Notice that a photon cannot create an electron alone since electric charge would not then be conserved. The inverse of pair production also occurs: if an electron collides with a positron, the two **annihilate** each other and their energy, including their mass, appears as electromagnetic energy of photons. Because of this process, positrons usually do not last long in nature.

Electron–positron annihilation is the basis for the type of medical imaging known as PET, as discussed in Section 31–8.

EXAMPLE 27–9 **Pair production.** (*a*) What is the minimum energy of a photon that can produce an electron–positron pair? (*b*) What is this photon's wavelength?

APPROACH The minimum photon energy E equals the rest energy (m_0c^2) of the two particles created, via Einstein's famous equation $E = m_0c^2$ (Eq. 26–8). There is no energy left over, so the particles produced will have zero KE. The wavelength is $\lambda = c/f$ where $E = hf$ for the original photon.

SOLUTION (*a*) Because $E = m_0c^2$, and the mass created is equal to two electron rest masses, the photon must have energy

$$E = 2(9.11 \times 10^{-31}\,\mathrm{kg})(3.0 \times 10^{8}\,\mathrm{m/s})^2 = 1.64 \times 10^{-13}\,\mathrm{J} = 1.02\,\mathrm{MeV}$$

Minimum energy to produce e^+e^- pair is 1.02 MeV

$(1\,\mathrm{MeV} = 10^6\,\mathrm{eV} = 1.60 \times 10^{-13}\,\mathrm{J})$. A photon with less energy cannot undergo pair production.

(*b*) Since $E = hf = hc/\lambda$, the wavelength of a 1.02-MeV photon is

$$\lambda = \frac{hc}{E} = \frac{(6.63 \times 10^{-34}\,\mathrm{J\cdot s})(3.0 \times 10^{8}\,\mathrm{m/s})}{(1.64 \times 10^{-13}\,\mathrm{J})} = 1.2 \times 10^{-12}\,\mathrm{m},$$

which is 0.0012 nm. Such photons are in the gamma-ray (or very short X-ray) region of the electromagnetic spectrum (Fig. 22–8).

NOTE Photons of higher energy (shorter wavelength) can also create an electron–positron pair, with the excess energy becoming kinetic energy of the particles.

Pair production cannot occur in empty space, for momentum could not be conserved. In Example 27–9, for instance, energy is conserved, but only enough energy was provided to create the electron–positron pair at rest and thus with no momentum to carry away the initial momentum of the photon. Indeed, it can be shown that at any energy, an additional massive object, such as an atomic nucleus, must take part in the interaction to carry off some of the momentum.

27–7 Wave–Particle Duality; the Principle of Complementarity

The photoelectric effect, the Compton effect, and other experiments have placed the particle theory of light on a firm experimental basis. But what about the classic experiments of Young and others (Chapter 24) on interference and diffraction which showed that the wave theory of light also rests on a firm experimental basis?

We seem to be in a dilemma. Some experiments indicate that light behaves like a wave; others indicate that it behaves like a stream of particles. These two theories seem to be incompatible, but both have been shown to have validity. Physicists finally came to the conclusion that this duality of light must be accepted as a fact of life. It is referred to as the **wave–particle duality**. Apparently, light is a more complex phenomenon than just a simple wave or a simple beam of particles.

Wave–particle duality