

Topic 13 | The Photon

A Case Study in Quantum Physics

The interference effects discussed in Chapter 35, and similar effects to be discussed in Chapter 36, show clearly the *wave* nature of light. But many other phenomena show a different aspect of the nature of light, in which it seems to behave as a stream of *particles*. For example, when a photograph of an interference pattern is made by using extremely weak monochromatic light and electronic image amplification, the pattern does not build up uniformly. Instead, first a light spot appears at one point, then another spot appears at another point, and so on. As the pattern emerges, the regions of maximum intensity have the greatest number of spots, the regions of zero intensity have none, and so forth.

This behavior suggests that the energy in a light wave is not a continuous stream, but rather is *quantized* into a succession of little bundles of energy. These bundles are called *quanta* or **photons**. We don't notice this effect in ordinary photography because the total number of spots is extremely large.

The concept of quantization of energy was introduced by the German physicist Max Planck in 1900. He used this concept as a computational technique in a calculation aimed at predicting the energy distribution among various wavelengths in the spectrum of radiation from hot objects. Einstein recognized in 1905 that the quantization of energy was far more than a computational trick and that instead it was a fundamental aspect of the nature of light. He used this concept to analyze the photoelectric effect, a process in which electrons are liberated from a conducting surface when light strikes it. Einstein assumed that an electron at the surface absorbs one photon and thus gains enough energy to escape from the surface.

Einstein assumed that the energy E of an individual photon was proportional to the frequency f of the light, with a proportionality constant h that is now called **Planck's constant**:

$$E = hf = \frac{hc}{\lambda} \quad (\text{energy of a photon}), \quad (\text{T13.1})$$

where c is the speed of light and $\lambda = c/f$ is the wavelength of the radiation in vacuum. Detailed measurements of the spectra of blackbody radiation and of the photoelectric effect confirmed the correctness of the photon concept and also enabled physicists to determine the numerical value of Planck's constant. To four significant figures,

$$h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}$$

Thus light has a dual personality that includes aspects of *both* waves and particles. Light can form interference patterns that are similar to those of sound and water waves. But if the light in the pattern is examined closely enough, it is found to be made of particle-like photons. This duality is present not only in visible light but in the entire spectrum of electromagnetic radiation. In some experiments and with some frequency ranges, one aspect or the other may predominate, but fundamentally, both are always present. The following example shows why the particle aspects of *visible* light are normally not evident. Example T13.2 shows why these same particle aspects are dominant for gamma rays, which have much higher frequency than visible light.

Example T13.1

The familiar red light emitted by a helium-neon laser (used in grocery checkout scanners and many other applications) has a wavelength of 632.8 nm. If the power output is 1.00 mW, how many photons of this light does the laser emit each second?

SOLUTION

First we use Eq. (T13.1) to find the energy of each photon:

$$E = \frac{hc}{\lambda} = \frac{(6.626 \times 10^{-34} \text{ J}\cdot\text{s})(3.00 \times 10^8 \text{ m/s})}{632.8 \times 10^{-9} \text{ m}}$$
$$s = 3.14 \times 10^{-19} \text{ J}$$

A power output of 1.00 mW means that the laser is emitting $1.00 \times 10^{-3} \text{ J}$ of energy each second; the number of photons per second is

$$\frac{1.00 \times 10^{-3} \text{ J/s}}{3.14 \times 10^{-19} \text{ J/photon}} = 3.18 \times 10^{15} \text{ photons/s}$$

Even this very low-power source of light emits an *enormous* number of photons each second, far too many to distinguish individually. Quantization is ordinarily not evident for visible light because each photon has only a tiny amount of energy.

Example T13.2

A gamma-ray photon emitted during the decay of a radioactive cobalt-60 nucleus has an energy of $2.135 \times 10^{-13} \text{ J}$. What are the frequency and wavelength of this electromagnetic radiation?

SOLUTION

From Eq. (T13.1) we have

$$f = \frac{E}{h} = \frac{2.135 \times 10^{-13} \text{ J}}{6.626 \times 10^{-34} \text{ J}\cdot\text{s}} = 3.222 \times 10^{20} \text{ Hz}$$

This is roughly a million times larger than frequencies of visible light. The wavelength λ is

$$\lambda = \frac{c}{f} = \frac{3.00 \times 10^8 \text{ m/s}}{3.222 \times 10^{20} \text{ Hz}} = 9.31 \times 10^{-13} \text{ m}$$

Particle aspects are much more evident for gamma rays than for visible light because an individual gamma-ray photon has roughly a million times more energy than a visible-light photon. With this much energy an individual gamma-ray photon is relatively easy to detect with any of several types of particle detectors, such as a Geiger counter or a solid-state detector.

Conversely, the *wave* properties of visible light are easy to see in interference patterns, but interference effects with gamma rays with wavelength of $9.31 \times 10^{-13} \text{ m}$ are very difficult to detect. If we use gamma rays with $\lambda = 9.31 \times 10^{-13} \text{ m}$, the distance from the center of the pattern to the third bright fringe with $m = 3$ is:

$$y_3 = R \frac{m\lambda}{d} = (1.0 \text{ m}) \frac{3(9.31 \times 10^{-13} \text{ m})}{0.20 \times 10^{-3} \text{ m}} = 1.4 \times 10^{-8} \text{ m}$$

This is too small to measure easily, which shows that interference effects for these gamma rays are hard to detect.

Momentum of Photons and Particles

Any material particle that has kinetic energy has momentum as well, and photons also have momentum. Einstein showed, as part of his special theory of relativity, that a photon with energy E has momentum \vec{p} with magnitude p given by

$$E = pc \quad (\text{T13.2})$$

Using the relation $c = \lambda f$ and rearranging, we find

$$p = \frac{E}{c} = \frac{hf}{c} = \frac{h}{\lambda} \quad (\text{T13.3})$$

The direction of p is the direction in which the electromagnetic wave is traveling.

The phenomenon of *radiation pressure* is associated with the momentum carried by electromagnetic waves. Equation (T13.3) shows us that this momentum is quantized. Just as the pressure that a gas exerts on a wall of its container results from the momentum change of gas molecules during impact, radiation pressure results from the momentum change of photons when they strike a surface and are absorbed or reflected.

We've seen that electromagnetic waves have particle-like properties, with the magnitude of the photon momentum given by $p = h/\lambda$. Nature is full of beautiful and sometimes surprising symmetries. In 1924 the French physicist Louis de Broglie suggested that particles as well as electromagnetic waves might have the dual wave-particle nature that we have described. If $p = h/\lambda$ holds for particles such as electrons as well as for photons, then a moving particle has a wavelength. Let's consider an electron (mass $m = 9.11 \times 10^{-31}$ kg) in the electron beam of a cathode-ray tube. An electron accelerated through a potential difference of 100 V has a speed $v = 5.93 \times 10^6$ m/s. The momentum of this electron is

$$\begin{aligned} p &= mv = (9.11 \times 10^{-31} \text{ kg})(5.93 \times 10^6 \text{ m/s}) \\ &= 5.40 \times 10^{-24} \text{ kg} \cdot \text{m/s} \end{aligned}$$

According to de Broglie's hypothesis, the wavelength λ is

$$\begin{aligned} \lambda &= \frac{h}{p} = \frac{6.626 \times 10^{-34} \text{ J} \cdot \text{s}}{5.40 \times 10^{-24} \text{ kg} \cdot \text{m/s}} \\ &= 1.23 \times 10^{-10} \text{ m} = 0.123 \text{ nm} \end{aligned}$$

This value is comparable to the spacing of atoms in a crystal. In 1927, the American physicists Clinton Davisson and Lester Germer observed interference effects in the scattering of an electron beam from the surface of a crystal of nickel. They inferred correctly that their results demonstrated the wave properties of electrons. Measurements of the interference pattern enabled them to determine the wavelengths of the electrons and to confirm de Broglie's hypothesis directly.

Electron beams are now used routinely in electron microscopes. The small wavelengths make it possible to see details that are far smaller than the wavelengths of visible light and hence beyond the range of optical microscopes.

The number of photons in the universe is not a conserved quantity; photons are created and destroyed in many processes. This lack of permanence may seem to distinguish photons from other particles such as electrons that we think of as having a permanent existence. But electrons (and all other particles) can also be created and destroyed, within the limitations imposed by various conservation laws including energy, momentum, angular momentum, electric charge, and others. Thus, ultimately, there is no fundamental distinction between photons and the other particles found in nature. Each type of particle has its individual characteristics and modes of interaction, but all are described with the same general language.