Interactions of Photons with Matter

If an intense beam of light is directed at the surface of an absorbing material, the energy of the photons is mostly absorbed by that surface. As a result, the surface heats up. But the Compton effect shows that photons transfer momentum as well. The sum of the impacts on the surface of all of the photons per unit of time results in pressure on the surface. This pressure is not normally discernible. (We do not feel the pressure of light when we walk out into sunlight or stand under a strong lamp.) Today, however, using very sensitive equipment, we can actually measure the pressure of light on a surface and confirm that the relationship $p = \frac{h}{\lambda}$ is a valid expression for the momentum of an individual photon.

pair production the creation of a pair of particles (an electron and a positron) as a result of a collision of a high-energy photon with a nucleus

We have seen, with both the photoelectric effect and the Compton effect, that when a photon comes into contact with matter, there is an interaction. Five main interactions are possible:

1. The most common interaction is simple reflection, as when photons of visible light undergo perfectly elastic collisions with a mirror.
2. In the case of the photoelectric effect, a photon may liberate an electron, being absorbed in the process.
3. In the Compton effect, the photon emerges with less energy and momentum, having ejected a photoelectron. After its interaction with matter, the photon still travels at the speed of light but is less energetic, having a lower frequency.
4. A photon may interact with an individual atom, elevating an electron to a higher energy level within the atom. In this case, the photon completely disappears. All of its energy is transferred to the atom, causing the atom to be in an energized, or "excited," state. (We will examine the details of this interaction later in this chapter.)
5. A photon can disappear altogether, creating two particles of nonzero mass in a process called **pair production** (see Section 13.1). Pair production requires a photon of very high energy (>1.02 MeV) and, correspondingly, a very short wavelength (as with X-ray and gamma-ray photons). When such a photon collides with a heavy nucleus, it disappears, creating an electron (${}_{0}^{-}e$) and a particle of equal mass but opposite charge, the positron (${}_{0}^{+}e$) (**Figure 20**). This creation of mass from energy obeys Einstein's mass–energy equivalence equation $E = mc^2$.

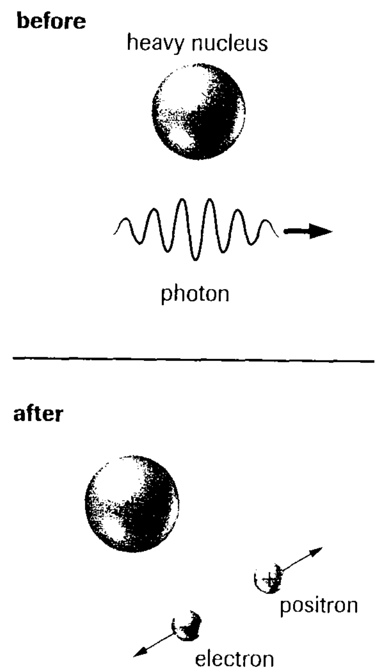

Figure 20
Representation of pair production

▸ Practice

Understanding Concepts

17. Show that the units of $\frac{h}{\lambda}$ are units of momentum.

18. Calculate the momentum of a photon whose wavelength is 5.00×10^2 nm.

19. Calculate the momentum of a photon whose frequency is 4.5×10^{15} Hz.

20. Calculate the momentum of a 1.50×10^2 eV photon.

21. Calculate the wavelength of a photon having the same momentum as an electron moving at 1.0×10^6 m/s.

Answers

18. 1.33×10^{-27} kg·m/s
19. 9.9×10^{-27} kg·m/s
20. 8.00×10^{-26} kg·m/s
21. 0.73 nm

LEARNING TIP

Photon Pressure

If a surface is highly reflective, each photon undergoes twice as great a change in momentum as it would in absorption, and the radiation pressure on the surface is twice as great as the radiation pressure on an absorptive surface. This is analogous to comparing a bouncing ball with a chunk of sticky putty.

▸ Practice

Understanding Concepts

1. Calculate the de Broglie wavelength associated with each of the following:
   (a) a 2.0-kg ball thrown at 15 m/s
   (b) a proton accelerated to 1.3×10^5 m/s
   (c) an electron moving at 5.0×10^4 m/s

2. Calculate the de Broglie wavelengths, in metres, associated with a 3.0-eV photon and a 5.0-eV electron.

3. Calculate the de Broglie wavelength associated with an artillery shell having a mass of 0.50 kg and a speed of 5.00×10^2 m/s.

4. Calculate the energy, in electron volts, required to give an electron an associated de Broglie wavelength of 0.15 nm.

5. An electron is accelerated through a potential difference of 1.00×10^2 V. Calculate the associated de Broglie wavelength.

6. (a) Calculate the momentum of an electron that has an associated de Broglie wavelength of 1.0×10^{-10} m.
   (b) Calculate the speed of the same electron.
   (c) Calculate the kinetic energy of the same electron.

Answers

1. (a) 2.2×10^{-35} m
   (b) 3.0×10^{-12} m
   (c) 1.5×10^{-8} m
2. 4.1×10^{-7} m; 5.5×10^{-10} m
3. 2.7×10^{-36} m
4. 67 eV
5. 1.23×10^{-10} m
6. (a) 6.6×10^{-24} kg·m/s
   (b) 7.3×10^6 m/s
   (c) 2.7×10^{-17} J, or 1.52×10^2 eV