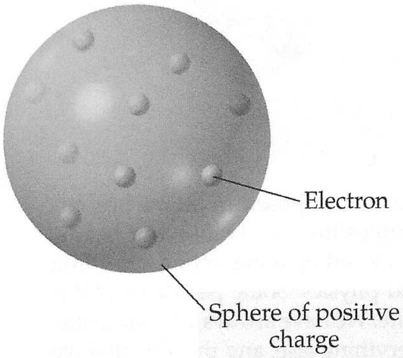
4.3 The Nuclear Atom

By the end of the nineteenth century, scientists were convinced that matter was composed of atoms, the permanent, indestructible building blocks from which all substances are constructed. However, an English physicist named J. J. Thomson (1856–1940) complicated the picture by discovering an even smaller and more fundamental particle called the **electron**. Thomson discovered that electrons are negatively charged, that they are much smaller and lighter than atoms, and that they are uniformly present in many different kinds of substances. The indestructible building block called the atom could apparently be "chipped."

Electric charge is more fully defined in Section 4.4. For now, think of it as an inherent property of electrons that causes them to interact with other charged particles.

The discovery of negatively charged particles within atoms raised the question of a balancing positive charge. Atoms were known to be charge-neutral, so it was believed that they must contain positive charge that balanced the negative charge of electrons. But how did the positive and negative charges within the atom fit together? Were atoms just a jumble of even more fundamental particles? Were they solid spheres, or did they have some internal structure? Thomson proposed that the negatively charged electrons were small particles held within a positively charged sphere. This model, the most popular of the time, became



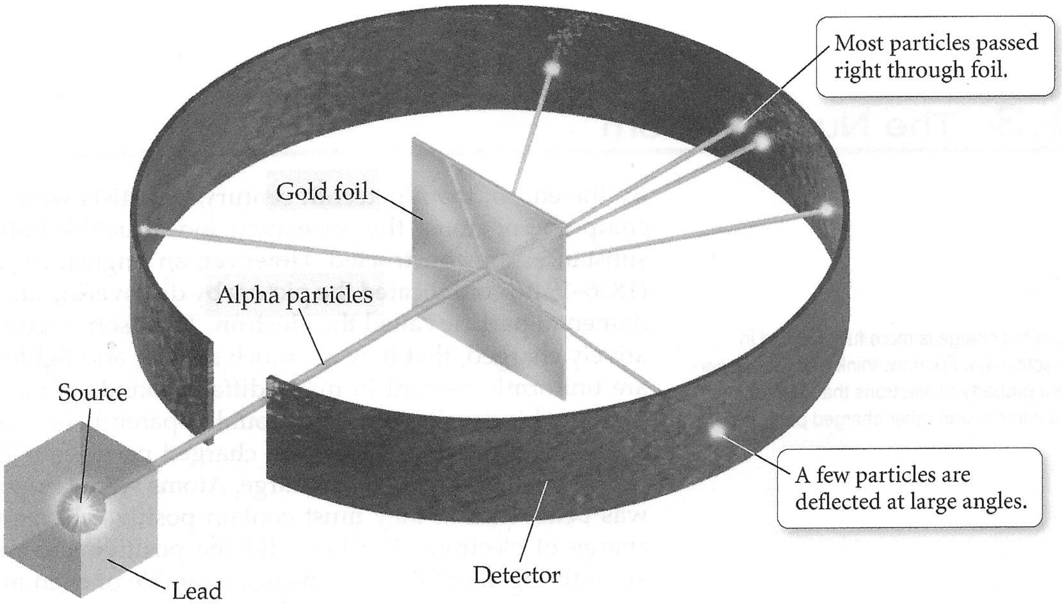
▲ **FIGURE 4.3 Plum pudding model of the atom** In the model suggested by J. J. Thomson, negatively charged electrons (yellow) were held in a sphere of positive charge (red).

known as the plum pudding model (plum pudding is an English dessert) (◀ Figure 4.3). The picture suggested by Thomson was—to those of us not familiar with plum pudding—like a blueberry muffin, where the blueberries are the electrons and the muffin is the positively charged sphere.

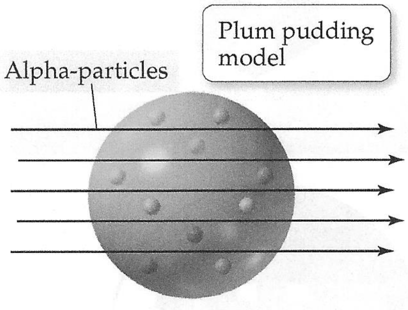
In 1909, Ernest Rutherford (1871–1937), who had worked under Thomson and adhered to his plum pudding model, performed an experiment in an attempt to confirm it. His experiment instead proved it wrong. In his experiment, Rutherford directed tiny, positively charged particles—called alpha-particles—at an ultrathin sheet of gold foil (▼ Figure 4.4). Alpha-particles are about 7000 times more massive than electrons and carry a positive charge. These particles were to act as probes of the gold atoms' structure. If the gold atoms were indeed like blueberry muffins or plum pudding—with their mass and charge spread throughout the entire volume of the atom—these speeding probes should pass right through the gold foil with minimum deflection. Rutherford's results were not as he expected. A majority of the particles did pass directly through the foil, but some particles were deflected, and some (1 in 20,000) even bounced back. The results puzzled Rutherford, who found them "about as credible as if you had fired a 15-inch shell at a piece of tissue paper and it came back and hit you." What must the structure of the atom be in order to explain this odd behavior?

Rutherford created a new model to explain his results (▶ Figure 4.5). He concluded that matter must not be as uniform as it appears. It must contain large regions of empty space dotted with small regions of very dense matter. In order to explain the deflections he observed, the mass and positive charge of an atom must all be concentrated in a space much smaller than the size of the atom itself. Based on this idea, he developed the **nuclear theory of the atom**, which has three basic parts:

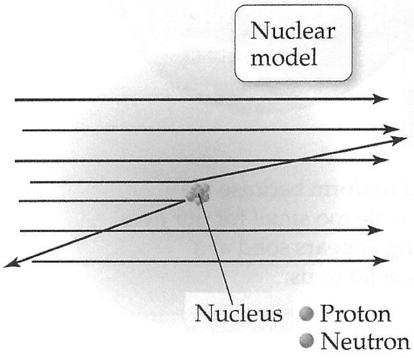
1. Most of the atom's mass and all of its positive charge are contained in a small core called the *nucleus*.
2. Most of the volume of the atom is empty space through which the tiny, negatively charged electrons are dispersed.
3. There are as many negatively charged electrons outside the nucleus as there are positively charged particles (*protons*) inside the nucleus, so that the atom is electrically neutral.



▲ **FIGURE 4.4 Rutherford's gold foil experiment** Tiny particles called alpha-particles were directed at a thin sheet of gold foil. Most of the particles passed directly through the foil. A few, however, were deflected—some of them at sharp angles.



(a) Rutherford's expected result

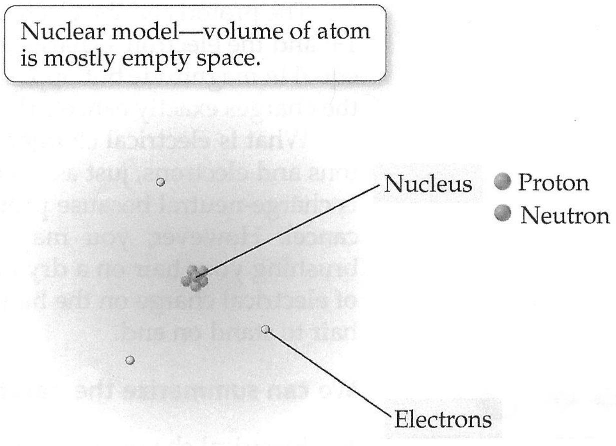


(b) Rutherford's actual result

◀ **FIGURE 4.5 Discovery of the atomic nucleus** **(a)** Expected result of Rutherford's gold foil experiment. If the plum pudding model were correct, the alpha-particles would pass right through the gold foil with minimal deflection. **(b)** Actual result of Rutherford's gold foil experiment. A small number of alpha-particles were deflected or bounced back. The only way to explain the deflections was to suggest that most of the mass and all of the positive charge of an atom must be concentrated in a space much smaller than the size of the atom itself—the nucleus. The nucleus itself is composed of positively charged particles (protons) and neutral particles (neutrons).

Later work by Rutherford and others demonstrated that the atom's **nucleus** contains both positively charged **protons** and neutral particles called **neutrons.** The dense nucleus makes up more than 99.9% of the mass of the atom, but occupies only a small fraction of its volume. The electrons are distributed through a much larger region, but don't have much mass (▼ Figure 4.6). For now, you can think of these electrons like the water droplets that make up a cloud—they are dispersed throughout a large volume but weigh almost nothing.

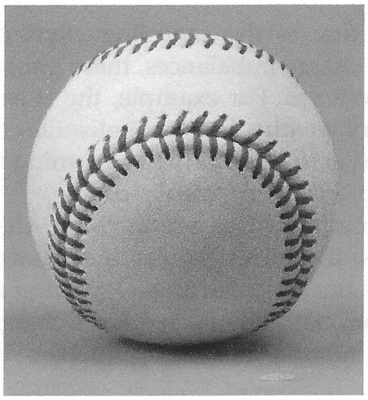
Rutherford's nuclear theory was a success and is still valid today. The revolutionary part of this theory is the idea that matter—at its core—is much less uniform than it appears. If the nucleus of the atom were the size of this dot ·, the average electron would be about 10 m away. Yet the dot would contain almost the entire mass of the atom. Imagine what matter would be like if atomic structure broke down. What if matter were composed of atomic nuclei piled on top of each other like marbles? Such matter would be incredibly dense; a single grain of sand composed of solid atomic nuclei would have a mass of 5 million kg (or a weight of about 10 million lb). Astronomers believe that black holes and neutron stars are composed of this kind of incredibly dense matter.



▶ **FIGURE 4.6 The nuclear atom** In this model, 99.9% of the atom's mass is concentrated in a small, dense nucleus that contains protons and neutrons. The rest of the volume of the atom is mostly empty space occupied by negatively charged electrons. The number of electrons outside the nucleus is equal to the number of protons inside the nucleus. In this image, the nucleus is greatly enlarged and the electrons are portrayed as particles.

4.4 The Properties of Protons, Neutrons, and Electrons

Protons and neutrons have very similar masses. In SI units, the mass of the proton is 1.67262×10^{-27} kg, and the mass of the neutron is a close 1.67493×10^{-27} kg. A more common unit to express these masses, however, is the **atomic mass unit (amu)**, defined as one-twelfth of the mass of a carbon atom containing six protons and six neutrons. In this unit, a proton has a mass of 1.0073 amu and a neutron has a mass of 1.0087 amu. Electrons, by contrast, have an almost negligible mass of 0.00091×10^{-27} kg, or approximately 0.00055 amu.



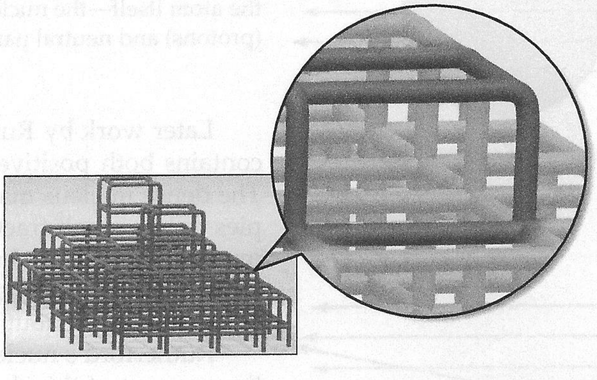
◀ If a proton had the mass of a baseball, an electron would have the mass of a rice grain. The proton is nearly 2000 times as massive as an electron.

EVERYDAY CHEMISTRY

Solid Matter?

If matter really is mostly empty space as Rutherford suggested, then why does it appear so solid? Why can I tap my knuckles on the table and feel a solid thump? Matter appears solid because the variation in the density is on such a small scale that our eyes can't see it. Imagine a jungle gym 100 stories high and the size of a football field. It is mostly empty space. Yet if you viewed it from an airplane, it would appear as a solid mass. Matter is similar. When you tap your knuckles on the table, it is much like one giant jungle gym (your finger) crashing into another (the table). Even though they are both primarily empty space, one does not fall into the other.

CAN YOU ANSWER THIS? *Use the jungle gym analogy to explain why most of Rutherford's alpha-particles went right through the gold foil and why a few bounced back. Remember that his gold foil was extremely thin.*



▲ Matter appears solid and uniform because the variation in density is on a scale too small for our eyes to see. Just as this scaffolding appears solid at a distance, so matter appears solid to us.

The proton and the electron both have electrical **charge**. The proton's charge is 1+ and the electron's charge is 1−. The charges of the proton and the electron are equal in magnitude but opposite in sign, so that when the two particles are paired, the charges exactly cancel. The neutron has no charge.

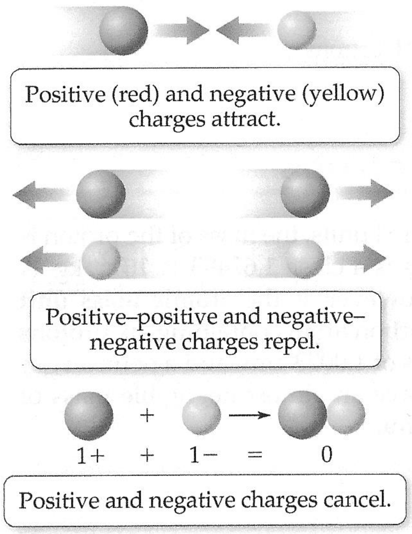
What is electrical charge? Electrical charge is a fundamental property of protons and electrons, just as mass is a fundamental property of matter. Most matter is charge-neutral because protons and electrons occur together and their charges cancel. However, you may have experienced excess electrical charge when brushing your hair on a dry day. The brushing action results in the accumulation of electrical charge on the hair strands, which then repel each other, causing your hair to stand on end.

We can summarize the nature of electrical charge as follows (◀ Figure 4.7)

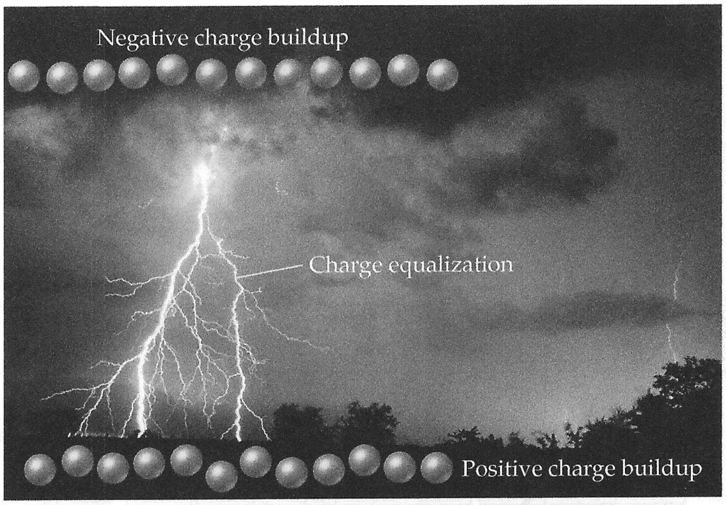
- Electrical charge is a fundamental property of protons and electrons.
- Positive and negative electrical charges attract each other.
- Positive–positive and negative–negative charges repel each other.
- Positive and negative charges cancel each other so that a proton and an electron, when paired, are charge-neutral.

Note that matter is usually charge-neutral due to the canceling effect of protons and electrons. When matter does acquire charge imbalances, these imbalances usually equalize quickly, often in dramatic ways. For example, the shock you receive when touching a doorknob during dry weather is the equalization of a charge imbalance that developed as you walked across the carpet. Lightning is an equalization of charge imbalances that develop during electrical storms.

If you had a sample of matter—even a tiny sample, such as a sand grain—that was composed of only protons or only electrons, the forces around that matter would be extraordinary, and the matter would be unstable. Fortunately, matter is not that way—protons and electrons exist together, canceling each other's charge and making matter charge-neutral. Table 4.1 summarizes the properties of protons, neutrons, and electrons.



▲ **FIGURE 4.7 The properties of electrical charge**



▶ Matter is normally charge-neutral, having equal numbers of positive and negative charges that exactly cancel. When the charge balance of matter is disturbed, as in an electrical storm, it quickly rebalances, often in dramatic ways such as lightning.

TABLE 4.1 Subatomic Particles

	Mass (kg)	Mass (amu)	Charge
proton	1.67262×10^{-27}	1.0073	1+
neutron	1.67493×10^{-27}	1.0087	0
electron	0.00091×10^{-27}	0.00055	1−

✓ **CONCEPTUAL CHECKPOINT 4.1**

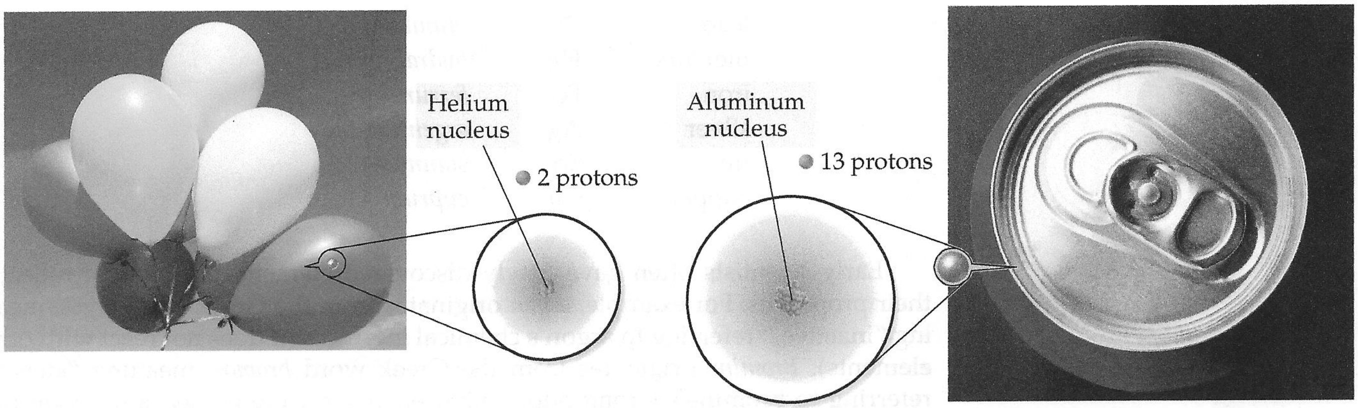
An atom composed of which of these particles would have a mass of approximately 12 amu and be charge-neutral?

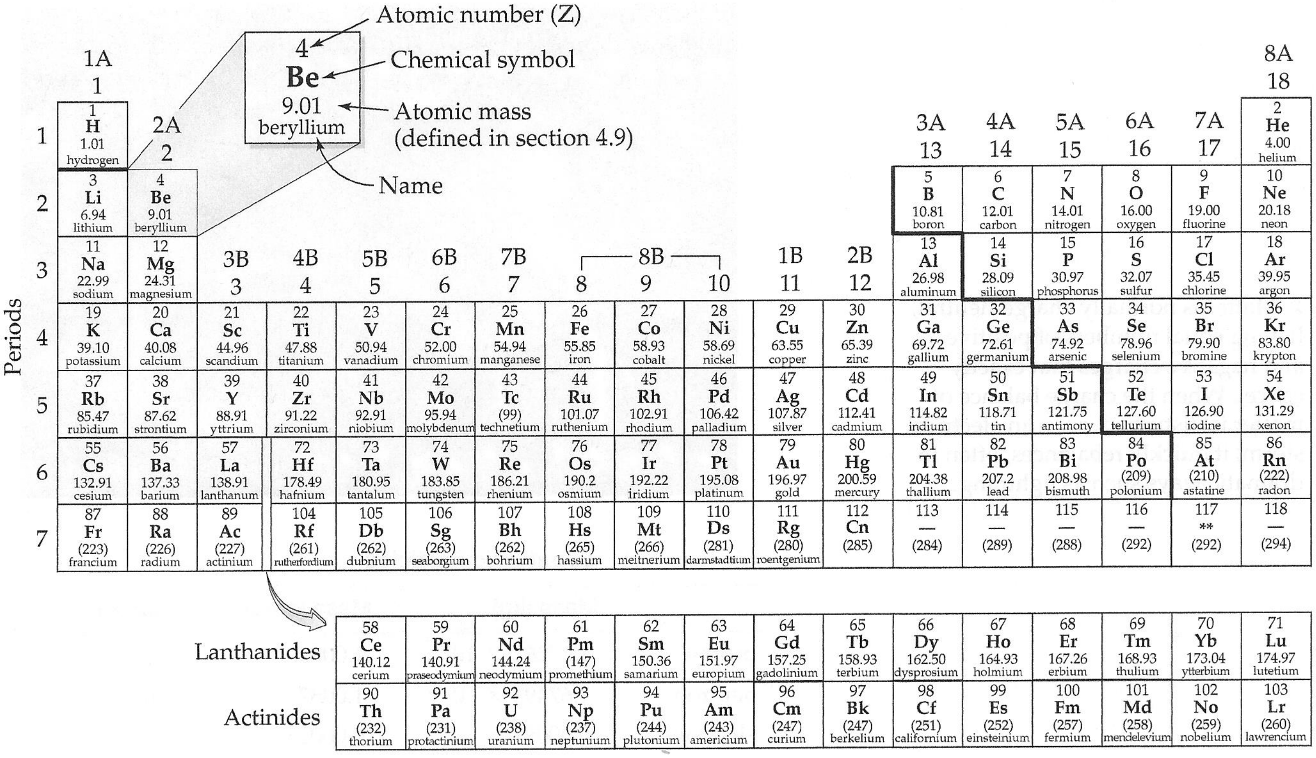
(a) 6 protons and 6 electrons
(b) 3 protons, 3 neutrons, and 6 electrons
(c) 6 protons, 6 neutrons, and 6 electrons
(d) 12 neutrons and 12 electrons

4.5 Elements: Defined by Their Numbers of Protons

We have seen that atoms are composed of protons, neutrons, and electrons. However, it is the number of protons in the nucleus of an atom that identifies it as a particular element. For example, atoms with 2 protons in their nucleus are helium atoms, atoms with 13 protons in their nucleus are aluminum atoms, and atoms with 92 protons in their nucleus are uranium atoms. The number of protons in an atom's nucleus defines the element (▼ Figure 4.8). Every aluminum atom has

▼ **FIGURE 4.8 The number of protons in the nucleus defines the element**





Periods	1A 1	2A 2	3B 3	4B 4	5B 5	6B 6	7B 7	8B 8	8B 9	8B 10	1B 11	2B 12	3A 13	4A 14	5A 15	6A 16	7A 17	8A 18
1	1 H 1.01 hydrogen																	2 He 4.00 helium
2	3 Li 6.94 lithium	4 Be 9.01 beryllium											5 B 10.81 boron	6 C 12.01 carbon	7 N 14.01 nitrogen	8 O 16.00 oxygen	9 F 19.00 fluorine	10 Ne 20.18 neon
3	11 Na 22.99 sodium	12 Mg 24.31 magnesium											13 Al 26.98 aluminum	14 Si 28.09 silicon	15 P 30.97 phosphorus	16 S 32.07 sulfur	17 Cl 35.45 chlorine	18 Ar 39.95 argon
4	19 K 39.10 potassium	20 Ca 40.08 calcium	21 Sc 44.96 scandium	22 Ti 47.88 titanium	23 V 50.94 vanadium	24 Cr 52.00 chromium	25 Mn 54.94 manganese	26 Fe 55.85 iron	27 Co 58.93 cobalt	28 Ni 58.69 nickel	29 Cu 63.55 copper	30 Zn 65.39 zinc	31 Ga 69.72 gallium	32 Ge 72.61 germanium	33 As 74.92 arsenic	34 Se 78.96 selenium	35 Br 79.90 bromine	36 Kr 83.80 krypton
5	37 Rb 85.47 rubidium	38 Sr 87.62 strontium	39 Y 88.91 yttrium	40 Zr 91.22 zirconium	41 Nb 92.91 niobium	42 Mo 95.94 molybdenum	43 Tc (99) technetium	44 Ru 101.07 ruthenium	45 Rh 102.91 rhodium	46 Pd 106.42 palladium	47 Ag 107.87 silver	48 Cd 112.41 cadmium	49 In 114.82 indium	50 Sn 118.71 tin	51 Sb 121.75 antimony	52 Te 127.60 tellurium	53 I 126.90 iodine	54 Xe 131.29 xenon
6	55 Cs 132.91 cesium	56 Ba 137.33 barium	57 La 138.91 lanthanum	72 Hf 178.49 hafnium	73 Ta 180.95 tantalum	74 W 183.85 tungsten	75 Re 186.21 rhenium	76 Os 190.2 osmium	77 Ir 192.22 iridium	78 Pt 195.08 platinum	79 Au 196.97 gold	80 Hg 200.59 mercury	81 Tl 204.38 thallium	82 Pb 207.2 lead	83 Bi 208.98 bismuth	84 Po (209) polonium	85 At (210) astatine	86 Rn (222) radon
7	87 Fr (223) francium	88 Ra (226) radium	89 Ac (227) actinium	104 Rf (261) rutherfordium	105 Db (262) dubnium	106 Sg (263) seaborgium	107 Bh (262) bohrium	108 Hs (265) hassium	109 Mt (266) meitnerium	110 Ds (281) darmstadtium	111 Rg (280) roentgenium	112 Cn (285)	113 — (284)	114 — (289)	115 — (288)	116 — (292)	117 ** (292)	118 — (294)

Lanthanides	58 Ce 140.12 cerium	59 Pr 140.91 praseodymium	60 Nd 144.24 neodymium	61 Pm (147) promethium	62 Sm 150.36 samarium	63 Eu 151.97 europium	64 Gd 157.25 gadolinium	65 Tb 158.93 terbium	66 Dy 162.50 dysprosium	67 Ho 164.93 holmium	68 Er 167.26 erbium	69 Tm 168.93 thulium	70 Yb 173.04 ytterbium	71 Lu 174.97 lutetium
Actinides	90 Th (232) thorium	91 Pa (231) protactinium	92 U (238) uranium	93 Np (237) neptunium	94 Pu (244) plutonium	95 Am (243) americium	96 Cm (247) curium	97 Bk (247) berkelium	98 Cf (251) californium	99 Es (252) einsteinium	100 Fm (257) fermium	101 Md (258) mendelevium	102 No (259) nobelium	103 Lr (260) lawrencium

▲ **FIGURE 4.9 The periodic table of the elements**

**Element 117 is currently under review by IUPAC.

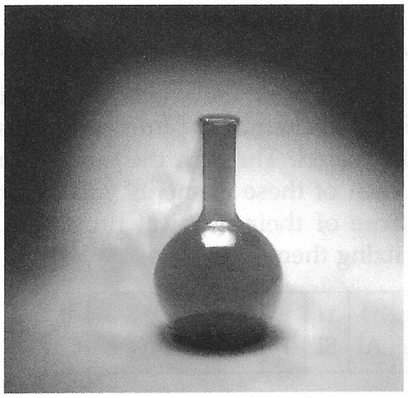
13 protons in its nucleus; if it had a different number of protons, it would be a different element. The number of protons in the nucleus of an atom is its **atomic number** and is given the symbol **Z**.

The periodic table of the elements (▲ Figure 4.9) lists all known elements according to their atomic numbers. Each element is represented by a unique **chemical symbol**, a one- or two-letter abbreviation for the element that appears directly below its atomic number on the periodic table. The chemical symbol for helium is He; for aluminum, Al; and for uranium, U. The chemical symbol and the atomic number always go together. If the atomic number is 13, the chemical symbol must be Al. If the atomic number is 92, the chemical symbol must be U. This is just another way of saying that the number of protons defines the element.

Most chemical symbols are based on the English name of the element. For example, the symbol for carbon is C; for silicon, Si; and for bromine, Br. Some elements, however, have symbols based on their Latin names. For example, the symbol for potassium is K, from the Latin *kalium*, and the symbol for sodium is Na, from the Latin *natrium*. Additional elements with symbols based on their Greek or Latin names include the following:

lead	Pb	*plumbum*
mercury	Hg	*hydrargyrum*
iron	Fe	*ferrum*
silver	Ag	*argentum*
tin	Sn	*stannum*
copper	Cu	*cuprum*

Early scientists often gave newly discovered elements names that reflected their properties. For example, *argon* originates from the Greek word *argos*, meaning "inactive," referring to argon's chemical inertness (it does not react with other elements). *Bromine* originates from the Greek word *bromos*, meaning "stench," referring to bromine's strong odor. Other elements were named after countries.



▲ The name *bromine* originates from the Greek word *bromos,* meaning "stench." Bromine vapor, seen as the red-brown gas in this photograph, has a strong odor.

Curium
96
Cm
(247)

▲ Curium is named after Marie Curie, a chemist who helped discover radioactivity and also discovered two new elements. Curie won two Nobel Prizes for her work.

For example, polonium was named after Poland, francium after France, and americium after the United States of America. Still other elements were named after scientists. Curium was named after Marie Curie, and mendelevium after Dmitri Mendeleev. Every element's name, symbol, and atomic number are included in the periodic table (inside front cover) and in an alphabetical listing (inside back cover) in this book.

EXAMPLE 4.1 Atomic Number, Atomic Symbol, and Element Name

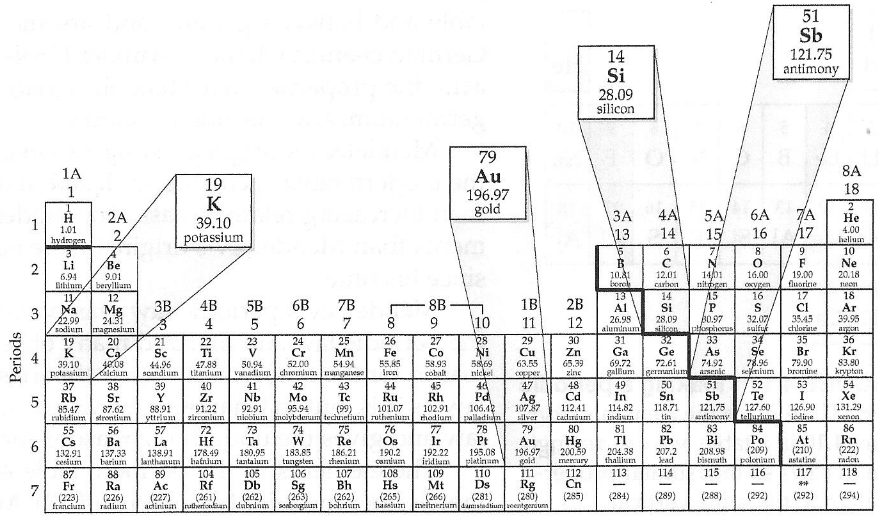
Find the atomic symbol and atomic number for each element.

(a) silicon
(b) potassium
(c) gold
(d) antimony

SOLUTION

As you become familiar with the periodic table, you will be able to quickly locate elements on it. For now, it might be easier to find them in the alphabetical listing on the inside back cover of this book, but you should also find their position in the periodic table.

Element	Symbol	Atomic Number
silicon	Si	14
potassium	K	19
gold	Au	79
antimony	Sb	51



▶SKILLBUILDER 4.1 | Atomic Number, Atomic Symbol, and Element Name

Find the name and atomic number for each element.

(a) Na
(b) Ni
(c) P
(d) Ta

▶**FOR MORE PRACTICE** Problems 41, 42, 45, 46, 47, 48, 49, 50.

4.8 Isotopes: When the Number of Neutrons Varies

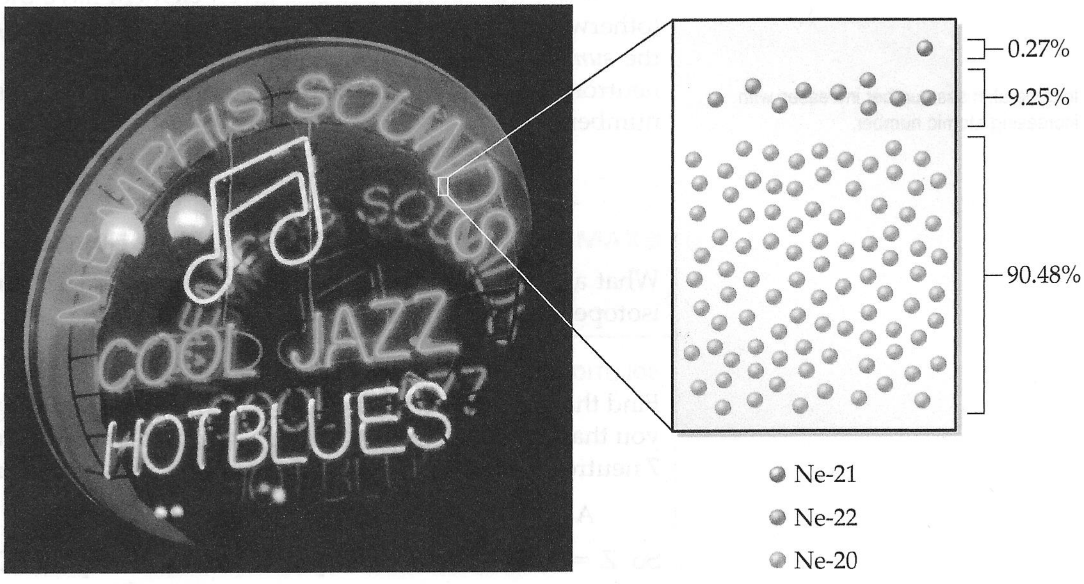
All atoms of a given element have the same number of protons; however, they do not necessarily have the same number of neutrons. Since neutrons and protons have nearly the same mass (approximately 1 amu), and since the number of neutrons in the atoms of a given element can vary, all atoms of a given element *do not* have the same mass (contrary to what John Dalton originally proposed in his atomic theory). For example, all neon atoms in nature contain 10 protons, but they may have 10, 11, or 12 neutrons (▼ Figure 4.15). All three types of neon atoms exist, and each has a slightly different mass. Atoms with the same number of protons but different numbers of neutrons are called **isotopes**. Some elements, such as beryllium (Be) and aluminum (Al), have only one naturally occurring isotope, while other elements, such as neon (Ne) and chlorine (Cl), have two or more.

There are a few exceptions to this rule, such as boron, but they are beyond our scope in this text.

For a given element, the relative amounts of each different isotope in a naturally occurring sample of that element is always the same. For example, in any natural sample of neon atoms, 90.48% of them are the isotope with 10 neutrons, 0.27% are the isotope with 11 neutrons, and 9.25% are the isotope with 12 neutrons as summarized in Table 4.2. This means that out of 10,000 neon atoms, 9048 have

TABLE 4.2 Neon Isotopes

Symbol	Number of Protons	Number of Neutrons	A (Mass Number)	Percent Natural Abundance
Ne-20 or $^{20}_{10}$Ne	10	10	20	90.48%
Ne-21 or $^{21}_{10}$Ne	10	11	21	0.27%
Ne-22 or $^{22}_{10}$Ne	10	12	22	9.25%



▶ **FIGURE 4.15**
Isotopes of neon
Naturally occurring neon contains three different isotopes, Ne-20 (with 10 neutrons), Ne-21 (with 11 neutrons), and Ne-22 (with 12 neutrons).

Percent means "per hundred." 90.48% means that 90.48 atoms out of 100 are the isotope with 10 neutrons.

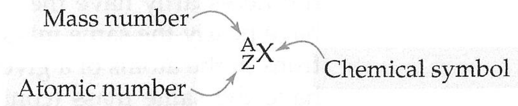
10 neutrons, 27 have 11 neutrons, and 925 have 12 neutrons. These percentages are referred to as the **percent natural abundance** of the isotopes. The preceding numbers are for neon only; all elements have their own unique percent natural abundance of isotopes.

The sum of the number of neutrons and protons in an atom is its **mass number** and is given the symbol **A**.

A = Number of protons + Number of neutrons

For neon, which has 10 protons, the mass numbers of the three different naturally occurring isotopes are 20, 21, and 22, corresponding to 10, 11, and 12 neutrons, respectively.

Isotopes are often symbolized in the following way:



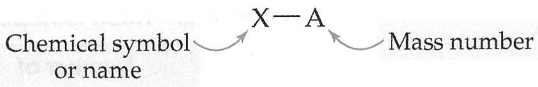
where X is the chemical symbol, A is the mass number, and Z is the atomic number.

For example, the symbols for the neon isotopes are:

$${}^{20}_{10}\text{Ne} \quad {}^{21}_{10}\text{Ne} \quad {}^{22}_{10}\text{Ne}$$

Notice that the chemical symbol, Ne, and the atomic number, 10, are redundant: If the atomic number is 10, the symbol must be Ne, and vice versa. The mass numbers, however, are different, reflecting the different number of neutrons in each isotope.

A second common notation for isotopes is the chemical symbol (or chemical name) followed by a hyphen and the mass number of the isotope.



In this notation, the neon isotopes are:

Ne-20	neon-20
Ne-21	neon-21
Ne-22	neon-22

Notice that all isotopes of a given element have the same number of protons (otherwise they would be a different element). Notice also that the mass number is the *sum* of the number of protons and the number of neutrons. The number of neutrons in an isotope is the difference between the mass number and the atomic number.

In general, mass number increases with increasing atomic number.

EXAMPLE 4.7 Atomic Numbers, Mass Numbers, and Isotope Symbols

What are the atomic number (Z), mass number (A), and symbols of the carbon isotope with 7 neutrons?

SOLUTION

Find that the atomic number (Z) of carbon is 6 (from the periodic table). This tells you that carbon atoms have 6 protons. The mass number (A) for the isotope with 7 neutrons is the sum of the number of protons and the number of neutrons.

$$A = 6 + 7 = 13$$

So, $Z = 6$, $A = 13$, and the symbols for the isotope are C-13 and ${}^{13}_{6}\text{C}$.

▶SKILLBUILDER 4.7 | Atomic Numbers, Mass Numbers, and Isotope Symbols

What are the atomic number, mass number, and symbols for the chlorine isotope with 18 neutrons?

▶FOR MORE PRACTICE Example 4.12; Problems: 85, 87, 89, 90.

EXAMPLE 4.8 Numbers of Protons and Neutrons from Isotope Symbols

How many protons and neutrons are in the chromium isotope $^{52}_{24}\text{Cr}$?

	SOLUTION
The number of protons is equal to Z (lower left number).	$\#p^{+} = Z = 24$
The number of neutrons is equal to A (upper left number) −Z (lower left number).	$\#n = A - Z$ $= 52 - 24$ $= 28$

▶SKILLBUILDER 4.8 | Numbers of Protons and Neutrons from Isotope Symbols

How many protons and neutrons are in the potassium isotope $^{39}_{19}\text{K}$?

▶FOR MORE PRACTICE Example 4.13; Problems 91, 92.

CONCEPTUAL CHECKPOINT 4.4

If an atom with a mass number of 27 has 14 neutrons, it is an isotope of which element?

(a) silicon
(b) aluminum
(c) cobalt
(d) niobium

CONCEPTUAL CHECKPOINT 4.5

Throughout this book, we represent atoms as spheres. For example, a carbon atom is represented by a black sphere as shown here. In light of the nuclear theory of the atom, would C-12 and C-13 look different in this representation of atoms? Why or why not?