By the 1950s and 1960s many new types of particles similar to the neutron and proton were discovered, as well as many "midsized" particles called *mesons* whose masses were mostly less than nucleon masses but more than the electron mass. Physicists felt that all of these particles could not be fundamental, and must be made up of even smaller constituents, which were given the name *quarks*.

Today, the basic constituents of matter are considered to be **quarks** (they make up the protons and neutrons of atomic nuclei as well as mesons) and **leptons** (a class that includes electrons, positrons, and neutrinos); in addition there are the "carriers of force" including *gluons* and the photon. The theory that describes our present view is called the **standard model**. How we came to our present understanding of elementary particles is the subject of this Chapter.

One of the exciting recent developments of the last few years is an emerging synthesis between the study of elementary particles and astrophysics (Chapter 33). In fact, very recent observations in astrophysics have led to the conclusion that the greater part of the mass–energy content of the universe is not ordinary matter but two mysterious and invisible forms known as "dark matter" and "dark energy" which cannot be explained by the standard model in its present form.

32–1 High-Energy Particles and Accelerators

In the years after World War II, it was found that if the incoming particle in a nuclear reaction has sufficient energy, new types of particles can be produced. The earliest experiments used **cosmic rays**—particles that impinge on the Earth from space. In the laboratory, various types of particle accelerators have been constructed to accelerate protons or electrons, although heavy ions can also be accelerated. These **high-energy accelerators** have been used to probe the nucleus more deeply, to produce and study new particles, and to give us information about the basic forces and constituents of nature. Because the projectile particles are at high energy, this field is sometimes called **high-energy physics**.

Wavelength and Resolution

Particles accelerated to high energy can probe the interior of nuclei and nucleons that they strike. An important factor is that faster-moving projectiles can reveal more detail. The wavelength of projectile particles is given by de Broglie's wavelength formula (Eq. 27–8),

de Broglie wavelength

$$\lambda = \frac{h}{p}, \tag{32–1}$$

showing that the greater the momentum p of the bombarding particle, the shorter its wavelength. As discussed in Chapter 25 on optical instruments, resolution of details in images is limited by the wavelength: the shorter the wavelength, the finer the detail that can be obtained. This is one reason why particle accelerators of higher and higher energy have been built in recent years: to probe ever deeper into the structure of matter, to smaller and smaller size.

EXAMPLE 32–1 **High resolution with electrons.** What is the wavelength, and hence the expected resolution, for a beam of 1.3-GeV electrons?

APPROACH Because 1.3 GeV is much larger than the electron rest mass, we must be dealing with relativistic speeds. The momentum of the electrons is found from Eq. 26–10, and the wavelength $\lambda = h/p$.