EXAMPLE 32–3 **Speed of a 1.0-TeV proton.** What is the speed of a 1.0-TeV proton produced at Fermilab?

APPROACH $\text{KE} = 1.0\,\text{TeV} = 1.0 \times 10^{12}\,\text{eV}$ is much greater than the rest mass of the proton, $0.938 \times 10^{9}\,\text{eV}$, so relativistic calculations must be used. In particular, we use Eq. 26–6:

$$\text{KE} = (\gamma - 1)m_0c^2 = \frac{m_0c^2}{\sqrt{1 - v^2/c^2}} - m_0c^2.$$

SOLUTION Compared to the KE of $1.0 \times 10^{12}\,\text{eV}$, the rest energy ($\approx 10^{-3}\,\text{TeV}$) can be neglected, so we write

$$\text{KE} = \frac{m_0c^2}{\sqrt{1 - v^2/c^2}}.$$

Then

$$1 - \frac{v^2}{c^2} = \left(\frac{m_0c^2}{\text{KE}}\right)^2$$

or

$$\frac{v}{c} = \sqrt{1 - \left(\frac{m_0c^2}{\text{KE}}\right)^2} = \sqrt{1 - \left(\frac{938 \times 10^6\,\text{eV}}{1.0 \times 10^{12}\,\text{eV}}\right)^2}$$

$$v = 0.9999996c.$$

The proton is traveling at a speed extremely close to c, the speed of light.

32–2 Beginnings of Elementary Particle Physics—Particle Exchange

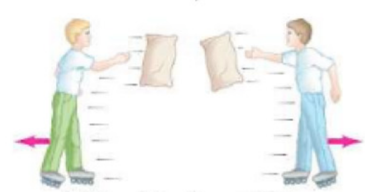
The accepted model for elementary particles today views *quarks* and *leptons* as the basic constituents of ordinary matter. To understand our present-day view we need to begin with the ideas leading up to its formulation.†

Elementary particle physics might be said to have begun in 1935 when the Japanese physicist Hideki Yukawa (1907–1981) predicted the existence of a new particle that would in some way mediate the strong nuclear force. To understand Yukawa's idea, we first consider the electromagnetic force. When we first discussed electricity, we saw that the electric force acts over a distance, without contact. To better perceive how a force can act over a distance, we used the idea of a **field**. The force that one charged particle exerts on a second can be said to be due to the electric field set up by the first. Similarly, the magnetic field can be said to carry the magnetic force. Later (Chapter 22), we saw that electromagnetic (EM) fields can travel through space as waves. Finally, in Chapter 27, we saw that electromagnetic radiation (light) can be considered as either a wave or as a collection of particles called *photons*. Because of this wave–particle duality, it is possible to imagine that the electromagnetic force between charged particles is due to

(1) the EM field set up by one charged particle and felt by the other, or
(2) an exchange of photons (γ particles) between them.

It is (2) that we want to concentrate on here, and a crude analogy for how an exchange of particles could give rise to a force is suggested in Fig. 32–6. In part (a), two children start throwing heavy pillows at each other; each throw and each catch results in the child being pushed backward by the impulse. This is the equivalent of a repulsive force. On the other hand, if the two children exchange pillows by grabbing them out of the other person's hand, they will be pulled toward each other, as when an attractive force acts.

FIGURE 32–6 Forces equivalent to particle exchange. (a) Repulsive force (children throwing pillows at each other). (b) Attractive force (children grabbing pillows from each other's hands).



(a) Repulsive force (children throwing pillows)

(b) Attractive force (children grabbing pillows from each other's hands)

†Just telling you how it is today would not be a scientific discussion; nor would it give understanding—see footnote on page 769.