Check Your Understanding

12. How did Einstein's model of photons change the view of a beam of energy leaving a flashlight?
   a. A beam of light energy is now considered a continual stream of wave energy, not photons.
   b. A beam of light energy is now considered a collection of photons, each carrying its own individual energy.

13. True or false—Visible light is the only type of electromagnetic radiation that can cause the photoelectric effect.
   a. false
   b. true

14. Is the photoelectric effect a direct consequence of the wave character of EM radiation or the particle character of EM radiation?
   a. The photoelectric effect is a direct consequence of the particle nature of EM radiation.
   b. The photoelectric effect is a direct consequence of the wave nature of EM radiation.
   c. The photoelectric effect is a direct consequence of both the wave and particle nature of EM radiation.
   d. The photoelectric effect is a direct consequence of neither the wave nor the particle nature of EM radiation.

15. Which aspects of the photoelectric effect can only be explained using photons?
   a. aspects 1, 2, and 3
   b. aspects 1, 2, and 4
   c. aspects 1, 2, 4 and 5
   d. aspects 1, 2, 3, 4 and 5

16. In a photovoltaic cell, what energy transformation takes place?
   a. Solar energy transforms into electric energy.
   b. Solar energy transforms into mechanical energy.
   c. Solar energy transforms into thermal energy.
   d. In a photovoltaic cell, thermal energy transforms into electric energy.

17. True or false—A current is created in a photoconductive cell, even if only one electron is expelled from a photon strike.
   a. false
   b. true

18. What is a photon and how is it different from other fundamental particles?
   a. A photon is a quantum packet of energy; it has infinite mass.
   b. A photon is a quantum packet of energy; it is massless.
   c. A photon is a fundamental particle of an atom; it has infinite mass.
   d. A photon is a fundamental particle of an atom; it is massless.

21.3 The Dual Nature of Light

Section Learning Objectives

By the end of this section, you will be able to do the following:

- Describe the Compton effect
- Calculate the momentum of a photon
- Explain how photon momentum is used in solar sails
- Explain the particle-wave duality of light

Section Key Terms

Compton effect	particle-wave duality	photon momentum

Photon Momentum

Do photons abide by the fundamental properties of physics? Can packets of electromagnetic energy possibly follow the same rules as a ping-pong ball or an electron? Although strange to consider, the answer to both questions is yes.

Despite the odd nature of photons, scientists prior to Einstein had long suspected that the fundamental particle of electromagnetic radiation shared properties with our more macroscopic particles. This is no clearer than when considering the photoelectric effect, where photons knock electrons out of a substance. While it is strange to think of a massless particle exhibiting momentum, it is now a well-established fact within the scientific community. Figure 21.10 shows macroscopic evidence of **photon momentum**.

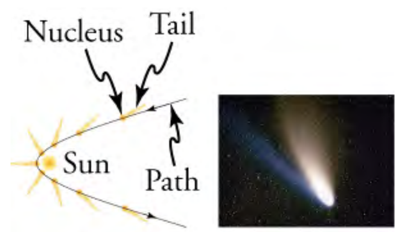

Figure 21.10 The tails of the Hale-Bopp comet point away from the Sun, evidence that light has momentum. Dust emanating from the body of the comet forms this tail. Particles of dust are pushed away from the Sun by light reflecting from them. The blue, ionized gas tail is also produced by photons interacting with atoms in the comet material. (credit: Geoff Chester, U.S. Navy, via Wikimedia Commons)

Figure 21.10 shows a comet with two prominent tails. Comet tails are composed of gases and dust evaporated from the body of the comet and ionized gas. What most people do not know about the tails is that they always point *away* from the Sun rather than trailing behind the comet. This can be seen in the diagram.

Why would this be the case? The evidence indicates that the dust particles of the comet are forced away from the Sun when photons strike them. Evidently, photons carry momentum in the direction of their motion away from the Sun, and some of this momentum is transferred to dust particles in collisions. The blue tail is caused by the solar wind, a stream of plasma consisting primarily of protons and electrons evaporating from the corona of the Sun.

Momentum, The Compton Effect, and Solar Sails

Momentum is conserved in quantum mechanics, just as it is in relativity and classical physics. Some of the earliest direct experimental evidence of this came from the scattering of X-ray photons by electrons in substances, a phenomenon discovered by American physicist Arthur H. Compton (1892–1962). Around 1923, Compton observed that X-rays reflecting from materials had decreased energy and correctly interpreted this as being due to the scattering of the X-ray photons by electrons. This phenomenon could be handled as a collision between two particles—a photon and an electron at rest in the material. After careful observation, it was found that both energy and momentum were conserved in the collision. See Figure 21.11. For the discovery of this conserved scattering, now known as the **Compton effect**, Arthur Compton was awarded the Nobel Prize in 1929.

Shortly after the discovery of Compton scattering, the value of the photon momentum, $\mathbf{p} = \frac{h}{\lambda}$,

was determined by Louis de Broglie. In this equation, called the de Broglie relation, h represents Planck's constant and λ is the photon wavelength.

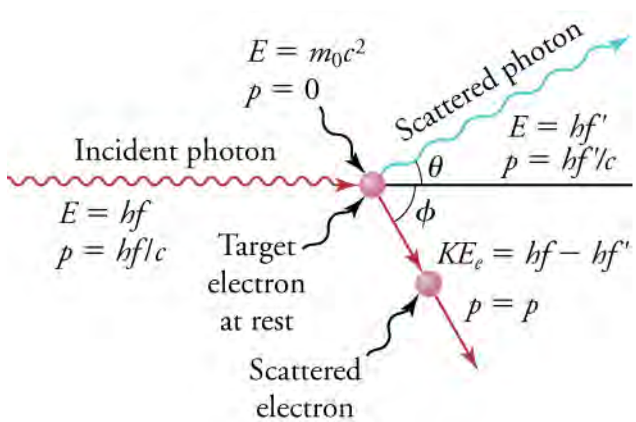

Figure 21.11 The Compton effect is the name given to the scattering of a photon by an electron. Energy and momentum are conserved, resulting in a reduction of both for the scattered photon.

We can see that photon momentum is small, since $\mathbf{p} = h/\lambda$. and h is very small. It is for this reason that we do not ordinarily observe photon momentum. Our mirrors do not recoil when light reflects from them, except perhaps in cartoons. Compton saw the effects of photon momentum because he was observing X-rays, which have a small wavelength and a relatively large momentum, interacting with the lightest of particles, the electron.

WORKED EXAMPLE

Electron and Photon Momentum Compared

(a) Calculate the momentum of a visible photon that has a wavelength of 500 nm. (b) Find the velocity of an electron having the same momentum. (c) What is the energy of the electron, and how does it compare with the energy of the photon?

Strategy

Finding the photon momentum is a straightforward application of its definition: $\mathbf{p} = h/\lambda$. If we find the photon momentum is small, we can assume that an electron with the same momentum will be nonrelativistic, making it easy to find its velocity and kinetic energy from the classical formulas.

Solution for (a)

Photon momentum is given by the de Broglie relation.

$$\mathbf{p} = \frac{h}{\lambda} \tag{21.12}$$

Entering the given photon wavelength yields

$$\mathbf{p} = \frac{6.63 \times 10^{-34} J \cdot s}{5.00 \times 10^{-7}\text{m}} = 1.33 \times 10^{-27}\text{kg} \cdot \text{m/s}. \tag{21.13}$$

Solution for (b)

Since this momentum is indeed small, we will use the classical expression $p = mv$ to find the velocity of an electron with this momentum. Solving for v and using the known value for the mass of an electron gives

$$v = \frac{\text{p}}{m} = \frac{1.33 \times 10^{-27}\text{kg} \cdot \text{m/s}}{9.11 \times 10^{-31}\text{kg}} = 1{,}459.9 \text{ m/s} \approx 1{,}460 \text{ m/s}. \tag{21.14}$$

Solution for (c)

The electron has kinetic energy, which is classically given by

$$KE_e = \frac{1}{2}mv^2. \tag{21.15}$$

Thus,

$$KE_e = \frac{1}{2}(9.11 \times 10^{-31}\text{kg})(1{,}456\text{m/s})^2 = 9.64 \times 10^{-25}\text{J}. \tag{21.16}$$

Converting this to eV by multiplying by $\frac{(1 \text{ eV})}{(1.602 \times 10^{-19}\text{J})}$ yields

$$KE_e = 6.02 \times 10^{-6}\text{eV}. \tag{21.17}$$

The photon energy E is

$$E = \frac{hc}{\lambda} = \frac{\left(6.63 \times 10^{-34}\text{J} \cdot \text{s}\right)\left(3.00 \times 10^{8} \text{ m/s}\right)}{5.00 \times 10^{-7}\text{m}} = 3.98 \times 10^{-19} \text{ J} = 2.48 \text{ eV}, \tag{21.18}$$

which is about five orders of magnitude greater.

Discussion

Even in huge numbers, the total momentum that photons carry is small. An electron that carries the same momentum as a 500-nm photon will have a 1,460 m/s velocity, which is clearly nonrelativistic. This is borne out by the experimental observation that it takes far less energy to give an electron the same momentum as a photon. That said, for high-energy photons interacting with small masses, photon momentum may be significant. Even on a large scale, photon momentum can have an effect if there are enough of them and if there is nothing to prevent the slow recoil of matter. Comet tails are one example, but there are also proposals to build space sails that use huge low-mass mirrors (made of aluminized Mylar) to reflect sunlight. In the vacuum of space, the mirrors would gradually recoil and could actually accelerate spacecraft within the solar system. See the following figure.

TIPS FOR SUCCESS

When determining energies in particle physics, it is more sensible to use the unit eV instead of Joules. Using eV will help you to recognize differences in magnitude more easily and will make calculations simpler. Also, eV is used by scientists to describe the binding energy of particles and their rest mass, so using eV will eliminate the need to convert energy quantities. Finally, eV is a convenient unit when linking electromagnetic forces to particle physics, as one eV is the amount energy given to an electron when placed in a field of 1-V potential difference.

Practice Problems

19. Find the momentum of a 4.00-cm wavelength microwave photon.

a. 0.83×10^{-32} kg · m/s
b. 1.66×10^{-34} kg · m/s
c. 0.83×10^{-34} kg · m/s
d. 1.66×10^{-32} kg · m/s

20. Calculate the wavelength of a photon that has the same momentum of a proton moving at 1.00 percent of the speed of light.

a. 2.43×10^{-10} m
b. 2.43×10^{-12} m
c. 1.32×10^{-15} m
d. 1.32×10^{-13} m

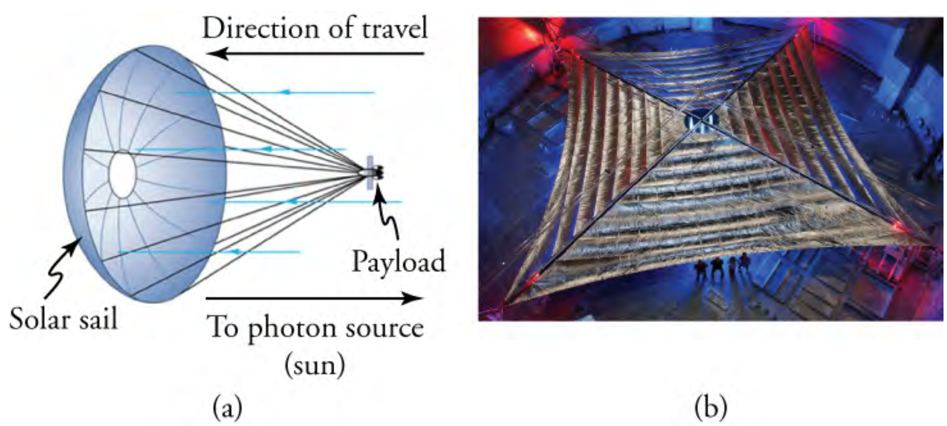

Figure 21.12 (a) Space sails have been proposed that use the momentum of sunlight reflecting from gigantic low-mass sails to propel spacecraft about the solar system. A Russian test model of this (the Cosmos 1) was launched in 2005, but did not make it into orbit due to a rocket failure. (b) A U.S. version of this, labeled LightSail-1, is scheduled for trial launches in 2016. It will have a 40 m2 sail. (credit: Kim Newton/NASA)

LINKS TO PHYSICS

LightSail-1 Project

“Provide ships or sails adapted to the heavenly breezes, and there will be some who will brave even that void.”

— Johannes Kepler (in a letter to Galileo Galilei in 1608)

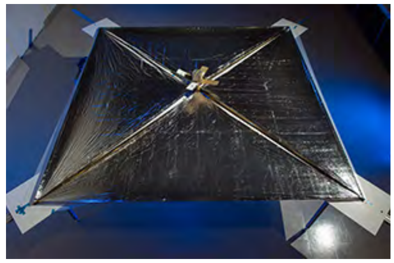

Figure 21.13 NASA's NanoSail-D, a precursor to LightSail-1, with its sails deployed. The Planetary Society will be launching LightSail-1 in early 2016. (credit: NASA/MSFC/D, Wikimedia Commons)

Traversing the Solar System using nothing but the Sun's power has long been a fantasy of scientists and science fiction writers alike. Though physicists like Compton, Einstein, and Planck all provided evidence of light's propulsive capacity, it is only recently that the technology has become available to truly put these visions into motion. In 2016, by sending a lightweight satellite into space, the LightSail-1 project is designed to do just that.

A citizen-funded project headed by the Planetary Society, the 5.45-million-dollar LightSail-1 project is set to launch two crafts into orbit around the Earth. Each craft is equipped with a 32-square-meter solar sail prepared to unfurl once a rocket has launched it to an appropriate altitude. The sails are made of large mirrors, each a quarter of the thickness of a trash bag, which will receive an impulse from the Sun's reflecting photons. Each time the Sun's photon strikes the craft's reflective surface and bounces off, it will provide a momentum to the sail much greater than if the photon were simply absorbed.

Attached to three tiny satellites called CubeSats, whose combined volume is no larger than a loaf of bread, the received momentum from the Sun's photons should be enough to record a substantial increase in orbital speed. The intent of the LightSail-1 mission is to prove that the technology behind photon momentum travel is sound and can be done cheaply. A test flight in May 2015 showed that the craft's Mylar sails could unfurl on command. With another successful result in 2016, the Planetary Society will be planning future versions of the craft with the hopes of eventually achieving interplanetary satellite travel. Though a few centuries premature, Kepler's fantastic vision may not be that far away.

If eventually set into interplanetary launch, what will be the effect of continual photon bombardment on the motion of a craft similar to LightSail-1?

a. It will result in continual acceleration of the craft.
b. It will first accelerate and then decelerate the craft.
c. It will first decelerate and then accelerate the craft.
d. It will result in the craft moving at constant velocity.

Particle-Wave Duality

We have long known that EM radiation is like a wave, capable of interference and diffraction. We now see that light can also be modeled as particles—massless photons of discrete energy and momentum. We call this twofold nature the **particle-wave duality**, meaning that EM radiation has properties of both particles and waves. This may seem contradictory, since we ordinarily deal with large objects that never act like both waves and particles. An ocean wave, for example, looks nothing like a grain of sand. However, this so-called duality is simply a term for properties of the photon analogous to phenomena we can observe directly, on a macroscopic scale. See Figure 21.14. If this term seems strange, it is because we do not ordinarily observe details on the quantum level directly, and our observations yield either particle-like *or* wave-like properties, but never both simultaneously.

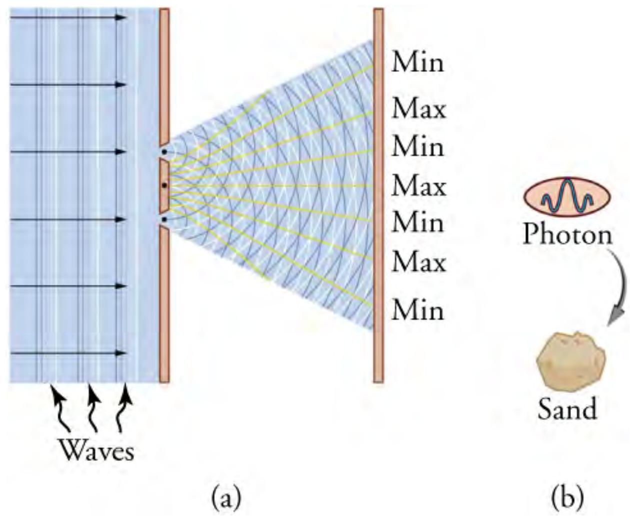

Figure 21.14 (a) The interference pattern for light through a double slit is a wave property understood by analogy to water waves. (b) The properties of photons having quantized energy and momentum and acting as a concentrated unit are understood by analogy to macroscopic particles.

Since we have a particle-wave duality for photons, and since we have seen connections between photons and matter in that both have momentum, it is reasonable to ask whether there is a particle-wave duality for matter as well. If the EM radiation we once thought to be a pure wave has particle properties, is it possible that matter has wave properties? The answer, strangely, is yes. The consequences of this are tremendous, as particle-wave duality has been a constant source of scientific wonder during the twentieth and twenty-first centuries.

Check Your Understanding

21. What fundamental physics properties were found to be conserved in Compton scattering?
    a. energy and wavelength
    b. energy and momentum
    c. mass and energy
    d. energy and angle

22. Why do classical or relativistic momentum equations not work in explaining the conservation of momentum that occurs in Compton scattering?
    a. because neither classical nor relativistic momentum equations utilize mass as a variable in their equations
    b. because relativistic momentum equations utilize mass as a variable in their formulas but classical momentum equations do not
    c. because classical momentum equations utilize mass as a variable in their formulas but relativistic momentum equations do not
    d. because both classical and relativistic momentum equations utilize mass as a variable in their formulas

23. If solar sails were constructed with more massive materials, how would this influence their effectiveness?
    a. The effect of the momentum would increase due to the decreased inertia of the sails.
    b. The effect of the momentum would reduce due to the decreased inertia of the sails.
    c. The effect of the momentum would increase due to the increased inertia of the sails.
    d. The effect of the momentum would be reduced due to the increased inertia of the sails.

24. True or false—It is possible to propel a solar sail craft using just particles within the solar wind.
    a. true
    b. false

25. True or false—Photon momentum more directly supports the wave model of light.
    a. false
    b. true

26. True or false—wave-particle duality exists for objects on the macroscopic scale.

a. false
b. true

27. What type of electromagnetic radiation was used in Compton scattering?

a. visible light
b. ultraviolet radiation
c. radio waves
d. X-rays