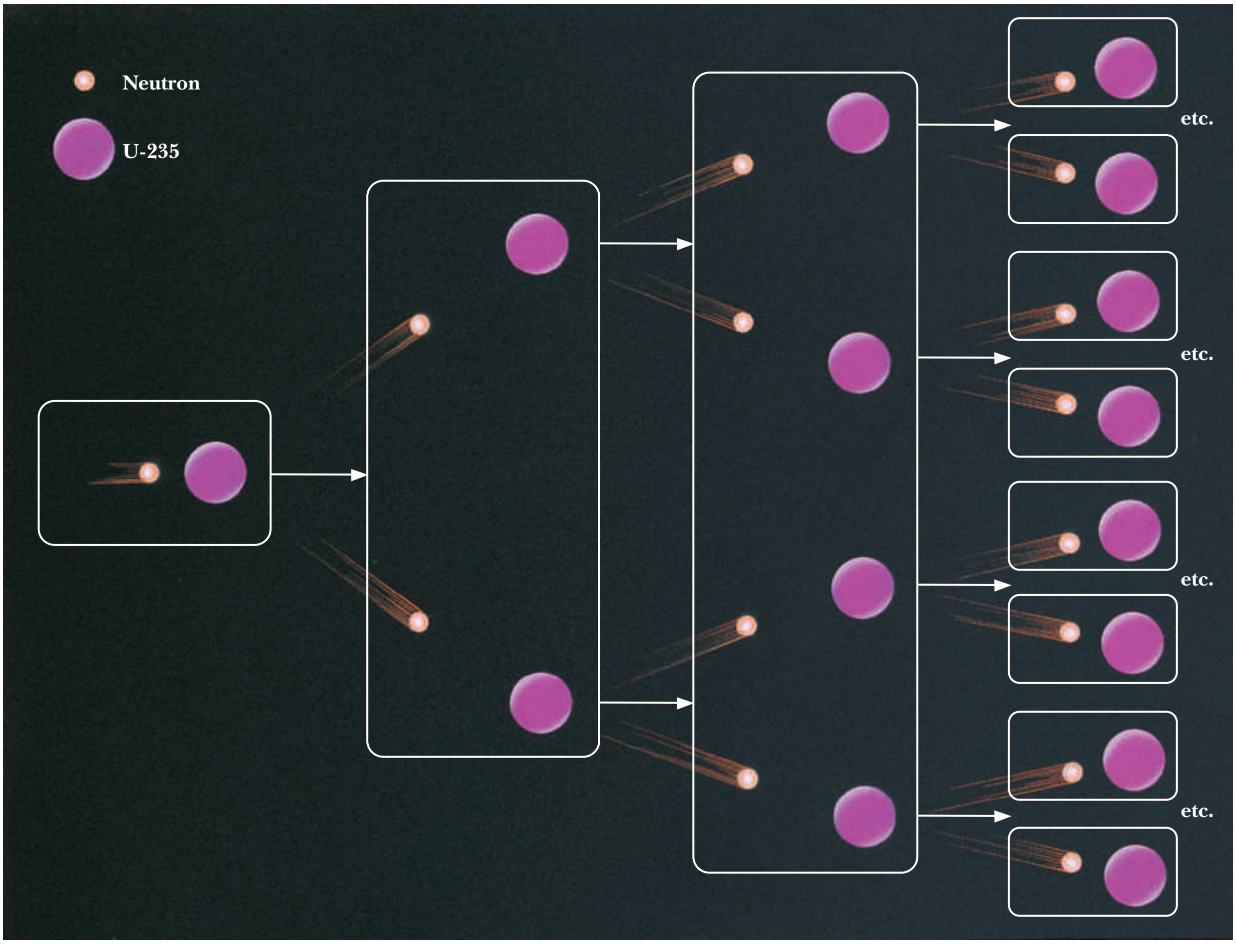


Figure 26-10 A chain reaction occurs because each fission reaction releases two or more neutrons that can initiate further fission reactions.

Imagine the floor of your room completely covered with mousetraps. Each mousetrap is loaded with three marbles, as shown in Figure 26-11, so that when a trap is tripped, the three marbles fly into the air. What happens if you throw a marble into the room? It will strike a trap, releasing three marbles. Each of these will trigger another trap, releasing its marbles. In the beginning the number of marbles released will grow geometrically. The number of marbles will be 1, 3, 9, 27, 81, 243, . . . In a short time the air will be swarming with marbles. Because the number of mousetraps is limited, the process dies out. However, the number of atoms in a small sample of uranium-235 is large (on the order of 10^{20}), and the number of fissionings taking place can grow extremely large, releasing a lot of energy. If the chain reaction were to continue in the fashion we have described, a sample of uranium-235 would blow up.

But our piece of uranium ore doesn't blow up; it doesn't even get warm because most of the neutrons do not go on to initiate further fission reactions. Several factors affect this dampening of the chain reaction. One is size. Most of the neutrons leave a small sample of uranium before they encounter another uranium nucleus—a situation analogous to putting only a dozen mousetraps on the floor. If you trigger one trap, one of its marbles is unlikely to trigger another trap, but occasionally it happens. As the sample of material gets bigger, fewer and fewer of the neutrons escape the material.

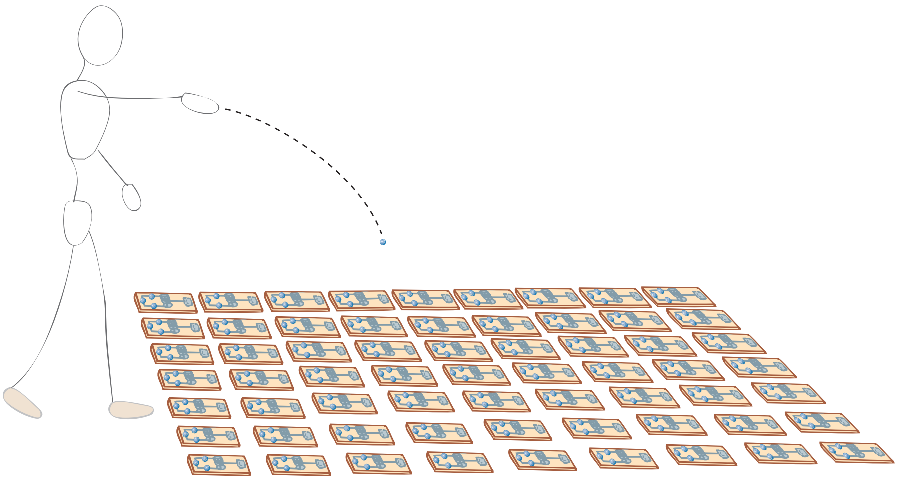


Figure 26-11 A chain reaction of mousetraps is initiated when the first marble is thrown into the array. Each mousetrap releases three marbles, which can trip additional mousetraps.

But even a large piece of uranium ore does not blow up. Naturally occurring uranium consists of two isotopes. Only 0.7% of the nuclei are uranium-235; the remaining 99.3% are uranium-238. These uranium-238 nuclei will occasionally fission, but usually they capture the neutrons and decay by beta minus or alpha emission. Captured neutrons cannot go on to initiate other fission reactions. The chain reaction is **subcritical**, and the process dies out. To make our analogy correspond to a piece of naturally occurring uranium, we would need 140 unloaded mousetraps for each loaded one.

Extracting useful energy from fission is much easier if the percentage of uranium-235 is increased through what is known as enrichment. Any enrichment scheme is difficult because the atoms of uranium-235 and uranium-238 are chemically the same, making it difficult to devise a process that preferentially interacts with uranium-235. Their masses differ by only a little more than 1%. The various enrichment processes take advantage of the slight differences in the charge-to-mass ratios, the rates of diffusion of their gases through membranes, resonance characteristics, or their densities. The enrichment processes must be repeated many times because only a small gain is made each time.

If enough enriched uranium is quickly assembled, the chain reaction can become **supercritical**. On average more than one neutron from each fission reaction initiates another reaction, and the number of reactions taking place grows rapidly. This process was used in the nuclear bombs exploded near the end of World War II, showing that Rutherford vastly underestimated the power of the fission reaction.

Nuclear Reactors

Harnessing the tremendous energy locked up in nuclei requires controlling the chain reaction. The process must not become either subcritical or supercritical because the energy must be released steadily at manageable rates. In a nuclear reactor, the conditions are adjusted so that an average of one neutron per fission initiates further fission reactions. Under these conditions the chain reaction is **critical;** it is self-sustaining. Energy is released at a steady rate and extracted from the reactor to generate electricity.

Several factors can be adjusted to ensure the criticality of the reactor. We have seen that the amount of uranium fuel (the core) must be large enough so that the fraction of neutrons escaping from it is small. It is also important

Meitner | *A Physicist Who Never Lost Her Humanity*

When the name Lise Meitner (1878–1968) is mentioned, scientists most often think of a person who should have shared in the Nobel Prize but did not for both gender and political reasons. Before World War II, Meitner was at the top of her field in experimental physics and directed the department of nuclear physics at the Kaiser Wilhelm Institute in Berlin. Her associate, Otto Hahn, directed the radiochemistry department. The two had discovered protactinium in 1917, and they had been at the forefront of research on radioactivity ever since. German admirers referred to her as "Our Madame Curie." Before Meitner was driven, penniless and alone, from Germany, she had been investigating many of the phenomena for which Enrico Fermi received the Nobel Prize in 1938.

Lise Meitner

Photo by Francis Simon, courtesy of AIP Emilio Segre Visual Archives

She was in exile in Sweden when she received news from her coworkers in Berlin that inexplicable chemical results occurred when uranium was bombarded with neutrons. After a traditional Swedish Christmas dinner, Meitner and her young nephew, Otto Frisch, went out into the evening snow to ponder the Berlin findings. They sat on a log calculating possibilities and suddenly discovered that, in Frisch's words, "Whenever mass disappears energy is created, according to Einstein's formula. . . . So here was the source of that energy; it all fitted." It was hard to believe because no serious scientist expected atoms to fission. Frisch returned to Copenhagen to tell Bohr, and Bohr in turn brought the terrible news to New York shortly after the New Year in 1939.

Hahn received the Nobel Prize for the discovery, which he attributed solely to his discipline, chemistry. After the war, Heisenberg, Hahn, and other non-Nazi Germans who had remained in the Third Reich were credited with work for which Meitner should have received her due. But the woman who had, against all odds, moved into the male domain of science, who had a Jewish grandparent, and who was not physically present in Germany during the war, received only minimal credit lest it reflect darkly on the scientific establishment in wartime Germany. In a strange way, she was also a casualty of the cold war. The Western alliance needed to rebuild a strong Germany to shore up defenses against the Soviet Union. Therefore, Lise Meitner would not share in the credit for opening the field of nuclear energy.

Only later did Meitner receive due recognition. The United States honored Meitner as the first female recipient of the Fermi Award from its Atomic Energy Commission; Glenn Seaborg presented the medal to her in Vienna in 1966. Twenty years earlier she had been named Woman of the Year by the Women's National Press Club at a banquet presided over by President Harry Truman. The name meitnerium (Mt) has now been accepted for element 109. She is buried in Bramley, Hampshire, England, under a stone with the inscription that heads this biographical sketch.

—Pierce C. Mullen, historian and author

Sources: Ruth Lewin Sime, *Lise Meitner: A Life in Physics* (Berkeley: University of California Press, 1996); O. R. Frisch et al., *Trends in Atomic Physics: Essays Dedicated to Lise Meitner, Otto Hahn, and Max von Vaue on the Occasion of Their 80th Birthday* (New York: Interscience, 1959).

that the nonfissionable uranium-238 nuclei not capture too large a fraction of the neutrons, which can be accomplished by enriching the fuel, reducing the speed of the neutrons, or both.

The likelihood that a neutron will cause a uranium-235 nucleus to fission varies with the speed of the incoming neutron. Initially, you may think that faster neutrons would be more likely to split the uranium-235 nucleus because they would impart more energy to the nucleus. This is not the case because the splitting of the nucleus is a quantum-mechanical effect. Slow neutrons are much more likely to initiate the fission process. An added benefit is that the probability of a uranium-238 nucleus capturing a neutron decreases as the neutron speed decreases.

The neutrons are primarily slowed by elastic collisions with nuclei. A material (called the **moderator**) is added to the core of the reactor to slow the neutrons without capturing too many of them. Neutrons can transfer the most energy to another particle when their masses are the same. (In fact, a head-on collision will leave the neutron with little or no kinetic energy.) Hydrogen would seem to be the ideal moderator, but its probability of capturing the

The Vallecitos boiling-water reactor and surrounding facilities.

neutron is large. The material with the next lightest nucleus, deuterium, is fine but costly, and because it is a gas, it is hard to get enough mass into the core to do the job. Canadian reactors use deuterium as the moderator but in the form of water, called *heavy water* because of the presence of the heavy hydrogen. The world's first reactor used graphite (a form of carbon) as the moderator. Most current U.S. reactors use ordinary water as the moderator, requiring the use of enriched fuel.

Reactors require control mechanisms for fine-tuning and for adjusting to varying conditions as the fuel is used. Inserting rods of a material that is highly absorbent of neutrons controls the chain reaction. Boron is quite often used. The control rods are pushed into the core to decrease the number of neutrons available to initiate further fission reactions. The mechanical insertion and withdrawal of control rods could not control a reactor if all the neutrons were given off promptly in the usual 10^{-14} second. A small percentage of the neutrons are given off by the fission fragments and may take seconds to appear. These delayed neutrons allow time to adjust the reactor to fluctuations in the fission rate.

The last thing needed to make a reactor a practical energy source is a way of removing the heat from the core so that it can be used to run electric generators, which is accomplished in a variety of ways. In boiling-water reactors, water flows through the core and is turned to steam. Pressurized-water reactors use water under high pressure so that it doesn't boil in the reactor. Still other reactors use gases. A diagram of a nuclear reactor is shown in Figure 26-12.

Breeding Fuel

We are exhausting many of our energy sources. This is as true for fission reactors as it is for coal- and oil-powered plants. It is estimated that there is only enough uranium to run existing reactors for the 30–40 years of expected operation of each reactor. If uranium-235 were the only fuel, the nuclear-power age would turn out to be short-lived.

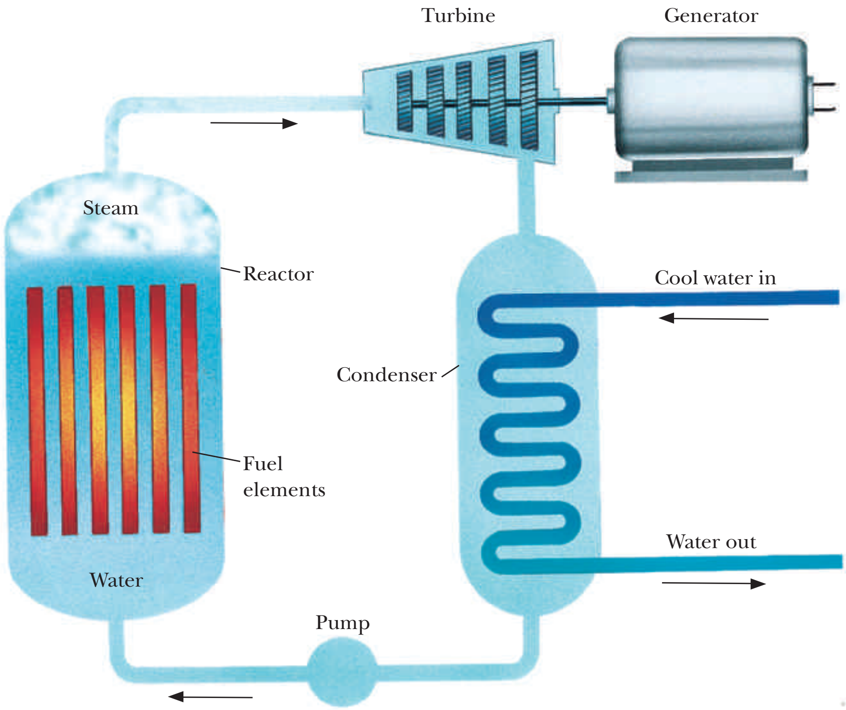


Figure 26-12 A schematic drawing of a nuclear reactor used to generate electricity.

Imagine, however, that somebody suggests that it is possible to make new fuel for these reactors. Does this claim sound like a sham? Does it imply that we can get something for nothing? The claim is not a sham, but it is also not getting something for nothing. The laws of conservation of mass and energy still hold. The new process takes an isotope that does not fission and through a series of nuclear reactions transmutes that isotope into one that does.

When a $^{238}_{92}U$ nucleus captures a neutron, it usually undergoes two beta minus decays to become plutonium, as diagrammed in Figure 26-13. The important point is that $^{239}_{94}Pu$ is a fissionable nucleus that can be used as fuel in fission reactors. (A similar process transmutes $^{232}_{90}Th$ into $^{232}_{92}U$, another fissionable nucleus.)

Some plutonium is produced in a normal reactor because there is uranium-238 in the core. However, not much is produced because the neutrons are slowed to optimize the fission reaction. Special reactors have been designed so that an average of more than one neutron from each fission reaction is captured by uranium-238. Such a reactor generates more fuel than it uses and is therefore known as a *breeder reactor*. Because most of the uranium is uranium-238 and because there is about the same amount of $^{232}_{90}Th$, these reactors greatly extend the amount of available fuel.

As with most other energy options, there are serious concerns about breeder reactors. Briefly, these concerns center on the technology of running these reactors, the assessment of the risks involved, and the security of the plutonium that is produced. Plutonium-239 is bomb-grade material that can be separated relatively inexpensively from uranium because it has different chemical properties.

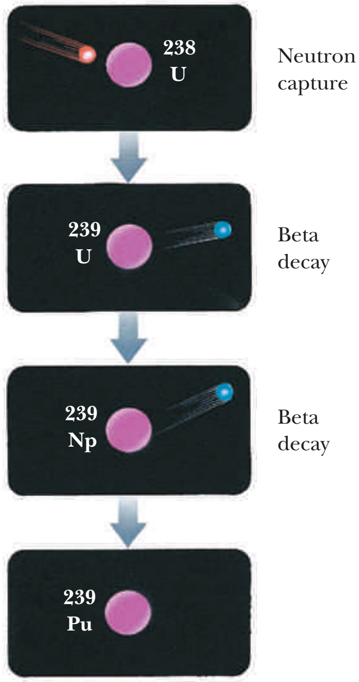


Figure 26-13 A scheme for converting uranium-238 to plutonium-239.

Fusion Reactors

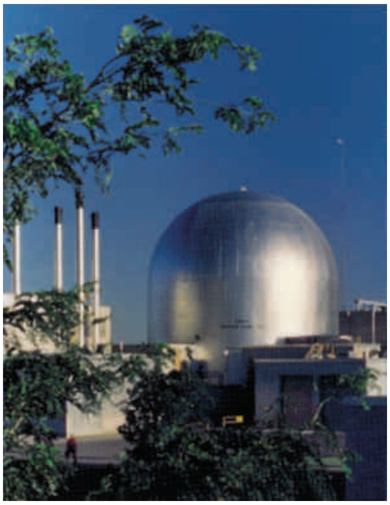
There are other nuclear energy options. Returning to the binding energy curve in Figure 26-5 reveals another way to get energy from nuclear reactions. The increase in the curve for the average binding energy per nucleon for the light nuclei indicates that some light nuclei can be combined to form heavier ones with a release of energy. For instance, a deuteron ($^{2}_{1}H$) and a triton ($^{3}_{1}H$) can be fused to form helium with a release of a neutron and 17.8 million electron volts:

$$^{2}_{1}H + ^{3}_{1}H \rightarrow ^{4}_{2}He + n + 17.8\text{ MeV}$$

Although this process releases a lot of energy per gram of fuel, it is much more difficult to initiate than fission. The interacting nuclei have to be close enough together so that the nuclear force dominates. (This wasn't a problem with fission because the incoming particle was an uncharged neutron.) The particles involved in the **fusion** reaction won't overcome the electrostatic repulsion of their charges to get close enough unless they have sufficiently high kinetic energies.

High kinetic energies mean high temperatures. The required temperatures are on the order of millions of degrees, matching those found inside the Sun. In fact, the source of the Sun's energy is fusion. The first occurrence of fusion on Earth was in the explosion of hydrogen bombs in the 1950s. The extremely high temperatures needed for these bombs was obtained by exploding the older fission bombs (commonly called atomic bombs).

Making a successful fusion power plant involves harnessing the reactions of the hydrogen bomb and the Sun. Fusion requires not only high temperature but also the confinement of a sufficient density of material for long enough that the reactions can take place and return more energy than was necessary



Idaho National Laboratory and the U.S. Department of Energy

A breeder reactor at the National Reactor Laboratory in Idaho.

Everyday Physics | *Natural Nuclear Reactors*

In 1972 the remains of naturally occurring nuclear reactors were discovered in Gabon, a country in equatorial Africa. Using the long-lived radioactive products of the fission reactions as clocks, scientists calculated that the reactors were active 1–2 billion years ago and operated for as long as 1 million years. These reactor sites are important resources because researchers can examine the migration of nuclear waste over a billion years, information that is useful for designing disposal facilities for human-manufactured nuclear waste.

Besides a supply of uranium with an enriched amount of uranium-235, the conditions required for a nuclear reactor to occur naturally are the same as those required for nuclear power plants: (1) a high concentration of uranium, (2) a critical size, (3) a moderator, and (4) few neutron absorbers. The 17 known natural reactors all occurred in uranium deposits with high concentrations of uranium ore. It is believed that water served as the moderator and as the control mechanism. If the reactors got too hot, the water vaporized, reducing the concentration of water molecules. This in turn slowed the reaction rate, reducing the temperature of the reactor and allowing water to flow into the region once again.

Could such reactors exist today? No; the ratio of uranium-235 to uranium-238 at the time the reactors were active was 3%, just sufficiently large to allow water to serve as a moderator. Since that time, the ratio of uranium-235 to uranium-238 has decreased to the current 0.7% because uranium-235 has a shorter half-life.

These ancient nuclear reactors were also the first breeder reactors. Besides breeding plutonium-239, the reactors operated for so long that part of the plutonium-239 decayed by alpha particle decay to form additional uranium-235.

1. What useful information do we gain from the study of these ancient nuclear reactors?
2. Why is it no longer possible for naturally occurring uranium deposits to form nuclear reactors?

Courtesy of F. Gauthier-Lafaye/CNRS

This natural nuclear reactor is located in the Oklo Uranium Mine in Gabon, Africa. The yellowish rock is uranium oxide.

to initiate the process. At first this task may seem impossible and dangerous. Whether it is possible is still being determined. Most people in this field believe that it is a technological problem that can be solved. The characterization of fusion as dangerous is false and arises from confusion about the concepts of heat and temperature (Chapter 13). Heat is a flow of energy; temperature is a measure of the average molecular kinetic energy. Something can have a very high temperature and be quite harmless. Imagine, for example, the vast differences in potential danger between a thimble and a swimming pool full of boiling water. The thimble of water has very little heat energy and thus is relatively harmless. The same is true of fusion reactors. Although the fuel is very hot, it is a rarefied gas at these temperatures. So the problem is not with it melting the container but rather the reverse—the container will cool the fuel.

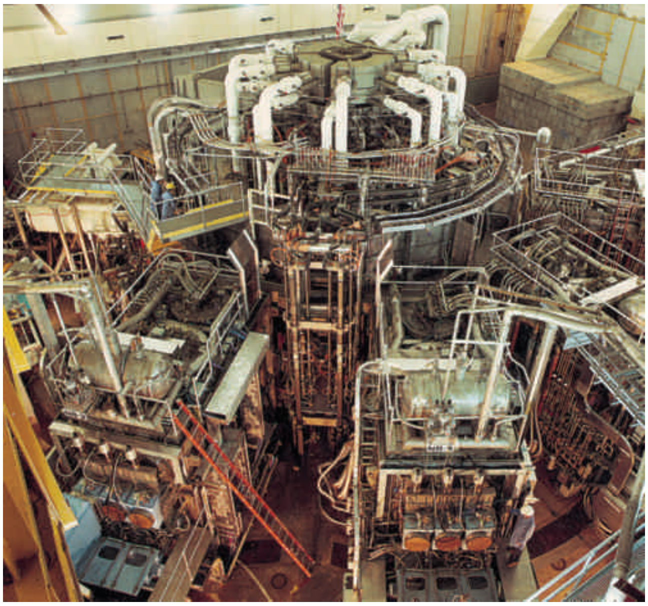
Two schemes are being investigated for creating the conditions necessary for fusion. One method is to confine the plasma fuel in a magnetic "bottle" (Figure 26-14). The *magnetic field* interacts with the charged particles and keeps them in the bottle. The other, *inertial confinement*, uses tiny pellets of solid fuel. As these pellets fall through the reactor, they are bombarded from many directions by laser beams. This produces rapid heating of the pellet's outer surface, causing a compression of the pellet and even higher temperatures in the center.

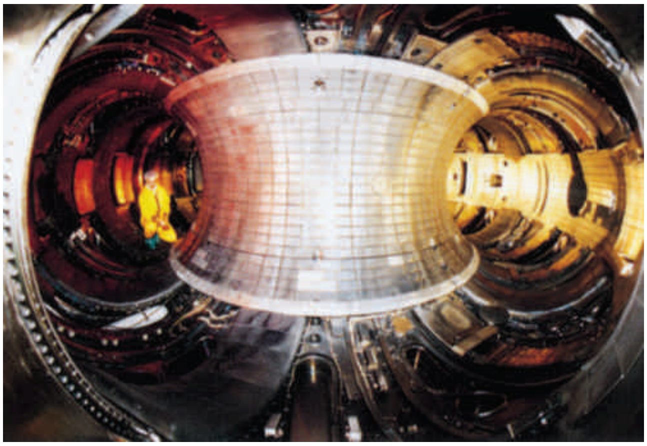
To date, no one has been able to simultaneously produce all the conditions required to get more energy out of the process than was needed to initiate it. Successes have been limited to achieving some of these conditions but not all at the same time. Fusion reactors on a commercial scale seem many years away.

Some of the features of fusion, however, make it an attractive option. The risks are believed to be much lower than for fission reactors, and there is a lot of fuel. One possible reaction uses deuterium. Deuterium occurs naturally as one atom out of every 6000 hydrogen nuclei and thus is a constituent of water. This heavy water is relatively rare compared with ordinary water, but there is enough of it in a pail of water to provide the equivalent energy of 700 gallons of gasoline!

Solar Power

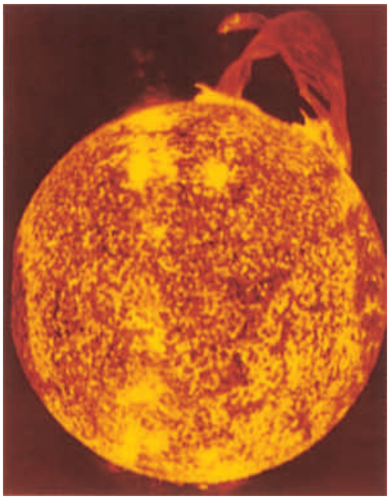
Throughout history people have puzzled about the source of the Sun's energy. What is the fuel? How long has it been burning? And how long will it continue to emit its life-supporting heat and light?





Princeton University Plasma Physics Laboratory (both)

Figure 26-14 The tokamak at Princeton University uses a magnetic bottle to confine the plasma so that fusion reactions will occur.



NASA

The source of the Sun's energy is the fusion of hydrogen into helium in its core.

Many schemes have been suggested—some reasonable, some absurd. Early people thought of the Sun as an enormous "campfire" because fires were the only known source of heat and light. But calculations showed that if wood or coal were the Sun's fuel, it could not have been around for long. Its lifetime would be much shorter than estimates of how long the Sun had already existed. Another idea involved a Sun heated by the constant bombardment of meteorites, which could account for the long lifetime of the Sun (the collisions continued indefinitely) but which also predicted that the mass of the Sun would increase. Earth would then spiral into the Sun because of the ever-increasing gravitational force. Another scheme had the Sun slowly collapsing under its own gravitational attraction. The loss in gravitational potential energy would be radiated into space. The flaw in this last scenario became apparent from geologic data suggesting that Earth was much older than the Sun. Also, if we mentally uncollapse the Sun, going back in time, we find that the Sun would extend beyond Earth's orbit at a time less than the assumed age of Earth.

The source of the Sun's power was a major conflict at the beginning of the 20th century. Astronomers were suggesting that the Sun was approximately 100,000 years old, but geologists and biologists were saying that Earth was much older. Both sides couldn't be right. The discovery of radioactivity and other nuclear reactions showed that the geologists and biologists were right. Scientists now believe that our entire solar system formed from interstellar debris left over from earlier stars. As the matter collapsed, it heated up because of the loss in gravitational potential energy. At some point the temperature in the interior of the Sun became high enough to initiate nuclear fusion. Now we have a Sun in which hydrogen is being converted into helium via the fusion reaction. The amount of energy released by the Sun is such that the mass of the Sun is decreasing at a rate of 4.3 billion kilograms per second! Yet this is such a small fraction of the Sun's mass that the change is hardly noticeable.

Knowing the mechanism and the mass of the Sun, we can calculate its lifetime. Our Sun is believed to be about 4.5 billion years old and will probably continue its present activity for another 4.5 billion years.

FLAWED REASONING

Your friend voices the following concern: "Scientists claim that a fusion reactor would never melt down like Chernobyl. Isn't the Sun a perfect example of a fusion reactor that is out of control?" **How might you respond?**

ANSWER Fusion reactors should be much safer than fission reactors. The two types of reactors have very different answers to the question, "What's the worst that could happen?" In a fission reactor, the core can go supercritical and produce much more energy than can be controlled, and a meltdown of the core could occur. In a fusion reactor, the fusion process stops, and little additional energy is produced. The fuel in the Sun is held close together at high temperatures by the enormous gravitational pressure at its core. This mechanism is not possible on Earth.

Summary

Nuclei stay together despite the electromagnetic repulsions between protons because of a nuclear force. This strong force between two nucleons has a very short range, is about 100 times stronger than the electric force, has a repulsive core, and is independent of charge. A second force in the nucleus, the weak force involved in the beta-decay process, is also short-ranged but very weak, only about one-billionth the strength of the strong force.

Information about nuclei initially came from particles ejected during radioactive decays. If a nucleus is above the line of stability, it has extra neutrons, which usually results in a neutron decaying into a proton and an electron via beta minus decay. If the isotope is below the line of stability, alpha or beta plus decay or electron capture increases the number of neutrons relative to the number of protons.

Later, the particles from radioactive decays were used as probes to study the structure of stable nuclei. Finally, particle accelerators produced beams of charged particles with much higher momenta and, consequently, much smaller wavelengths. The largest of these accelerators produce beams with energies in excess of 1 trillion electron volts.

The average binding energy per nucleon varies for the stable nuclei; some nuclei are more tightly bound than others, reaching a maximum near iron. Combining light nuclei or splitting heavier nuclei releases energy. The energy differences between nuclei are large enough to be detected as mass differences.

Bombarding uranium with neutrons splits the uranium nuclei, releasing large amounts of energy. Typical reaction energies are 100 million times larger than those of chemical reactions. The fission reaction is a practical energy source because a single reaction emits two or three neutrons that can trigger additional fission reactions.

Another way of releasing energy, fusion, combines light nuclei to form heavier ones. Fusion requires high temperatures and the confinement of a sufficient density of material for long enough so the reactions can take place and return more energy than was needed to initiate the process. This technology is still being developed. The Sun, however, is a working fusion reactor.

CHAPTER 26 *Revisited*

Nuclear energy can be used to heat water and make steam to turn turbines, just like the other options. The differences are at the front end—releasing the energy to make the steam. With coal, oil, and natural gas, we burn the fuel. In conventional nuclear power plants, we create a controlled chain reaction of nuclear disintegrations. Future fusion reactors will combine hydrogen nuclei to form heavier nuclei. With all nuclear reactors, the questions revolve around the use, production, and disposal of radioactive materials. Because radioactivity is unalterable by normal means, we need to isolate these materials from the biosphere. This is a formidable technological challenge.

Key Terms

binding energy The amount of energy required to take a nucleus apart.

chain reaction A process in which the fissioning of one nucleus initiates the fissioning of others.

critical Describes a chain reaction in which an average of one neutron from each fission reaction initiates another reaction.

fission The splitting of a heavy nucleus into two or more lighter nuclei.

fusion The combining of light nuclei to form a heavier nucleus.

line of stability The locations of the stable nuclei on a graph of the number of neutrons versus the number of protons.

moderator A material used to slow the neutrons in a nuclear reactor.

particle accelerator A device for accelerating charged particles to high velocities.

strong force The force responsible for holding the nucleons together to form nuclei.

subcritical Describes a chain reaction that dies out because an average of less than one neutron from each fission reaction causes another fission reaction.

supercritical Describes a chain reaction that grows rapidly because an average of more than one neutron from each fission reaction causes another fission reaction, an extreme example of which is the explosion of a nuclear bomb.

weak force The force responsible for beta decay.

Questions and exercises are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions and exercises are answered in Appendix B.
indicates more challenging questions and exercises.
WebAssign Many Conceptual Questions and Exercises for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. What electric potential difference is required to accelerate a proton to an energy of 5 million electron volts?

2. What electric potential difference is required to accelerate an alpha particle to an energy of 40 million electron volts?

3. An electron, a positron, and a proton are each accelerated through a potential difference of 1 million volts. Which of these, if any, acquires the largest kinetic energy? Explain your reasoning.

4. An electron, a positron, and a proton are each accelerated through a potential difference of 1 million volts. Which of these, if any, acquires the greatest final speed? Explain your reasoning.

5. Which acquires a larger kinetic energy when accelerated by the same potential difference, a proton or an alpha particle? Why?

6. Which acquires a greater final speed when accelerated by the same potential difference, a proton or an alpha particle? Why?

7. Why is a circular accelerator more suitable for protons than electrons?

8. If the Stanford Linear Accelerator were to be used to accelerate positrons instead of electrons, would the positron source be at the same end as the electron source or at the opposite end? Explain.

9. List the four fundamental forces in order of decreasing strength.

10. Which of the forces in nature is associated with beta decay?

11. How do we know that there must be a strong force?

12. What evidence do we have to support the idea that the strong force is stronger than the electromagnetic force?

13. What are the similarities and the differences between the strong force and the electromagnetic force?

14. For the electric force, the charge of the particles determines whether it is attractive or repulsive. What determines whether the strong force is attractive or repulsive?

15. What is released when a neutron and a proton combine to form a deuteron?

16. Which nucleus would have the greater total binding energy, ${}^{56}_{26}\text{Fe}$ or ${}^{112}_{48}\text{Cd}$? Explain.

17. Which of the following has the largest mass: 96 protons and 138 neutrons, ${}^{234}_{96}\text{Cm}$, or ${}^{110}_{46}\text{Pd}$ plus ${}^{124}_{50}\text{Sn}$? How do you know this?

18. Which of the following has the smallest mass: 96 protons and 138 neutrons, ${}^{234}_{96}\text{Cm}$, or ${}^{110}_{46}\text{Pd}$ plus ${}^{124}_{50}\text{Sn}$? Explain.

19. Both ${}^{12}_{7}\text{N}$ and ${}^{12}_{5}\text{B}$ decay to the stable nucleus ${}^{12}_{6}\text{C}$. Which of these three nuclei has the smallest mass? How do you know this?

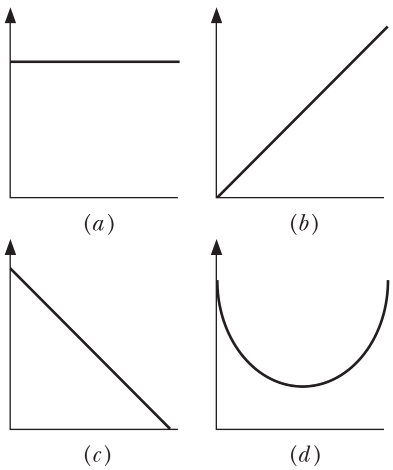
20. ${}^{14}_{6}\text{C}$ decays to ${}^{14}_{7}\text{N}$ via beta minus decay. Which nucleus has the larger mass? Why?

21. ${}^{17}_{7}\text{N}$ beta decays to ${}^{17}_{8}\text{O}$ with a reaction energy of 8.68 million electron volts. ${}^{17}_{9}\text{F}$ beta plus decays to ${}^{17}_{8}\text{O}$ with a reaction energy of 2.76 million electron volts. Which parent nucleus has the greater mass? Explain.

22. ${}^{24}_{11}\text{Na}$ with a mass of 23.991 atomic mass units beta decays to ${}^{24}_{12}\text{Mg}$. ${}^{24}_{13}\text{Al}$ with a mass of 24.000 atomic mass units decays by electron capture to ${}^{24}_{12}\text{Mg}$. Which reaction has the greater decay energy? How do you know this?

23. The nuclear fusion process in stars much more massive than our Sun continues to fuse lighter elements together to form heavier ones with the release of energy. Use Figure 26-5 to explain why iron-56 is the heaviest element produced in this fashion.

24. Suppose the curves for the average binding energy were those shown in the following figure. Would fission and fusion be possible in each case? If so, for approximately what range of nucleon number would they occur?



25. How do the numbers of neutrons and protons compare for most stable nuclei with small atomic numbers? How do we account for this?

26. What general statement about the relative numbers of neutrons and protons can you make about nuclei with large atomic numbers? How do we account for this?

27. Why can't a stable nucleus contain only protons?

28. You may have learned the law "Matter can neither be created nor destroyed." Is this statement in agreement with modern physics?

29. Would you expect the nucleus $^{114}_{55}Cs$ to be stable? If not, how would you expect it to decay?

30. Would you expect the nucleus $^{144}_{55}Cs$ to be stable? If not, how would you expect it to decay?

31. What is the most likely decay mode for $^{27}_{10}Ne$?

32. How would you expect an unstable nucleus of $^{35}_{19}K$ to decay?

33. What is nuclear fission?

34. Would a uranium nucleus release more or less energy by splitting into three equal mass nuclei rather than two? Explain.

35. How many neutrons are released in the following fission reaction?

$$^1_0n + ^{235}_{92}U \rightarrow ^{140}_{54}Xe + ^{94}_{38}Sr + (?)^1_0n$$

36. Assume that a $^{235}_{92}U$ nucleus absorbs a neutron and fissions with the release of three neutrons. If one of the fission fragments is $^{144}_{56}Ba$, what is the other?

37. Why can the fissioning of $^{235}_{92}U$ produce a chain reaction?

38. What factors determine whether a piece of uranium undergoes a subcritical or supercritical reaction?

39. Why is it important for fission reactions to emit neutrons?

40. Why is it critical for nuclear fission chain reactions that heavier elements have a greater ratio of neutrons to protons than lighter elements?

41. In which device, a nuclear reactor or a nuclear bomb, does the greater number of neutrons per fission event go on to initiate another reaction?

42. Why don't chain reactions occur in naturally occurring deposits of uranium?

43. Why does a nuclear reactor have control rods?

44. What is the difference between a moderator and a control rod in a fission reactor?

45. The fissioning of plutonium-239 yields an average of 2.7 neutrons per reaction compared to 2.5 for uranium-239. Which substance would have the smaller critical mass?

46. Would it have been easier or harder to develop fission reactors if the average number of neutrons released per fission of uranium-235 were 2.0 instead of 2.5?

47. What is bred in a breeder reactor?

48. What problem is solved by a breeder reactor?

49. What is nuclear fusion?

50. Why are high temperatures required for nuclear fusion?

51. The temperature of the plasma in a typical household fluorescent light is 20,000°C. Why can you touch an operating light without being burned?

52. In a tokamak fusion reactor, magnetic fields are used to hold plasma that must be heated to temperatures comparable to those in the Sun's core. If this "magnetic bottle" were to fail, would the reactor melt down? Why or why not?

53. What advantages would a fusion reactor have over a fission reactor?

54. What are the two basic approaches to developing fusion reactors?

55. Why do scientists believe that the Sun is 4.5 billion years old?

56. What are the conditions in the interiors of stars that make fusion possible?

57. What is the basic difference between fusion and fission?

58. Does $E = mc^2$ apply to both fusion and fission? What about an explosion of dynamite?

Exercises

59. A proton is accelerated through a potential difference of 10^5 V. Find the proton's momentum and its wavelength.

60. An alpha particle is accelerated through a potential difference of 10^5 V. Find the alpha particle's momentum and its wavelength.

61. A proton is accelerated through a potential difference of 4×10^{11} V. Show that a nonrelativistic calculation yields a final velocity greater than the speed of light.

62. A proton is accelerated through a potential difference of 4×10^{11} V. For energies much greater than the rest-mass energy ($E_0 = mc^2 = 938$ MeV, for a proton), a relativistic treatment yields a momentum of E/c, where c is the speed of light. What wavelength does this proton have?

63. Given that 1 amu equals 1.66×10^{-27} kg, show that 1 amu has an energy equivalent of 931 MeV.

64. On average, how many fission reactions of uranium-235 would it take to release 1 J of energy?

65. Given that the neutral nitrogen atom with seven neutrons has a mass of 14.003 074 amu, what is its total binding energy?

66. Calculate the total binding energy of the $^{12}_{6}C$ nucleus.

67. The mass of the neutral lithium-7 atom is 7.016 004 amu. Find the mass of the bare lithium-7 nucleus.

68. The mass of the neutral tritium atom is 3.016 049 amu. Find the mass of the bare nucleus, called the triton.

69. How much energy is released when ${}^{3}_{1}\mathrm{H}$ decays to form ${}^{3}_{2}\mathrm{He}$? The masses of the neutral hydrogen and helium atoms are 3.016 049 and 3.016 029 amu, respectively.

70. How much energy is released when ${}^{14}_{6}\mathrm{C}$ decays to form ${}^{14}_{7}\mathrm{N}$? The masses of the neutral carbon and nitrogen atoms are 14.003 242 and 14.003 074 amu, respectively.

71. How much energy is released in the alpha decay of ${}^{239}_{94}\mathrm{Pu}$? The masses of the neutral plutonium, uranium, and helium atoms are 239.052 158, 235.043 925, and 4.002 603 amu, respectively.

72. How much energy is released in the alpha decay of ${}^{214}_{84}\mathrm{Po}$? The masses of the neutral polonium, lead, and helium atoms are 213.995 190, 209.990 069, and 4.002 603 amu, respectively.

73. Use Figure 26-5 to estimate the energy released if ${}^{239}_{94}\mathrm{Pu}$ fissions to become ${}^{96}_{40}\mathrm{Zr}$ and ${}^{141}_{54}\mathrm{Xe}$ with the release of two neutrons.

74. Use Figure 26-5 to estimate the energy released if ${}^{236}_{92}\mathrm{U}$ fissions to become ${}^{142}_{45}\mathrm{Ba}$ and ${}^{91}_{36}\mathrm{Kr}$ with the release of three neutrons.

75. Show that the given fusion reaction releases 17.6 MeV of energy. The masses of the deuteron and triton are 2.013 55 and 3.015 50 amu, respectively.

$${}^{2}_{1}\mathrm{H} + {}^{3}_{1}\mathrm{H} \rightarrow {}^{4}_{2}\mathrm{He} + {}^{1}_{0}\mathrm{n}$$

76. How much energy is released in the following fusion reaction? The masses of deuteron and triton are given in Exercise 75.

$${}^{2}_{1}\mathrm{H} + {}^{2}_{1}\mathrm{H} \rightarrow {}^{3}_{1}\mathrm{H} + {}^{1}_{1}\mathrm{p}$$

77. In the first cycle of a fission chain reaction, a single nucleus fissions and produces three neutrons. If every free neutron initiates a new fission event, then three nuclei fission in the second cycle, for a total of four. What is the total number of fission events after five cycles?

78. In the first cycle of a fission chain reaction, a single nucleus fissions and produces two neutrons. If every free neutron initiates a new fission event, then two nuclei fission in the second cycle, for a total of three. If each fission event releases 210 MeV on average, what is the total energy released after eight cycles?

79. Given that the mass of the Sun is decreasing at the rate of 4.3×10^{9} kg/s, what is the present energy radiated by the Sun each second?

80. Use the information in Exercise 79 to approximate how much mass the Sun has lost during its lifetime. How does this compare with its current mass of 2×10^{30} kg?

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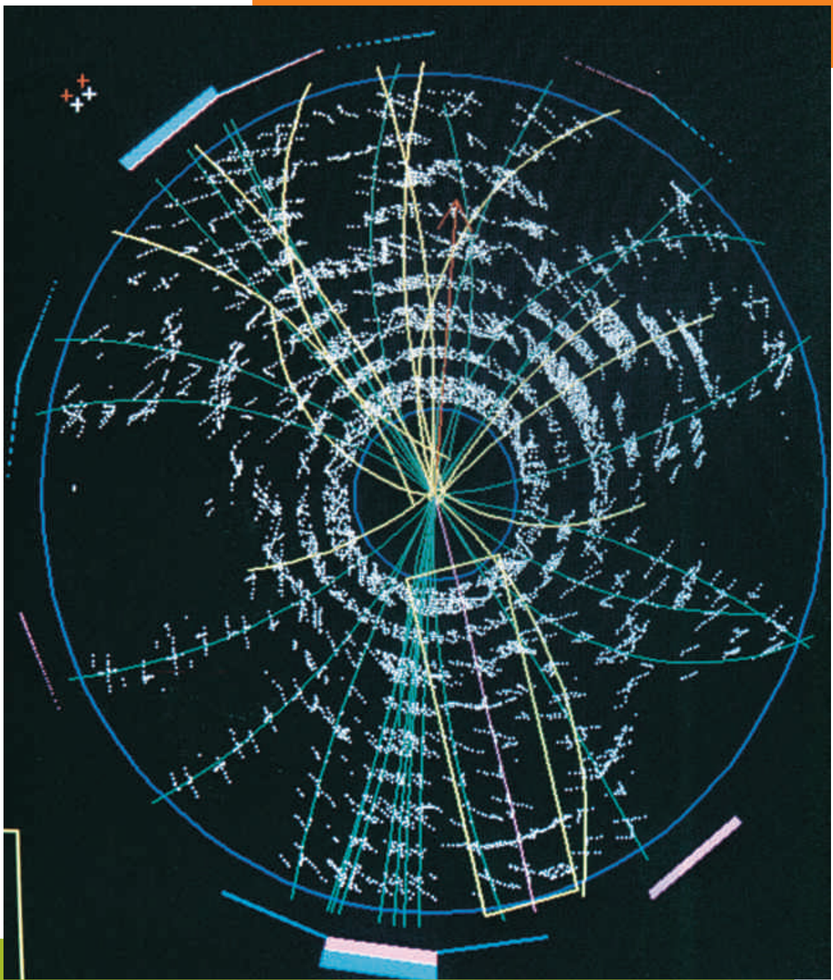
27

Elementary Particles

▶Throughout recorded history we have searched for the primary building blocks of nature. Aristotle's four "elements" became the chemical elements, which gave way to electrons, protons, and neutrons. As we delved deeper, we found new, fascinating layers. Have we found the ultimate building blocks? If not, where will our search end?

(See page 614 for an answer to this question.)



Fermi National Accelerator Library

A computer-generated reconstruction of a collision in the Collider Detector at Fermilab. It is possible that the collision of a proton and an antiproton produced a top quark and antiquark.

THE idea that all of the diverse materials in the world around us are composed of a few simple building blocks is appealing; because of its appeal, the idea has existed for more than 20 centuries. The search for these elementary components of matter is fueled by the desire to simplify our understanding of nature.

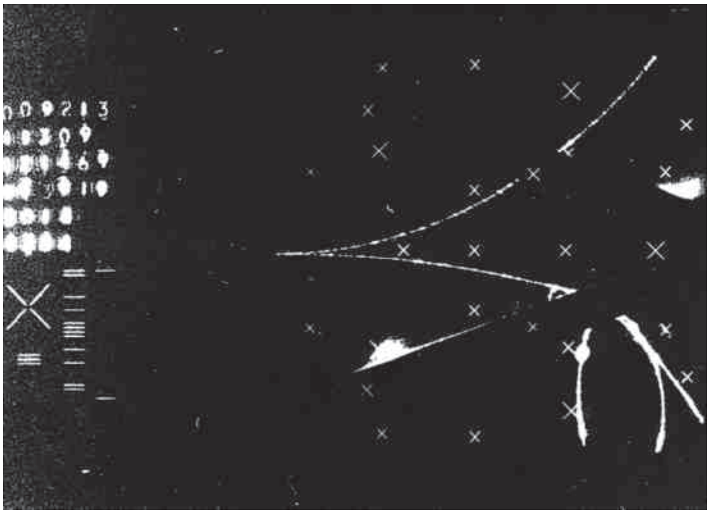
The search began with the Aristotelian world view, which assumed that everything was made of four basic elements: earth, fire, air, and water. During the 18th and 19th centuries, these four were eventually replaced by the modern chemical elements. Although the initial list numbered only a few dozen elements, it grew to more than 100 entries. A hundred different building blocks are not as appealing as four. Things improved, however, when atoms were discovered to be divisible and composed of three even more basic building blocks. The elementary particles described in 1932 consisted of the three constituents of atoms—the electron, proton, and neutron—and the quantum of light—the photon. These four building blocks restored an elegant simplicity to the physics world view.

This beautiful picture did not survive for long. As experimenters probed deeper and deeper into the subatomic realm, new particles were discovered. The experimenters were constantly confronted with new, seemingly bizarre observations. The first, and perhaps most bizarre, observation occurred during the same year the neutron was discovered and resulted in the discovery of an entirely new kind of matter.

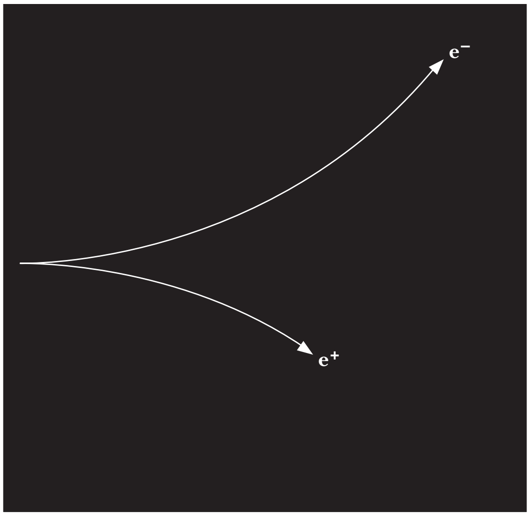
Extended presentation available in the *Problem Solving* supplement

Antimatter

A new type of particle was discovered in 1932. When high-energy photons (gamma rays) collided with nuclei, two particles were produced: one was an electron, the other an unknown. Double spirals in bubble-chamber photographs showed tracks of the pairs of particles that were created (Figure 27-1). This **pair production** is a dramatic example of Einstein's equation $E = mc^2$; energy (the massless gamma ray) is converted into mass (the pair of particles). The curvature of the new particle's path in the bubble chamber's magnetic



(*a*)



(*b*)

Figure 27-1 (a) A bubble-chamber photograph and (b) a drawing of the tracks of a positron–electron pair.

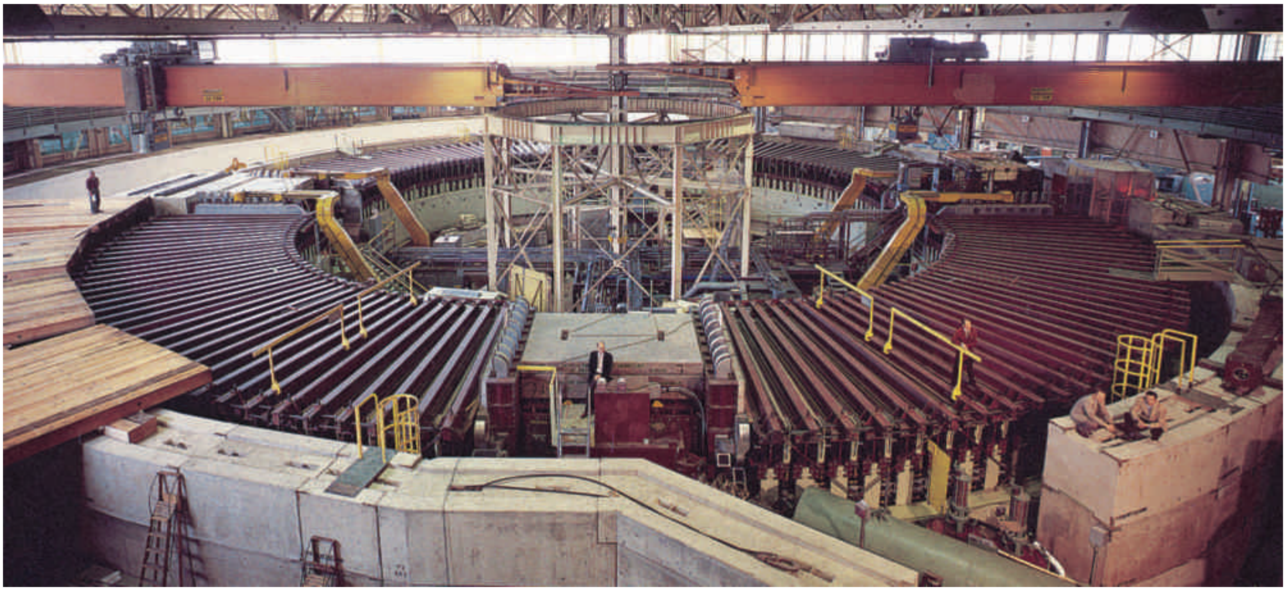
field revealed that it had the same charge-to-mass ratio as an electron, but because it curved in the opposite direction, it had a positive charge. All the properties of this new particle were of the same magnitude as the electron's, although some properties had the opposite sign. For example, the masses were identical, and the electric charges were the same size but opposite in sign. This positively charged electron was named the **positron** and is the **antiparticle** of the electron.

The prediction of the existence of the positron was contained in a quantum-mechanical theory for the electron developed by the English physicist P.A.M. Dirac in 1928. Until its discovery, however, Dirac's "other electron" seemed more like a mathematical oddity in the theory than a physical possibility. After its discovery, the full significance of Dirac's ideas was recognized.

Dirac's theory contained similar predictions for the antiparticles of the proton and neutron, and after the discovery of the positron they were assumed to exist. Finding these heavier antiparticles took two decades. A primary reason for the delay was the large amount of energy needed. To create a pair of particles, the available energy has to be larger than the energy needed to create the rest masses of the two particles. (The special theory of relativity tells us that mass and energy are equivalent. Therefore, it takes energy to create the masses of the particles.) Protons and neutrons are so much more massive than electrons that the production of their antiparticles had to await the development of huge accelerators to achieve these great energies. The antiproton was observed in 1955 and the antineutron in 1956.

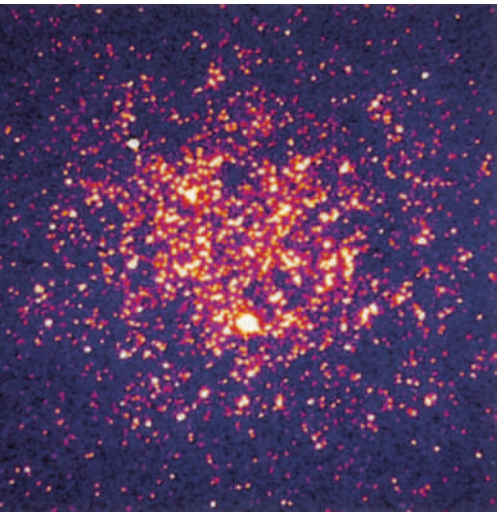
Antiparticles are usually designated by putting a bar over the symbol of the corresponding particle. Thus, an antiproton becomes $\overline{\mathrm{p}}$ and an antineutron $\overline{\mathrm{n}}$. However, the positron is usually written as e^+.

Antiparticles don't survive long around matter. When particles and antiparticles come into contact, they annihilate, converting their combined mass into energy. This process is the reverse of pair production. Because the world we know is assumed to be "regular" matter, antiparticles have little chance of surviving. Once they are created, their lifetimes are determined by how long it takes them to meet their corresponding particle. The positron is slowed by collisions with particles and is eventually captured by an electron. They orbit



University of California, Lawrence Livermore Nat'l Laboratory & the U.S. Department of Energy

The antinucleons were discovered at the Bevatron, a particle accelerator in Berkeley, California.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Could any of these stars be composed of antimatter?

each other briefly to form an "atom." In a time typically much less than a millionth of a second, the two annihilate, converting their combined mass back into photons.

If an antiparticle did not meet its counterpart, annihilation would not occur, and the antiparticle would exist for a long time. This means that antiatoms could be formed from antielectrons, antiprotons, and antineutrons. The only reason that this doesn't usually happen is the extremely low probability of these antiparticles finding each other in a world so predominantly composed of ordinary particles. However, under special circumstances, this can be achieved. Antideuterium—an antinucleus consisting of one antiproton and one antineutron—has been observed, and in 1995 antihydrogen atoms were produced for very brief periods of time.

The existence of antiatoms leads to the fascinating question of whether antiworlds may exist somewhere in the universe. There doesn't seem to be any reason to believe they don't exist. Antiatoms should behave the same as atoms. In particular, they would display the same spectral lines. And, because photons and antiphotons are identical, looking at a distant star won't reveal whether it is composed of matter or antimatter. However, evidence shows that each cluster of galaxies must be either matter or antimatter. If there were matter and antimatter galaxies in a single cluster, the intergalactic dust particles would annihilate, giving off characteristic photons. These photons have not been observed.

Because radio waves are composed of photons, we would have no trouble communicating via radio with antihumans on an antiworld. Although distances make the possibility extremely unlikely, any attempt to communicate by visiting would result in an explosion larger than any bomb that we could build. The entire mass of the spaceship and an equal mass of the antiworld would annihilate each other.

The discovery of antiparticles provided a reassuring demonstration that the conservation laws of momentum and energy hold in the subatomic world. Every annihilation yields at least two photons. Suppose, for example, a positron–electron pair were orbiting each other as shown in Figure 27-2(a). If we are at rest relative to the pair, they have equal energies and equal but oppositely directed momenta. Before the annihilation they have a total energy that is twice the mass of one of them, but their total momentum is zero because they are traveling in opposite directions. If only one photon were produced by the annihilation, the total momentum would not be zero but would be equal to that of the photon—an obvious violation of the conservation of momentum. This situation never occurs; at least two photons are always produced in the annihilation. The photons' total momentum is zero, as illustrated in Figure 27-2(b). The conservation rules have been extremely useful in helping us understand the details of the elementary particles' interactions.

Q: Would a decay into three photons be forbidden by the laws of conservation of linear momentum and energy?

A: No. The momenta of three photons can be arranged in many ways to get a total momentum of zero and a given total energy. Therefore, these two laws do not forbid this process from occurring.

The Puzzle of Beta Decay

In Chapter 25 we saw that one element can spontaneously change into another element by undergoing beta decay. On the nucleon level, this means that a

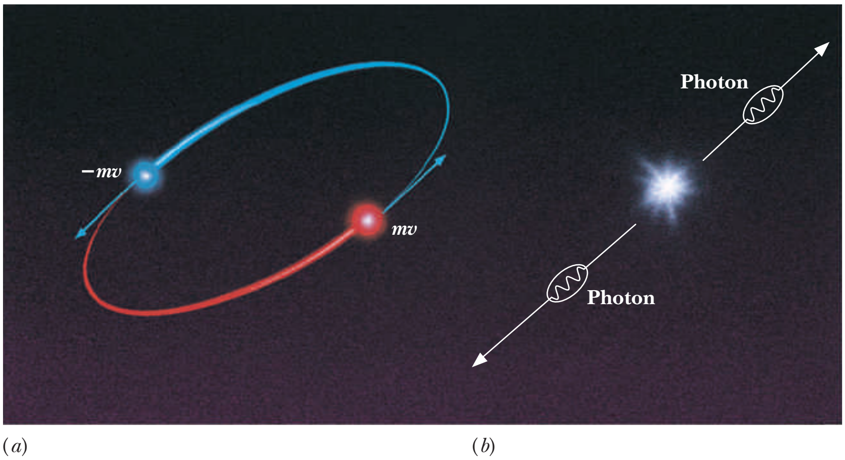

Figure 27-2 The two photons produced in an electron–positron annihilation have equal but oppositely directed momenta to match the zero momentum of the electron–positron pair.

neutron turns into a proton, or vice versa. This process led to an interesting puzzle because beta decay did not appear to satisfy the basic conservation laws for energy and linear momentum.

Imagine you are sitting in a reference system in which a neutron is at rest. The linear momentum of the neutron is zero, and its energy is that associated with its rest mass. If we assume that beta decay changes the neutron into a proton by emitting an electron, momentum can be conserved only if the electron goes off in one direction and the newly created proton recoils in the opposite direction with the same size momentum (Figure 27-3). The value of these momenta is determined by the requirement that energy also be conserved. Because this can happen only in one way, it was expected that the electron must always emerge with the same kinetic energy.

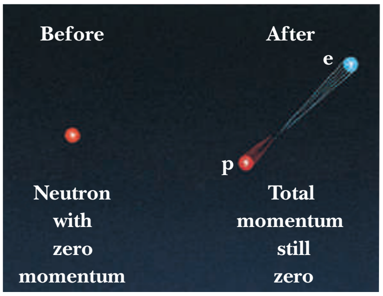

Figure 27-3 If beta decay of a neutron produced only a proton and an electron, they would have to emerge with equal but oppositely directed momenta.

This was the expected result, but experiments showed that this doesn't happen. The ejected electrons do not have a single kinetic energy. The graph of experimental data in Figure 27-4 shows a continuous range of kinetic energies from zero up to a maximum value that is equal to the value predicted previously.

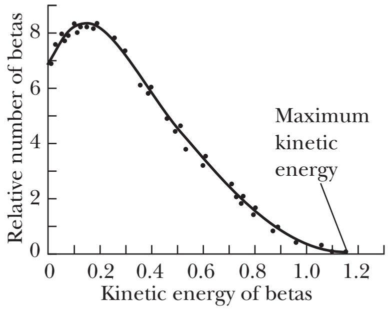

Figure 27-4 The spectrum of kinetic energies of electrons emitted in the beta decay of neutrons.

Scientists were in a dilemma. There seemed to be two choices: they could abandon the conservation laws or assume that one or more additional particles were emitted along with the electron. In 1930 Pauli proposed that a third particle, the **neutrino,** was involved. (*Neutrino* means "little neutral one.") Using the conservation laws, he even predicted its properties. The neutrino has to be neutral because charge is already conserved. The fact that the electron sometimes emerges with all the kinetic energy predicted for the decay without the neutrino means that the neutrino sometimes carries away little or no energy. For this to be possible, the neutrino's rest mass must be very small because it would require some energy to produce its rest mass.

◀ discovery of the neutrino

Even though the neutrino was not observed, faith in its existence continued to grow. It was such a nice solution to the beta-decay puzzle that experimental verification of the neutrino's existence seemed to be only a matter of time. "Only a matter of time" eventually became 26 years. In 1956 Clyde Cowan and Frederick Reines finally detected neutrinos, using an intense beam of radiation from a nuclear reactor (Figure 27-5). The observed reaction had an antineutrino $\overline{\nu}$ strike a proton, yielding a neutron and a positron.

$$\overline{\nu} + \mathrm{p} \rightarrow \mathrm{n} + \mathrm{e}^+$$

The properties of the neutrino were confirmed by the study of the dynamics of this interaction. Its rest mass had been shown to be very small; it was often assumed to be zero. However, in 1980 some experimental results indicated

Savannah River Laboratory (both)

Figure 27-5 This apparatus was used by Cowan and Reines at the nuclear reactor in Savannah River, South Carolina, to detect the neutrino.

that the mass of the neutrino may not be exactly zero, and recent experiments have indicated that the neutrino mass is not zero (Chapter 28).

These results could affect our understanding of the evolution of stars and the universe. Neutrinos are so abundant in the universe that they may contribute enough mass to the universe that it may eventually quit expanding and collapse under its own gravitational attraction (Chapter 28).

The long delay in detecting neutrinos was due to the extremely weak interaction of neutrinos with other particles; neutrinos do not participate in the electromagnetic or the strong interactions, only in the weak interactions. In fact, the neutrinos' interaction with other particles is so weak that only one of a trillion neutrinos passing through Earth is stopped.

Exchange Forces

During the development of Newton's law of universal gravitation, a nagging question arose about forces: what is it that reaches through empty space and pulls on the objects? Newton's idea of an action at a distance seemed unsatisfactory. A couple of hundred years later, the concept of a field provided an alternative (Chapter 20). One object creates a change in space (the field), and a second object responds to this field. At least empty space was filled with something, but it was still somewhat unsatisfying.

With the discovery of the quantum of energy, a new problem arose. An object moving through a field would gain energy continuously. However, the fact that the energy was quantized (Chapter 24) meant that the object should receive energy only in discrete lumps. This conclusion led to a picture of elementary particles interacting with each other through the exchange of still other elementary particles. Electrons, for example, exchange photons.

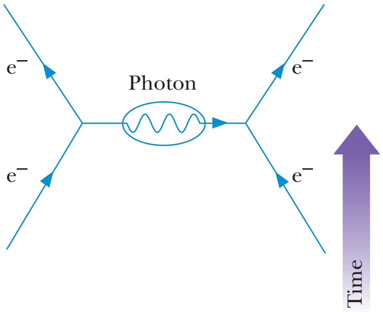

Figure 27-6 A Feynman diagram of the interaction between two electrons through the exchange of a photon.

Instead of an electron being repelled by another electron because of an action at a distance or by a field, each electron continuously emits and absorbs photons. Because we are talking about effects that are entirely quantum mechanical, it is risky (if not foolhardy) to rely too heavily on classical analogies. Uncomfortable as it seems, we should be content to say that the interaction properties can be explained by the assumption that photons are exchanged and, depending on the photon properties, the particles attract or repel each other. Richard Feynman created a way of showing these interactions graphically. Imagine the Feynman diagram in Figure 27-6 as a graph in

Feynman | *Surely You're Joking, Mr. Feynman*

The word *play* occurs often in scientists' writings. Newton said that he felt as if he were a child playing on the seashore as the great ocean of undiscovered law lay before him. A brilliant physicist, Richard Feynman (1918–1988), made play a central element in his work on what he called "strange particles" and in his conceptual breakthrough that led to the development of quantum electrodynamics (QED). Faith is an occupational hazard for physicists; doubt is a supreme virtue. In one of his many talks to students at the California Institute of Technology (Cal Tech), Feynman invited them to join him in studying nanotechnology—the study of very small things. The talk was titled "There's Plenty of Room at the Bottom." Most of us would like to head for the top, but Feynman played with words to invite them to explore the very small, where nature provides immense challenges. Playfulness provides us with the gusto and enthusiasm to explore our natural world.

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Richard Feynman

Feynman was a playful prodigy as a child. He was the son of Jewish parents, a second-generation Russian father and a Polish mother. As a child in Far Rockaway, New York, he devoured science and mathematics. Afraid of being seen as a sissy, he developed a vigorous and almost combative playful style. In mathematics he moved ahead on his own at a furious pace, even inventing his own notation for trigonometric functions. He soon realized that no one else could use his notation and returned to the conventional notation. He was an undergraduate at MIT and even there began an unconventional course of study that led him to neglect required subjects such as history. When he petitioned to become a doctoral candidate, his mentor at MIT urged that he transfer to Princeton where he would be better challenged. Admission to Princeton in the late 1930s was difficult for a young Jewish student. Unspoken but real quotas existed in elite universities. When he presented his first seminar at Princeton, the audience included Einstein, Pauli, and John von Neumann, the inventor of game theory. Feynman received his Ph.D. in physics in 1942 and then joined the project to construct an atomic bomb at Los Alamos, New Mexico.

It was a taxing effort to restrain the boisterous young theorist. Feynman challenged the system by playing bongo drums at odd hours, sending coded letters to friends to frustrate the censors, and picking locks on safes containing classified documents and inserting little notes for the security staff. He described these high jinks in an autobiographical work he published 30 years later: *Surely You're Joking, Mr. Feynman* (New York: Norton, 1985).

After spending time on the faculty at Cornell University, in 1950 Feynman moved to Cal Tech in Pasadena. There he produced his magisterial works on the interaction of particles and atoms in radiation fields. His lifelong fascination with spacetime led him to develop *Feynman diagrams,* an innovative system that provided a visual representation of particle interactions. Along with Julian Schwinger and Shinichiro Tomonaga, he was awarded the Nobel Prize in 1965 for this work. He called his Nobel Prize "a pain in the neck" because of the increased demands on his time.

He was always interested in practical applications of science and later in life said that he wished he had taken up administration in large-scale enterprises such as NASA because they offered unique new challenges. Feynman was called in to help investigate the tragic *Challenger* explosion. He demonstrated that when O rings (round rubber rings) are chilled, as they had been on that frosty night in Florida, they inevitably fail. He urged NASA engineers and managers to develop more rigorous procedures for testing all components under realistic conditions. In cases like this, it behooves scientists and engineers to beware their little bit of ignorance.

Stomach cancer afflicted him in later years. Before he died at age 69, he wrote, "The vastness of nature stretches my imagination. Stuck on this carousel my little eye can catch one-million-year-old light. . . . It does not harm the mystery to know a little about it."

—Pierce C. Mullen, historian and author

Sources: Jagdish Mehra, *The Beat of a Different Drum: The Life and Science of Richard Feynman* (New York: Oxford University Press, 1994); James Gleick, *Genius: The Life and Science of Richard Feynman* (New York: Pantheon, 1992); Richard P. Feynman, *What Do You Care What Other People Think?* (New York: Norton, 1987).

which the vertical dimension is time. Two electrons approaching each other exchange a photon and repel each other.

We should rely on the quantum-mechanical explanation, and yet analogies sometimes make things plausible. Consider the following: Imagine two people standing on skateboards, as shown in Figure 27-7. One throws a basketball to the other. The person throwing the basketball gives it some momentum and therefore must acquire some momentum in the backward direction. The person catching the basketball must absorb this momentum and therefore acquires momentum in the direction away from the thrower. The total interaction behaves as a repulsive force between the two people. Although this anal-

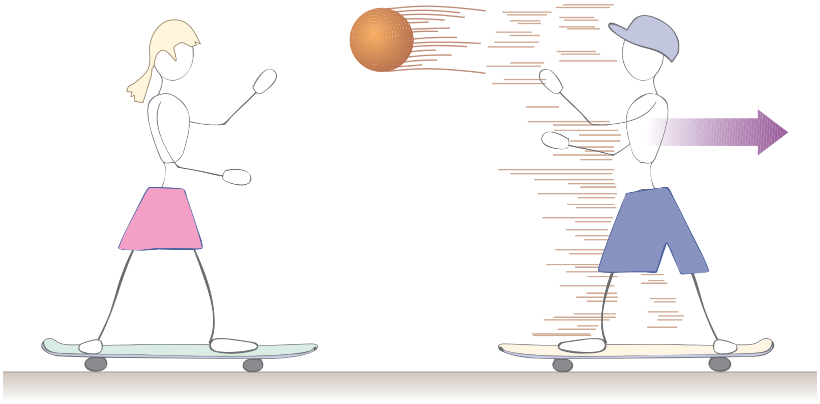


Figure 27-7 A classical analogy of a repulsive exchange force is tossing a basketball back and forth.

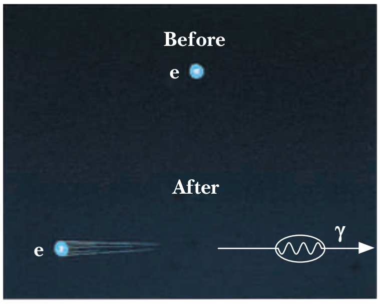


Figure 27-8 The emission of a real photon by an isolated particle violates the laws of conservation of energy and momentum.

ogy illustrates that exchanging particles can affect particles at a distance and is easy to visualize, it fails for an attractive force. We must return to the reality that these are quantum-mechanical effects and that our commonsense world view does not serve us well in the subatomic world of elementary particles.

We can ask whether the idea of exchanging photons accounts for the observations. It does; however, it also poses a new problem. Imagine an electron at rest in space. If we explain its effect on other particles by saying it emits photons, it must recoil after the emission because of the conservation of momentum. But if it recoils, it has kinetic energy. In fact, the emitted photon also has some energy. These energies are over and above the rest mass of the electron and thus in violation of the law of conservation of energy (Figure 27-8). The same argument can be made for the electron that feels the interaction by absorbing the photon.

Once again we are confronted with a situation in which energy and momentum are not conserved. Only in this case, the solution is different; we are not bailed out by the discovery of a new particle. This violation exists. However, it does not mean the abandonment of the conservation rules. Overall, momentum and energy are conserved. The violations created by the emission of the photon are canceled by the absorption of the photon by the other particle. It is only during the time that the photon travels from one particle to the other that the violation exists.

We invoke the uncertainty principle (Chapter 24) to understand this situation. One form of the uncertainty principle says that we can determine the energy of a system only to within an uncertainty ΔE that is determined by the time Δt taken to measure the energy. The product of these two uncertainties is always greater than Planck's constant. This is our escape from the dilemma. If a violation of energy conservation by an amount ΔE takes place for less than a time Δt, no physical measurement can verify the violation. We now believe that unmeasurable violations of the conservation of energy (and momentum) can and do take place. (We have to be a bit careful with this resolution of the problem because we are assigning a classical type of trajectory to the photon as we tried to do with electrons in atoms. Once again it is really a quantum-mechanical effect; energy and momentum are conserved for the interaction.)

Because photons have no rest mass, their energies can be very small. Therefore, the violation of energy conservation due to the emission of a photon can be very small. Very small energy violations can last for very long times, and these photons can travel large distances before they are reabsorbed, which explains the infinite range of the electromagnetic force. The fact that the electromagnetic force decreases with distance is explained by the observation that exchange photons that have long ranges have low energies (and momenta) and therefore produce smaller effects.

Exchange Particles

Although it may sound bizarre, the idea of exchanging particles explains more than previous models. This new concept of a force satisfies the requirements of quantum mechanics and provides a way of understanding all forces. As an example, because the different forces have different characteristics, presumably they have different exchange particles.

In 1935 Japanese physicist Hideki Yukawa used this radical idea to show why the nuclear force abruptly "shuts off" after a very short distance. Yukawa reasoned that the short range of the strong force required the exchange particle to have a nonzero mass. The mere creation of its mass requires an energy violation. This minimum energy violation must be at least as large as the rest-mass energy, which means that there is a limit to the time in which the violation can occur and therefore a maximum distance the particle can travel before it must be absorbed by another particle. In other words, the exchange of nonzero rest-mass particles means that the force has a limited range.

Finding the Yukawa exchange particle was difficult. It couldn't be detected in flight between two nucleons because of the consequences of the uncertainty principle. The hope was that it might show up in other interactions. We observe photons, for example, when they are created in jumps between atomic levels, not from being "caught" between two electrically charged particles.

During the 1930s cosmic rays were the only known source of particles with energy high enough to create the new exchange particles. Cosmic rays are continually bombarding Earth's atmosphere, creating many other particles that rain down on Earth in extensive showers. In 1938 a new particle was discovered in a cosmic-ray shower that had a mass 207 times that of the electron and a charge equal to the electron's charge. For a while it was thought that this was the particle predicted by Yukawa, but it did not interact strongly with protons and neutrons. Therefore, the new particle, now known as the **muon,** could not be the exchange particle for the strong force.

The search for Yukawa's particle continued, and it was finally discovered 10 years later in yet another cosmic-ray experiment. The **pion** (short for *pi meson*) has a mass between that of the electron and the proton and comes with three possible charges: +1, 0, and −1 times that on the electron. Although the pion is no longer considered an exchange particle, it played a pivotal role in the acceptance of the idea of exchange forces. (We return to the question of the exchange particle for the strong force in a later section.)

The success of this model for the interactions between particles led to the hypothesis that all forces are due to the exchange of particles. The gravitational force is presumably due to the exchange of **gravitons.** Because of the similarities between the gravitational force and the electromagnetic force, the graviton should have properties similar to the photon. It should have no rest mass and travel with the speed of light. Although the graviton has not been observed, most physicists believe it exists.

The exchange particles for the weak force, however, have been detected. The weak force occurs through the exchange of particles known as **intermediate vector bosons.** These three particles were discovered in 1983: the W comes in two charge states, +1 and −1, and the Z^0 is neutral. One of the reasons it was so difficult to discover these particles is that they are very massive, each one having more than 100 times the mass of the proton. Their discovery had to wait for the construction of new accelerators.

The Elementary Particle Zoo

By 1948 the discovery of antiparticles and exchange particles had nearly tripled the number of known elementary particles. And the situation got worse.

FLAWED REASONING

While discussing the difference between the ranges of the electric force and the weak force, your classmate asserts, "Particles with mass, such as the intermediate vector bosons, cannot travel at the speed of light as photons can. This is what limits the range of the weak force." **How do you respond to this?**

ANSWER It is not the speed of the intermediate vector bosons that limits their range, but their rest mass. The Heisenberg uncertainty principle allows a particle to be created and exchanged in violation of energy conservation as long as the particle exists for a short enough time that the violation cannot be physically observed. The larger the energy required to create the particle, the shorter the time it can exist. Photons can have arbitrarily small energies because they have no rest mass. They can exist for arbitrarily long times and travel arbitrarily large distances. However, intermediate vector bosons have large rest masses, providing a lower limit on the amount of energy required to create them. They can exist for very short times and travel extremely short distances.

During the next seven years, four other particles were discovered. Because the behavior of these particles did not match that of the known particles, they became known as the **strange particles.** The existence of the neutrino was confirmed in 1956. A second type of neutrino was discovered in 1962, and even a third type exists.

The 1960s also witnessed the discovery of another new phenomenon. Particles were discovered that live for such a short time that they decay into other particles before they travel distances that are visible even under a microscope. Typical lifetimes for these particles are 10^{-23} second (the time it takes light to travel across a nucleus!).

Q: What does the uncertainty principle say about the mass of a particle that has such a short lifetime?

A: The uncertainty in the energies (and consequently in their masses because of the equivalence of mass and energy) must be large because the product of the uncertainties in the energy and the lifetime must exceed Planck's constant. This has been confirmed by many experiments.

Before long the number and variety of particles became so large that physicists began calling the collection a zoo. The proliferation of new particles had once again destroyed the hope that the complex structures in nature could be built from a relatively small number of simple building blocks. The number of "elementary" particles exceeded a few hundred, and the number continued to grow. Particle physicists began to feel organizational problems similar to those of zookeepers.

Much as zookeepers build order into their zoos by grouping the animals into families, particle physicists began grouping the elementary particles into families. Making families helps organize information and may result in new discoveries. When confronted with many seemingly unrelated facts, scientists often begin by looking for patterns. Mendeleev developed the periodic table of chemical elements using this technique. A Swiss mathematics teacher, Johann Balmer, decoded the data on the spectral lines of the hydrogen atom by arranging and rearranging the wavelengths. In the process he discovered a formula that gave the correct results. Both of these discoveries were empirical relationships, not results derived from fundamental understandings of nature. They served, however, to classify the data and provide some guidance for further experimental work.

Elementary particle physics was in a similar condition. Large amounts of data had been accumulated. Scientists were looking for patterns that might provide clues for the development of a comprehensive theory. Just as any collection of buttons can be classified in many ways—size, color, shape, and so forth—the elementary particles can be classified in different ways. (Of course, macroscopic attributes such as color and size don't apply here.) One fruitful way is to group them according to the types of interaction in which they participate.

All particles participate in the gravitational interaction—even the massless photon, because of the equivalence of mass and energy. Therefore, this interaction doesn't yield any natural divisions for the particles. Furthermore, gravitation is so small at the nuclear level that it usually isn't included in discussions of particle behavior.

The particles that participate in the strong interaction are called **hadrons.** This family includes most of the elementary particles. The hadrons are further divided into two subgroups according to their spin quantum numbers. The **baryons** have spins equal to $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$, . . . of the quantum unit of spin, whereas the **mesons** have whole-number units of spin. The best-known baryons are the neutron and proton. Table 27-1 lists some common hadrons and their properties. There are others but their lifetimes are extremely short—less than a billionth of most of those listed.

The **lepton** family includes the electron, the muon, the tau (discovered in 1977), and their associated neutrinos. The tau lepton is even more massive than the muon. The word *lepton* means "light particle" and refers to the observation that (with the exception of the tau) leptons are less massive than hadrons. In fact, they appear to be pointlike, having no observable size and

Table 27-1 *Properties of Some of the Hadrons*

Name	Symbol	Spin ($h/2\pi$)	Rest Mass (MeV/c^2)	Half-Life (s)	Strangeness
Baryons					
Proton	p	$\frac{1}{2}$	938.3	Stable	0
Neutron	n	$\frac{1}{2}$	939.6	614	0
Lambda	Λ^0	$\frac{1}{2}$	1116	1.82×10^{-10}	−1
Sigma	Σ^+	$\frac{1}{2}$	1189	0.56×10^{-10}	−1
	Σ^0	$\frac{1}{2}$	1193	5.1×10^{-20}	−1
	Σ^-	$\frac{1}{2}$	1197	1.03×10^{-10}	−1
Xi	Ξ^0	$\frac{1}{2}$	1315	2.01×10^{-10}	−2
	Ξ^-	$\frac{1}{2}$	1321	1.14×10^{-10}	−2
Omega	Ω^-	$\frac{3}{2}$	1672	0.57×10^{-10}	−3
Mesons					
Pion	π^+	0	139.6	1.80×10^{-8}	0
	π^0	0	135.0	5.8×10^{-17}	0
	π^-	0	139.6	1.80×10^{-8}	0
Kaon	K^+	0	493.7	8.85×10^{-9}	+1
	K^0*	0	497.6	6.21×10^{-11}	+1
				3.59×10^{-8}	

*The K^0 has two lifetimes, 50% decay via each mode.

Table 27-2 *Properties of the Leptons*

Name	Symbol	Spin ($h/2\pi$)	Rest Mass (MeV/c^2)	Half-Life (s)
Electron	e^-	$\frac{1}{2}$	0.511	Stable
Electron neutrino	ν_e	$\frac{1}{2}$	$\neq 0$	—
Muon	μ^-	$\frac{1}{2}$	105.7	1.52×10^{-6}
Mu neutrino	ν_μ	$\frac{1}{2}$	$\neq 0$	—
Tau	τ^-	$\frac{1}{2}$	1777	2.01×10^{-13}
Tau neutrino	ν_τ	$\frac{1}{2}$	$\neq 0$	—

no evidence of any internal structure. Table 27-2 lists the known leptons. The questions of the masses and stability of the neutrinos are rather complex issues and are discussed in the next chapter.

All leptons and hadrons participate in the weak interaction. The only particles that fail to get listed in the hadron or lepton families are exchange particles.

Conservation Laws

Conservation laws provide insight into the puzzles of the elementary particles. We have already seen how the conservation laws were used to unravel beta decay. In some situations new conservation laws have been invented as a result of the experiences of viewing many particle collisions. The success of the conservation laws has been responsible for a guiding philosophy: *if it can happen, it will.* That is, any process not forbidden by the conservation laws will occur.

The classical laws of conserving energy (mass–energy), linear momentum, angular momentum (including spin), and electric charge are valid in the elementary particle realm. Any reaction or decay that occurs satisfies these laws. For instance, the neutron decays into a proton, an electron, and an antielectron neutrino via beta decay,

allowed ▶

$$n \rightarrow p + e^- + \bar{\nu}_e$$

but has never been observed to decay via

forbidden ▶

$$n \rightarrow p + e^+ + \nu_e$$

Q: Why is this second alternative forbidden?

A: The second alternative is forbidden by charge conservation because the initial state (the neutron) has zero charge and the final state (proton, positron, and neutrino) has a charge of +2.

A little less obvious are situations that are forbidden because they violate energy conservation. A particle cannot decay in a vacuum unless the total rest mass of the products is less than the decaying particle's rest mass. To see this, view the decay from a reference system at rest with respect to the original particle. The principle of relativity (Chapter 9) states that conclusions made in one reference system must hold in another. In the rest system, the total energy is the rest-mass energy of the particle. After the decay, however, the energy consists of the rest-mass energies of the products *plus* their kinetic energies. There has to be enough energy to create the decay particles even if they have no kinetic energy. Some of these decays that are forbidden by the conservation of energy can, however, occur in nuclei because the decaying particle can acquire kinetic energy from other nucleons to produce the extra mass. In reactions involving collisions of particles, kinetic energies must also be included in calculating conservation of energy.

Additional conservation laws were created as more information about the elementary particles became known. The total number of baryons is constant in all processes. So the concept of baryon number and its conservation was invented to reflect this discovery. Baryons are assigned a value of +1, antibaryons a value of −1, and all other particles a value of 0. In any reaction the sum of the baryon numbers before the reaction must equal the sum afterward. For example, suppose a negative pion collides with a proton. One result that could not happen is

$$\pi^- + \mathrm{p} \rightarrow \pi^+ + \overline{\mathrm{p}}$$

$$0 \;+\; 1 \;\neq\; 0 \;-\; 1 \text{ baryon numbers}$$

◀ forbidden

because the baryon number is +1 before and −1 after. On the other hand, we could expect to observe

$$\pi^- + \mathrm{p} \rightarrow \mathrm{p} + \overline{\mathrm{p}} + \mathrm{p} + \pi^-$$

$$0 \;+ 1 \;=\; 1 \;-\; 1 \;+\; 1 \;+\; 0 \text{ baryon numbers}$$

◀ allowed

if the kinetic energy of the pion is sufficiently high.

Similarly, we don't expect the proton to decay by a process such as

$$\mathrm{p} \rightarrow \pi^0 + \mathrm{e}^-$$

$$1 \;\neq\; 0 \;+\; 0 \text{ baryon numbers}$$

◀ forbidden

In fact, the proton cannot decay at all because it is the baryon with the smallest mass. Any decay that would be allowed by baryon conservation would require more energy than the rest mass of the proton. Some recent results have indicated that the conservation of baryon number may not be strictly obeyed. The proton may possibly decay, but its half-life is known to be at least a billion trillion times the age of the universe!

There is no comparable conservation of meson number. Mesons can be created and destroyed, provided the other conservation rules are not violated. There are no conservation laws for the number of any of the exchange particles.

A conservation law for leptons has been discovered, but it is more complicated than that for baryons. There are separate lepton conservation laws for electrons, muons, and presumably taus. Furthermore, the neutrino associated with the electron is not the same as that associated with the muon or tau. The bookkeeping procedure is slightly more detailed, but the procedure is essentially the same. The electron, muon, and tau lepton numbers must be separately conserved.

Some quantities are conserved by one type of interaction but not another. Each new particle is studied and grouped according to its properties: how fast it decays, its mass, its spin, and so on. One group of particles became known as the strange particles because their half-lives didn't seem to fit into the known interactions. If they decayed via the strong interaction, their half-lives should be about 10^{-23} second. If they decayed via the electromagnetic interaction, the predicted half-lives should be about 10^{-16} second. However, these particles are observed to live about 10^{-10} second, at least a million times longer than they "should" live. Something must be prohibiting these decays. A property called **strangeness** and an associated conservation law were invented. The various strange particles were given strangeness values, and the conservation law stated that any process that proceeds via the strong or electromagnetic interaction conserves strangeness, whereas those that proceed via the weak interaction can change the strangeness by a maximum of 1 unit.

The idea of a strangeness quantum number that is conserved seems quite foreign to our experiences. And it should. This attribute is clearly in the nuclear realm; we don't see its manifestation in our everyday world. In fact, we should probably be cautious about the feeling of comfort we have with other quantities. Consider electric charge. Most of us feel quite comfortable talking about the conservation of electric charge, perhaps because electricity is familiar to us. Imagine a world in which we had no experience with electricity. We would feel uneasy if someone suggested that if we assign a $+1$ to protons, a -1 to electrons, and 0 to neutrons, we might have conservation of something called "cirtcele" (electric spelled backward). It isn't unreasonable that unfamiliar quantities emerge as scientists explore the subatomic realm.

Are You On the Bus?

Q: Given the values of strangeness in Table 27-1, would you expect the decay of the lambda particle to a proton and a pion to proceed via the strong or weak interaction? Does this agree with its lifetime?

A: Because the strangeness numbers assigned to the lambda and the proton differ by 1, it should be a weak decay. The mean lifetime agrees with this conclusion.

Quarks

The continual rise in the number of elementary particles once again raised the question of whether the known particles were the simplest building blocks. At the moment the leptons appear to be elementary; there is no evidence that they have any size or internal structure. The exchange particles also appear to be truly elementary for the same reasons. On the other hand, there is experimental evidence that the hadrons have some internal structure.

Particle physicists asked themselves, "Is it possible to imagine a smaller set of particles with properties that could be combined to generate all the known hadrons?" The most successful of the many attempts to build the hadrons is the **quark** model proposed by two American physicists, Murray Gell-Mann and George Zweig, in 1964. Their original model hypothesized the existence of three **flavors** of quarks (and their corresponding antiquarks), now called the "up" (u), "down" (d), and "strange" (s) quarks. The strange quark has a strangeness number of -1, whereas the other quarks have no strangeness. Each quark has $\frac{1}{2}$ unit of spin and a baryon number of $\frac{1}{3}$.

Perhaps the boldest claim made in this model is the assignment of fractional electric charge to the quarks. There has never been any evidence for the existence of anything other than whole-number multiples of the charge on the electron. These fractional charges should (but apparently don't) make the quarks easy to find. Yet the scheme works. The quark model has had remarkable successes describing the overall characteristics of the hadrons.

The properties assigned to the various flavors of quark are given in Table 27-3. The antiquarks have signs opposite to their related quarks for the baryon number, charge, and some other properties such as strangeness.

To see how this concept works, let's "build" a proton. We must first list the proton's properties: a proton has baryon number $+1$, strangeness 0, and

Table 27-3 *Properties of the Quarks*

Flavor	Symbol	Charge	Spin	Baryon No.	Strangeness	Charm	Bottomness	Topness
Down	d	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	0
Up	u	$+\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	0
Strange	s	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	-1	0	0	0
Charm	c	$+\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	$+1$	0	0
Bottom	b	$-\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	$+1$	0
Top	t	$+\frac{2}{3}$	$\frac{1}{2}$	$\frac{1}{3}$	0	0	0	$+1$

electric charge +1. Examination of the quarks' properties confirms that the proton can be made from two up quarks and one down quark (uud), as shown in Figure 27-9. Other baryons can be created with different combinations of three quarks.

Q: What three quarks form a neutron (baryon number +1, strangeness 0, and electric charge 0)?

A: udd.

The mesons have 0 baryon number, so they must be composed of equal numbers of quarks and antiquarks. The simplest assumption is one of each. For instance, the positive pion (Figure 27-10) is composed of an up quark and a down antiquark ($u\bar{d}$), giving it a charge of +1, a spin of zero, and a strangeness of 0.

All of this was fine until 1974. In that year a neutral meson called J/ψ with a mass three times the mass of the proton was discovered. What made the particle unusual was its "long" lifetime. It was expected to decay in a typical time of 10^{-23} second, but it lived 1000 times longer than this. The quark model was able to account for this anomaly only with the addition of a fourth quark that possessed a property called **charm** (c). The J/ψ particle represents a bound state of a charmed quark and its antiquark ($c\bar{c}$). The next year a charmed baryon (udc) was observed, adding further support for the existence of this quark.

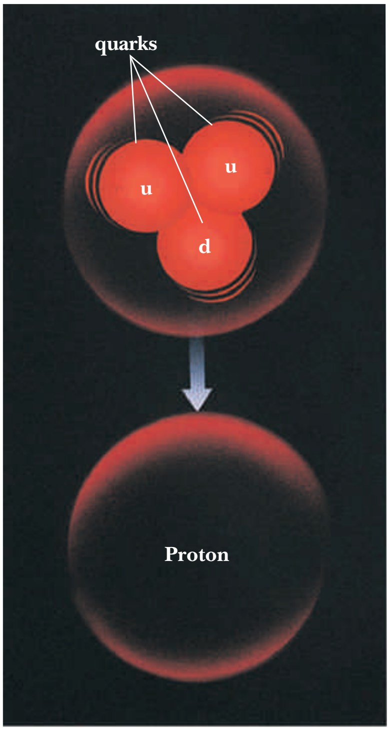


Figure 27-9 The proton is made of two up quarks and a down quark.

Based on symmetry arguments, the existence of a fourth quark had been proposed several years earlier. At that time, four leptons were known—the electron, the muon, and their two neutrinos. Why should there be four leptons and only three quarks? This discomfort with asymmetry led to the idea that there should be four quarks. The nice symmetry was quickly destroyed with the discovery of the tau lepton!

With the discovery of the tau and the presumed existence of its corresponding tau neutrino, two additional quarks were predicted so that there would be six leptons and six quarks. The discovery of the upsilon in 1977 was the first evidence for the fifth quark. The upsilon is a bound state of the **bottom** flavor of quark and its antiquark ($b\bar{b}$). There is also evidence for "bare bottom"—baryons and mesons that contain a bottom quark without a bottom antiquark. The sixth quark has the flavor called **top,** and its existence was confirmed in 1995.

Q: What two different combinations of up and down quarks and antiquarks would yield a neutral pion?

A: $u\bar{u}$ and $d\bar{d}$.

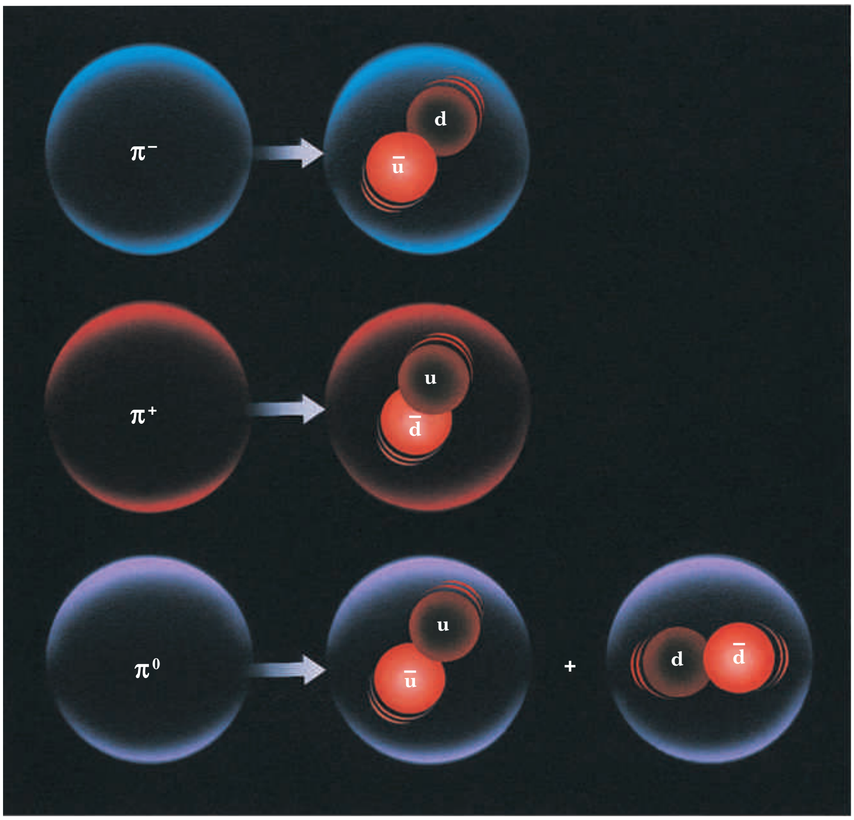


Figure 27-10 Each pion is composed of a quark and an antiquark.

Gluons and Color

Earlier we attributed the force between hadrons to the exchange of other hadrons such as pions. If the hadrons are actually composite particles made of quarks, we need to take our earlier idea one level further and ask what holds the quarks together in hadrons. The particles exchanged by quarks are known as **gluons.** (They "glue" the quarks together.)

Another problem of the simple quark theory is illustrated by the omega minus (Ω^-) particle, which has a strangeness of -3. It should be composed of three strange quarks with all three spins pointing in the same direction to account for its $\frac{3}{2}$ units of spin. However, the exclusion principle (Chapter 24) forbids identical particles with $\frac{1}{2}$ unit of spin from having the same set of quantum numbers. The exclusion principle can be satisfied if quarks have a new quantum number. This new quantum number has been named *color* and has three values: red, green, and blue. All observable particles must be "white" in color; that is, if the colors are considered to be lights, they must combine to form white light (Chapter 17). Therefore, baryons consist of three quarks, one of each color, and mesons consist of a colored quark and an antiquark that has the complementary color (Figure 27-11).

Although the idea of the color quantum number began as an ad hoc way of accommodating the exclusion principle, it soon became a central feature of the quark model. Each quark is assumed to carry a *color charge,* similar to electric charge, and the force between quarks is called the *color force.* This theory requires that there be eight varieties of gluon, which differ only in their color properties. The quarks interact with each other through the exchange of gluons.

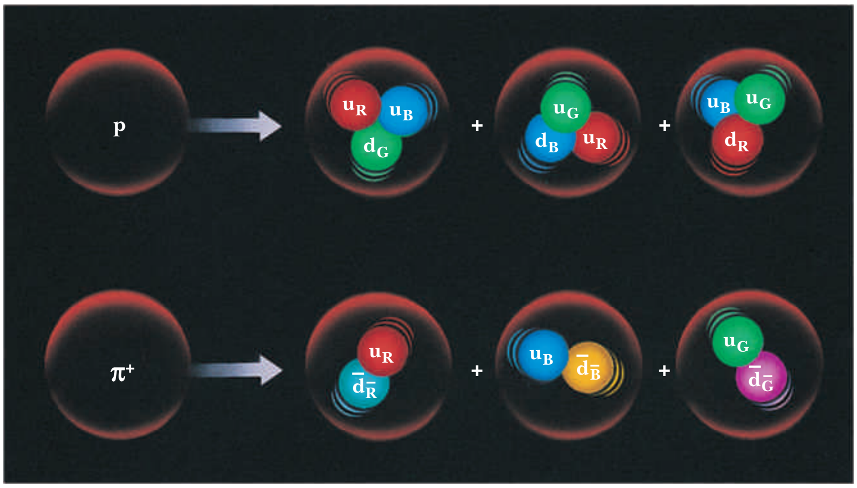


Figure 27-11 The addition of the color quantum number increases the possible combinations of quarks (and antiquarks) that make up particles such as the proton and the positive pion.

FLAWED REASONING

A classmate claims: "In Chapter 23 we learned that blue photons have more energy than red photons. Therefore, blue quarks must have more energy than red quarks, with green quarks somewhere in the middle." **How do you respond to this?**

ANSWER Your classmate is reading too much into a name. The Pauli exclusion principle demanded the existence of an additional quantum number to explain some of the quark combinations that were observed. Murray Gell-Mann decided to call this new quantum number *color* because it can take on three distinct values and only certain combinations of these values are allowed by nature. Just as white light can be made by combining red, green, and blue light or by combining any of these three colors with their complementary color, hadrons are composed of one quark of each of the three colors or a quark and an antiquark of the complementary color. Gell-Mann recognized this coincidence and used the term *color* to make the new concept more intuitive.

The strong force that holds the nucleons together to form nuclei is due to the color force between the quarks making up the nucleons. Therefore, gluons have replaced the mesons as the exchange particles of the strong force.

Summary

The search for elementary components of matter began with Aristotle's basic elements—earth, fire, air, and water—and has led us through the chemical elements to the constituents of atoms—electrons, protons, and neutrons—to quarks.

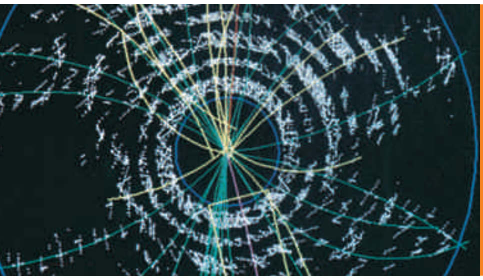
Antimatter, an entirely new kind of matter, is produced by pair production or by the collisions of energetic particles. Antiparticles of all the fundamental particles exist but don't survive long because particles and antiparticles annihilate each other when they come into contact.

The apparent failure of the conservation laws in beta decay led Pauli to propose the existence of the neutrino. The neutrino is electrically neutral, has a very small rest mass, and interacts extremely weakly with other particles.

Newton's idea of an action at a distance was replaced by the concept of a field, which in turn has been replaced by a picture of elementary particles interacting with each other through the exchange of still other elementary particles. The electromagnetic force occurs via the exchange of photons, the strong (or color) force via the eight gluons, the weak force via the intermediate vector bosons (W and Z^0), and the gravitational force via gravitons.

The discovery of the antiparticles, the muon, the tau, their neutrinos, and the large collection of mesons and baryons quickly destroyed the concept of the elementary particles as being elementary. Some sense was brought to the particle zoo through the use of the conservation laws and classifying them according to their interactions. Further simplification came with the quark model.

The quark model has had remarkable success describing the overall characteristics of the elementary particles. The universe appears to be made of six leptons and six quarks (each in three colors). The baryons, for example, consist of three quarks, one in each of the three colors, whereas the mesons consist of a quark and an antiquark of the complementary color.



CHAPTER 27 *Revisited*

Nobody knows where the search for the fundamental building blocks will end. The current theory of quarks and leptons is appealing in its completeness, and no experiments have contradicted our belief that these particles do not have internal structures. Maybe the search has ended. Maybe not.

Key Terms

antiparticle A subatomic particle with the same size properties as those of the particle, although some may have the opposite sign. The positron is the antiparticle of the electron.

baryon A type of hadron having a spin of $\frac{1}{2}$, $\frac{3}{2}$, $\frac{5}{2}$ . . . times the smallest unit. The most common baryons are the proton and the neutron.

bottom The flavor of the fifth quark.

charm The flavor of the fourth quark.

flavor The types of quark: up, down, strange, charm, bottom, or top.

gluon An exchange particle responsible for the force between quarks. There are eight gluons that differ only in their color quantum numbers.

graviton The exchange particle responsible for the gravitational force.

hadron The family of particles that participates in the strong interaction. Baryons and mesons are the two subfamilies.

intermediate vector boson The exchange particle of the weak nuclear interaction: the W^+, W^-, and Z^0 particles.

lepton The family of elementary particles that includes the electron, muon, tau, and their associated neutrinos.

meson A type of hadron with whole-number units of spin. This family includes the pion, kaon, and eta.

muon A type of lepton; often called a heavy electron.

neutrino A neutral lepton; one exists for each of the charged leptons—the electron, the muon, and the tau.

pair production The conversion of energy into matter in which a particle and its antiparticle are produced. This usually refers to the production of an electron and a positron (antielectron).

pion The least massive meson. The pion has three charge states: +1, 0, and −1.

positron The antiparticle of the electron.

quark A constituent of hadrons. Quarks come in six flavors of three colors each. Three quarks make up the baryons, whereas a quark and an antiquark make up the mesons.

strangeness The flavor of the third quark.

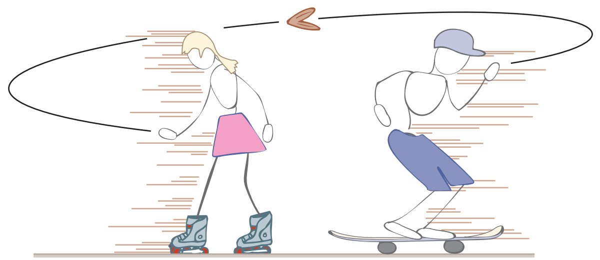
strange particle A particle with a nonzero value of strangeness. In the quark model, it is made up of one or more quarks carrying the quantum property of strangeness.

top The flavor of the sixth quark.

Questions are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions are answered in Appendix B.
indicates more challenging questions.
WebAssign Many Conceptual Questions for this chapter may be assigned online at WebAssign.

Conceptual Questions

1. What particles were on the list of "elementary particles" in 1932?
2. Which particles on the list of "elementary particles" in 1932 are not on the current list?
3. What is the antiparticle of an electron? How does the charge of the antielectron compare to the charge of the electron?
4. What is the antiparticle of the photon? How does the charge of the antiphoton compare with the charge of the photon?
5. Do antiparticles have negative mass? Explain.
6. How much energy would be given off if an antiproton and an antineutron combined to form an antideuteron?
7. What is the ultimate fate of an antiparticle here on Earth?
8. The rest mass of the positron is 0.511 million electron volt. Why is more than 0.511 million electron volt released when a positron is annihilated?
9. The bubble-chamber tracks of an electron and a positron are clearly distinguishable. Why could you not use a bubble chamber to identify the pair production of a neutron–antineutron pair?
10. Particles and antiparticles annihilate when they come in contact. However, objects that are orbiting one another do not touch. Use the concept of probability clouds to explain why an electron and a positron "orbiting" each other can annihilate.
11. Explain why momentum conservation requires the emission of at least two photons when a positron and an electron annihilate. (The photon has a momentum equal to E/c.) For simplicity, assume that the electron and positron are at rest in your reference system.
12. Which elementary particles could be used to communicate with an antiworld?
13. The initial observations of beta decay indicated that some of the classical conservation laws might be violated. Which (if any) were obeyed without the invention of the neutrino?
14. Ten identical bombs are designed to each explode into two equal fragments—one red and one blue. If all 10 bombs are exploded and the energy of the red fragment is measured, it will be the same in each trial because of the laws of conservation of energy and the conservation of momentum. However, if the 10 identical bombs were instead designed to explode into three equal fragments—one red and two blue—the energy of the red fragment could now be different in each explosion. Use these results to interpret Figure 27-4 as requiring the existence of the neutrino.
15. Through which force does the neutrino interact with the rest of the world?
16. Why did it take so long for experimentalists to detect the neutrino?
17. Why would the whole theory of exchange particles have been considered absurd before the development of quantum mechanics?
18. One attempt at creating an analogy of an attractive exchange force uses boomerangs. The person on the right throws a boomerang toward the right, gaining momentum toward the left. The boomerang travels along a semicircle and is caught coming in from the left. When she catches the boomerang, the person on the left gains some momentum toward the right. Why is this not a good analogy?



19. The existence of intermediate vector bosons was predicted many years before they were detected in an accelerator. Why did this discovery take so long when scientists knew what they were looking for?
20. If the Heisenberg uncertainty principle allows energy conservation to be violated, why is energy conservation still a useful principle?
21. How does the uncertainty principle explain the infinite range of the electromagnetic interaction?
22. How does the uncertainty principle account for the decrease in the strength of the coulomb (electrostatic) force with increasing distance? How would this be different if photons had a rest mass?
23. What feature of the electromagnetic interaction requires the exchange particles to be massless?
24. What argument can be used to support the idea that the graviton has zero rest mass?
25. What are the differences between baryons and mesons?

26. Which particles do not participate in the strong interaction?

27. What are the important differences between the hadrons and the leptons?

28. What particles belong to the lepton family?

29. Do neutrons interact via the weak force? Explain.

30. Particles and antiparticles have the same properties except for the sign of some of them. Which particles in Table 27-1 could be particle–antiparticle pairs?

31. Roughly what would you expect for the lifetime of the decay $\Omega^- \rightarrow \Xi^0 + \pi^-$?

32. Roughly what would you expect for the lifetime of the decay $K^0 \rightarrow \pi^+ + \pi^-$?

33. Why can't a proton beta decay outside the nucleus?

34. If free protons can decay, the lifetime is greater than a billion trillion times the age of the universe. Does this necessarily mean that there has not yet been a free proton decay in the universe?

35. What does the X stand for in the pion decay $\pi^+ \rightarrow \mu^+ + X$?

36. What does the X stand for in the antimuon decay $\mu^+ \rightarrow \nu_e + \bar{\nu}_i + X$?

37. Name at least one conservation law that prohibits each of the following:

    a. $\mu^- \rightarrow e^- + \nu_e + \bar{\nu}_i$
    b. $p \rightarrow \pi^+ + \pi^+ + \pi^-$
    c. $\Omega^- \rightarrow \Lambda^0 + \pi^-$

38. Name at least one conservation law that prohibits each of the following:

    a. $\pi^- + p \rightarrow \Sigma^+ + \pi^0$
    b. $\mu^- \rightarrow \pi^- + \nu_i$
    c. $\Sigma^0 \rightarrow \Lambda^0 + \pi^0$

39. If you observe the decay $X \rightarrow \Lambda^0 + \gamma$ with a lifetime of approximately 10^{-20} second, what can you say about the (a) baryon number, (b) strangeness, and (c) charge of X?

40. A particle X is observed to decay by $X \rightarrow \pi^+ + \pi^-$ with a lifetime of 10^{-10} second. What are possible values for the (a) baryon number, (b) strangeness, and (c) charge of X?

41. That the lifetime of the π^0 is roughly 10^{-16} second indicates that the pion decays via the electromagnetic interaction. What would you guess would be the products of this decay?

42. The lifetime of the π^- is roughly 10^{-8} second. What decay products would you expect?

43. What combinations of quarks correspond to the antiproton and the antineutron?

44. What combination of quarks makes up the negative pion?

45. The K^- particle is the antiparticle of the K^+ particle. What combination of quarks makes up the K^- particle? What value does it have for strangeness?

46. Which hadron corresponds to the combination of a strange antiquark and an up quark?

47. The Δ^{++} particle has charge +2 and strangeness 0. What combination of quarks makes up the Δ^{++} particle?

48. Which hadron is composed of two up quarks and a strange quark?

49. What quarks make up a Ξ^0?

50. What combination of quarks corresponds to the Σ^-?

51. What quark and antiquark make up a K^0? Would this particle be its own antiparticle?

52. Why is the π^0 its own antiparticle?

53. In the quark model, is it possible to have a baryon with strangeness −1 and charge +2? Explain.

54. Why is it impossible to make a meson of charge +1 and strangeness −1?

55. A particle consists of a top quark and its corresponding antiquark. Is this particle a meson or a baryon? What is its charge?

56. What charge would a baryon have if it were composed of an up quark, a strange quark, and a top quark?

57. In the original quark model, the Ω^- was believed to be composed of three strange quarks. This assumption causes problems because quarks are expected to obey the Pauli exclusion principle. How did physicists get around this problem?

28 Frontiers

▶When Albert Einstein conceived the general theory of relativity, he believed that the universe was static; the universe was neither expanding nor contracting. To account for this, he added a term to his equations known as the *cosmological constant* to prevent the universe from collapsing under the influence of its own gravity. Later, when astronomers showed that the universe was expanding rather rapidly, Einstein felt that the introduction of the cosmological constant was his biggest blunder. Will the universe continue to expand forever, or will the expansion slow and the universe collapse upon itself?

(See page 630 for the answer to this question.)

NASA

The imaginary sea serpent's head in this Hubble Space Telescope photograph of the Eagle Nebula is actually a cloud of molecular hydrogen and dust in which new stars are forming.

THE physics world view is a dynamic one. Ideas are constantly being proposed, debated, and tested against the material world. Some survive the scrutiny of the community of physicists; some don't. The inclusion of new ideas often forces the modification or outright rejection of previously accepted ones. Some firmly accepted ideas in the world view are difficult to discard; in the long run, however, experimentation wins out over personal biases.

In this chapter we look at a few selected areas on the frontiers of physics research. The ideas presented in this chapter are not as firmly established as those presented in the earlier chapters. Some of the ideas discussed here will survive and others will not. But that is the nature of an evolving science.

In their search for new physics, researchers do not have carte blanche to make up any theory they please. New theories must agree with the increasingly large body of experimental results and be compatible with the well-established theories. This puts stringent constraints on what can be proposed.

In the first chapter we quoted Newton: "I do not know what I may appear to the world, but to myself I seem to have been only like a boy playing on the sea-shore, and diverting myself in now and then finding a smoother pebble or a prettier shell than ordinary, whilst the great ocean of truth lay all undiscovered before me." With the help of some of our colleagues, let's go looking for prettier shells.

Gravitational Waves

When Einstein proposed his general theory of relativity in 1916, he also postulated the existence of gravitational waves. In many ways gravitational waves are analogous to electromagnetic waves, which we discussed in Chapter 22. The acceleration of electric charges produces electromagnetic waves that we experience as light, radio, radar, TV, and X rays. Gravitational waves result from the acceleration of masses. Both types of waves carry energy through space, travel at the speed of light (3×10^8 m/s), and decrease in intensity as the inverse square of the distance from the source.

Because electromagnetic waves are so easily detected by a $10 radio and our eyes, why have gravitational waves not been detected? The first reason is that the gravitational force is weaker than the electromagnetic force by a factor of 10^{43}. Except in the most favorable cases, gravitational waves are weaker by this same factor. In addition, the detectors are less sensitive in intercepting gravitational waves by at least another factor of 10^{43}.

The detection of gravitational waves is one of the most fundamental challenges in modern physics. Joseph Weber, a physicist at the University of Maryland, pioneered the efforts to detect gravitational waves in the 1960s. He used a large, solid cylinder, 2 meters long and weighing several tons, as a detector. A passing gravitational wave causes vibrations in the length of the cylinder due to the differences in the forces on atoms in various parts of the cylinder. The detection system is amazingly sensitive; it can detect changes in the length of the cylinder of 2×10^{-16} meter, about one-fifth the radius of a proton. However, a cylinder can vibrate for many other reasons, such as passing trucks. To eliminate these vibrations, Weber used two cylinders placed 1000 miles apart and required that both vibrate together.

Although there may be many sources of gravitational waves, only a few should emit strong enough signals and be close enough to be within the range of current instruments. The details of the various processes are not well understood, so the calculations are rough estimates. When a supernova occurs, a large burst of gravitational waves should be given off. This process may give off a large enough pulse to be detected but is expected to only happen once every


Courtesy of Caltech/LIGO

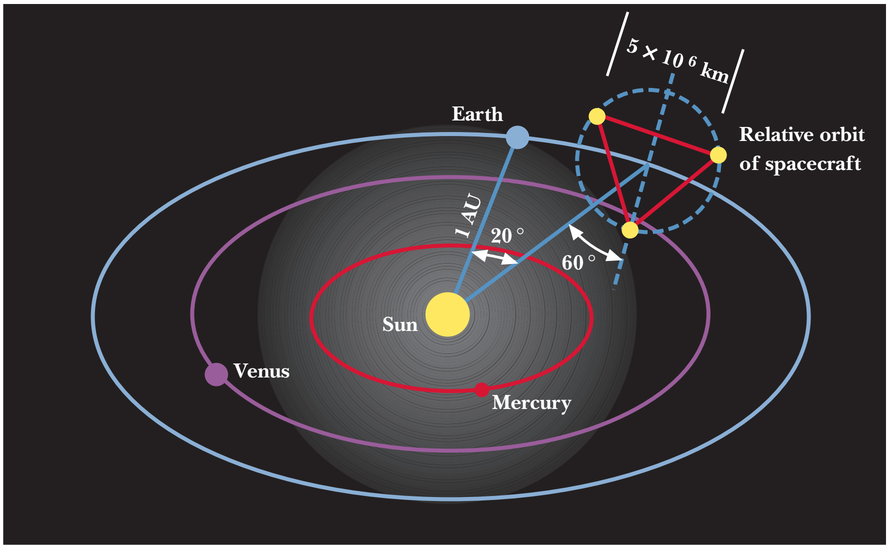
Figure 28-1 Aerial view of the end station and one arm of the LIGO facility in Louisiana.

15 years within the galaxy. Gravitational waves should also be given off strongly from a pair of neutron stars or black holes orbiting each other at close range.

In 1991 the U.S. Congress approved the construction of the Laser Interferometer Gravitational-Wave Observatory (LIGO). LIGO consists of identical facilities in the states of Washington and Louisiana (Figure 28-1), widely separated locations to eliminate extraneous vibrations. Each facility is looking for changes in the distance between pairs of mirrors 4 kilometers apart. The distances are measured by splitting a laser beam into two beams that travel at right angles to each other, bounce off mirrors, and are then recombined. When the beams recombine, slight changes in the distances to the distant mirrors alter the brightness of the light. This observatory should ultimately be a million times more sensitive than Weber's experiment.

The next generation of gravitational wave detectors will be built in space. The Laser Interferometer Space Antenna (LISA) will consist of three satellites at the corners of an equilateral triangle that is 5 million kilometers on a side. The group of satellites will lag 20 degrees behind Earth in its orbit around the Sun, as shown in Figure 28-2. The experimental technique is the same as for LIGO, but the longer arms will provide sensitivity in the low-frequency gravitational wave band from 0.0001 to 1 hertz, compared with LIGO's high-frequency band from 10 to 1000 hertz. In the low-frequency band, LISA will observe gravitational waves generated by binary systems or by the massive black holes at the centers of many galaxies, including our own Milky Way Galaxy. The schedule calls for LISA to be operational in 2012.

Although we do not have direct evidence of gravitational waves, there is strong indirect evidence for the existence of gravitational waves. In 1974 Joseph Taylor and Russell Hulse discovered a pair of neutron stars orbiting each other at close range. Neutron stars have masses slightly larger than the mass of our Sun but are only about 10 kilometers in diameter. At these great densities, electrons and protons combine to form neutrons, so the star consists almost entirely of neutrons. The two neutron stars orbit each other every 8 hours and reach orbital speeds of 0.13% of the speed of light. One of the neutron stars is a pulsar that emits a pulse of radiation every 59 milliseconds.



Redrawn courtesy of Jet Propulsion Lab/Calif. Institute of Tech., Pasadena, CA.

Figure 28-2 The orbit of the LISA satellites.

This acts as a clock that is as good as any atomic clock that we have on Earth. This clock allows very precise timings of the orbits, and 30 years of measurements indicate that the orbital period is decreasing. In fact, it is decreasing at precisely the rate expected from the loss of energy due to gravitational radiation according to Einstein's theory of general relativity. The 1993 Nobel Prize in physics was awarded to Taylor and Hulse for this work.

Physicists expect that gravitational waves will soon be detected directly; it is only a matter of continuing to develop the technology for improving the sensitivity of the detectors.

Unified Theories*

The view that the elementary building blocks in nature are the 6 leptons, the 6 quarks, and the 13 exchange particles is a great simplification of the hundreds of subnuclear particles that have been discovered since 1932. The list of elementary particles totals 25, a reasonably small number for building the many diverse materials in the world. But can we reduce the complexity even more?

The present scheme contains two distinct classes of particles—the leptons and the quarks. Leptons have whole-number units of the electron charge, whereas quarks have charges that are multiples of one-third of the basic unit. Quarks participate in the strong interaction through their color, whereas leptons are colorless and do not participate. Leptons are observed as free particles, but quarks have yet to be isolated—in fact, current theory predicts they cannot be isolated. There have been no observations that indicate that leptons can turn into quarks, and vice versa. Why should there be two classes? Why not only one?

Similarly, we have four different forces—gravitational, electromagnetic, weak, and strong (or color). Each appears to have its own strength, and there are three different dependencies on distance and 13 different exchange particles. Why should there be four forces? Why not only one?

Physicists have asked similar questions for a long time and have sought to reduce the number of particles and the number of forces as far as possible,

* Written with the assistance of William Hiscock, Department of Physics, Montana State University.

ideally to one class of particles and one force. Theorists don't aim to eliminate (or overlook) the differences that are so apparent but rather to show that these are all manifestations of something much more basic and therefore more elementary.

Much progress has been made. Before the beginning of the 20th century, Maxwell showed that electricity and magnetism were really two different aspects of a common force, the electromagnetic force. During the 1960s, Sheldon Glashow, Steven Weinberg, and Abdus Salam developed the electroweak theory that unified the weak and electromagnetic interactions.

The electroweak theory and the color theory of the strong interaction are the main components of the *standard model* of elementary particles that evolved in the early 1970s. This model seems to explain every experiment that can be done. However, even though the model seems to be complete, its mathematical complexity is such that many calculations cannot be done with presently available techniques.

The unification efforts continue; some success has been achieved in combining the electroweak interaction and the color interaction in what are called *grand unified theories*. These theories predict that baryon number is not strictly conserved, and as a consequence the proton should decay, although the predicted lifetime far exceeds the present age of the universe. So far, experiments have not seen any hint of proton decay, and this has ruled out some of the simpler grand unified theories.

If efforts to produce a grand unified theory succeed, there will still be the separate existence of the gravitational force. To reach the ultimate goal, gravity must also be included in an ultimate "theory of everything." Since 1984 many physicists have been working on a promising candidate for such a theory, *superstring* theory. In superstring theory, the fundamental objects from which all matter and forces are built are not point particles but tiny loops of material that cannot be further subdivided. The size of these loops defines the smallest distance in nature, which in most superstring theories is the *Planck length*, about 10^{-35} meter, less than a billion-billionth the size of a proton. The Planck length comes from combining gravity with Planck's constant h from quantum mechanics. Although experiment has yet to confirm any of these proposed further simplifications or unifications, theoretical physicists continue to explore what sorts of simple fundamental models are compatible with what is already known.

Cosmology

A cosmic connection exists between all the forces and particles that we have studied. The connection is made in the Big Bang model of the creation of the universe. Experimental evidence indicates that the universe had a beginning and that this beginning involved such incredibly high densities and temperatures that everything was a primordial "soup" beyond which it is impossible to look. According to this model, the universe erupted in a Big Bang about 14 billion years ago.

Theorists divide the development of the universe into seven stages (Figure 28-3). Immediately after the Big Bang, up until something like 10^{-44} second, the conditions were so extreme that the laws of physics as we now know them did not exist. As the universe expanded, it cooled, the four forces developed their individual characteristics, and the particles that we currently observe were formed. The particular details of what happened early in the process are speculative but rest on firmer ground as time unfolds.

During the second stage—between 10^{-44} and 10^{-37} second—the gravitational force emerges as a separate force, leaving the electromagnetic and the

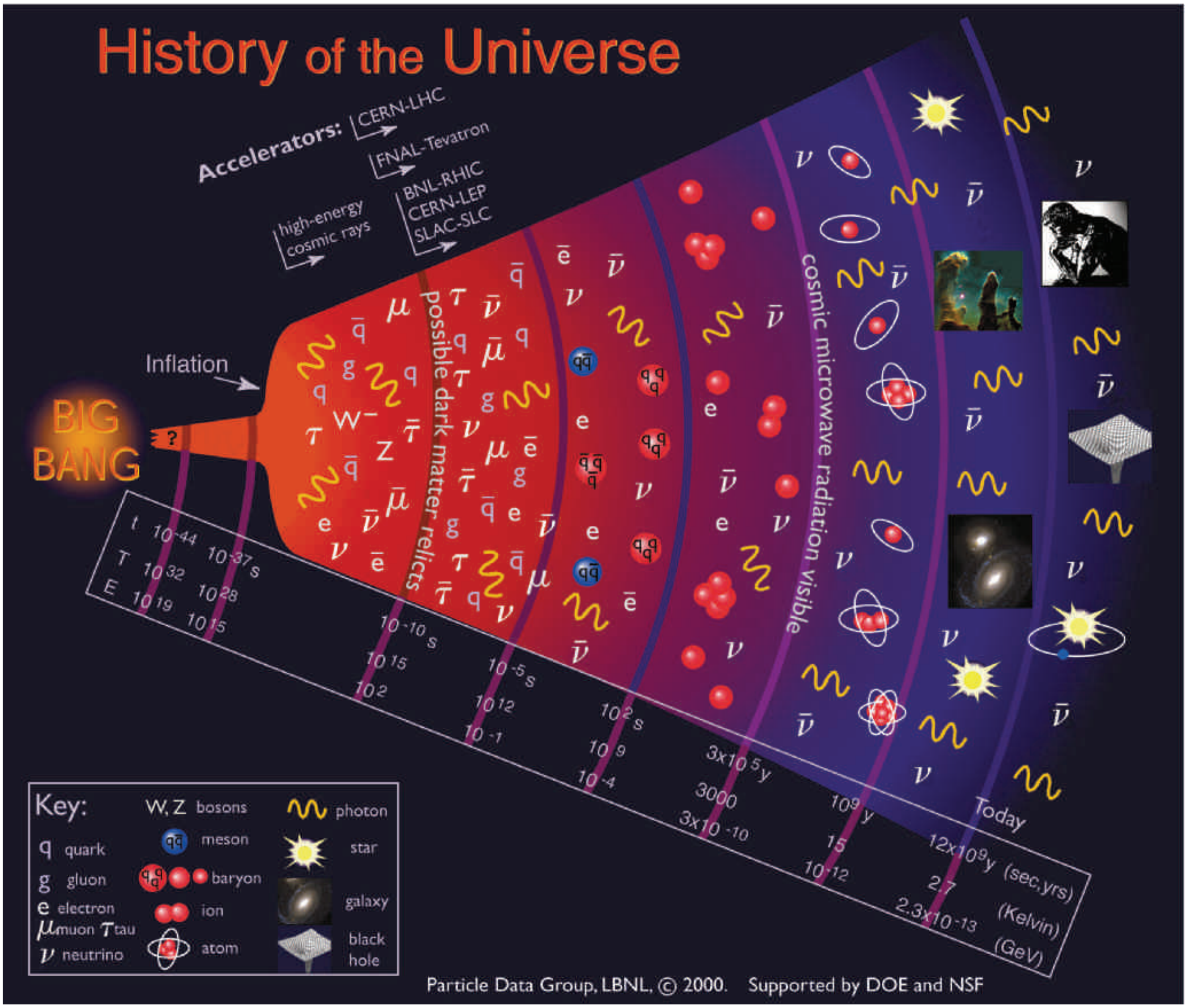


Figure 28-3 The history of the universe.

two nuclear forces unified, as described by the grand unification theories (Figure 28-4). During this time the energies of particles and photons are so great that there is continual creation and annihilation of massive particle–antiparticle pairs.

During the third stage—between 10^{-37} and 10^{-10} second—temperatures drop from approximately 10^{28} K to approximately 10^{15} K, and the strong force splits off from the electroweak force, resulting in three forces.

Near the beginning of the fourth stage—which ends only a microsecond after the Big Bang—further cooling results in the electroweak force splitting into the weak force and the electromagnetic force, giving us the four forces we can now detect. The universe is filled with radiation (photons), quarks, leptons, and their antiparticles. The temperatures are still too hot for quarks to stick together to form protons and neutrons.

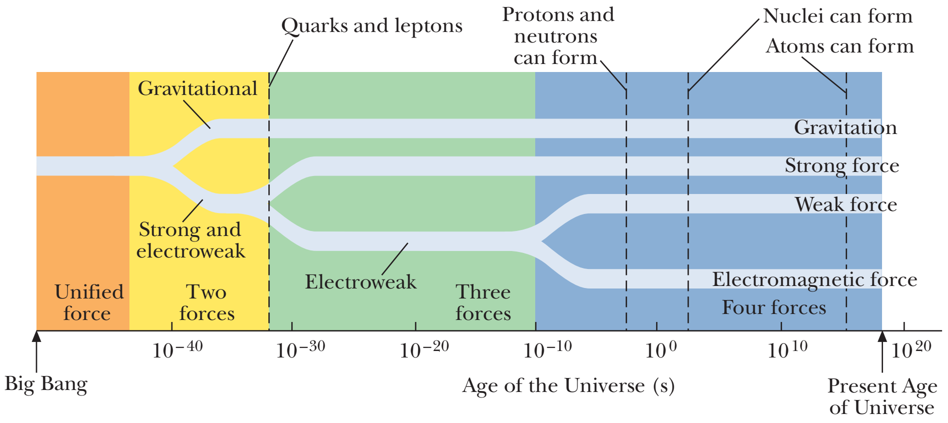


Figure 28-4 As the universe expands and cools, the single original force splits into new forces that eventually become the four forces that we currently observe in nature.

The fifth stage takes us up to 3 minutes after the Big Bang. By this time the temperature has dropped to 1 billion K, which is still much hotter than the interior of our Sun. At the end of this stage, typical photons can no longer form electron–positron pairs, and some neutrons and protons have formed helium nuclei, with about 25% of the universe's mass as helium and the rest as hydrogen. The model predicts, and the observations agree, that there should be one neutron for every seven protons. (Because of the extra mass of the neutron, it is harder to convert protons into neutrons than it is to convert neutrons into protons.)

The sixth stage ends when the temperature drops to approximately 3000 K, about 300,000 years after the Big Bang. Suddenly, matter becomes transparent to photons, and the photons can travel throughout the universe. This moment defines the boundaries of the observable universe: looking out into space is just like looking backward in time to this beginning. The radiation we see from objects at a distance of 1 billion light-years left there 1 billion years ago. Therefore, we are seeing the object as it was in the past, not as it is at the present.

The final stage begins with the formation of atoms and includes the formation of the galaxies, stars, and planets, such as Earth.

Cosmic Background Radiation

In 1965 Bell Laboratory scientists Arno Penzias and Robert Wilson made an accidental discovery that has had a tremendous impact on our view of the universe. While testing a sensitive microwave receiver (Figure 28-5), Penzias and Wilson detected a faint background "hiss" that caused problems with their satellite communications. They tried thoroughly cleaning the receiver after evicting a flock of pigeons, and they tried cooling the electronics. However, the background persisted. In addition, the intensity of the background was the same, regardless of the direction they pointed their microwave detector. This suggested that the source was outside the solar system, or even outside the galaxy.

Luckily, Penzias and Wilson learned that a group of scientists at Princeton University had predicted the existence of a *cosmic background radiation*. This radiation would have been emitted at the time the universe became transparent to visible radiation some 300,000 years after the Big Bang. Although the radiation had a temperature of 3000 K at that time, the radiation has cooled as the universe expanded and should now appear with a temperature of approximately 3 K!

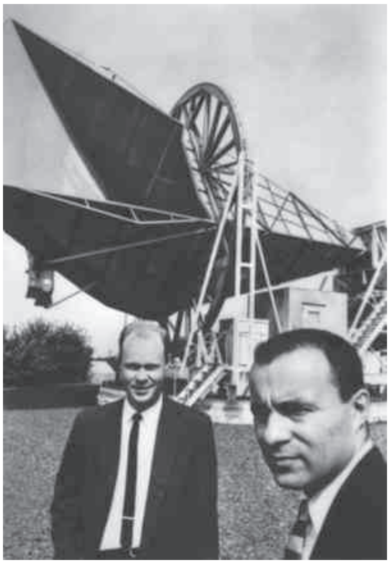


Photo by Robert Isear. Courtesy of AIP Emilio Segre Visual Archives. Physics Today Collection.

Figure 28-5 Arno Penzias (right) and Robert Wilson stand in front of their microwave receiver.

Penzias and Wilson caused quite a stir in the scientific community when they announced that they had already detected the cosmic background radiation. Because their measurement was at a single wavelength, they could not determine the temperature. However, measurements by other groups quickly showed that the radiation is an excellent match for a temperature of 2.725 K, in agreement with the prediction.

The cosmic background radiation's existence and properties are the most compelling experimental evidence supporting the Big Bang model. Penzias and Wilson received the Nobel Prize in 1978 for their discovery.

This discovery, however, led to a new problem. The temperature was very accurately the same in all directions. How could a universe full of galaxies, stars, and planets form from something that was so uniform? More recent data from satellite measurements show variations in temperature on the order of 0.0002 K, which may be sufficient to account for the structure of the universe.

Dark Matter and Dark Energy*

It has to be one of the most discomforting results of modern science: only about 5% of the universe is made of *ordinary* matter—the kind of matter that makes up stars, planets, rocks, and people.

Besides permitting the possibility that space is expanding, Einstein's general theory of relativity opened the door to the possibility that the idea of a flat space—one in which parallel lines never converge or diverge—may be a local illusion. For more than 90 years, scientists have been dealing with the possibility of a curved space. The overall density of matter in the universe determines the shape of space (loosely speaking, whether it is concave, flat, or convex).

Recent results measuring minute ripples in the cosmic background radiation—the microwave radiation that is the remaining signature from the time the cooling universe first became transparent to its own radiation—confirm that we appear to live in a universe with exactly the critical matter density to make space flat on cosmic scales. Because this would seem far too unlikely to occur by chance, scientists have been searching for mechanisms that would favor a flat universe. They have generally settled on a mechanism called *inflation*—a period in which the universe grew by a factor of up to 10^{30} in as little as 10^{-36} second early in our universe's history—to explain why it developed exactly the critical density to be flat. The conundrum is that the density of all ordinary matter that we can find accounts for only about 5% of this critical density. So, what is the other 95%?

The first major clue that something is out there that we cannot see came from careful studies of the motions of stars within galaxies. A galaxy is a collection of billions of stars (like our own Milky Way Galaxy) in which individual stars orbit about the galactic center. For instance, the Sun takes about 250 million years to complete one orbit around our galaxy. The speed at which a star moves about its galactic center depends on the distribution of matter within the galaxy; the gravitational pull of the matter holds the star in its orbit. By measuring the distribution of ordinary visible matter within a galaxy, we can predict how fast the stars near the outside should be moving. These stars consistently move faster than predicted, indicating that there must be some unseen matter within the galaxies. This unseen matter has been dubbed *dark matter.*

The first question that scientists asked about dark matter is whether it is simply ordinary matter that is too cool to be seen by conventional methods—so-called *M*assive *A*strophysical *C*ompact *H*alo *O*bjects (MACHOs)—or some

* Essay by Jeff Adams, Physics Department, Montana State University.

form of exotic matter made of something other than our familiar protons, neutrons, and electrons—so-called *W*eakly *I*nteracting *M*assive *P*articles (WIMPs). Yes, this was the battle between the MACHOs and the WIMPs! Although the less exotic MACHOs do constitute some of the dark matter, most scientists agree that some kind of exotic matter of a form not yet identified must necessarily comprise the bulk of the dark matter. But this is still not enough to get us to the critical mass density required for a flat universe. The most recent estimates are that about 25% of the universe's matter is in the form of exotic dark matter. But along with the 5% from ordinary matter, this leaves 70% unaccounted for.

Recently, scientists studying extremely distant supernovae—extremely bright stellar explosions—have discovered that the most distant supernovae are actually somewhat dimmer than would be expected if the universe's expansion were slowing at a rate expected because of the pull of gravity. The explanation for these dimmer than expected supernovae is that the universe's expansion rate is actually increasing—placing the supernovae farther away. This implies that some large-scale pressure in the universe must be counteracting the mutual pull of gravity caused by both ordinary and dark matter. This pressure force has been attributed to a *dark energy*, which must be uniformly distributed throughout the universe. Furthermore, the density of dark energy could be exactly what is needed to make up the missing 70% to achieve the critical density for a flat universe. (Einstein told us that energy has an equivalent mass.) For now, scientists can say little about this dark energy. And yet evidence is converging that dark energy may well be the most pervasive matter in the universe.

Neutrinos*

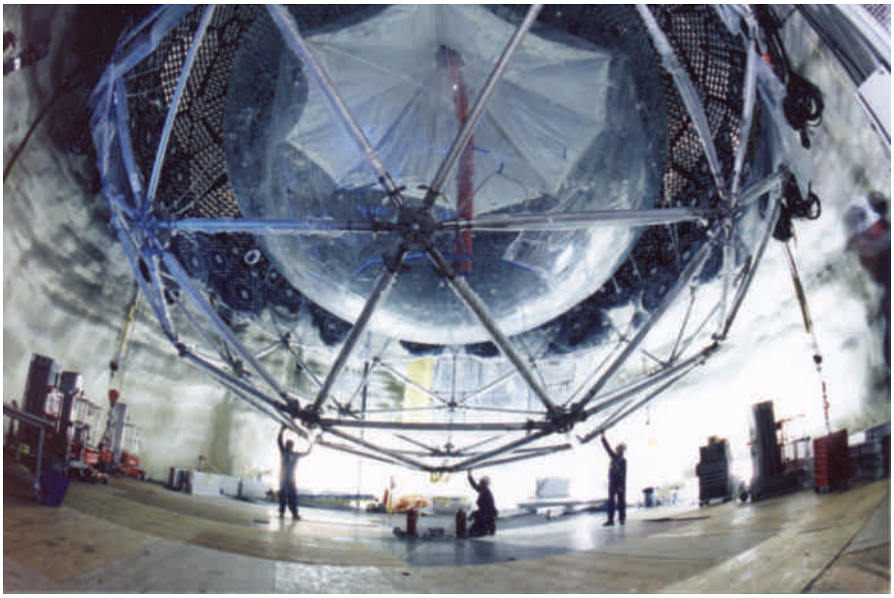
Neutrinos are unique among elementary particles in that much of what we know about them comes from sources beyond our control. We learned a lot in the early days of neutrino physics from reactor and accelerator experiments, but in the last few years our most precise information has come from observing neutrinos from the Sun, cosmic rays, and a single supernova. These results have been hard won. The experiments themselves are long and difficult; they have to be performed in mines and tunnels far from the comforts and infrastructure of great laboratories in order to escape cosmic radiation that would swamp the tiny neutrino signals. It has also been necessary to fine-tune our theoretical understanding of the sources to an extraordinary degree to unravel fundamental neutrino physics from the data.

The 2002 Nobel Prize committee recognized two early pioneers in this field. Ray Davis of the University of Pennsylvania was the first to attempt the detection of solar neutrinos. He used hundreds of tons of cleaning fluid placed deep in a mine in South Dakota. The cleaning fluid was a cheap and safe form of chlorine, an efficient absorber of neutrinos. His first results obtained in the early 1970s showed the first hint that neutrinos were more complicated than the mathematical models suggested. Masatoshi Koshiba initiated a series of water-tank experiments in a mine in northern Japan that showed similar hints in the flux of neutrinos produced by cosmic rays striking Earth's atmosphere. The team he assembled went on to make the first real-time, directional measurement of solar neutrinos and to observe a small neutrino burst from supernova SN1987A—the first time ever that nonelectromagnetic radiation had been observed from an identifiable source beyond our solar system.

* Essay by Chris Waltham, Department of Physics and Astronomy, University of British Columbia and Sudbury Neutrino Observatory.

Courtesy of SNO Institute (both)

Artist's concept of the SNO detector. The acrylic vessel holds the heavy water. The framework holds the light sensors. The entire chamber is flooded with ordinary water to support the acrylic chamber and avoid problems of light transmission from the chamber.



The SNO detector during construction.

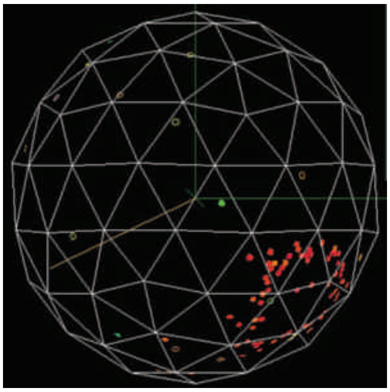
The puzzle unearthed by Davis, Koshiba, and their collaborators showed up in the unexpectedly low rate of electron neutrinos coming from the Sun and a strange ratio of electron neutrinos to muon neutrinos seen in the cosmic ray signals. The results all seemed to point to an arcane feature of quantum mechanics, which allowed the possibility that the three neutrino types (called *flavors*)—electron, muon, and tau—could mutate one into another if their masses differed by a tiny amount. This "neutrino oscillation" was first proposed in the 1960s by the Italian-Soviet physicist Bruno Pontecorvo. This in itself was a challenge to the prevailing notion that neutrinos were massless.

These strong experimental hints and weighty theoretical ideas required a major assault on the neutrino problem. Two types of experiment were designed and built to acquire crucial neutrino data. Radiochemical experiments, similar to Davis's but based on gallium, were mounted underneath the Apennines and the Caucasus Mountains. These provided a first look at the neutrinos arising directly from proton–proton fusion in the Sun. In Canada a unique supply of heavy water was used to construct the Sudbury Neutrino Observatory (SNO), which became operational in 1999. The heavy water allowed us to unravel the neutrino flavors for the first time. Besides this new experimental evidence, theoretical astrophysicists have tightened the models of the solar interior and of cosmic rays. The gains have been impressive, especially in the case of the Sun; we can now truly claim to have a precision understanding of the solar interior and its thermonuclear furnace. As a result, the peculiarities of the neutrinos themselves have been thrown into sharp relief.

The picture that has emerged is as follows: the Sun is powered by thermonuclear reactions that produce electron neutrinos in the numbers expected. This mechanism of energy production has been conjectured since the 1930s, but now we have hard proof. However, the neutrinos we see at Earth are only 34% electron neutrino; the other 66% are of the muon and tau types.

Cosmic rays produce muon and electron neutrinos in Earth's atmosphere, as expected, but about half of the muon neutrinos reach us as tau neutrinos.

The quantum mechanics of Pontecorvo has the following explanation. Neutrinos are born as distinct flavors—electron, muon, and tau—but propagate as distinct mass types—say, 1, 2, and 3. Unlike their charged electron, muon, and tau counterparts, the flavors and the masses do not correspond. Each is a thorough, distinct mix of the other. Because the masses 1, 2, and 3 are slightly different, they travel at different speeds and get out of phase with one another after a while. Hence, an electron neutrino produced in a nuclear reaction will soon start to look a bit "muonish" or "tauish" after traveling for a while. In a vacuum, neutrino 1 seems to be mostly electron, with a dash of muon and tau; neutrino 2 is a more-or-less equal mix of all three; neutrino 3 is approximately equal parts muon and tau. In the dense core of the Sun (and to a lesser extent, Earth's core), matter effects change these mixtures. A neutrino created with an electron flavor in the Sun propagates as almost pure neutrino 2. Once outside the Sun, this neutrino finds itself a mix of all three flavors, and this results in the electron fraction of 34% that we actually measure.


Courtesy of Chris Kyba and SNO Institute

Computer reconstruction of a probable SNO solar-neutrino event. When a neutrino strikes the heavy water of the SNO detector, a faint cone of light spreads out from that point to SNO's light sensors. The green dots indicate which light sensors detected light.

A detailed look at the neutrino flavors actually observed tells us a lot about the tiny mass difference between neutrinos 1, 2, and 3. Neutrinos 1 and 2 are of the order 0.01 eV/c^2 apart, while 2 and 3 are of the order 0.1 eV/c^2 apart. These mass differences are tiny; the next lightest particle, the electron, is a whopping 0.5 million eV/c^2. At present we do not know much more about the neutrino mass differences than their orders of magnitude (the electron mass is known to six significant figures). In addition, we do not know the overall mass scale, although recent evidence from observing ripples in the cosmic microwave background radiation suggests that the sum of all three neutrino masses cannot be larger than 0.7 eV/c^2. This result from the Wilkinson Microwave Anisotropy Probe in 2003 demonstrates how properties of the smallest units of matter determine the largest-scale structure of the universe.

What does it all mean? It's not clear at the moment. We are at one of those junctures in fundamental physics where a temporary increase in complexity hints at a deeper understanding just around the corner. Many new experiments are being designed for underground labs in Canada, the United States, Japan, and Europe to improve the measurements. Meanwhile, theorists are working hard to understand the fundamental mechanism of mass generation, which gives rise to these seemingly bizarre results.

We should not forget supernovae, which are still a bit of a mystery. The best calculations on the fastest computers still cannot produce a satisfying bang. It is clear, however, that real supernovae cannot go *bang* without neutrinos. We need more data, and the world's neutrino detectors stand ready for the next little burst of supernova neutrinos, whenever that may come.

Quarks, the Universe, and Love*

How does physics offer answers to questions about the workings of the world, or, more broadly, the universe? Albert Einstein, *Time* magazine's Person of the Twentieth Century, expressed both puzzlement and hope when he wrote, "The most incomprehensible thing about the universe is that it is comprehensible." One can interpret Einstein's remark as saying that we cannot comprehend why the universe is the way it is, but despite that, it happens that we can describe the universe in terms of physical laws that apply not only on Earth but also everywhere in the universe.

How is it that we can describe the universe with physical laws discovered by earthbound scientists? Richard Feynman, arguably the most admired and

* Essay by Robert S. Panvini, Department of Physics, Vanderbilt University.

influential physicist of the second half of the 20th century, gave us many clues. One of his most memorable insights is that the single most important finding of science is that everything is made of atoms. Once everything is seen as being made of atoms, one may infer that understanding the laws that govern the behavior of individual atoms and their constituents, including the quarks, leads with sufficient effort to understanding complex systems containing huge numbers of atoms. This is called the *reductionist view*. It assumes that any physical system, no matter how complex, may be understood in terms of its component parts.

The study of the origin and fate of the universe is called *cosmology*. Using the laws of physics, we can reconstruct the history of the universe, which began about 14 billion years ago with the Big Bang. A chart of the history of the universe (Figure 28-3) shows that before the universe was a few millionths of a second old, it was an incredibly dense and hot mixture of matter and antimatter in the form of elementary particles, including quarks and antiquarks. As time progressed, the universe expanded and cooled. By the time the universe was about 3 minutes old, quarks had combined to form protons and neutrons, antiquarks had combined to form antiprotons and antineutrons, quarks had combined with antiquarks to form mesons, and protons and neutrons had combined to form elements. As the cooling process continued even further, atoms were formed as electrons bound to atomic nuclei. The force of gravity played a more dominant role as the universe approached 1 billion years old. Gravity attracted atoms to each other, forming stars and clusters of stars. Stars then became sources of energy as atoms were drawn inward by each star's enormous gravitational attraction. As nuclei collided at the center of stars, they underwent nuclear fusion and released energy in the form of electromagnetic radiation that we see as sunlight. Planets were formed by smaller clusters of atoms, too few to have sufficient gravitational pull to initiate the nuclear fusion that characterizes a star.

The most amazing thing in the history of the universe, at least from our perspective, happened when one special planet—Earth—was formed. We may discover other planets like Earth someday, but what is special about Earth is that some of the atoms collected to form highly complex molecules and combinations of molecules, and enough of these complex molecules, in combination with other less complex molecules, formed living creatures, including dogs, cats, fish, mosquitoes, alligators, and people.

Remember how we got to this point. Fourteen billion years ago, everything was in the form of elementary particles. The quarks of an atom's nucleus were part of the primordial soup, as were electrons that eventually combined with the nuclei to form atoms. Atoms collected to form stars and planets, and then, on at least one special planet, atoms really got fancy and life was formed.

We finish this essay with questions, not answers. If atoms are mostly made of quarks (and electrons) and if everything is made of atoms, including people, what causes very large numbers of quarks, in the form of atoms, to exhibit the complex properties of living things? The characteristic of human beings that seems most different from inanimate matter includes consciousness and the realization of emotion, including love. Perhaps the reductionist view does not apply to systems as complex as living creatures. If not, why not? Whatever the ultimate answer, it will be fascinating to discover.

The Search Goes On

In Chapter 1 we set ourselves the task of expanding your world view. We began with a commonsense world view and carefully added bits and pieces of the physics world view. It is impossible for us to know which pieces have become parts of your own world view. Experience has shown us that expansion of a world view enables a person to see new connections between events. Some "see" sound waves, others feel the pull of gravity in a new way, and still others report experiencing new beauties in a rainbow or a red sunset.

This expansion of the world view produces different kinds of wonderment in different people. Some of us look at individual phenomena and marvel at the connections that can be made between seemingly unrelated things. Others wonder about the possibility of making sense out of the universe.

We hope that you have gained some insight into the ways the physics world view evolves. We hope, for example, that you know that there is no single, static physics world view. Rather, there is a central core of relatively stable components surrounded by a fuzzy, fluid boundary. Metaphorically, it is an organism with spurts of growth, and regions of maturation, decay, death, and even rebirth.

Part of our purpose was to show you that this growth proceeds within definite constraints; it is certainly not the case that "anything goes." Although intuitive feelings motivate new paths, they often result in dead ends. There were many more dead-end paths than we mentioned in this book. We picked up new ideas and discarded old ones. But within the space of this book, we couldn't follow the many blind paths that occurred in building the current physics world view. For the most part we had to follow the main paths.

Even the main paths, however, demonstrate why scientists believe what they believe. As one journeys from Aristotle's motions to Newton's inventions of concepts such as gravity and force, it is tempting to look back in amusement at the more primitive ideas. Perhaps you had these feelings. This superiority should have quickly vanished as we adopted the spacetime ideas of Einstein and the wave–particle duality of the submicroscopic world. All these notions are creations of the human mind. Our task in building a world view is to create, but to create in a way different from the artist or poet.

The creations are different because we have a different answer to the question of why we believe what we believe. Our ideas must agree with nature's results. For a new idea to replace an old one, it must do all that the old idea did and more. Old ideas fail because experiments give results that don't agree with these ideas. The new ideas must meet the challenge: they must account for the observations that were in agreement with the old theory and encompass the anomalous data. Einstein's idea of a warped spacetime includes Newton's concepts of gravity, but does much more.

People may claim that a particular idea is a lot of malarkey. For example, they may claim that the speed of light is not the maximum speed limit in the universe. For these critics to make a contribution, they will need to determine ways of testing their ideas. Their theories must be able to make predictions that can be tested by experiments.

So science has an interesting "split personality." During the birth of an idea, its personality is strongly dependent on the personal, intuitive feeling of the scientist. But science also has a strong, cold, and impersonal style of ruthlessly discarding ideas that have failed. No idea escapes this threat of abandonment. No single idea is so appealing that it can circumvent the tests of nature.

It is appealing to think that perpetual-motion machines could exist and would solve our energy crisis, that the visual positions of the celestial objects give insight into the future, or that there is some magic potion that can free us from the entropy of old age. These ideas are appealing to most people. However, the appeal of an idea is not the only criterion for inclusion into the physics world view.

Now we arrive at our final point: the search goes on and the world view continually evolves. The locations of future growth spurts, however, are virtually impossible to predict. A survey of physicists would yield various possibilities. The differences depend on the responder's area of expertise and, perhaps, a few most cherished ideas.

And so the search goes on.

CHAPTER 28 *Revisited*

The most recent experimental evidence indicates that the universe's rate of expansion may actually be increasing and will therefore continue to expand forever. This and other experimental evidence has led to the idea that the universe is filled with "dark energy" that causes the increase in the rate of expansion.

Questions are paired so that most odd-numbered are followed by a similar even-numbered.
Blue-numbered questions are answered in Appendix B.
indicates more challenging questions.
WebAssign **Many Conceptual Questions for this chapter may be assigned online at WebAssign.**

Conceptual Questions

1. What are three possible sources of gravity waves?
2. Why are gravity waves so hard to detect?
3. The Bohr model failed to account for the stability of atoms. Classical orbiting electrons would be constantly accelerating, would be constantly radiating energy in the form of electromagnetic waves, and would spiral into the nucleus. If orbiting planets are constantly radiating energy in the form of gravitational waves, why don't the planets spiral into the Sun?
4. The Planck model accounts for the stability of atoms by asserting that atoms radiate only when an electron jumps from one allowed orbit to another allowed orbit. Do planets radiate gravitational waves continually, or just when they change orbits? Explain.
5. What indirect evidence has been found to support the existence of gravitational waves?
6. Neutron stars are a little more massive than our Sun. Why would a binary system of neutron stars be a strong source of gravitational waves?
7. If the predicted lifetime for the proton far exceeds the present age of the universe, is it foolish to design an experiment to observe proton decay? Explain.
8. Current theories predict that the lifetime of the proton far exceeds the present age of the universe. Does this mean that a proton has never decayed? Explain.
9. Which of the fundamental forces of nature is not included in the grand unification theories?
10. What does superstring theory try to do that other grand unified theories do not?
11. What are the fundamental building blocks of matter and force in the current superstring theories?
12. How big are the fundamental building blocks in current superstring theories?
13. How old is the universe?
14. There was a period of time right after the Big Bang when the laws of physics as we know them did not exist and it was not necessary to take college physics classes. How long did this period last?
15. Which of the fundamental forces was the first to become distinct from the others after the Big Bang?
16. How long did it take after the Big Bang before the four fundamental forces of nature were distinct from each other? Can you blink your eyes this fast?
17. Why do neutrino experiments have to be performed in mineshafts deep below Earth's surface?
18. The fusion reactions in the Sun are now well understood. These reactions predict a much higher ratio of electron neutrinos compared with the other two flavors than is observed here on Earth. How do scientists account for this discrepancy?
19. What evidence led scientists to believe that the universe is "flat"?
20. What observation led scientists to conclude that the rate of expansion of the universe is increasing?
21. Describe the reductionist world view in your own words.
22. A friend claims, "My Uncle Fred wrote a book that explains everything. In his theory, shooting stars are angels traveling faster than light and dinosaurs were killed in the Great Flood. I don't know why Einstein is more famous than my uncle. After all, relativity is *just a theory*." Should Einstein be more famous than Uncle Fred? Explain.

Appendix A

Nobel Laureates in Physics

The Nobel Prizes are awarded under the will of Alfred Nobel (1833–1896), the Swedish chemist and engineer who invented dynamite and other explosives. The annual distribution of prizes began on December 10, 1901, the anniversary of Nobel's death. No Nobel Prizes were awarded in 1916, 1931, 1934, 1940, 1941, or 1942. You can learn a lot more about the Nobel Prizes in all categories at the Nobel Prize Internet Archive: http://nobelprizes.com.

1901 **Wilhelm Roentgen*** (Germany), for the discovery of X rays.

1902 **Hendrik Lorentz** and **Pieter Zeeman** (both Netherlands), for investigation of the influence of magnetism on radiation.

1903 **Henri Becquerel*** (France), for the discovery of radioactivity, and **Pierre*** and **Marie Curie***† (France), for the study of radioactivity.

1904 **Lord Rayleigh** (Great Britain), for the discovery of argon.

1905 **Philipp Lenard** (Germany), for research on cathode rays.

1906 **Sir Joseph Thomson*** (Great Britain), for research on the electrical conductivity of gases.

1907 **Albert A. Michelson*** (United States), for spectroscopic and metrologic investigations.

1908 **Gabriel Lippmann** (France), for photographic reproduction of colors.

1909 **Guglielmo Marconi** (Italy) and **Karl Braun** (Germany), for the development of wireless telegraphy.

1910 **Johannes van der Waals** (Netherlands), for research concerning the equation of the state of gases and liquids.

1911 **Wilhelm Wien** (Germany), for laws governing the radiation of heat.

1912 **Gustaf Dalén** (Sweden), for the invention of automatic regulators used in lighting lighthouses and light buoys.

1913 **Heike Kamerlingh Onnes*** (Netherlands), for investigations into the properties of matter at low temperatures and the production of liquid helium.

1914 **Max von Laue** (Germany), for the discovery of the diffraction of X rays by crystals.

1915 **Sir William Bragg** and **Sir Lawrence Bragg** (both Great Britain), for the analysis of crystal structure using X rays.

1916 No award.

*These winners are mentioned in the text.
†Marie Curie also received a Nobel Prize in chemistry in 1911.

1917 **Charles Barkla** (Great Britain), for the discovery of the characteristic X-rays of the elements.

1918 **Max Planck*** (Germany), for the discovery of the quantum theory of energy.

1919 **Johannes Stark** (Germany), for the discovery of the Doppler effect in canal rays and the splitting of spectral lines by electric fields.

1920 **Charles Guillaume** (Switzerland), for the discovery of anomalies in nickel–steel alloys.

1921 **Albert Einstein*** (Germany), for the explanation of the photoelectric effect.

1922 **Niels Bohr*** (Denmark), for the investigation of atomic structure and radiation.

1923 **Robert A. Millikan*** (United States), for work on the elementary electric charge and the photoelectric effect.

1924 **Karl Siegbahn** (Sweden), for investigations in X-ray spectroscopy.

1925 **James Franck** and **Gustav Hertz** (both Germany), for the discovery of laws governing the impact of electrons on atoms.

1926 **Jean B. Perrin** (France), for work on the discontinuous structure of matter and the discovery of equilibrium in sedimentation.

1927 **Arthur H. Compton** (United States), for the discovery of the Compton effect, and **Charles Wilson** (Great Britain), for a method of making the paths of electrically charged particles visible by vapor condensation (cloud chamber).

1928 **Sir Owen Richardson** (Great Britain), for the discovery of the Richardson law of thermionic emission.

1929 **Prince Louis de Broglie*** (France), for the discovery of the wave nature of electrons.

1930 **Sir Chandrasekhara Raman** (India), for work on light diffusion and discovery of the Raman effect.

1931 No award.

1932 **Werner Heisenberg*** (Germany), for the development of quantum mechanics.

1933 **Erwin Schrödinger*** (Austria) and **Paul A.M. Dirac*** (Great Britain), for the discovery of new forms of atomic theory.

1934 No award.

1935 **Sir James Chadwick*** (Great Britain), for the discovery of the neutron.

1936 **Victor Hess** (Austria), for the discovery of cosmic radiation, and **Carl D. Anderson** (United States), for the discovery of the positron.

1937 **Clinton J. Davisson*** (United States) and **Sir George P. Thomson** (Great Britain), for the discovery of the diffraction of electrons by crystals.

1938 **Enrico Fermi*** (Italy), for identification of new radioactive elements and the discovery of nuclear reactions effected by slow neutrons.

1939 **Ernest Lawrence** (United States), for development of the cyclotron.

1940–1942 No awards.

1943 **Otto Stern** (United States), for the discovery of the magnetic moment of the proton.

1944 **Isidor I. Rabi** (United States), for work on nuclear magnetic resonance.

1945 **Wolfgang Pauli*** (Austria), for discovery of the Pauli exclusion principle.

1946 **Percy Bridgman** (United States), for studies and inventions in high-pressure physics.

1947 **Sir Edward Appleton** (Great Britain), for discovery of the Appleton layer in the ionosphere.

1948 **Lord Patrick Blackett** (Great Britain), for discoveries in nuclear physics and cosmic radiation using an improved Wilson cloud chamber.

1949 **Hideki Yukawa*** (Japan), for prediction of the existence of mesons.

1950 **Cecil Powell** (Great Britain), for the photographic method of studying nuclear process and discoveries about mesons.

1951 **Sir John Cockcroft** (Great Britain) and **Ernest Walton** (Ireland), for work on the transmutation of atomic nuclei.

1952 **Felix Bloch** and **Edward Purcell** (both United States), for the discovery of nuclear magnetic resonance in solids.

1953 **Frits Zernike** (Netherlands), for the development of the phase contrast microscope.

1954 **Max Born** (Great Britain), for work in quantum mechanics, and **Walter Bothe** (Germany), for work in cosmic radiation.

1955 **Polykarp Kusch** (United States), for measurement of the magnetic moment of the electron, and **Willis E. Lamb, Jr.** (United States), for discoveries concerning the hydrogen spectrum.

1956 **William Shockley, Walter Brattain,** and **John Bardeen** (all United States), for development of the transistor.

1957 **Tsung-Dao Lee** and **Chen Ning Yang** (both China), for discovering violations of the principle of parity.

1958 **Pavel Cerĕnkov, Ilya Frank,** and **Igor Tamm** (all U.S.S.R.), for the discovery and interpretation of the Cerĕnkov effect.

1959 **Emilio Segrè** and **Owen Chamberlain** (both United States), for confirmation of the existence of the antiproton.

1960 **Donald Glaser** (United States), for the invention of the bubble chamber.

1961 **Robert Hofstadter** (United States), for determination of the size and shape of nuclei, and **Rudolf Mössbauer** (Germany), for the discovery of the Mössbauer effect of gamma-ray absorption.

1962 **Lev D. Landau** (U.S.S.R.), for theories about condensed matter (superfluidity in liquid helium).

1963 **Eugene Wigner, Maria Goeppert-Mayer*** (both United States), and **J. Hans D. Jensen*** (Germany), for research on the structure of nuclei.

1964 **Charles Townes** (United States), **Nikolai Basov,** and **Alexsandr Prokhorov** (both U.S.S.R.), for work in quantum electronics leading to the construction of instruments based on maser-laser principles.

1965 **Richard Feynman,* Julian Schwinger*** (both United States), and **Shinichiro Tomonaga*** (Japan), for research in quantum electrodynamics.

1966 **Alfred Kastler** (France), for work on atomic energy levels.

1967 **Hans Bethe** (United States), for work on the energy production of stars.

1968 **Luis Alvarez** (United States), for the study of subatomic particles.

1969 **Murray Gell-Mann*** (United States), for the study of subatomic particles.

1970 **Hannes Alfvén** (Sweden), for theories in plasma physics, and **Louis Néel** (France), for discoveries in antiferromagnetism and ferrimagnetism.

1971 **Dennis Gabor*** (Great Britain), for the invention of the hologram.

1972 **John Bardeen,* Leon Cooper,*** and **John Schrieffer*** (all United States), for the theory of superconductivity.

1973 **Ivar Giaever** (United States), **Leo Esaki** (Japan), and **Brian Josephson** (Great Britain), for theories and advances in the field of electronics.

1974 **Antony Hewish** (Great Britain), for the discovery of pulsars, and **Martin Ryle** (Great Britain), for radio-telescope probes of outer space.

1975 **James Rainwater** (United States), **Ben Mottelson,** and **Aage Bohr** (both Denmark), for the development of the theory of the structure of nuclei.

1976 **Burton Richter** and **Samuel Ting** (both United States), for discovery of the subatomic J/ψ particles.

1977 **Philip Anderson, John van Vleck** (both United States), and **Nevill Mott** (Great Britain), for work underlying computer memories and electronic devices.

1978 **Arno Penzias*** and **Robert Wilson*** (both United States), for the discovery of the cosmic microwave background radiation, and **Pyotr Kapitsa** (U.S.S.R.), for research in low-temperature physics.

1979 **Steven Weinberg,* Sheldon Glashow*** (both United States), and **Abdus Salam*** (Pakistan), for developing the theory that the electromagnetic force and the weak force are facets of the same phenomenon.

1980 **James Cronin** and **Val Fitch** (both United States), for work concerning the asymmetry of subatomic particles.

1981 **Nicolaas Bloembergen** and **Arthur Schawlow** (both United States), for contributions to the development of laser spectroscopy, and **Kai Siegbahn** (Sweden), for contributions to the development of high-resolution electron spectroscopy.

1982 **Kenneth Wilson** (United States), for the study of phase transitions in matter.

1983 **Subramanyan Chandrasekhar** (United States), for theoretical studies of the processes important in the evolution of stars, and **William Fowler** (United States), for studies of the formation of the chemical elements in the Universe.

1984 **Carlo Rubbia** (Italy) and **Simon van der Meer** (Netherlands), for work in the discovery of intermediate vector bosons.

1985 **Klaus von Klitzing** (Germany), for the discovery of the quantized Hall effect.

1986 **Ernst Ruska** (Germany), for the design of the electron microscope, and **Gerd Binning** (Germany) and **Heinrich Rohrer** (Switzerland), for the design of the scanning tunneling microscope.

1987 **K. Alex Müller** (Switzerland) and **J. Georg Bednorz** (Germany), for development of a "high-temperature" superconducting material.

1988 **Leon Lederman*, Melvin Schwartz,** and **Jack Steinberger** (all United States), for the development of a new tool for studying the weak nuclear force and the discovery of the muon neutrino.

1989 **Norman Ramsay** (United States), for various techniques in atomic physics, and **Hans Dehmelt** (United States) and **Wolfgang Paul** (Germany), for the development of techniques for trapping single charged particles.

1990 **Jerome Friedman, Henry Kendall** (both United States), and **Richard Taylor** (Canada), for experiments important to the development of the quark model.

1991 **Pierre de Gennes** (France), for discovering methods for studying order phenomena in complex forms of matter.

1992 **Georges Charpak** (France), for his invention and development of particle detectors.

1993 **Russell Hulse*** and **Joseph Taylor*** (both United States), for discovering evidence of gravity waves.

1994 **Bertram Brockhouse** (Canada) and **Clifford Shull** (United States), for pioneering contributions to the development of neutron-scattering techniques for studies of condensed matter.

1995 **Martin Perl** and **Frederick Reines*** (both United States), for pioneering experimental contributions to lepton physics.

1996 **David Lee, Douglas Osheroff,** and **Robert Richardson** (all United States), for their discovery of superfluidity in helium-3.

1997 **Steven Chu** (United States), **Claude Cohen-Tannoudji** (Algeria), and **William Phillips** (United States), for the development of methods to cool and trap atoms with laser light.

1998 **Robert Laughlin** (United States), **Horst Störmer** (Germany), and **Daniel Tsui** (China), for their discovery of a new form of quantum fluid with fractionally charged excitations.

1999 **Gerardus 't Hooft** and **Martinus Veltman** (both Netherlands), for elucidating the quantum structure of electroweak interactions.

2000 **Zhores I. Alferov** (Russia) and **Herbert Kroemer** (United States), for developing semiconductor heterostructures used in high-speed- and opto-electronics, and **Jack St. Clair Kilby** (United States), for his part in the invention of the integrated circuit.

2001 **Eric A. Cornell, Wolfgang Ketterle,** and **Carl E. Wieman** (all United States), for the achievement of Bose–Einstein condensation in dilute gases of alkali atoms and for early fundamental studies of the properties of the condensates.

2002 **Raymond Davis, Jr.,*** **Riccardo Giacconi** (both United States), and **Masatoshi Koshiba*** (Japan), for pioneering contributions to astrophysics.

2003 **Alexei A. Abrikosov, Vitaly L. Ginzburg** (both Russia), and **Anthony J. Leggett** (Great Britain and United States), for pioneering contributions to the theory of superconductors and superfluids.

2004 **David J. Gross, H. David Politzer,** and **Frank Wilczek** (all United States), for the discovery of asymptotic freedom in the theory of the strong interaction.

2005 **Roy J. Glauber** (United States), for his contribution to the quantum theory of optical coherence, and **John L. Hall** (United States) and **Theodor W. Hänsch** (Germany), for their contributions to the development of laser-based precision spectroscopy, including the optical frequency comb technique.

2006 **John C. Mather** and **George F. Smoot** (both United States), for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation.

2007 **Albert Fert** (France) and **Peter Grünberg** (Germany), for the discovery of Giant Magnetoresistance.

2008 **Yoichiro Nambu** (United States), for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics; and **Makkoto Kobayashi** and **Toshihide Maskawa** (both Japan), for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature.

Appendix B

Answers to Most Odd-Numbered Questions and Exercises

CHAPTER 1

Questions

1. A physics world view incorporates data from outside the range of human sensations.
3. It does not have any scientific basis.
5. It must (a) account for known data, (b) make testable predictions, and (c) have a scientific basis.
7. The more prestigious the scientist who proposes the theory, the more likely the scientific community will commit resources to test the theory.
9. United States
11. About 170 cm
13. About 2.5 m
15. About 85 kg
17. 10^3 miles (3000 miles) or 10^3 kilometers (4800 km) or 10^6 meters

Exercises

19. 86,400 s
21. 109 yd
23. 39.4 in.
25. (a) 8.976 × 104 in. (b) 7.07×10^{-13} g
27. (a) 4300 g (b) 0.000 081 2 m
29. (a) 1.56 × 102 (b) 3.4 × 108
31. 10^4 times

Chapter 2

Questions

1. The puck speeds up and then slows down.
3. In the middle
5. ●● ● ● ● ● ● ● ● ● ● ● ● ●●
7. ●● ● ● ● ● ● ● ● ● ● ●●
9. The truck
11. Less than 45 mph
13. They had the same average speed, but Chris had higher instantaneous speeds.
15. The average speed is greater than the instantaneous speed at C and less than the instantaneous speed at D.
17. Determine the time it takes to travel between mile markers.
19. No, the average speed doesn't tell us any instantaneous speeds.
21. A stopwatch and an odometer give average speed; a speedometer gives instantaneous speed.
23. Velocity has a direction.
25. They both have zero acceleration.
27. Anything that changes the speed (or direction) is an accelerator.
29. The bicycle has the greatest acceleration.
31. The motorcycle
33. Carlos could be going 60 mph and slowing while Andrea is going 5 mph and speeding up.
35. They are falling in a vacuum.
37. 40 m/s
39. It stays the same.
41. It will be beside you.
43. They hit at the same time.
45. Galileo concluded that the object falls with a constant acceleration when air resistance is ignored. Aristotle hypothesized that the object quickly reaches a constant speed.
47. The heavier ball hits first.
49. The marble has the greater acceleration.
51. The accelerations are the same.
53. The increasing upward force due to the air resistance causes the downward acceleration to continually decrease.
55. Greater than

Exercises

57. 3530 km/h
59. 66 mph
61. 6.05 mph
63. 480 miles
65. 2.4 mph
67. 4 s, compared to 10 s for humans
69. 25 h; no
71. 12.5 mph/s
73. 5 mph/s
75. 27 m/s
77. 13 m/s
79. 20 m
81.

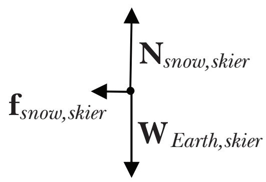
Time (s)	Height (m)	Velocity (m/s)
0	80	0
1	75	10
2	60	20
3	35	30
4	0	40

83. 30 m/s; 3 s
85. 1.3 m/s

Chapter 3

Questions

1. The snacks appear to fall straight down.
3. An unbalanced force (friction) opposes the motion of the car.
5. The net force on each car is zero.
7. Because of its inertia
9. Because of your inertia
11. The inertia of the anvil keeps it from moving.
13. No, inertia refers to how hard it is to speed up or slow down.
15. No, the net force will not normally point in the direction of any of the individual forces.
17. 50 N; 130 N
19. The wagon now accelerates (speeds up indefinitely) because the net force is not zero.
21. East; still east
23. The net force is up.
25. It doubles.
27. 4 m/s^2
29. Her mass doesn't change.
31. It triples.
33. For a skier slowing down and moving to the right:



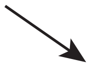
35. If there is no air resistance
37. Upward force of resistance balances downward force of gravity, so acceleration is zero.
39. The acceleration of each is zero, so the net force on each must be zero.
41. Newton's first law is always valid. There must be other forces opposing the friction so that the net force is zero.
43. The frictional force is equal to 400 N because the net force is zero.
45. 250 N
47. They are equal and opposite by Newton's third law.
49. They are equal and opposite by Newton's third law.
51. Zero
53. According to Newton's third law, there is a reaction force on the cannon.
55. The frictional force of the floor on your feet
57. 40 N
59. The forces act on different objects. The frictional force of the ground on the horse's hooves allows the horse to move the cart.
61. By Newton's second law because the net force is zero

Exercises

63. 14 N; 2 N; 10 N
65. 250 N backward
67. 3 m/s^2
69. 900,000 m/s^2
71. 120 N
73. 1.67 m/s^2
75. 75 kg
77. 5 N down
79. 4 m/s^2
81. 162 N
83. 10 N
85. 3 m/s^2

Chapter 4

Questions

1. At each point the instantaneous velocity is in the direction of motion (tangent to the circle), and the net force is toward the center of the circle.
3. Gravity provides the required centripetal force.
5. The velocity is tangent to the path; all the others point radially inward.
7. They point in opposite directions; they have the same length.
9. The speed changes.
11. Southwest
13. (a)  (b) 
15. (a) Speeding up in a straight line (b) Speeding up and turning left
17. It must point southward and eastward. The angle would be greater than 90°.
19. (a) Any example that is moving down and speeding up would work, such as a falling rock. (b) Any example that is moving up and slowing down would work, such as an elevator slowing as it reaches the tenth floor from the lobby.
21. It is down while you are speeding up and up while you are slowing down.
23. The friction force exerted by the ground on the bicycle
25. The tension force must be greater than the monkey's weight.
27. At the bottom
29. It must be nearly uniform.
31. Doubling speed would quadruple acceleration; reducing radius to half would only double acceleration.
33. Only the force of gravity
35. The ball's velocity is horizontal toward home plate; the net force and acceleration are vertically downward.
37. The accelerations would be the same. Acceleration is independent of horizontal velocity.
39. They hit at the same time. They start with the same vertical velocity.
41. The demonstration works.
43. Kicks the ball at a larger angle
45. 5 N, by Newton's third law
47. The diagram contains only the gravitational force exerted by the Sun.
49. Point C is most likely nearest the object's center of mass.

Exercises

51. (a) 5 m/s west (b) 5 m/s east (c) 15 m/s east
53. 50 m/s at 37° north of west
55. 5 m/s^2 (53° north of east)
57. (a) 2 m/s^2 (b) 240 N
59. (a) 3.16×10^7 s (b) 9.42×10^{11} m (c) $5.96 \times 10^{(3}$ m/s^2 (d) 3.56×10^{22} N
61. 45 m/s; 8 m/s
63. 125 m; 200 m
65. 2 s; 60 m
67. 9.83 m/s^2

Chapter 5

Questions

1. None
3. Same, by Newton's third law
5. Same
7. The surface area quadruples for cube and sphere.
9. 200 N
11. Because the Moon's acceleration does not depend on its mass
13. Twice as great
15. Because it is also moving sideways fast enough to match Earth's curvature.
17. He is in free fall.
19. They are in free fall.
21. No
23. The gravitational forces are very small.
25. Atmospheric friction, though weak, still acts.
27. Send a satellite to orbit Venus.
29. Larger
31. A slow decrease in size of the planetary orbits
33. No, Paris is not on the equator.
35. The satellite would appear to move westward.
37. Because the mass of Earth is so much larger than that of the Moon, it has a much smaller orbit about their common center of mass.
39. Nearer low tide
41. Half the rotational period, 4 h 55 min
43. d; the effects of the Moon and Sun act together.
45. The effects reinforce, producing a larger bulge.
47. The extra tidal force is minuscule.
49. Decreases with the square of the distance
51. Not possible

Exercises

53. 0.006 m/s^2
55. $g/9 = 1.11$ m/s^2
57. 60 N
59. $\frac{1}{2} F_{\text{old}}$; no
61. 0.25 $\mathbf{F}_{\text{Earth}}$
63. 12,660 km; 6290 km
65. 1.07×10^{-7} N compared to 200 N
67. 200 N

69. $3.8\ m/s^2$
71. 264,000 km; 3060 m/s
73. 1.93
75. 40 N

Chapter 6

Questions

1. Its numerical value does not change.
3. Toby is correct.
5. They have large inertia.
7. The net force on an object is equal to the change in its momentum divided by the time required to make the change.
9. They lengthen the time for your leg to stop.
11. Same
13. The impulses are equal.
15. 8 kg · m/s directed up
17. Jeff feels the greater force because his flowerpot experienced the greater change in momentum.
19. They lengthen the interaction time and decrease the forces.
21. At each interaction there are equal and opposite momentum changes. The total momentum is conserved at all times.
23. 4 N acting for 4 s
25. Conservation of linear momentum requires the bullet to go one way and the rifle the other.
27. The net force exerted by the exhaust gases on the rocket–plate system is nearly zero.
29. Earth's large mass allows it to acquire an equal and opposite momentum to the ball without a measurable velocity.
31. At rest
33. Moving to the left
35. 250 kg · m/s
37. Zero
39. They give the rowboat momentum away from the dock.
41. It is conserved.
43. Not without outside help unless the astronaut has something to throw
45. Path B
47. Path D

Exercises

49. 36,000 kg·m/s
51. 62 m/s
53. 5625 N
55. 35,000 kg·m/s (= 35,000 N·s)
57. Impulse = 45,000 N · s; F_{av} = 5625 N
59. 180 N upward
61. 900 N
63. 1.5 m/s
65. Zero
67. 66,800 kg · m/s (north)
69. 2.5 m/s

Chapter 7

Questions

1. The initial momentum of the system is zero.
3. Conservation of momentum
5. Yes
7. Motorboat pulling a water skier
9. Minivan
11. Same kinetic energies
13. Two balls leave the other side with the same speed as the incoming balls.
15. How high she lifted the ball
17. Decrease
19. Kinetic energies are the same; momentum is greater for the heavier sled.
21. Frictional forces and air resistance do an equal amount of negative work.
23. Less than
25. Both cars stop in the same distance.
27. No, the kinetic energy lost by one object during a collision could be converted to many different forms of energy.
29. 4 N through 7 m do more work.
31. The choice for the zero of potential energy is arbitrary. Only differences in potential energy are important.
33. The gain in the kinetic energy equals the loss in the gravitational potential energy, keeping the mechanical energy the same.
35. Potential energy is a maximum at either end, and kinetic energy is a maximum at the bottom.
37. It will decrease.
39. As the satellite moves closer to Earth, its gravitational potential energy decreases, and its kinetic energy increases. The reverse happens as the satellite moves farther from Earth.
45. The work done in plowing through the dirt or sand reduces the kinetic energy of the truck.
47. The chemical potential energy of the battery is converted to thermal energy in the socks.
49. We cannot recover the energy lost because of frictional effects.
51. If the winch will run for more than 1 s, it can do more than 600 J of work.
53. A unit of energy
55. A kilowatt-hour is a unit of energy.

Exercises

57. 630,000 J
59. Momentum is not conserved; therefore, the collision could not have taken place.
61. 10 J
63. 1.6 J
65. 4 N
67. Negative for the next 6 months; zero for the year
69. 396 kJ
71. (a) −8.7 J (b) 0 (c) 0
73. 30 J
75. 144 kJ
77. 2.73 horsepower
79. 120 Wh = 0.12 kWh

Chapter 8

Questions

1. Rotational speed is the same for all points on a rotating body.
3. The same
5. Toward the North Star
7. Rotational inertia
9. None
11. $\mathbf{F}_2$ because it acts farther from the pivot
13. The force on the nail is larger because it acts through a smaller radius than that of the force applied to the handle.
15. Your torque about the base of the ladder is balanced by the torque exerted by the window—the higher you climb, the greater your torque.
17. Because Sam has to exert the greater force, Sam must be closer to the center of mass.
19. The flywheel of larger radius has the greater rotational inertia and is harder to stop.
21. Increases; decreases
23. Sphere
25. There is no appreciable external torque acting on Earth.

27. The front–back location can be determined by separately weighing the front and back tires on a truck scale. The ratio of those two readings will give the ratio of the distances of the center of mass from the two axles. The same procedure works for the left-right position.
29. Below the foot of the figure
31. One diagram should show that the force acting at the center of mass lies inside the base for the upside-down cone even when it is tipped.
33. Stable equilibrium
35. The wall prevents you from rocking backward, to keep your center of mass over your feet.
37. The jumper's body is curved as it passes over the bar, causing the center of mass to lie outside the jumper's body below the bar.
39. The cylinder wins! Both have the same kinetic energy, but the hoop has more of this energy in the form of rotational kinetic energy because of its larger rotational inertia.
41. To counteract the torque of the main rotor acting on the helicopter. This torque is a reaction to the torque applied to the main rotor.
43. Tuck
45. The lower rotational inertia requires a larger rotational speed to conserve angular momentum.
47. No, one part of its body has angular momentum in one direction while the rest of its body has an equal angular momentum in the opposite direction.
49. The grooves give the bullet angular momentum so that it doesn't tumble in flight.
51. The push exerted by the exhaust gases produces a torque on the merry-go-round.
53. In the same (horizontal) direction
55. The car would not go around corners because of the large angular momentum of the flywheel. Use two flywheels rotating in opposite directions.
57. Clockwise
59. Polaris appears stationary because Earth's spin axis is aligned with it.
61. (a) Toward the ground (b) Toward the sky (c) Toward the ground (d) Zero

Exercises

63. 200 rpm, or 3.33 rev/s
65. 2.78×10^{-4} rev/s
67. -2500 rpm/s
69. 210 N · m
71. 1800 N · m
73. 2 m
75. Left-hand side will fall because it has larger torque.
77. $N_C = 793\text{ N} \Rightarrow N_W = 910\text{ N} - 793\text{ N} = 117\text{ N}$
79. 300 kg · m²/s
81. $L_M = 0.132L_E$; Earth has the larger angular momentum.

Chapter 9

Questions

1. No, Newton's first law is true only in inertial reference frames.
3. Alice would not see any motion of the jar relative to her. Someone sitting on a shelf would see the jar fall freely.
5. No experiment can distinguish between the two.
7. The ball lands on the white spot.
9. Both would agree that there are no horizontal forces.
11. The woman would claim that the ball began with zero kinetic energy, whereas the observer on the ground would calculate a nonzero initial kinetic energy. Both observers would agree on the change in kinetic energy.
13. They would not agree on the value of the kinetic energy at an instant, but they would both agree that the change in kinetic energy is zero.
15. Forward because of its inertia
17. If the velocity is to the right, it is speeding up; if the velocity is to the left, it is slowing down.
19. The ball will land farther from her feet than the white spot. The inertial force will be in the direction opposite to the acceleration, independent of the velocity.
21. It would initially be zero and increase in the direction away from her.
23. The woman would claim that there is a constant horizontal force directed away from her. The observer on the ground would claim that there is no horizontal force.
25. Greater, because the inertial force acts in the same direction as the gravitational force
27. Less, because the inertial force acts in the opposite direction to the gravitational force
29. Same
31. Inertial forces act backward in the noninertial reference system of the accelerating plane.
33. The same, because you are comparing masses. The weights increase by the same amount during the acceleration.
35. If the train's velocity is to the west, it must be speeding up; if its velocity is to the east, it must be slowing down.
37. (a) Up (b) Up (c) Down
39. Up is not defined.
41. (a) Constant velocity (b) Slowing down
43. The "up" direction is toward the ground.
45. Your figure should have the plants leaning toward the center.
47. The centrifugal force pulls the mud off.
49. Parallax would be easier to observe.
51. No, because there is no Coriolis force on the equator
53. There is no Coriolis force on the equator.

Exercises

55. 40 m/s; 10 m/s
57. (a) 70 mph (b) 30 mph backward
59. (a) 4 m/s² downward (b) 6 m/s² upward
61. 0; 25 J; 25 J
63. 1500 N
65. 390 N
67. 100 N
69. 240 N
71. 10 m/s²

Chapter 10

Questions

1. Because the physical laws are the same in all inertial systems, it is impossible to determine your speed.
3. No, the speed of light is an absolute quantity.
5. 70 mph
7. He will obtain a speed equal to *c*.
9. No, the special theory of relativity does not allow one to travel backward in time.
11. No, the supernova in the Whirlpool galaxy happened first.
13. The flash at the front of the train occurred first.
15. The one at the back of the skateboard. The third person must have a speed to the right that is larger than that of the skateboard.
17. A could not have triggered B, so the order could be reversed.
19. Less than 3 min
21. Same note
23. Shorter
25. Greater

27. Peter will be the younger.
29. It is not possible to travel backward in time.
31. The observers would agree because the clocks move toward or away from the light by the same amount.
33. Earth's reference system
35. Less than 100 m
37. Less than 400 m
39. Same
41. (a) The caboose entered first. (b) The tunnel is longer. (c) Yes.
43. Decrease
45. Matter and energy can be converted to each other.
47. The energy radiated away causes the mass to decrease.
49. Special relativity does not include noninertial reference systems, which are included in the general theory.
51. No
53. Blake is comparing the gravitational masses. Jordan is comparing the inertial masses.
55. The penny
57. Passengers in spaceship A
59. Over laboratory distances, the bending of light is less than the diameter of an atom.
61. (a) Slower because of the stronger gravitational field
(b) Slower because of the centripetal acceleration

Exercises

63. 500s = 8 min 20 s; 1.28 s
65. 300 s = 5 min
67. 1.09
69. 0.379 ns
71. 28.4 h
73. 69 m
75. 200 m
77. 1.31×10^{13} m
79. 672 N
81. 0.866 c
83. 5 m/s^2 backward
85. 11 m/s^2 downward
87. 5 m
89. $3 \times 180° = 540°$. It is almost a great circle, but it has slight bends in three places; for instance, at one pole and both crossings of the equator.

Chapter 11

Questions

1. Lack of predictive power
3. Seal off the machine, thus taking away essentials such as food and water for a period of time.
5. The next brown can may sink. A model can never be proven true.
7. The atomistic nature of matter is not important for most day-to-day activities.
9. Water, salt, and granite are not elements.
11. It is a compound because the mercury combines with something in the air.
13. Compounds are new substances with their own properties that result from substances combining according to the law of definite proportions.
15. 14 amu
17. 1 g of hydrogen
19. They have the same number of molecules.
21. 32 g
23. The ideal gas model does not apply to liquids, but the particles must be much closer together in the liquid.
25. Ball
27. Increased pressure at lower elevation results in decreased volume.
29. More molecules will be hitting the walls per unit time.
31. The perfume molecules travel very crooked paths.
33. To amplify the rise in the narrow tube
35. Atmospheric pressure and the purity of the water must be maintained.
37. 39°C
39. 39°C
41. 273 K
43. Average kinetic energy of the molecules
45. The average kinetic energies are equal because they are at the same temperature.
47. The particles have more kinetic energy. Therefore, they are moving faster and strike the walls more frequently and with more momentum.
49. Volume
51. Temperature drops to one-fourth on the Kelvin scale.
53. The particles strike the walls more frequently, producing a larger average impulse with the walls of the container.
55. The more energetic molecules leave via evaporation, lowering the average kinetic energy and therefore the temperature of the remaining water.

Exercises

57. 3 g
59. 18 g
61. 20 sandwiches; 1200 g; 800 g of ham
63. 5.02×10^{22} atoms
65. 3.35×10^{25} molecules
67. 1 nitrogen and 3 hydrogens
69. 10^{16}
71. 382 kPa $\approx$ 3.7 atm
73. $\frac{1}{3}$ L
75. 240 balloons
77. 3.2 atm

Chapter 12

Questions

1. Solid, liquid, gas, and plasma
3. They have the same densities.
5. Magnesium
7. The gold atoms must be closer together.
9. They are not the same because the crystals have different shapes.
11. Diamond has strong bonds in all directions; graphite has stronger bonds between atoms in two-dimensional layers.
13. The interatomic forces are stronger.
15. Spherical
17. The surface tension allows the surface of the water to rise without overflowing.
19. The water molecules are more strongly attracted to the glass than to each other.
21. Gas particles are neutral, whereas the particles in a plasma are electrons and charged ions.
23. The reduced surface area in the case of the gravel requires greater pressure.
25. The volume of liquid water is less than that of vapor, resulting in lower pressure in the can.
27. Denver has a lower atmospheric pressure, so fewer horses would be needed.
29. Denver would always be listed as a low-pressure region.
31. Your ears would hurt the same in both.
33. Same
35. Greater for the cold water

37. It is the atmospheric pressure that determines the maximum height.
39. With the pump at the bottom, you can apply much higher pressures.
41. The purple liquid has the larger density.
43. Higher in salt water
45. The buoyant forces are the same.
47. The reduction in volume reduces the buoyant force and causes you to sink.
49. Lead will float and gold will sink.
51. The volume does not change. Expelling water reduces weight.
53. The buoyant force is the same because they both displace the same volume.
55. It stays the same because the volume below the surface is the same as the volume of the ice when melted.
57. The fast-moving air creates lower pressure above the dime, which results in a net upward force.
59. So the balls will drop over the net
61. The wind blowing by the base reduces the outside pressure.

Exercises

63. 2.7 g/cm^3; aluminum
65. 0.3 g/cm^3
67. 1200 kg
69. 0.07 m^3
71. 1 cm^3
73. 100,000 N; 100,000 Pa; same
75. 7.5 in.
77. 15 $lb/in.^2$
79. 750 kg/m^3; float
81. 5 N
83. 0.9 g/cm^3
85. 79,300 N

Chapter 13

Questions

1. The gravitational potential energy is converted to thermal energy.
3. The heat seemed to be produced endlessly, implying that it was not a substance.
5. Both change the internal energy of a system and are measured in joules. Heat operates at a microscopic level, whereas work is a macroscopic concept.
7. If the thermometer is initially at a different temperature, heat must flow.
9. Yes, if they start with different temperatures.
11. Temperature is not a physical quantity and therefore cannot flow between objects.
13. Heat is a flow of thermal energy, whereas temperature is a measure of the average kinetic energy of the atoms and molecules. Notice that temperature is not a form of energy.
15. Neither student is correct.
17. Under all conditions
19. Water
21. No
23. More
25. It takes a tremendous amount of thermal energy to change the temperature of the water in the oceans.
27. It will freeze if heat is removed and melt if heat is added.
29. It requires a lot of thermal energy to melt the ice without changing its temperature. Also, ice is not a good conductor of thermal energy.
31. Less than 40°C
33. More internal energy in steam
35. The internal energy must increase by the first law. However, if the increase in internal energy causes a change of state, the system can remain at a fixed temperature.
37. The molecules of the rod exchange kinetic energy via collisions.
39. The order from best to worst is polyurethane foam, static air, glass, and concrete.
41. It will not freeze.
43. Stainless steel has a thermal conductivity that is about one-sixth that of iron.
45. The ground beneath the road keeps the road warm for a while.
47. The air beneath the clouds is shielded from the Sun and is cooler. Being cooler, the air is denser and creates a downdraft.
49. Both cars are heated by radiation.
51. The vacuum reduces conduction and convection, and the silvering reduces radiation.
53. Expansion and contraction of the roof
55. The spacing would be smaller on the wide portion.

Exercises

57. 5000 cal
59. 800 J; 190 cal
61. 10 Cal
63. 16 J
65. 330 J
67. 0.278 cal/g·°C
69. 124 cal
71. –1°C; +4°C
73. (a) 1600 cal (b) 1600 cal (c) It stays the same.
75. 6771 kJ
77. 1.73×10^6 J; 1188 kJ
79. 0.8 mm

Chapter 14

Questions

1. It converts heat to mechanical energy.
3. This would violate the second law of thermodynamics because heat will not naturally flow between two reservoirs at the same temperature.
5. The second law
7. Yes
9. Yes, provided the water that the tube accesses is at a different temperature.
11. You cannot get more energy out than you put in.
13. First: You cannot get more energy out than you put in. Second: You cannot convert all the heat to mechanical work.
15. About 20% of the thermal energy available in the food that is consumed shows up as mechanical work.
17. The efficiency increases.
19. Heat engine A is more efficient.
21. This would allow the hot region to operate at a higher temperature.
23. Because an efficiency of 1 or more means that the mechanical energy produced is as large as or larger than the thermal input.
25. In the shade
27. No
29. Temperature rises
31. A refrigerator will always need a motor.
33. The statement implies that work must be expended to make the thermal energy flow from a cooler region to a hotter region.
35. Greater than 1
37. Both strategies are equally invalid.
39. Sums 2 and 12 have highest order; sum 7 has the lowest order.
41. There are more ways of getting this sum than any other.

43. There is only one way of getting this arrangement.
45. The universe continually becomes more disordered.
47. The disorder increases as collisions cause all the particles to reach a common kinetic energy.
49. The entropy of the universe increases.
53. The order increases. Entropy must increase elsewhere.
55. It is highly unlikely for all the molecules to move in the same direction at the same time.
57. No, because atomic motions are symmetric with time. The direction of time in the release of air from a balloon, however, would be observable.
59. b
61. Electricity
63. If the oven heats the kitchen, the baseboard heaters will run less.

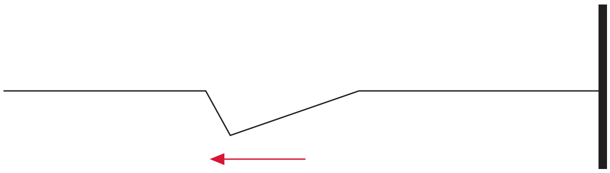
Exercises

65. 700 kJ
67. 5000 cal (each minute)
69. 0.25, or 25%
71. 2250 J
73. 9000 cal/min; 0.25
75. 0.0273, or 2.73%
77. 750 K = 477°C
79. 800 J
81. 800 J (each second)
83. 1600 J (each second)
85. HHHH, HHHT, HHTH, HTHH, THHH, HHTT, HTTH, TTHH, HTHT, THTH, THHT, HTTT, THTT, TTHT, TTTH, TTTT
87. $\frac{5}{36}$, or 13.9%
89. $\frac{6}{216} = \frac{1}{36}$, or 2.78%

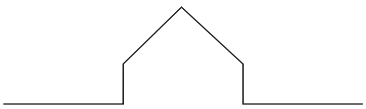
Chapter 15

Questions

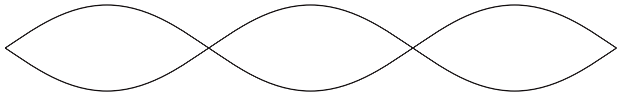
1. Its inertia carries it through the equilibrium point.
3. Down toward the equilibrium point in both cases
5. The period will increase, and the frequency will decrease.
7. A 3-kg block
9. The period stays the same.
11. The period is 60 s, and the frequency is 1/(60 s) = 0.017 Hz.
13. Move the mass down to lengthen the period.
15. The exhaust system has a natural frequency at 2000 rpm.
17. 1 Hz and 0.5 Hz
19. No
21. It is a longitudinal wave because the medium is a fluid.
23. No
25. Tension and mass per unit length
27. The reflected pulse will be on the opposite side and will cancel with the first one.
29.



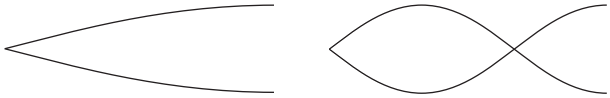
31.



33. Frequency and wavelength
35. The wave with the lower frequency
37. The wavelength is doubled.
39. The frequency stays the same, but the spacing decreases.
41.



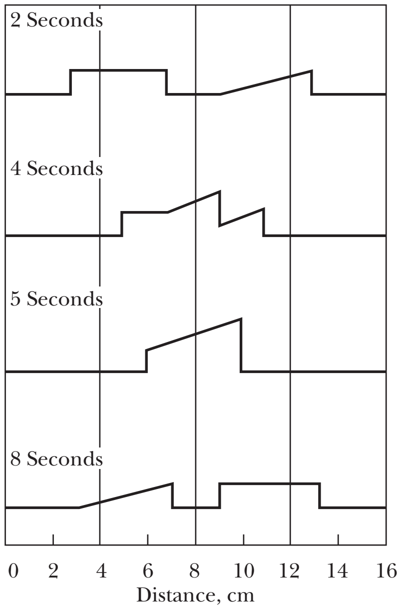
43. Five times as high
45. Three antinodes
47.



49. One-half the rope's length
51. Twice the length of the rod
53. Antinode
55. The spacing decreases.
57. Increase
59. Decrease

Exercises

61. 3 s
63. 0.167 Hz
65. 3 cm
67. 0.628 s
69. 4
71. 4.45 s
73.



75. 4.17 m/s
77. 75 cm/s
79. 15 m
81. 343 Hz
83. 6 m; (6 m)/2 = 3 m; (6 m)/3 = 2 m; (6 m)/4 = 1.5 m; (6 m)/5
85. 1.5 Hz

Chapter 16

Questions

1. Interference and superposition
3. Temperature
5. Water
7. The speed of light is much faster than the speed of sound.
9. Sound waves of all frequencies have the same speed.
11. The intensity is reduced to one-hundredth.
13. Yes
15. Mainly frequency
17. Equal to
19. 400 Hz
21. Increasing the tension or decreasing its mass per unit length
23. Twice the length of the string
25. One quarter the distance from either end; no
27. No
29. The same
31. Nodes
33. Twice the length of the pipe
35. The wavelength doubles.
37. Open at both ends
39. Decreases
41. Equal to
43. The unique blend of higher harmonics is hard to reproduce electronically.
45. Increases
47. You cannot tell.
49. Increases
51. The frequency of the whistle decreases as the train passes by.
53. Speed
55. The frequency is decreasing, and the sound is getting louder.
57. Billy's has the higher frequency.
59. Both produce a sharp rise in pressure.
61. You hear nothing until the shock wave arrives. You will then hear the characteristic boom-boom followed by engine noise.

Exercises

63. 0.003 82 s
65. 0.275 m
67. 343 Hz
69. 17.2 m
71. 2.74 km
73. 600 m
75. 40 dB
77. 125 Hz, 250 Hz, 375 Hz, 500 Hz, . . .
79. 470 Hz
81. $f_1 = 71.5$ Hz, $f_3 = 215$ Hz, $f_5 = 358$ Hz, . . .
83. 17.4 cm
85. 75 Hz
87. 260 Hz or 264 Hz

Chapter 17

Questions

1. Unless there is dust in the air, none of the light gets scattered into the eyes until the light hits the wall.
3. No light scatters back toward your eyes.
5. Point source
7. Shrinking
9. There will be no umbra when the shadow is not long enough to reach the screen. This occurs when the Moon's shadow does not reach Earth.
11. The image gets brighter and fuzzier.
13. The image is upside down and left–right reversed.
15. C
17. A
19. 0.7 m
21. B and C
23. One; infinite
25. Half her height; no
27. The images are progressively farther from the observer. They are virtual.
29. To produce a beam of light
31. The concave mirror
33. Concave
35. The image is very close to the mirror on the back side and only slightly magnified. Moving away makes the image get larger and move away.
37. The light actually converges to form a real image; there is no light at the location of a virtual image.
39. No; virtual
41. At the focal point
43. The speed of light is much faster than the speed of sound.
45. The time delay to send a signal to Earth and get a response was on the order of 20 min.
47. Magenta
49. Red; green; black
51. The letter would blend into the background because both would appear red.
53. With light beams you are adding colors, whereas with pigments you are subtracting colors. Red paint absorbs all but red, and green paint then absorbs the red, leaving muddy brown.
55. Magenta
57. Cyan
59. The sky would appear green, and the Sun would appear magenta.

Exercises

61. 20-cm diameter
65. 5 m
67. 36.9°
69. 10 m
71. The image is real, inverted, and reduced in size.
73. The image is located 30 cm in front of the mirror and is 3 cm tall.
75. The image is located 30 cm behind the mirror.
77. The image is located 20 cm behind the mirror and is two-thirds as big.
79. The image is located 40 cm in front of the mirror.
81. 0.1 ms; it is 1/2000 as big.
83. 16 ms
85. 9.46×10^{15} m

Chapter 18

Questions

1. C
3. C
5. The bending of light at the surface
7. Greater at the water–air surface
9. The light rays hit the sides of the light pipe at angles greater than the critical angle.
11. 141 million miles
13. Decrease (remember that the Moon is shortened in the vertical direction)
15. The Sun appears to rise before it actually does. Therefore, sunrise is earlier.
17. They are shortened in the vertical direction, yielding oval shapes.
19. Assuming that there is no deflection of the spear as it enters the water, you would aim low, because the fish appears to be higher than it actually is.

21. No
23. The bend will not be a problem for the blue light, but red light will leak out.
25. Yellow and green
27. The angle formed by the line from the Sun to the raindrop and the line from your eye to the raindrop must have a fixed value for a given color.
29. In the west at about midmorning
31. Diverging lens
33. Send the two beams in parallel to the optic axis and find the point where they cross.
35. Send the two beams in parallel to the optic axis and trace their diverging paths. Extend the paths backward to find their crossing point.
37. Converging lens
39. Through the principal focal point
41. The image becomes dimmer.
43. The lens with the larger index of refraction
45. The light converges to form the image and then diverges again. Your eye must be to the right of the image to see this diverging light.
47. Real image
49. To regulate the amount of light entering the eye
51. Dispersion occurs when light is refracted, not reflected.
53. Converging
55. Converging
57. Larger
59. Consider the symmetry of the letters.

Exercises

61. 23°; 20°
63. From Figure 18-2, the fish is down 32° from normal, or 13° below image of the fish.
65. 39°–40°
67. 48°
71. The image is virtual, located at the other focal point, and the magnification is 2.
73. 20 cm on the near side of the lens
75. Farther than $2f$ from the lens
77. The diverging lens will spread the principal rays slightly, such that their convergence will be shifted to the right.
79. The image is virtual, erect, and reduced in size.
81. 2.5 diopters
83. 0.143 m
85. −0.5 m; diverging

Chapter 19

Questions

1. The particles must be moving very fast to not have noticeable deflections due to gravity.
3. Friction would change the component of the momentum parallel to the surface, and an inelastic collision would change the normal component. Either change would affect the angle of reflection.
5. Less than
7. The light particles experience forces directed into the material with the higher index of refraction.
9. Frequency
11. Red light
13. Amplitude
15. The wave equation $(v = \lambda f)$ predicts that if the wavelength decreases while the frequency remains constant, the speed decreases.
17. From a slow medium to a fast medium
19. Red light has a longer wavelength.
21. All colors emerge at the same angle.
23. Blue light
25. Decrease
27. Yellow light
29. Phase
31. Diffraction effects are more pronounced for sound because the wavelength is much longer.
33. Decrease
35. 300 nm
37. Molecules are smaller than the wavelength of visible light.
39. No
41. Thinner
43. Thicker
45. Yes
47. Rotate the lens of one pair 90° relative to the lens of another. If both lenses are polarized, no light will pass through.
49. Tilt your head by 90°.
51. Objects at different depths in the hologram move relative to one another when the hologram is viewed from different angles.
53. Monochromatic light with a constant phase relationship
55. A powerful laser can expose the film before the person can move less than the wavelength of the light.

Exercises

57. 1.88×10^8 m/s
59. 2.42
61. 1.5
63. 1.85
65. 211 m
67. 4.74×10^{14} Hz
69. 396 nm
71. 244 nm
73. 0.006 84°
75. 1.38×10^{-2} arcseconds
77. 100 nm
79. 221 nm

Chapter 20

Questions

1. Insulator
3. Metal rod
5. The moisture allows some of the charge to leave the balloon.
7. To prevent the buildup of charge that may cause sparks
9. Either the fur and plastic produced opposite charges on the rods or one rod is not charged.
11. Neutral objects have equal positive and negative charges.
13. The north pole of a magnet is attracted to positive objects and negative objects but not to neutral objects. It must also be electrically neutral.
15. Repel
17. Zero
19. The balloon induces a charge in the wall.
21. The induced charges on the near sides are always opposite the charged object, producing attraction.
23. Bring the charged rod next to the electroscope. If the leaves get closer together, the rod is negative. If the leaves get farther apart, the rod is positive.
25. Bring the rod near the electroscope and touch the electroscope with your hand.
27. The negative charges flow through the hand to the ground, neutralizing the electroscope.
29. Sphere A is negative, and sphere B is neutral.
31. Touching a charged sphere to a neutral one yields two spheres with one-half charge on each one, using two neutral spheres yields charges of one-third, and so on.

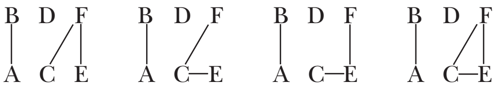
33. Diagram d indicates equal and opposite forces required by Newton's third law.
35. The force increases by a factor of 9.
37. The force increases by a factor of 9.
39. 3
41. The gravitational force is always attractive, the elementary electric charge is not proportional to inertial mass, electric charge comes in one size, and gravity is much weaker.
43. You have very little net electric charge, and the gravitational force is too weak.
45. Because they have different masses
47. 60 N directed to the left
49. The same force at any point between the plates
51. Equal in size, opposite in direction, and force on proton is upward.
53. b > a > c = d, and tangent to the field lines.
55. Greater
57. The speed at point B is less than v_o.
59. Work required to bring 1 coulomb from reference zero to point in question
61. Moves toward lower electric potential energy and lower electric potential

Exercises

63. -1.6×10^{-19} C
65. 1.47×10^{-17} C
67. 4.05×10^{10} N
69. 2.13×10^{-6} N (attractive)
71. 1.23×10^{36}
73. 400 N/C north; 8 N south
75. 4×10^{10} N/C toward the charge
77. 2.16×10^{11} N/C outward
79. 3.6×10^{10} N/C toward the 2-C charge
81. 4.8×10^{-16} N; 2.87×10^{11} m/s^2
83. 20 J
85. 24 mJ
87. 39,000 V

Chapter 21

Questions

1. Lifetime
3. 18 V
5. Differences are voltage, maximum current available, and maximum charge available; both supply direct current.
7. c; a
9. b; d
11. Turn the battery end for end.
13. No difference
15. 

17. A volt is a measure of potential difference, and an ampere is a measure of current.
19. Water, volume per unit time, and pressure
21. All of them
23. Doubles
25. The small resistance yields large currents.
27. Wire 20 bulbs in series.
29. Equal to
31. Increase; decrease
33. Increased; decreased
35. Greater
37. Less than
39. Batteries in series with the bulbs in parallel
41. A is the brightest; B and C are equally dim.
43. Stay the same
45. They will all be shorted.
47. They are equally bright.
49. They all go out.
51. A is shorted out; the others get brighter.
55. Parallel
57. The power is cut in half.
59. The same
61. 120-W bulb

Exercises

63. 240 Ω
65. 12 A
67. 4 V
69. 1 A
71. 6 Ω; 2 A
73. 6 A; 2 Ω
75. 11.7 A
77. 0.2 A
79. 3 A; 36 W
81. 4800 W
83. 240 Ω
85. 0.16 kWh
87. 36¢

Chapter 22

Questions

1. Both ends of the unmagnetized rod will attract both ends of the other two rods.
3. The second experiment
5. No
7. 4
9. The north pole of a compass needle points in the direction of the field.
11. Clockwise
13. Opposite
15. Down at A; up at B
17. Into the page
19. The magnetic field from one wire cancels that from the other wire.
21. Out of the page
23. He could strike the needle while holding it in Earth's magnetic field.
25. Decrease
27. 4 N/m in the opposite direction, by Newton's third law
29. If two parallel wires each carry a current of 1 ampere, the force per unit length on each wire will be 2×10^{-7} newtons per meter.
31. Magnetic north pole
33. 150 east of north
35. The cosmic rays spiral along the magnetic field lines toward the South Pole.
37. No
39. They are bent in opposite directions. The electron will have the larger acceleration because of its smaller mass.
41. Up; counterclockwise
43. Toward; push against it
45. Equal to
47. Inserting the south end into the coil or removing the north end
49. Larger
51. To reverse the direction of the current in the loop, ensuring that the torque is in the same direction
53. The electric and magnetic fields are perpendicular to the direction of travel and to each other. They oscillate in phase and travel at the speed of light.

55. Sound
57. They have different frequencies and wavelengths.
59. By modulating the amplitude of the carrier wave
61. 102.1 MHz

Exercises

63. 4.5×10^5 G
65. 4.3×10^{-4} T
67. 1.2×10^{-12} N; 1.32×10^{18} m/s^2
69. 8×10^{-4} N; 0.267 m/s^2
71. 37.5 μC
73. 1.5×10^6 m/s
75. 0.12 T
77. 20 turns
79. 0.025 A; 20
81. 20 A
83. 1.28 s
85. 12.2 cm; about one-fifth the size of the oven
87. 1×10^{15} Hz
89. 200–545 m
91. 275 m

Chapter 23

Questions

1. The structure of the atom was not understood in Mendeleev's time.
3. Carbon
5. Each gas has its own unique collection of spectral lines.
7. Absorption
9. Element A and element B
11. There are many fewer lines in the absorption spectrum.
13. The wavelength of lines can be determined by position alone.
15. B
17. Their deflections by electric and magnetic fields; no
19. Excess
21. Because the ratio of the electron's charge to mass was already known, allowing the mass to be determined
23. They were electrically charged and had a mass less than that of the hydrogen atom.
25. Accelerating charges radiate away energy.
27. The intensity curves are the same for all materials.
29. Decreasing
31. Object B
33. A star's temperature determines the color it appears to be.
35. That the atomic oscillators have quantized energies that are whole-number multiples of a lowest energy, $E = hf$
37. The number emitted from the surface per unit of time
39. Different electrons require different amounts of energy to reach the surface.
41. Each photon in red light has an energy below the minimum.
43. (1) Only angular momenta equal to whole-number multiples of a smallest angular momentum are allowed. (2) Electrons do not radiate when they are in allowed orbits. (3) A single photon is emitted or absorbed when an electron changes orbits.
45. They are equal.
47. The spectrum is produced by a large number of hydrogen atoms.
49. The inner electrons shield part of the positive nucleus, resulting in one electron orbiting a hydrogen-like nucleus.
51. The first two shells are filled with two and eight electrons, and the outer shell has the remaining seven electrons.
53. It easily gives up its single outer electron and forms a bond with other atoms.
55. X-ray
57. The X-ray photon has higher energy, shorter wavelength, and higher frequency.

Exercises

59. 1.76×10^{11} C/kg
61. 2.7×10^3 kg/m^3; 2.7 times as much
63. 5×10^{-6} m
65. 3.32×10^{-19} J
67. 5.43×10^{14} Hz
69. 9.95×10^{-3} m
71. $h/2 = 1.06 \times 10^{-34}$ J·s
73. 8.48×10^{-10} m
75. 7.24×10^{14} Hz
77. 2.46×10^{15} Hz; above
79. 1:64
81. 8.29 keV

Chapter 24

Questions

1. *Successes:* Accounting for the stability of atoms, the numerical values for wavelengths of spectral lines in hydrogen and hydrogen-like atoms, and the general features of the periodic table. *Failures:* Could not account for why accelerating electrons didn't radiate; the spectral lines in nonhydrogen-like atoms; the splitting of spectral lines into two or more lines; the relative intensities of the spectral lines; details of the periodic table, including the capacity of each shell; and relativity.
3. 20 Hz
5. No, the electrons would still be accelerating.
7. Photoelectric effect
9. This implies that photons are massless.
11. Energy
13. Electrons and photons are neither particles nor waves; they simply exhibit behavior that we interpret as wavelike and particle-like.
15. No
17. The wavelengths associated with the electrons must form standing wave around the nucleus.
19. The wavelength is too small.
21. Both electrons and photons behave as waves when producing the pattern and as particles when detected.
23. Electrons are deflected by electric and magnetic fields, electrons have mass and charge, photons travel at the speed of light.
25. An interference pattern
27. Intensities
29. The probability of finding the "particle" at a particular location
31. In the middle of the box
33. You cannot meaningfully say that the electron was ever at one particular location in the box, and therefore it does not have to move.
35. Along the y axis, not too near the origin and not too far away
37. 6
39. $n = 1$, $\ell = 0$, $m_\ell = 0$, and $m_s = +\frac{1}{2}$; $n = 1$, $\ell = 0$, $m_\ell = 0$, and $m_s = -\frac{1}{2}$; $n = 2$, $\ell = 0$, $m_\ell = 0$, and $m_s = +\frac{1}{2}$; $n = 2$, $\ell = 0$, $m_\ell = 0$, and $m_s = -\frac{1}{2}$
41. The Heisenberg uncertainty principle places precise limits on our simultaneous knowledge of specific variables that are important for systems on the atomic scale. It should not be generalized to apply outside this domain.
43. Momentum and energy do not form a Heisenberg pair.
45. There must be uncertainty in the momentum and therefore in the wavelength. A range of wavelengths is used to describe a localized electron.
47. The electrons have precisely defined positions and velocities.
49. Einstein was troubled by the idea that the probability associated with quantum mechanics was all that can be known.
51. Energy

53. Nothing
55. The electrons return to their lower energy levels through a series of jumps, emitting visible light.
57. The electrons must remain in the excited energy levels for a relatively long time.
59. A photon induces an electron in an excited state to return to a lower state, producing a second, identical photon.

Exercises

61. 2.21×10^{-38} m
63. 2.88×10^{-11} m
65. 6.22×10^{-7} m
67. 7.28×10^{6} m/s
69. 1.66×10^{-25} kg·m/s
71. 1.77×10^{-33} kg·m/s
73. 1.33×10^{-23} kg·m/s
75. 3.32×10^{-36} m
77. 0.132 nm
79. 1.46×10^{7} m/s; 607 eV
81. 2.07×10^{-7} eV
83. 2.07×10^{-11} s

Chapter 25

Questions

1. Becquerel's radiation was found to occur naturally.
3. The wavelengths of visible light are much bigger than the size of nuclei.
5. Alpha and beta radiation
7. Alpha particles
9. Protons
11. A neutron or a proton
13. (a) Yttrium (b) Cerium (c) Bromine
15. (a) 12 neutrons, 12 protons, and 12 electrons (b) 32 neutrons, 27 protons, and 27 electrons (c) 126 neutrons, 82 protons, and 82 electrons
17. 90
19. ${}^{20}_{10}\mathrm{Ne}$
21. Decreases by 1
23. (a) ${}^{220}_{90}\mathrm{Th}$ (b) ${}^{193}_{81}\mathrm{Tl}$
25. (a) ${}^{18}_{8}\mathrm{O}$ (b) ${}^{90}_{39}\mathrm{Y}$
27. (a) ${}^{181}_{76}\mathrm{Os}$(b) ${}^{237}_{93}\mathrm{Np}$
29. (a) ${}^{28}_{14}\mathrm{Si}$ (b) ${}^{64}_{30}\mathrm{Zn}$
31. A neutron must leave the nucleus.
33. ${}^{64}_{28}\mathrm{Ni}$ or ${}^{64}_{30}\mathrm{Zn}$
35. (a) Beta plus (b) Alpha
37. 206Pb
39. ${}^{17}_{9}\mathrm{F}$
41. There would be a decrease of one proton and one neutron.
43. 4 kg
45. It could happen at any time because the process is random.
47. By determining the fraction of the radioactive ^{14}C that has decayed to ^{12}C
49. No
51. Gamma ray, electron, and alpha particle
53. Most natural radiation exposure comes from photons and electrons, for which there is little difference between rads and rems.
55. Nuclear power
57. It takes a long time for the effects to show up, and there are other causes.
59. Skin provides protection because alpha particles cannot penetrate very far

Exercises

61. 6 km
63. 1.99×10^{-26} kg
65. 192.2 amu; Ir
67. 1.007825 amu
69. 2 μCi
71. 64 trillion
73. 11,400 years
75. $\frac{1}{8}$
77. 50

Chapter 26

Questions

1. 5,000,000 V
3. They all acquire the same kinetic energy.
5. Alpha particle, because of its larger charge
7. The energy losses due to the radiation of the accelerating charges are less for massive particles.
9. Strong, electromagnetic, weak, gravitational
11. There must be a strong force to counteract the electric repulsive force and hold the nucleons together.
13. Both are fundamental forces that can be attractive or repulsive. The strong force is stronger, has a finite range, and changes from attractive to repulsive at short distances. The electromagnetic force has an infinite range and remains either attractive or repulsive.
15. A 2.2-MeV gamma ray
17. 96 protons and 138 neutrons
19. Carbon nucleus
21. Nitrogen-17
23. The process will continue until the nucleons are most tightly bound, which occurs in the region of the peak of the average-binding-energy curve at iron.
25. They are about equal because the energy spacing between proton states and neutron states is about the same.
27. It is energetically more favorable to add neutrons than it is to add protons.
29. It would decay via beta plus or electron capture, converting a proton into a neutron.
31. Beta minus decay
33. The splitting of a heavy nucleus into two or more lighter ones
35. Two
37. Because it releases more than one neutron on the average.
39. To initiate additional fission reactions
41. Nuclear bomb
43. To absorb enough neutrons to ensure that an average of one neutron from each fission process initiates another
45. Plutonium-239
47. New fuel is bred by converting an isotope that does not readily fission into one that does.
49. The combining of two or more light nuclei to form a heavier one.
51. The temperature is high, but the density is low, so there is little heat energy.
53. Fuel is much more available, and there is less risk.
55. Agrees with solar models and with the age of Earth, as determined by radioactive dating
57. Fusion is the combining of lighter elements to form heavier ones, whereas fission is the splitting of heavier elements to form lighter ones.

Exercises

59. 7.31×10^{-21} kg · m/s; 9.07×10^{-14} m
61. Use $E = \frac{1}{2}mv^2$ and solve for $v = 8.75 \times 10^{9}$ m/s $> c$.
63. Use $E = mc^2$ and convert units.
65. 105 MeV
67. 7.012 161 amu
69. 18.6 keV

71. 5.24 MeV
73. Approximately 200 MeV
75. Subtract the product and reactant masses and convert to million electron volts (MeV).
77. 121
79. 3.87×10^{26} W

Chapter 27

Questions

1. Electron, proton, neutron, and photon
3. Positron; same magnitude but opposite sign
5. No
7. It will mutually annihilate with its corresponding particle.
9. Because they are electrically neutral, they do not leave tracks.
11. The total linear momentum is zero. If a single photon were emitted, it would carry away momentum E/c, yielding nonzero total momentum.
13. Conservation of charge and nucleon number (or baryon number)
15. Weak
17. The uncertainty principle provides the mechanism to create exchange particles without violating conservation of energy.
19. The intermediate vector bosons are quite massive, and their discovery awaited more energetic particle accelerators.
21. Exchange photons with very little energy can exist for very long times and can therefore travel infinite distances.
23. Its infinite range
25. Mesons have spins that are whole numbers, whereas baryons have spins of $\frac{1}{2}, \frac{3}{2}, \ldots$
27. Hadrons are not elementary; they are composed of quarks. Hadrons also participate in the strong interaction.
29. Yes, as evidenced by its beta decay.
31. 10^{-10} s
33. It doesn't have enough rest-mass energy.
35. e^+
37. (a) Muon and electron lepton numbers (b) Spin and baryon number (c) Strangeness
39. (a) 1 (b) –1 (c) 0
41. Two photons
43. $\overline{\text{uud}}$ for the antiproton and $\overline{\text{udd}}$ for the antineutron
45. $\overline{\text{u}}$s; –1
47. uuu
49. dss
51. ds; no
53. No
55. It would be a neutral meson.
57. By assigning the color quantum number to the quarks

Chapter 28

Questions

1. Supernovae, orbiting neutron stars, and orbiting black holes
3. The energy radiated in the form of gravitational waves is very small.
5. Taylor and Hulse found a pair of neutron stars orbiting each other and measured the orbital period to be decreasing, as predicted by theory.
7. Not if we observe a large number of protons
9. Gravitational force
11. Tiny loops
13. 15 billion years
15. Gravitational
17. To escape cosmic radiation, which would swamp the tiny neutrino signals
19. Measurements of ripples in the cosmic-ray background
21. Any physical system, no matter how complex, may be understood in terms of its component parts.

Glossary

aberration A defect in a mirror or lens causing light rays from a single point to fail to focus at a single point in space.

absolute zero The lowest possible temperature: 0 K, −273°C, or −459°F.

absorption spectrum The collection of wavelengths missing from a continuous distribution of wavelengths because of the absorption of certain wavelengths by the atoms or molecules in a gas.

activity The rate at which a collection of radioactive nuclei decay. One curie corresponds to 3.7×10^{10} decays per second; also called radioactivity.

alloy A metal produced by mixing other metals.

alpha (α) radiation The type of radioactive decay in which nuclei emit alpha particles (helium nuclei).

alpha particle The nucleus of helium consisting of two protons and two neutrons.

ampere The SI unit of electric current; 1 coulomb per second. The current in each of two parallel wires when the magnetic force per unit length between them is 2×10^{-7} newton per meter.

amplitude The maximum distance from the equilibrium position that occurs in periodic motion.

angular momentum A vector quantity giving the rotational momentum. For an object orbiting a point, the magnitude of the angular momentum is the product of the linear momentum and the radius of the path, $L = mvr$. For a spinning object, it is the product of the rotational inertia and the rotational velocity, $L = I\omega$.

antinode One of the positions in a standing-wave or interference pattern where there is maximum movement; that is, the amplitude is a maximum.

antiparticle A subatomic particle with the same-size properties as those of the particle, although some may have the opposite sign. The positron is the antiparticle of the electron.

apparent weight The support force needed to maintain an object at rest relative to a reference system. For inertial systems, the apparent weight is equal in magnitude to the true weight, the gravitational force acting on the object.

Archimedes' principle The buoyant force is equal to the weight of the displaced fluid.

astigmatism An aberration, or defect, in a mirror or lens that causes the image of a point to spread out into a line.

atom The smallest unit of an element that has the chemical and physical properties of that element. An atom consists of a nucleus surrounded by an electron cloud.

atomic mass The mass of an atom in atomic mass units. Sometimes this refers to the atomic mass number—the number of neutrons and protons in the nucleus.

atomic mass unit One-twelfth the mass of a neutral carbon atom containing six protons and six neutrons.

atomic number The number of protons in the nucleus or the number of electrons in the neutral atom of an element. This number also gives the order of the elements in the periodic table.

average acceleration The change in velocity divided by the time it takes to make the change, $\overline{a} = \Delta v/\Delta t$; measured in units such as (meters per second) per second. An acceleration can result from a change in speed, a change in direction, or both.

average speed The distance traveled divided by the time taken, $\overline{s} = d/t$; measured in units such as meters per second or miles per hour.

average velocity The change in position—displacement—divided by the time taken, $\overline{v} = \Delta x/\Delta t$.

Avogadro's number The number of molecules in 1 mole of any substance. Equal to 6.02×10^{23} molecules.

baryon A type of hadron having a spin of $\frac{1}{2}, \frac{3}{2}, \frac{5}{2}, \ldots$ times the smallest unit. The most common baryons are the proton and neutron.

beats A variation in the amplitude resulting from the superposition of two waves that have nearly the same frequencies. The frequency of the variation is equal to the difference in the two frequencies.

Bernoulli's principle The pressure in a fluid decreases as its velocity increases.

beta (β) radiation The type of radioactive decay in which nuclei emit electrons or positrons (antielectrons).

beta particle An electron emitted by a radioactive nucleus.

binding energy The amount of energy required to take a nucleus apart. The analogous amount of energy for other bound systems.

black hole A massive star that has collapsed to such a small size that its gravitational force becomes so strong that not even light can escape from its "surface."

bottom The flavor of the fifth quark.

British thermal unit The amount of heat required to raise the temperature of 1 pound of water by 1°F.

buoyant force The upward force exerted by a fluid on a submerged or floating object. *See* Archimedes' principle.

calorie The amount of heat required to raise the temperature of 1 gram of water by 1°C.

camera obscura A room with a small hole in one wall, used by artists to produce images.

cathode ray An electron emitted from the negative electrode in an evacuated tube.

center of mass The balance point of an object. The location in an object that has the same translational motion as the object if it were shrunk to a point.

centi- A prefix meaning "one-hundredth.." A centimeter is $\frac{1}{1000}$ meter.

centrifugal An adjective meaning "center-seeking."

centrifugal force A fictitious force arising in a rotating reference system. It points away from the center, in the direction opposite to the centripetal acceleration.

centripetal An adjective meaning "center-fleeing."

centripetal acceleration The acceleration of an object directed toward the center of its circular path. For uniform circular motion, it has a magnitude v^2/r.

centripetal force The force on an object directed toward the center of its circular path. For uniform circular motion, it has a magnitude mv^2/r.

chain reaction A process in which the fissioning of one nucleus initiates the fissioning of others.

change of state The change in a substance between solid and liquid or between liquid and gas.

charge A property of an elementary particle that determines the strength of its electric force with other particles possessing charge. Measured in coulombs, or in integral multiples of the charge on the proton.

charged Possessing a net negative or positive charge.

charm The flavor of the fourth quark.

chromatic aberration A property of lenses that causes different colors (wavelengths) of light to have different focal lengths.

coherent A property of two or more sources of waves that have the same wavelength and maintain constant phase differences.

complementarity principle A complete description of an atomic entity, such as an electron or a photon, requires both a particle description and a wave description, but not at the same time.

complementary color For lights, two colors that combine to form white.

complete circuit A continuous conducting path from one end of a battery (or other source of electric potential) to the other end of the battery.
compound A combination of chemical elements that forms a new substance with its own properties.
conduction, thermal The transfer of thermal energy by collisions of the atoms or molecules within a substance.
conductor A material that allows the passage of electric charge or the easy transfer of thermal energy. Metals are good conductors.
conservation of angular momentum If the net external torque on a system is zero, the total angular momentum of the system does not change.
conservation of charge In an isolated system, the total charge is conserved.
conservation of energy The total energy of an isolated system does not change.
conservation of linear momentum The total linear momentum of a system does not change if there is no net external force.
conservation of mass The total mass in a closed system does not change even when physical and chemical changes occur.
conserved This term is used in physics to mean that a number associated with a physical property does not change; it is invariant.
convection The transfer of thermal energy in fluids by means of currents such as the rising of hot air and the sinking of cold air.
Coriolis force A fictitious force that occurs in rotating reference frames. It is responsible for the direction of the winds in hurricanes.
coulomb The SI unit of electric charge. The amount of charge passing a given point in a conductor carrying a current of 1 ampere. The charge of 6.25×10^{18} protons.
crest The peak of a wave disturbance.
critical Describes a chain reaction in which an average of one neutron from each fission reaction initiates another reaction.
critical angle The minimum angle of incidence for which total internal reflection occurs.
critical mass The minimum mass of a substance that will allow a chain reaction to continue without dying out.
crystal A material in which the atoms are arranged in a definite geometric pattern.
curie A unit of radioactivity; 3.7×10^{10} decays per second.
current A flow of electric charge; measured in amperes.
cycle One complete repetition of a periodic motion. It may start anywhere in the motion.
daughter nucleus The nucleus resulting from the radioactive decay of a parent nucleus.
definite proportions, law of When two or more elements combine to form a compound, the ratios of the masses of the combining elements have fixed values.
density A property of material equal to the mass of the material divided by its volume; measured in kilograms per cubic meter or grams per cubic centimeter.
diaphragm An opening that is used to limit the amount of light passing through a lens.
diffraction The spreading of waves passing through an opening or around a barrier.
diffuse reflection The reflection of rays from a rough surface. The reflected rays do not leave at fixed angles.
diopter A measure of the focal length of a mirror or lens, equal to the inverse of the focal length measured in meters.
disordered system A system with an arrangement equivalent to many other possible arrangements.
dispersion The spreading of light into a spectrum of color; the variation in the speed of a periodic wave due to its wavelength or frequency.
displacement A vector quantity giving the straight-line distance and direction from an initial position to a final position. In wave (or oscillatory) motion, the distance of the disturbance (or object) from its equilibrium position.
Doppler effect A change in the frequency of a periodic wave due to the motion of the observer, the source, or both.
efficiency The ratio of the work produced to the energy input. For an ideal heat engine, the Carnot efficiency is given by $1 - T_c/T_h$.
elastic A collision or interaction in which kinetic energy is conserved.
electric field The space surrounding a charged object where each location is assigned a vector equal to the force experienced by one unit of positive charge placed at that location; measured in newtons per coulomb.
electric field lines A representation of the electric field in a region of space. The electric field is tangent to the field line at any point, and its magnitude is proportional to the local density of field lines.
electric potential The electric potential energy divided by the object's charge; the work done in bringing a positive test charge of 1 coulomb from the zero reference location to a particular point in space; measured in joules per coulomb.
electric potential energy The work done in bringing a charged object from some zero reference location to a particular point in space.
electromagnet A magnet constructed by wrapping wire around an iron core. The electromagnet can be turned on and off by turning the current in the wire on and off.
electromagnetic wave A wave consisting of oscillating electric and magnetic fields. In a vacuum, electromagnetic waves travel at the speed of light.
electron A basic constituent of atoms; a lepton.
electron capture A decay process in which an inner atomic electron is captured by the nucleus. The daughter nucleus has the same number of nucleons as the parent but one less proton.
electron volt A unit of energy equal to the kinetic energy acquired by an electron or proton falling through an electric potential difference of 1 volt; equal to 1.6×10^{-19} joule.
element Any chemical species that cannot be broken up into other chemical species.
emission spectrum The collection of discrete wavelengths emitted by atoms that have been excited by heating or by electric currents.
entropy A measure of the order of a system. The second law of thermodynamics states that the entropy of an isolated system tends to increase.
equilibrium position A position where the net restoring force is zero.
equivalence principle Constant acceleration is completely equivalent to a uniform gravitational field.
ether The hypothesized medium through which light was believed to travel.
exclusion principle No two electrons can have the same set of quantum numbers. This statement also applies to protons, neutrons, and other baryons.
field A region of space where each location is assigned a value or a vector. *See* electric field, gravitational field, and magnetic field.
fission The splitting of a heavy nucleus into two or more lighter nuclei.
flavor The types of quarks: down, up, strange, charm, bottom, or top.
fluorescence The property of a material whereby it emits visible light when it is illuminated by ultraviolet light.
focal length The distance from a mirror or the center of a lens to its focal point.
focal point The location at which a mirror or a lens focuses rays parallel to the optic axis or from which such rays appear to diverge.

force A push or a pull, measured by the acceleration it produces on a standard, isolated object, $\mathbf{F}_{net} = m\mathbf{a}$; measured in newtons.
frequency The number of times a periodic motion repeats in a unit of time. It is equal to the inverse of the period, $f = 1/T$; measured in hertz.
fundamental frequency The lowest resonant frequency for an oscillating system.
fusion The combining of light nuclei to form a heavier nucleus.
gamma (γ) radiation The type of radioactive decay in which nuclei emit high-energy photons; the range of frequencies of the electromagnetic spectrum that lies beyond the X rays.
gas Matter with no definite shape or volume.
gauss A unit of magnetic field strength; 10^{-4} tesla.
geocentric model A model of the universe with Earth at its center.
gluon An exchange particle responsible for the force between quarks. The eight gluons differ only in their color quantum numbers.
gravitation, law of Universal $F = Gm_1m_2/r^2$, where F is the force between any two objects, G is a universal constant, m_1 and m_2 are the masses of the two objects, and r is the distance between their centers.
gravitational field The space surrounding an object where each location is assigned a vector equal to the gravitational force experienced by a 1-kilogram mass placed at that location.
gravitational mass The property of a particle that determines the strength of its gravitational interaction with other particles.
gravitational potential energy The work done by the force of gravity when an object falls from a particular point in space to the location assigned the value of zero, $GPE = mgh$.
graviton The exchange particle responsible for the gravitational force.
gravity wave A wave disturbance caused by the acceleration of masses.
ground state The lowest energy state of a system allowed by quantum mechanics.
grounding Establishing an electric connection to Earth in order to neutralize an object.
hadrons The family of particles that participate in the strong interaction. Baryons and mesons are the two subfamilies.
half-life The time during which one-half of a sample of a radioactive substance decays.
halo A ring of light that appears around the Sun or Moon. It is produced by refraction in ice crystals.
harmonic A frequency that is a whole-number multiple of the fundamental frequency.
heat Energy flowing because of a difference in temperature.
heat capacity The amount of heat required to raise the temperature of an object by 1°C.
heat engine A device for converting heat into mechanical work.
heat pump A reversible heat engine that acts as a furnace in winter and an air conditioner in summer.
heliocentric model A model of the universe with the Sun at its center.
hologram A three-dimensional record of visual information.
holography The photographic process for producing three-dimensional images.
hyperopia Farsightedness. Images of distant objects are formed beyond the retina.
ideal gas An enormous number of tiny particles separated by relatively large distances. The particles have no internal structure, are indestructible, and do not interact with each other except when they collide; all collisions are elastic.
ideal gas law $PV = nRT$, where P is the pressure, V is the volume, T is the absolute temperature, n is the number of moles, and R is the gas constant.
impulse The product of the force and the time during which it acts, $\mathbf{F}\Delta t$. This vector quantity is equal to the change in momentum.
in phase Describes two or more waves with the same wavelength and frequency that have their crests lined up.
index of refraction An optical property of a substance that determines how much light bends on entering or leaving it. The index is equal to the ratio of the speed of light in a vacuum to that in the substance.
inelastic A collision or interaction in which kinetic energy is not conserved.
inertia An object's resistance to a change in its velocity. *See* inertial mass.
inertia, law of *See* motion, Newton's first law of.
inertial force A fictitious force that arises in accelerating (noninertial) reference systems. Examples are centrifugal and Coriolis forces.
inertial mass An object's resistance to a change in its velocity; measured in kilograms.
inertial reference system Any reference system in which the law of inertia (Newton's first law of motion) is valid.
instantaneous speed The limiting value of the average speed as the time interval becomes infinitesimally small. The magnitude of the instantaneous velocity.
insulator A material that does not allow the passage of electric charge or is a poor conductor of thermal energy. Ceramics are good electrical insulators; wood and stationary air are good thermal insulators.
interference The superposition of waves.
intermediate vector bosons The exchange particles of the weak nuclear interaction: the $W^{+,}$ $W^{-,}$ and Z^0 particles.
internal energy The total microscopic energy of an object, which includes its atomic and molecular translational and rotational kinetic energies, its vibrational energy, and the energy stored in the molecular bonds.
inversely proportional A relationship in which two quantities have a constant product. If one quantity increases by a certain factor, the other decreases by the same factor.
inverse-square Describes a relationship in which a quantity is related to the reciprocal of the square of a second quantity. Examples include the force laws for gravity and electricity; the force is proportional to the inverse-square of the distance.
ion An atom with missing or extra electrons.
ionization The removal of one or more electrons from an atom.
isotope An element containing a specific number of neutrons in its nuclei. Examples are and , carbon atoms with six and eight neutrons, respectively.
joule The SI unit of energy, equal to 1 newton acting through a distance of 1 meter.
kilo- A prefix meaning "one thousand." A kilometer is 1000 meters.
kilogram The SI unit of mass. A kilogram of material weighs about 2.2 pounds on Earth.
kilowatt-hour A unit of energy; 3,600,000 joules. One kilowatt-hour of energy is transformed to other forms when a machine runs at a power of 1000 watts for 1 hour.
kinetic energy The energy of motion, mv^2; measured in joules.
kinetic friction The frictional force between two surfaces in relative motion. This force does not depend much on the relative speed.
Kirchhoff's junction rule The sum of the currents entering any junction in a circuit must equal the sum of the currents leaving that junction.
Kirchhoff's loop rule Along any path from the positive terminal to the negative terminal of a battery, the voltage drops across the resistive elements encountered must add up to the battery voltage.
laser A device that uses stimulated emissions to produce a coherent beam of electromagnetic radiation. *Laser* is the acronym for *l*ight *a*mplification by *s*timulated *e*mission of *r*adiation.

latent heat The amount of heat required to melt (or vaporize) a unit mass of a substance. The same amount of heat is released when a unit mass of the same substance freezes (or condenses); measured in calories per gram or kilojoules per kilogram.
lepton A family of elementary particles that includes the electron, muon, tau, and their associated neutrinos.
light ray A line that represents the path of light in a given direction.
line of stability The locations of the stable nuclei on a graph of the number of neutrons versus the number of protons.
linear momentum A vector quantity equal to the product of an object's mass and its velocity, $p = mv$.
liquid Matter with a definite volume that takes the shape of its container.
liquid crystal A liquid that exhibits a rough geometrical ordering of its atoms.
longitudinal wave A wave in which the vibrations of the medium are parallel to the direction the wave is moving.
macroscopic Describes the bulk properties of a substance such as mass, size, pressure, and temperature.
magnetic field The space surrounding a magnetic object, where each location is assigned a value determined by the torque on a compass placed at that location. The direction of the field is in the direction of the north pole of the compass.
magnetic monopole A hypothetical, isolated magnetic pole.
magnetic pole One end of a magnet; analogous to an electric charge.
magnitude The size of a vector quantity. For example, speed is the magnitude of a velocity.
mass *See* center of mass, critical mass, gravitational mass, and inertial mass.
matter-wave amplitude The wave solution to Schrödinger's equation for atomic and subatomic particles. The square of the matter-wave amplitude gives the probability of finding the particle at a particular location.
mechanical energy The sum of the kinetic energy and various potential energies, which may include the gravitational and the elastic potential energies.
meson A type of hadron with whole-number units of spin. This family includes the pion, kaon, and eta.
meter The SI unit of length equal to 39.37 inches, or 1.094 yards.
microscopic Describes properties not visible to the naked eye such as atomic speeds or the masses and sizes of atoms.
milli- A prefix meaning "one-thousandth." A millimeter is $\frac{1}{1000}$ meter.
mirage An optical effect that produces an image that looks as if it has been reflected from the surface of a body of water.
moderator A material used to slow the neutrons in a nuclear reactor.
mole The amount of a substance that has a mass in grams numerically equal to the mass of its molecules in atomic mass units.
molecule A combination of two or more atoms.
momentum Usually refers to linear momentum. *See* angular momentum, conservation of angular momentum, conservation of linear momentum, and linear momentum.
motion, Newton's first law of The velocity of an object remains constant unless an unbalanced force acts on the object.
motion, Newton's second law of $\mathbf{F}_{net} = m\mathbf{a}$. The net force on an object is equal to its mass times its acceleration. The net force and the acceleration are vectors that always point in the same direction.
motion, Newton's third law of If an object exerts a force on a second object, the second object exerts an equal force on the first object.
muon A type of lepton; often called a heavy electron.
myopia Nearsightedness. Images of distant objects are formed in front of the retina.
neutrino A neutral lepton; one exists for each of the charged leptons (electron, muon, and tau).
neutron The neutral nucleon; a member of the baryon and hadron families of elementary particles.
newton The SI unit of force. A net force of 1 newton accelerates a mass of 1 kilogram at a rate of 1 (meter per second) per second.
node One of the positions in a standing-wave or interference pattern where there is no movement; that is, the amplitude is zero.
noninertial reference system Any reference system in which the law of inertia (Newton's first law of motion) is not valid. An accelerating reference system is noninertial.
normal A line perpendicular to a surface or curve.
nucleon Either a proton or a neutron.
nucleus The central part of an atom that contains the protons and neutrons.
ohm The SI unit of electrical resistance. A current of 1 ampere flows through a resistance of 1 ohm under 1 volt of potential difference.
Ohm's law The resistance of an object is equal to the voltage across it divided by the current through it, $R = V/I$.
optic axis A line passing through the center of a curved mirror and the center of the sphere from which the mirror is made; a line passing through a lens and both focal points.
order of magnitude The value of a quantity rounded off to the nearest power of 10.
ordered system A system with an arrangement belonging to a group with the smallest number (possibly one) of equivalent arrangements.
oscillation A vibration about an equilibrium position or shape.
pair production The conversion of energy into matter in which a particle and its antiparticle are produced. This usually refers to the production of an electron and a positron (antielectron).
parallel Two circuit elements are wired in parallel when the current can flow through one or the other but not both. Elements that are wired parallel to each other are directly connected to each other at both terminals.
parent nucleus A nucleus that decays into a daughter nucleus.
particle accelerator A device for accelerating charged particles to high velocities.
penumbra The transition region between the darkest shadow and full brightness. Only part of the light from the source reaches this region.
period The shortest length of time it takes a periodic motion to repeat. It is equal to the inverse of the frequency, $T = 1/f$.
periodic wave A wave in which all the pulses have the same size and shape. The wave pattern repeats itself over a distance of 1 wavelength and over a time of 1 period.
phosphorescence The property of a material whereby it continues to emit visible light after it has been illuminated by ultraviolet light.
photoelectric effect The ejection of electrons from metallic surfaces by illuminating light.
photon A particle of light. The energy of a photon is given by the relationship $E = hf$, where f is the frequency of the light and h is Planck's constant. It is the exchange particle for the electromagnetic interaction.
pion The least massive meson. The pion has three charge states: +1, 0, and −1.
plasma The fourth state of matter in which one or more electrons have been stripped from the atoms forming an ion gas.
polarized A property of a transverse wave when its vibrations are all in a single plane.
positron The antiparticle of the electron.
pound The unit of force in the U.S. customary system; the weight of 0.454 kilogram on Earth.
power The rate at which energy is converted from one form to another, $P = (E/\Delta t;$ measured in joules per second, or watts. In electric circuits the power is equal to the current times the voltage, $P = IV$.
powers-of-ten notation A method of writing numbers in which a number between 1 and 10 is multiplied or divided by 10 raised to a power.

pressure The force per unit area of surface; measured in newtons per square meter, or pascals.

projectile motion A type of motion that occurs near Earth's surface when the only force acting on the object is that of gravity.

proportional A relationship in which two quantities have a constant ratio. If one quantity increases by a certain factor, the other increases by the same factor.

proton The positively charged nucleon; a member of the baryon and hadron families of elementary particles.

quantum (pl., **quanta**) The smallest unit of a discrete property. For instance, the quantum of charge is the charge on the proton.

quantum mechanics The rules for the behavior of particles at the atomic and subatomic levels.

quantum number A number giving the value of a quantized quantity. For instance, a quantum number specifies the angular momentum of an electron in an atom.

quark A constituent of hadrons. Quarks come in six flavors of three colors each. Three quarks make up the baryons, whereas a quark and an antiquark make up the mesons.

rad The acronym for *r*adiation *a*bsorbed *d*ose. A rad of radiation deposits 0.01 joule per kilogram of material.

radiation The transport of energy via electromagnetic waves; particles emitted in radioactive decay.

real image An image formed by the convergence of light.

reference system A collection of objects not moving relative to each other that can be used to describe the motion of other objects. *See* inertial reference system and noninertial reference system.

reflecting telescope A type of telescope using a mirror as the objective.

reflection, law of The angle of reflection (measured relative to the normal to the surface) is equal to the angle of incidence. The incident ray, the reflected ray, and the normal all lie in the same plane.

refracting telescope A type of telescope using a lens as the objective.

refraction The bending of light that occurs at the interface between two transparent media. It occurs when the speed of light changes.

refrigerator A heat engine running backward.

relativity, Galilean principle of The laws of motion are the same in all inertial reference systems.

relativity, general theory of An extension of the special theory of relativity to include the concept of gravity.

relativity, special theory of A comprehensive theory of space and time that replaces Newtonian mechanics when velocities get very large.

rem The acronym for *r*oentgen *e*quivalent in *m*ammals, a measure of the biological effects caused by radiation.

resistance The impedance to the flow of electric current; measured in volts per ampere, or ohms. The resistance is equal to the voltage across the object divided by the current through it, $R = V/I$.

resonance A large increase in the amplitude of a vibration when a force is applied at a natural frequency of the medium or object.

rest-mass energy The energy associated with the mass of a particle; given by $E_o = mc^2$, where c is the speed of light.

retroreflectors Three flat mirrors at right angles to each other that reflect light back to its source.

rotational acceleration The change in rotational speed divided by the time it takes to make the change.

rotational inertia The property of an object that measures its resistance to a change in its rotational speed.

rotational kinetic energy Kinetic energy associated with the rotation of a body, Ω.

rotational speed The angle of rotation or revolution divided by the time taken, .

rotational velocity A vector quantity that includes the rotational speed and the direction of the axis of rotation.

series An arrangement of resistances (or batteries) on a single pathway so that the current flows through each element.

shell A collection of electrons in an atom that have approximately the same energy.

shock wave The characteristic cone-shaped wave front that is produced whenever an object travels faster than the speed of the waves in the surrounding medium.

short circuit A path in an electric circuit that has very little resistance.

solid Matter with a definite size and shape.

sonar Sound waves in water.

spacetime A combination of time and three-dimensional space that forms a four-dimensional geometry expressing the connections between space and time.

special relativity, first postulate of The laws of physics are the same for all inertial reference systems.

special relativity, second postulate of The speed of light in a vacuum is a constant regardless of the speed of the source or the speed of the observer.

specific heat The amount of heat required to raise the temperature of a unit mass of a substance by 1 degree; measured in calories per gram-degree Celsius or joules per kilogram-kelvin.

spherical aberration A property of lenses and mirrors caused by grinding the surface to a spherical rather than a parabolic shape.

spring constant The amount of force required to stretch a spring by 1 unit of length; measured in newtons per meter.

stable equilibrium An equilibrium position or orientation to which an object returns after being slightly displaced.

standing wave The interference pattern produced by two waves of equal amplitude and frequency traveling in opposite directions. The pattern is characterized by alternating nodal and antinodal regions.

static friction The frictional force between two surfaces at rest relative to each other. This force is equal and opposite to the net applied force if the force is not large enough to make the object accelerate.

stimulated emission The emission of a photon from an atom because of the presence of an incident photon. The emitted photon has the same energy, direction, and phase as the incident photon.

strange particle A particle with a nonzero value of strangeness. In the quark model, it is made up of one or more quarks carrying the quantum property of strangeness.

strangeness The flavor of the third quark.

strong force The force responsible for holding the nucleons together to form nuclei.

subcritical Describes a chain reaction that dies out because an average of less than one neutron from each fission reaction causes another fission reaction.

supercritical Describes a chain reaction that grows rapidly because an average of more than one neutron from each fission reaction causes another fission reaction. An extreme example of this is the explosion of a nuclear bomb.

superposition The combining of two or more waves at a location in space.

Système International d'Unités The French name for the metric system, or International System (SI), of units.

temperature, absolute The temperature scale with its zero point at absolute zero and degrees equal to those on the Celsius scale. Also called the Kelvin temperature scale.

temperature, Celsius The temperature scale with the values of 0°C and 100°C for the temperatures of freezing and boiling water, respectively. Its degree is that of the Fahrenheit degree.

temperature, Fahrenheit The temperature scale with values of 32°F and 212°F for the temperatures of freezing and boiling water, respectively.

temperature, Kelvin The temperature scale with its zero point at absolute zero and a degree equal to that on the Celsius scale. Also called the absolute temperature scale.
terminal speed The speed obtained in free fall when the upward force of air resistance is equal to the downward force of gravity.
tesla The SI unit of magnetic field.
thermal energy Internal energy.
thermal equilibrium A condition in which there is no net flow of thermal energy between two objects. This occurs when the two objects obtain the same temperature.
thermal expansion The increase in size of a material when heated.
thermodynamics The area of physics that deals with the connections between heat and other forms of energy.
thermodynamics, first law of The increase in internal energy of a system is equal to the heat added plus the work done on the system.
thermodynamics, second law of There are three equivalent forms: (1) It is impossible to build a heat engine to perform mechanical work that does not exhaust heat to the surroundings. (2) It is impossible to build a refrigerator that can transfer heat from a lower temperature region to a higher temperature region without expending mechanical work. (3) The entropy of an isolated system tends to increase.
thermodynamics, third law of Absolute zero may be approached experimentally but can never be reached.
thermodynamics, zeroth law of If objects A and B are each in thermodynamic equilibrium with object C, then A and B are in thermodynamic equilibrium with each other. All three objects are at the same temperature.
top The flavor of the sixth quark.
torque The rotational analog of force. It is equal to the radius multiplied by the force perpendicular to the radius, $\tau = rF$. A net torque produces a change in an object's angular momentum.
total internal reflection A phenomenon that occurs when the angle of incidence of light traveling from a material with a higher index of refraction into one with a lower index of refraction exceeds the critical angle.
translational motion Motion along a path.
transverse wave A wave in which the vibrations of the medium are perpendicular to the direction the wave is moving.
trough A valley of a wave disturbance.
umbra The darkest part of a shadow where no light from the source reaches.
uncertainty principle The product of the uncertainty in the position of a particle along a certain direction and the uncertainty in the momentum along this same direction must be greater than Planck's constant, or $\Delta p_y \Delta y > h$. A similar relationship applies to the uncertainties in energy and time.
unstable equilibrium An equilibrium position or orientation that an object leaves after being slightly displaced.
vector A quantity with a magnitude and a direction. Examples are displacement, velocity, acceleration, momentum, and force.
velocity A vector quantity that includes the speed and the direction of the object; the displacement divided by the time taken, $\vec{\mathbf{v}}$.
vibration An oscillation about an equilibrium position or shape.
virtual image The image formed when light only appears to come from the location of the image.
viscosity A measure of the internal friction within a fluid.
volt The SI unit of electric potential, 1 joule per coulomb. One volt produces a current of 1 ampere through a resistance of 1 ohm.
watt The SI unit of power, 1 joule per second.
wave The movement of energy from one place to another without any accompanying matter.
wavelength The shortest repetition length for a periodic wave. For example, it is the distance from crest to crest or from trough to trough.
weak force The force responsible for beta decay. This force occurs through the exchange of the W and Z^0 particles. All leptons and hadrons interact via this force.
weight The force of gravitational attraction of Earth for an object. $\mathbf{W} = m\mathbf{g}$.
work The product of the force along the direction of motion and the distance moved, $W = Fd$. Measured in energy units, joules.
X ray A high-energy photon, usually produced by cathode rays or emitted by electrons falling to lower energy states in atoms; the range of frequencies in the electronic spectrum lying between the ultraviolet and the gamma rays.

Index

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Physical Constants

Atomic mass unit	amu $= 1.66 \times 10^{-27}$ kg
Avogadro's number	$N_A = 6.02 \times 10^{23}$ particles/mol
Bohr radius	$r_1 = 5.29 \times 10^{-11}$ m
Electron volt	eV $= 1.60 \times 10^{-19}$ J
Elementary charge	$e = 1.60 \times 10^{-19}$ C
Coulomb's constant	$k = 8.99 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2$
Gravitational constant	$G = 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2$
Mass of electron	$m_e = 9.11 \times 10^{-31}$ kg
Mass of neutron	$m_n = 1.675 \times 10^{-27}$ kg
Mass of proton	$m_p = 1.673 \times 10^{-27}$ kg
Planck's constant	$h = 6.63 \times 10^{-34} \text{ J} \cdot \text{s}$
Speed of light	$c = 3.00 \times 10^8$ m/s

Physical Data

Acceleration due to gravity	$g = 9.80 \text{ m/s}^2$
Density of water	$D_w = 1.00 \times 10^3 \text{ kg/m}^3$
Earth–Moon distance	$\mathrm{R}_{EM} = 3.84 \times 10^8$ m
Earth–Sun distance	$R_{ES} = 1.50 \times 10^{11}$ m
Mass of Earth	$M_E = 5.98 \times 10^{24}$ kg
Mass of Moon	$M_M = 7.36 \times 10^{22}$ kg
Mass of Sun	$M_S = 1.99 \times 10^{30}$ kg
Radius of Earth	$R_E = 6.37 \times 10^6$ m
Radius of Moon	$R_M = 1.74 \times 10^6$ m
Radius of Sun	$R_S = 6.96 \times 10^8$ m
Speed of sound (20°C, 1 atm)	$v_s = 343$ m/s
Standard atmospheric pressure	$P_{atm} = 1.01 \times 10^5$ Pa

Standard Abbreviations

A	ampere
amu	atomic mass unit
atm	atmosphere
Btu	British thermal unit
C	coulomb
°C	degree Celsius
cal	calorie
eV	electron volt
°F	degree Fahrenheit
ft	foot
g	gram
h	hour
hp	horsepower
Hz	Hertz
in.	inch
J	joule
K	kelvin
kg	kilogram
lb	pound
m	meter
min	minute
mph	mile per hour
N	newton
Pa	pascal
psi	pound per square inch
rev	revolution
s	second
T	tesla
V	volt
W	watt
Ω	ohm

Conversion Factors

Time

1 y	=	3.16×10^7 s
1 day	=	86,400 s
1 h	=	3600 s

Length

1 in.	=	2.54 cm
1 m	=	39.37 in. = 3.281 ft
1 ft	=	0.3048 m
1 km	=	0.621 mile
1 mile	=	1.609 km

Volume

1 m^3	=	35.32 ft^3
1 ft^3	=	0.02832 m^3
1 liter	=	1000 cm^3 = 1.0576 quart
1 quart	=	0.9455 liter

Mass

1 ton (metric)	=	1000 kg
1 amu	=	1.66×10^{-27} kg
1 kg weighs 2.2 lb		
454 g weighs 1 lb		

Force

1 N	=	0.2248 lb
1 lb	=	4.448 N

Speed

1 mph	=	1.609 km/h = 0.447 m/s
1 km/h	=	0.6215 mph
1 m/s	=	3.281 ft/s = 2.237 mph

Acceleration

1 m/s^2	=	3.281 ft/s^2
1 ft/s^2	=	0.3048 m/s^2

Energy

1 J	=	0.738 ft · lb = 0.2389 cal
1 cal	=	4.186 J
1 eV	=	1.6×10^{-19} J
1 kWh	=	3.6×10^6 J
931.43 MeV from mass of 1 amu		

Power

1 W	=	0.738 ft · lb/s
1 hp	=	550 ft · lb/s = 0.746 kW

Pressure

1 atm	=	1.013×10^5 Pa
1 atm	=	14.7 psi = 76.0 cm Hg

The Greek Alphabet

Alpha	α	A	Nu	ν	N
Beta	β	B	Xi	ξ	Ξ
Gamma	γ	Γ	Omicron	o	O
Delta	δ	Δ	Pi	π	Π
Epsilon	ε	E	Rho	ρ	P
Zeta	ζ	Z	Sigma	σ	Σ
Eta	η	H	Tau	τ	T
Theta	θ	Θ	Upsilon	υ	Υ
Iota	ι	I	Phi	ϕ	Φ
Kappa	κ	K	Chi	χ	X
Lambda	λ	Λ	Psi	ψ	Ψ
Mu	μ	M	Omega	ω	Ω