26 charge and matter

26-1 *ELECTROMAGNETISM – A PREVIEW*

The science of electricity has its roots in the observation, known to Thales of Miletus in 600 B.C., that a rubbed piece of amber will attract bits of straw. The study of magnetism goes back to the observation that naturally occurring "stones" (that is, magnetite) will attract iron. These two sciences developed quite separately until 1820, when Hans Christian Oersted (1777 – 1851) observed a connection between them, namely, that an electric current in a wire can affect a magnetic compass needle (Section 33-1).

The new science of electromagnetism was developed further by many workers of whom one of the most important was Michael Faraday (1791-1867). It fell to James Clerk Maxwell (1831-1879) to put the laws of electromagnetism in essentially the form in which we know them today. These laws, called Maxwell's equations, are displayed in Table 40-2, which you may want to examine at this time. These laws play the same role in electromagnetism that Newton's laws of motion and of gravitation do in mechanics.

Although Maxwell's synthesis of electromagnetism rests heavily on the work of his predecessors, his own contribution was central and vital. Maxwell deduced that light is electromagnetic in nature and that its speed can be found by making purely electric and magnetic measurements. Thus the science of optics was intimately connected with those of electricity and of magnetism. The scope of Maxwell's equations is remarkable, including as it does the fundamental principles of all large-scale electromagnetic and optical devices such as motors, radio, television, microwave radar, microscopes and telescopes.

The development of classical electromagnetism did not end with Maxwell. The English physicist Oliver Heaviside (1850-1925) and especially the Dutch physicist H. A. Lorentz (1853-1928) contributed substantially to the clarification of Maxwell's theory. Heinrich Hertz

(1857-1894)[*] took a great step forward when, more than twenty years after Maxwell set up his theory, he produced in the laboratory electromagnetic "Maxwellian waves" of a kind that we would now call short radio waves. It remained for Marconi and others to exploit the practical application of the electromagnetic waves of Maxwell and Hertz.

Present interest in electromagnetism takes two forms. At the level of engineering applications Maxwell's equations are used constantly and universally in the solution of a wide variety of practical problems. At the level of the foundations of the theory there is a continuing effort to extend its scope in such a way that electromagnetism is revealed as a special case of a more general theory. Such a theory would also include (say) the theories of gravitation and of quantum physics. This grand synthesis has not yet been achieved.

26-2
ELECTRIC CHARGE

The rest of this chapter deals with electric charge and its relationship to matter. We can show that there are *two kinds* of charge by rubbing a glass rod with silk and hanging it from a long thread as in Fig. 26-1. If a second rod is rubbed with silk and held near the rubbed end of the first rod, the rods will repel each other. On the other hand, a rod of plastic (Lucite, say) rubbed with fur will *attract* the glass rod. Two plastic rods rubbed with fur will repel each other. We explain these facts by saying that rubbing a rod gives it an *electric charge* and that the charges on the two rods exert forces on each other. Clearly the charges on the glass and on the plastic must be different in nature.

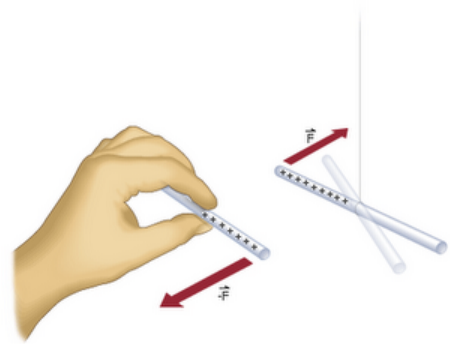

figure 26-1
Two positively charged glass rods repel each other.

Benjamin Franklin (1706-1790), who, among his other achievements, was the first American physicist[‡], named the kind of electricity that appears on the glass *positive* and the kind that appears on the plastic (sealing wax or shell-lac in Franklin's day) *negative*; these names have remained to this day. We can sum up these experiments by saying that *like charges repel and unlike charges attract*.

Electric effects are not limited to glass rubbed with silk or to plastic rubbed with fur. Any substance rubbed with any other under suitable conditions will become charged to some extent; by comparing the unknown charge with a glass rod which had been rubbed with silk or a plastic rod which had been rubbed with fur, it can be labeled as either positive or negative.

The modern view of bulk matter is that, in its normal or neutral state, it contains equal amounts of positive and negative electricity. If two bodies like glass and silk are rubbed together, a small amount of charge is transferred from one to the other, upsetting the electric neutrality of each. In this case the glass would become positive, the silk negative.

---

[*] "Heinrich Hertz," by P. and E. Morrison, Scientific American, December 1957.

[‡] The science historian I. Bernard Cohen of Harvard University says of Franklin in his book *Franklin and Newton*: "To say … that had Franklin 'Not been famous as a publisher and a statesman, he might never have been heard of as a scientist,' is absolutely wrong. Just the opposite is more nearly the case; his international fame and public renown as a scientist was in no small measure responsible for his success in international statesmanship." See also "The Lightning Discharge" by Richard E. Orville, *The Physics Teacher*, January 1976 for a description of Franklin's famous kite experiment and a review of modern concepts about the nature of lightning.

26-3
CONDUCTORS AND INSULATORS

A metal rod held in the hand and rubbed with fur will not seem to develop a charge. It is possible to charge such a rod, however, if it is furnished with a glass or plastic handle and if the metal is not touched with the hands while rubbing it. The explanation is that metals, the human body, and the earth are *conductors* of electricity and that glass, plastics, etc., are *insulators* (also called *dielectrics*).

In conductors, electric charges are free to move through the material whereas in insulators they are not. Although there are no perfect insulators, the insulating ability of fused quartz is about 10^{25} times as great as that of copper, so that for many practical purposes some materials behave as if they were perfect insulators.

In metals a fairly subtle experiment called the Hall effect (see Section 33-5) shows that only negative charge is free to move. Positive charge is as immobile as it is in glass or in another dielectric. The actual charge carriers in metals are the *free electrons*. When isolated atoms are combined to form a metallic solid, the outer electrons of the atom do not remain attached to the individual atoms but become free to move throughout the volume of the solid. For some conductors, such as electrolytes, both positive and negative charges can move.

A class of materials called *semiconductors* is intermediate between conductors and insulators in its ability to conduct electricity. Among the elements, silicon and germanium are well-known examples. Semiconductors have many practical applications, among which is their use in the construction of transistors. The way a semiconductor works cannot be described adequately without some understanding of the basic principles of quantum physics. Figure 26-2, however, suggests the principal features of the distinction between conductors, semiconductors, and insulators.

In solids, electrons have energies that are restricted to certain levels, the levels being confined to certain bands. The intervals between bands are forbidden, in the sense that electrons in the solid may not possess such energies. Electrons are assigned two to a level and they may not increase their energy (which means that they may not move freely through the solid) unless there are empty levels at higher energies into which they can readily move.

Figure 26-2*a* shows a conductor, such as copper. Band 1 is only partially filled, so that electrons can easily move to the higher empty levels and thus travel through the solid. Figure 26-2*b* shoes a (intrinsic) semiconductor such as silicon. Here band 1 is completely filled but band 2 is so close energetically that electrons can easily "jump" (absorbing energy from, say, thermal fluctuations) into the unfilled levels of that band. Figure 26-2*c* shows an insulator, such as sodium chloride. Here again band 1 is filled, but band 2 is too far above band 1 energetically to permit any appreciable number of the band-1 electrons to jump the energy gap.

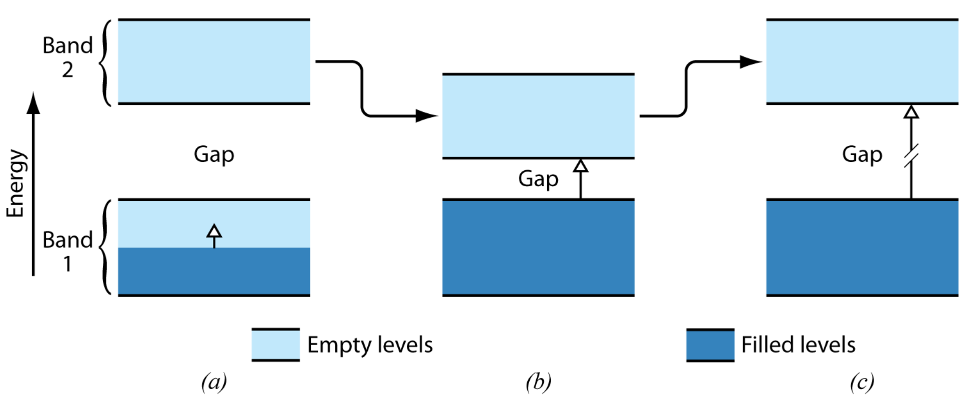

figure 26-2
Suggesting (*a*) a conductor, (*b*) an intrinsic semiconductor, and (*c*) an insulator. In (*b*) the gap is relatively small but in (*c*) it is relatively large. In intrinsic semiconductors the electrical conductivity can often be greatly increased by adding very small amounts of other elements such as arsenic or boron, a process called "doping".

26-4
COULOMB'S LAW

Charles Augustin Coulomb (1736-1806) measured electrical attractions and repulsions quantitatively and deduced the law that governs them. His apparatus, shown in Fig. 26-3, resembles the hanging rod of Fig. 26-1, except that the charges in Fig. 26-3 are confined to small spheres *a* and *b*.

If *a* and *b* are charged the electric force on *a* will tend to twist the suspension fiber. Coulomb canceled out this twisting effect by turning the suspension head through the angle θ needed to keep the two charges at the particular distance apart in which he was interested. The angle q is then a relative measure of the electric force acting on charge *a*. The device of Fig. 26-3 is called a *torsion balance*; a similar arrangement was used later by Cavendish to measure gravitational attractions (Section 16-3).

Coulonb's first experimental results can be represented by

$$F \propto \frac{1}{r^2}$$

Here *F* is the magnitude of the interaction force that acts on each of the two charges *a* and *b*; *r* is their distance apart. These forces, as Newton's third law requires, act along the line joining the charges but point in opposite directions. Note that the magnitude of the force on each charge is the same, even though the charges may be different.

The force between charges depends also on the magnitude of the charges. Specifically, it is proportional to their product. Although Coulomb did not prove this rigorously, he implied it and thus we arrive at

$$F \propto \frac{q_1 q_2}{r^2} \qquad (26\text{-}1)$$

where q_1 and q_2 are relative measures of the charges on spheres *a* and *b*. Equation 26-1, which is called *Coulomb's law*, holds only for charged objects whose sizes are much smaller than the distance between them. We often say that it holds only for *point charges*.

Coulomb's law resembles the inverse square law of gravitation, which was already more than 100 years old at the time of Coulomb's experiments; *q* plays the role of *m* in that law. In gravity, however, the forces are always attractive; this corresponds to the fact that there are two kinds of electricity but (apparently) only one kind of mass.

Our belief in Coulomb's law does not rest quantitatively on Coulomb's experiments. Torsion balance measurements are difficult to make to an accuracy of better than a few percent. Such measurements could not, for example, convince us that the exponent in Eq. 26-1 is exactly 2 and not, say 2.01. In Section 28-7 we show that Coulomb's law can also be deduced from an indirect experiment (1971) which shows that the exponent in Eq. 26-1 lies between the limits of $2 \pm 3 \times 10^{-16}$.

Although we have established the physical concept of electric charge, we have not yet defined a unit in which it may be measured. It is possible to do so operationally by putting equal charges *q* on the spheres of a torsion balance and by measuring the magnitude *F* of the force that acts on each when the charges are a measured distance *r* apart. One could the define *q* to have a unit value if a unit force acts on each charge when the charges are separated by a unit distance and one can give a name to the unit of charge so defined.*

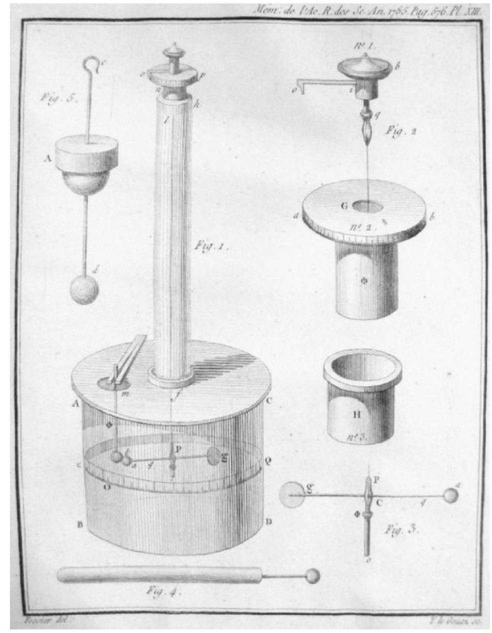

figure 26-3
Coulomb's torsion balance, from his 1785 memoir to the French Academy of Sciences.

* This scheme is the basis for the definition of the unit of charge called the *statcoulomb*. However, in this book we do not use this unit or the system of units of which it is a part; see Appendix L, however.

For practical reasons having to do with the accuracy of measurements, the SI unit of charge is not defined using a torsion balance but is derived from the unit of electric current. If the ends of a long wire are connected to the terminals of a battery, it is common knowledge that an *electric current* i is set up in the wire. We visualize this current as a flow of charge. The SI unit of current is the *ampere* (abbr. A). In Section 34-4 we describe the operational procedures in terms of which the ampere is defined.

The SI unit of charge is the *coulomb* (abbr. C). ***One coulomb*** *is defined as the amount of charge that flows through any cross section of a wire in* ***one second*** *if there is a steady current of* ***one ampere*** *in the wire*. In symbols

$$q = it \tag{26-2}$$

where q is in coulombs if I is in amperes and t is in seconds. Thus, if a wire is connected to an insulated metal sphere, a charge of 10^{-6} C can be put on the sphere if a current of 1.0 A exists in the wire for 10^{-6} s.

EXAMPLE 1

A copper penny has a mass of 3.1 g. Being electrically neutral, it contains equal amounts of positive and negative electricity. What is the magnitude q of these charges? A copper atom has a positive nuclear charge of 4.6×10^{-18} C and a negative electronic charge of equal magnitude.

The number N of copper atoms in a penny is found from the ratio

$$\frac{N}{N_o} = \frac{m}{M}$$

where N_o is the Avogadro number, m the mass of the coin, and M the atomic weight of copper. This yields, solving for N,

$$N = \frac{(6.0 \times 10^{23} \text{ atoms/mole})(3.1 \text{ g})}{64 \text{ g/mole}} = 2.9 \times 10^{22} \text{ atoms}$$

The charge q is

$$q = (4.6 \times 10^{-18} \text{ C/atom})(2.9 \times 10^{22} \text{ atoms}) = 1.3 \times 10^{5} \text{ C}$$

In a 100-watt, 110-volt light bulb the current is 0.91 ampere. Verify that it would take 40 h for a charge of this amount to pass through this bulb.

Equation 26-1 can be written as an equality by inserting a constant of proportionality. Instead of writing this simply as, say, k, it is usually written in a more complex way as $1/4\pi\varepsilon_o$ or

$$F = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2} \tag{26-3}$$

Certain equations that are derived from Eq. 26-3, but are used more often that it is, will be simpler in form if we do this.

In SI units we can measure $q1$, $q2$, r, and F in Eq. 26-3 in ways that do not depend on Coulomb's law. Numbers with units can be assigned to them. There is no choice about the so-called *permittivity constant* eo; it must have that value which makes the right hand side of Eq. 26-3 equal to the left-hand side. This (measured) value turns out to be*

$$\varepsilon_o = 8.854187818 \times 10^{-12} \text{ C}^2/\text{N}\cdot \text{m}^2 \tag{26-3}$$

* For practical reasons this value is not actually measured by direct application of Eq. 26-3 but in an equivalent although more circuitous way.

In this book the value 8.9×10^{-12} $C^2/N{\cdot}m^2$ will be accurate enough for most problems. For direct application of Coulomb's law or in any problem to which the quantity $1/4\pi\varepsilon_o$ occurs we may use, with sufficient accuracy for this book,

$$1/4\pi\varepsilon_o = 9.0 \times 10^9 \text{ N}\cdot\text{m}^2/\text{C}^2 \qquad (26\text{-}3)$$

EXAMPLE 2

Let the total positive and the total negative charges in a copper penny be separated to a distance such that their force of attraction is 1.0 lb (= 4.5 N). How far apart must they be?

We have (Eq. 26-3)

$$F = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2}.$$

Putting $q_1 q_2 = q$ (see Example 1) and solving for r yields

$$r = q\sqrt{\frac{1/4\pi\varepsilon_o}{F}} = 1.3\times10^5 \text{ C}\sqrt{\frac{9.0\times10^9 \text{ N}\cdot\text{m}^2/\text{C}^2}{4.5 \text{ N}}}$$
$$= 5.8\times10^9 \text{ m} = 3.6\times10^6 \text{ mi}.$$

This is 910 earth radii and it suggests that it is not possible to upset the electrical neutrality of gross objects by any very large amount. What would be the force bewteeen the two charges if they were placed 1.0 m apart?

If more than two charges are present, Eq. 26-3 holds for every pair of charges. Let the charges be q_1, q_2, q_3, etc.; we calculate the force exerted on any one (say q_1) by all the others from the vector equation

$$\mathbf{F}_1 = \mathbf{F}_{12} + \mathbf{F}_{13} + \mathbf{F}_{14} + \cdots, \qquad (26\text{-}4)$$

where $\mathbf{F}_{12}$, for example, is the force exerted on q_1 by q_2.

EXAMPLE 3

Figure 26-4 shows three fixed charges q_1, q_2, and q_3. What force acts on q_1? Assume that $q_1 = -1.0 \times 10^{-6}$ C, $q_2 = +3.0 \times 10^{-6}$ C, $q_3 = -2.0 \times 10^{-6}$ C, $r_{12} = 15$ cm, $r_{13} = 10$ cm, and $\theta = 30°$.

From Eq. 26-3, ignoring the signs of the charges, since we are interested only in the magnitudes of the forces,

$$F_{12} = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2}$$
$$= \frac{(9.0\times10^9 \text{ N}\cdot\text{m}^2/\text{C}^2)(1.0\times10^{-6} \text{ C})(3.0\times10^{-6} \text{ C})}{(1.5\times10^{-1} \text{ m})^2}$$
$$= 1.2 \text{ N}$$

and

$$F_{13} = \frac{(9.0\times10^9 \text{ N}\cdot\text{m}^2/\text{C}^2)(1.0\times10^{-6} \text{ C})(2.0\times10^{-6} \text{ C})}{(1.0\times10^{-1} \text{ m})^2}$$
$$= 1.8 \text{ N}$$

The directions of $\mathbf{F}_{12}$ and $\mathbf{F}_{13}$ are shown in the figure.

The components of the resultant force $\mathbf{F}_1$ acting on q_1 (see Eq. 26-4) are

$$F_{1x} = F_{12x} + F_{13x} = F_{12} + F_{13}\sin\theta$$
$$= 1.2 \text{ N} + (1.8 \text{ N})(\sin 30°) = 2.1 \text{ N}$$

and

$$F_{1y} = F_{12y} + F_{13y} = 0 + F_{13}\cos\theta$$
$$= -(1.8 \text{ N})(\cos 30°) = -1.6 \text{ N}$$

Find the magnitude of $\mathbf{F}_1$ and the angle it makes with the x-axis.

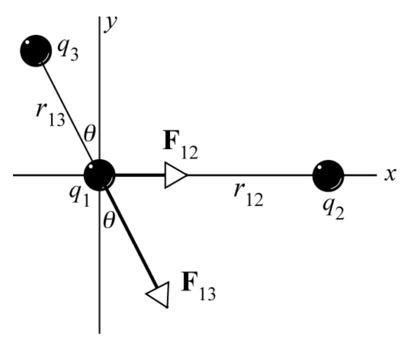

figure 26-4
Example 3. Showing the forces exerted on q_1 by q_2 and q_3.

26-5 *CHARGE IS QUANTIZED*

In Franklin's day electric charge was thought of as a continuous fluid, an idea that was useful for many purposes. The atomic theory of matter, however, has shown that fluids themselves, such as water and air, are not continuous, but are made up of atoms. Experiment shows that the "electric fluid" is not continuous either but that it is made up of integral multiples of a certain minimum electric charge. This fundamental charge, to which we give the symbol of e, has the magnitude $1.6021892 \times 10^{-19}$ C. Any physically existing charge q, no matter what its origin, can be written as ne where n is a positive or a negative integer.

When a physical property such as charge exists in discrete "packets" rather than in continuous amounts, the property is said to be *quantized*. Quantization is basic to modern quantum physics. The existence of atoms and of particles such as the electron and the proton indicates that *mass* is quantized also. Later you will learn that several other properties prove to be quantized when suitably examined on the atomic scale; among them are energy and angular momentum.

The quantum of charge e is so small that the "graininess" of electricity does not show up in large-scale experiments, just as we do not realize that the air we breathe is made up of atoms. In an ordinary 110-volt, 100-watt light bulb, for example, 6×10^{18} elementary charges enter and leave the bulb every second.

There exists today no theory that predicts the quantization of charge (or the quantization of mass, that is, the existence of fundamental particles such as protons, electrons, muons, pions, etc.). Even assuming quantization, the classical theory of electromagnetism and Newtonian mechanics are incomplete in that they do not correctly describe the behavior of charge and matter on the atomic scale. The classical theory of electromagnetism, for example, describes correctly what happens when a bar magnet is thrust through a closed copper loop; it fails, however, if we wish to explain the magnetism of the bar in terms of the atoms that make it up. The more detailed theories of quantum physics are needed for this and similar problems.

26-6 *CHARGE AND MATTER*

Matter as we ordinarily experience it can be regarded as composed of three kinds of particles, the proton, the neutron and the electron. Table 26-1 shows their masses and charges. Note that the masses of the neutron and the proton are approximately equal but that the electron is less massive by a factor of about 1840.

Table 26-1
Some properties of three particles

Particle	Symbol	Charge	Mass
Proton	p	$+e$	$1.6726485 \times 10^{-27}$ kg
Neutron	n	0	$1.6749543 \times 10^{-27}$ kg
Electron	e	$-e$	9.109534×10^{-31} kg

Atoms are made up of a dense, positively charged nucleus, surrounded by a cloud of electrons; see Fig. 26-5. The nucleus varies in radius from about 1×10^{-15} m for hydrogen to about 7×10^{-15} m for the heaviest atoms. The outer diameter of the electron cloud, that is, the diameter of the atom, lies in the range $1–3 \times 10^{-10}$ m, about 10^5 times larger than the nuclear diameter.

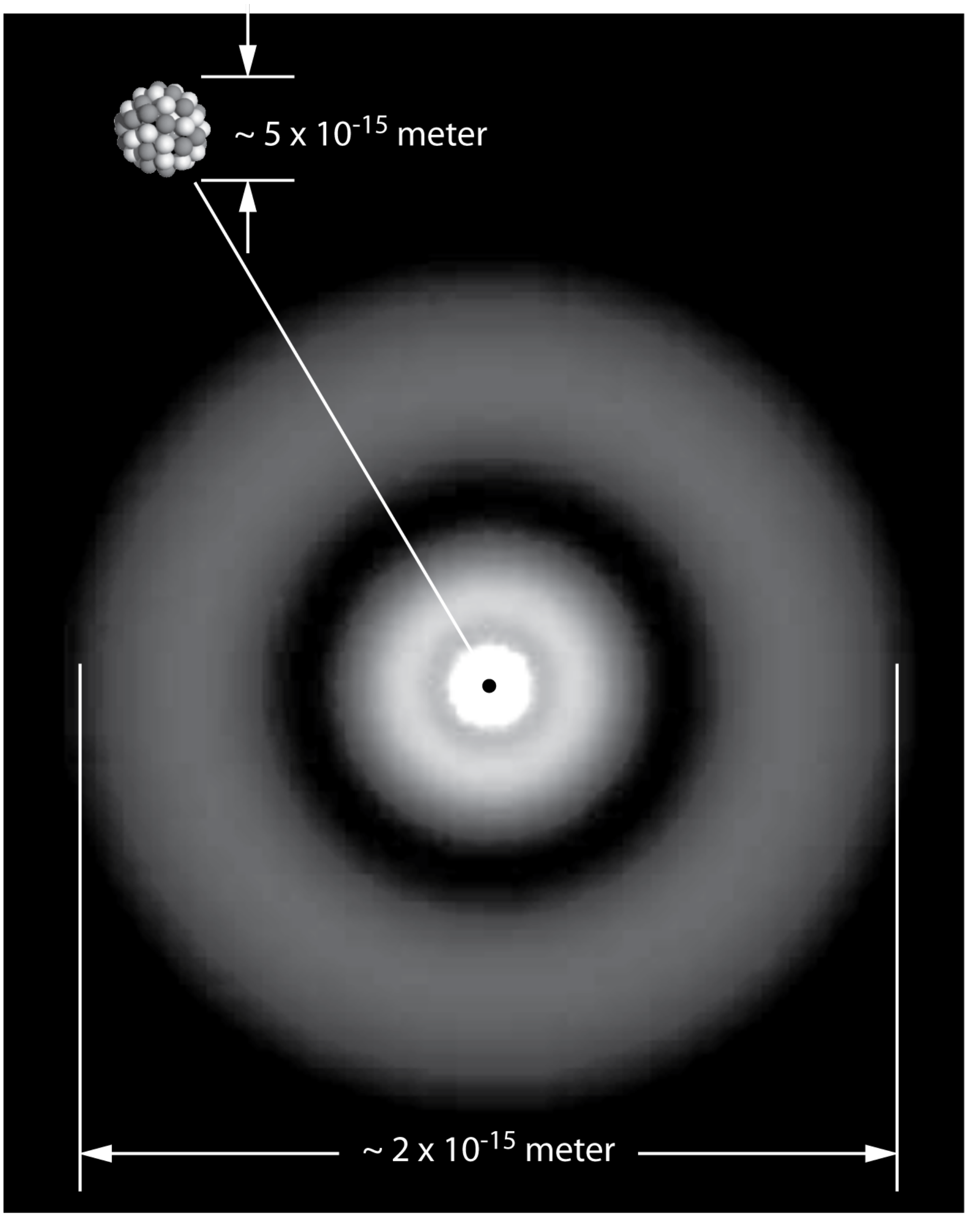

figure 26-5
An atom, suggesting the electron cloud and, above, an enlarged view of the nucleus.

EXAMPLE 4

The distance r between the electron and the proton in the hydrogen atom is about 5.3×10^{-11} m. What are the magnitudes of (*a*) the electrical force and (*b*) the gravitational force between these two particles?

From Coulomb's law,

$$F_e = \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2}$$

$$= \frac{(9.0 \times 10^9 \text{ N} \cdot \text{m}^2/\text{C}^2)(1.6 \times 10^{-19} \text{ C})^2}{(5.3 \times 10^{-11} \text{ m})^2}$$

$$= 8.1 \times 10^{-8} \text{ N}.$$

The gravitational force is given by Eq. 16-1, or

$$F_g = G\frac{m_1 m_2}{r^2}$$

$$= \frac{(6.7 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2)(9.1 \times 10^{-31} \text{ kg})(1.7 \times 10^{-27} \text{ kg})}{(5.3 \times 10^{-11} \text{ m})^2}$$

$$= 3.7 \times 10^{-47} \text{ N}$$

Thus the electrical force is about 10^{39} times stronger than the gravitational force.

The significance of Coulomb's law goes far beyond the description of the forces acting between charged spheres. This law, when incorporated into the structure of quantum physics, correctly describes (*a*) the electric forces that bind the electrons of an atom to its nucleus, (*b*) the forces that bind atoms together to form molecules, and (*c*) the forces that bind atoms of molecules together to form solids or liquids. Thus most of the forces of our daily experience that are not gravitational in nature are electrical. A force transmitted by a steel cable is basically an electrical force because, if we pass an imaginary place through the cable at right angles to it, it is only the attractive electrical interatomic forces acting between atoms on opposite sides of the plane that keep the cable from parting. We ourselves are an assembly of nuclei and electrons bound together in a stable configuration by Coulomb forces.

In the atomic nucleus we encounter a new force which is neither gravitational nor electrical in nature. This strong attractive force, which binds together the protons and neutrons that make up the nucleus, is called simply *the nuclear force* or *the strong interaction*. If this force were not present, the nucleus would fly apart at once because of the strong Coulomb repulsion force that acts between its protons. The nature of the nuclear force is only partially understood today and forms the central problem of present day researches in nuclear physics.

EXAMPLE 5

What repulsive Coulomb force exists between two protons in a nucleus of iron? Assume a separation of 4.0 10-15 m.

From Coulomb's law,

$$\begin{aligned} F_e &= \frac{1}{4\pi\varepsilon_o}\frac{q_1 q_2}{r^2} \\ &= \frac{(9.0\times10^9\ \mathrm{N\cdot m^2/C^2})(1.6\times10^{-19}\ \mathrm{C})^2}{(4.0\times10^{-15}\ \mathrm{m})^2} \\ &= 14\ \mathrm{N}. \end{aligned}$$

This enormous repulsive force (3.2 lb acting on a single proton) must be more than compensated for by the strong attractive nuclear forces. This example, combined with Example 4, shows that nuclear binding forces are much stronger than atomic binding forces. Atomic binding forces are, in turn, much stronger than gravitational forces for the same particles separated by the same distance.

The repulsive Coulomb forces acting between the protons in a nucleus make the nucleus less stable than it otherwise would be. The spontaneous emission of alpha particles from heavy nuclei and the phenomenon of nuclear fission are evidences of this instability.

The fact that heavy nuclei contain significantly more neutrons than protons is still another effect of the Coulomb forces. Consider Fig. 26-6 in which a particular atomic species is represented by a circle, the coordinates being Z, the number of protons in the nucleus (that is, *the atomic number*), and N, the number of neutrons in the nucleus (that is, the *neutron number*). Stable nuclei are represented by filled circles and radioactive nuclei, that is, nuclei that disintegrate spontaneously, emitting electrons or α-particles, by open circles. Note that all elements (xenon, for example, for which $Z = 54$; see arrow) exist in a number of different forms, called *isotopes*.

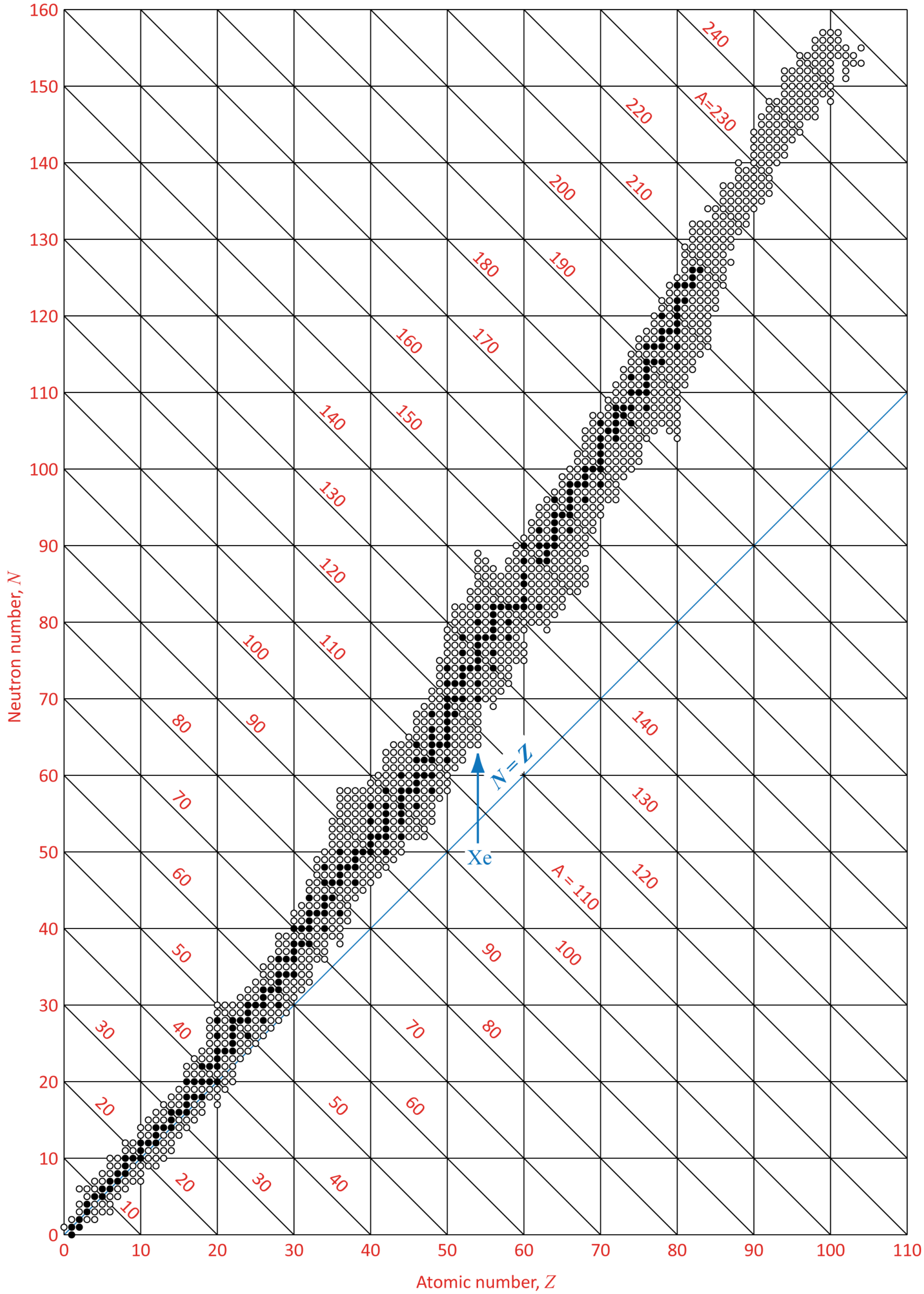

figure 26-6
The filled circles represent stable nuclei and the open ones represent radioactive nuclei. Note, for example, that xenon ($Z = 54$) has 26 isotopes, 9 of them stable and 17 radioactive. Each xenon isotope has 54 protons (and 54 extranuclear electrons for neutral atoms). The number of neutrons ranges from $N = 64$ to $N = 89$ and the mass number A ($= N + Z$) ranges from 118 to 143. No other element has as many isotopes.

Figure 26-6 shows that light nuclei, for which the Coulomb forces are relatively unimportant,* lie on or close to the line labeled "$N = Z$" and thus have about equal numbers of neutrons and protons. The heavier nuclei have a pronounced neutron excess, U^{238} having 92 protons and 238 – 92 or 146 neutrons.† In the absence of Coulomb forces we would assume, extending the $N = Z$ rule, that the most stable nucleus with 238 particles would have 119 protons and 119 neutrons. However, such a nucleus, if assembled, would fly apart at once because of Coulomb repulsion. Relative stability is found only if 27 of the protons are replaced by neutrons, thus diluting the total Coulomb repulsion. Even in U^{238} Coulomb repulsion is still very important because (*a*) this nucleus is radioactive and emits α-particles and (*b*) it may break up into two large fragments (fission) if it absorbs a neutron; both processes result in separation of the nuclear charge and are Coulomb repulsion effects. Figure 26-6 shows that all nuclei with $Z \geq 83$ are unstable.

We have pointed out that matter, as we ordinarily experience it, is made up of electrons, neutrons, and protons. Nature exhibits much more variety than this, however. There are very many more particles than these. Appendix F, which lists some properties of some of these particles, shows that, like the more familiar particles of Table 26-1, their charges are quantized, the quantum of charge again being *e*. An understanding of the nature of these particles and of their relationships to each other is one of the most significant research goals of modern physics.

26-7 *CHARGE IS CONSERVED*

When a glass rod is rubbed with silk, a positive charge appears on the rod. Measurement shows that a negative charge of equal magnitude appears on the silk. This suggests that rubbing does not create charge but merely transfers it from one object to another, disturbing slightly the electrical neutrality of each. This hypothesis of the *conservation of charge* has stood up under close experimental scrutiny both for large-scale events and at the atomic and nuclear level; no exceptions have ever been found.

An interesting example of charge conservation comes about when an electron (charge = – *e*) and a positron (charge = + *e*) are brought close to each other. The two particles may simply disappear, converting all their rest mass into energy according to the well-known $E = mc^2$ relationship; this annihilation process was described in Section 8-9. The energy appears in the form of two oppositely directed gamma rays, which are similar in character to X-rays; thus:

$$e^- + e^+ \rightarrow \gamma + \gamma \qquad (26\text{-}5)$$

The net charge is zero both before and after the event so that charge is conserved. Rest mass is *not* conserved, being turned completely into energy.

Another example of charge conservation is found in radioactive decay, of which the following process is typical:

$$U^{238} \rightarrow Th^{234} + He^4 \qquad (26\text{-}6)$$

---

* Coulomb force are important in relation to the strong nuclear attractive forces only for large nuclei, because Coulomb repulsion occurs between *every pair* of protons in the nucleus but the attractive nuclear force does not. In U238, for example, every proton exerts a force of repulsion on each of the other 91 protons. However, each proton (and neutron) exerts a nuclear attraction on only a small number of other neutrons and protons that happen to be near it. As we proceed to larege nuclei, the amount of energy associated with the repulsive Coulomb forces increases much fraster than that associated with the attractive nuclear forces.

† The superscript in this notation is the *mass number* $A = N + Z$). This is the total number of particles in the nucleus. See the sloping lines in Figure 26-6.

The radioactive "parent" nucleus, U^{238}, contains 92 protons (that is, its atomic number $Z = 92$). It disintegrates spontaneously by emitting an α-particle (He^4; $Z = 2$) transmuting itself into the nucleus Th234, with $Z = 90$. Thus the amount of charge present before disintegration ($+92e$) is the same as that present after the disintegration.

An additional example of charge conservation is found in nuclear reactions, of which the bombardment of Ca^{44} with cyclotron-accelerated protons is typical. In a particular collision a neutron may emerge from the nucleus, leaving Sc^{44} as a "residual" nucleus:

$$\mathrm{Ca}^{44} + p \rightarrow \mathrm{Sc}^{44} + n$$

The sum of the atomic numbers before the reaction (20+1) is exactly equal to the sum of the atomic numbers after the reactions (21+0). Again, charge is conserved.

A final example of charge conservation is the decay of the K-meson (see appendix F) which, in one mode, goes as

$$\mathrm{K}^0 \rightarrow \pi^+ + \pi^-$$

The resultant charge is zero both before and after this decay process.

questions

1. You are given two metal spheres mounted on portable insulating supports. Find a way to give them equal and opposite charges. You may use a glass rod rubbed with silk but may not touch it to the spheres. Do the spheres have to be of equal size for your method to work?
2. In Question 1, find a way to give the spheres equal charges of the same sign. Again, do the spheres need to be of equal size for your method to work?
3. A charged rod attracts bits of dry cork dust which, after touching the rod, often jump violently away from it. Explain.
4. In Section 26-2 can there not be four kinds of charge, that is, on glass, silk, plastic and fur? What is the argument against this?
5. If you rub a coin briskly between your fingers, it will not seems to become charged by friction. Why?
6. If you walk briskly down the carpeted corridor of a hotel, you often experience a spark upon touching a door knowb. *a*) What causes this? *b*) How might it be prevented?
7. Why do electrostatic experiments not work well on himd days?
8. An insulated rod is said to carry an electric charge. How could you verify this and determine the sign of the charge?
9. If a charged glass rod is held near one end of an insulated uncharged metal rod as in Fig. 26-7, electrons are drawn to one end, as shown. Whe does the flow of electrons cease? There is an almost inexhaustible supply of them in the metal rod.
10. In Fig. 26-7 does any electrical force act on the metal rod? Explain.
11. A person standing on an insulated stool touches a charged insulated conductor. Is the conductor discharged completely?
12. (*a*) A positively charged glass rod attracts a suspended object. Can we conclude that the object is negatively charged? (*b*) A positiviely charged glass rod repels a suspended object. Can we conclude that the object is positively charged?

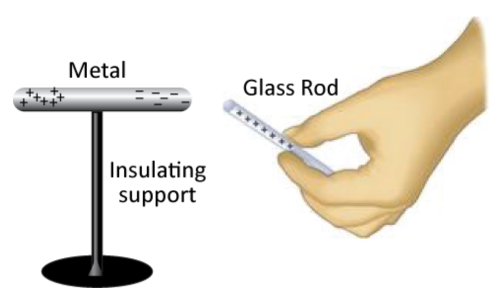

figure 26-7
Questions 9, 10

13. Is the Coulomb force that one charge exerts on another changed if other charges are brought nearby?
14. You are given a collection of small charged spheres, the sign and magnitude of the charge and the mass of the sphere being at your disposal. Do you think that a *stable* equilibrium position is possible, involving only electrostatic forces? Test several arrangements. A rigorous answer is not required.
15. Suppose that someone told you that in Eq. 26-3 the product of the charges q1q2) should be replaced by their algebraic sum (q1 + q2). What experimental facts refute this statement? What if the square root of their product were proposed?
16. The quantum of charge is 1.6 10-19 C. Is there a corresponding single quantum of mass?
17. A nucleus U238 splits into two identical parts. Are the nuclei so produced likely to be stable or radioactive?
18. In the decay mode

    what is the charge of the L particle? See Appendix F.
19. Verify the fact that the decay schemes for the elementary particles in Appendix F are consistent with charge conservation.
20. What does it mean to say that a physical quantity is *a*) quantized or *b*) conserved? Give some examples.