12.2 Photons and the Quantum Theory of Light

Figure 1 Laser light shows at concerts are one application of the particle nature of light.

Lasers are used everywhere, from concert light shows to grocery store checkout lines to cutting-edge research labs (**Figure 1**). Although classical physics says that light behaves as a wave, the discovery that light also has particle properties led to the development of the laser and other breakthroughs in light technology. In this section, you will read about photons ("particles" of light) and the nature of light, as well as some key experiments and discoveries that led to a deeper understanding of the nature of electromagnetic radiation.

The Work Function

Around 1800, Thomas Young performed his double-slit interference experiment, which provided the first clear evidence that light is a wave. Maxwell worked out his theory of electromagnetic waves about 60 years later. Then, physicists developed a detailed theory of light as an electromagnetic wave and thought that the nature of light was well understood. In the 1880s, however, studies of what happens when light shines onto metal gave some very puzzling results that the wave theory of light could not explain.

Metal contains electrons that are free to move around within the metal. However, these electrons are still bound as a whole to the metal because of their attraction to the positive charges of the metal atom nuclei. Energy is required to remove electrons from the atoms.

work function (W) the minimum energy needed to remove an electron bound to a metal surface

The minimum energy required to remove a single electron from a piece of metal is called the **work function**, W. The work function has units of energy. For convenience, researchers often give the value of the work function in electron-volts (eV) rather than joules. One electron-volt is defined as the amount of energy given to an electron that accelerates through a potential difference of one volt. To convert electron-volts to joules, use the following conversion factor:

$$1\ \text{eV} = 1.60 \times 10^{-19}\ \text{J}$$

You can measure the work function of a metal by applying an electric potential. In **Figure 2**, when the electric potential energy of the electrons exceeds the work function, electrons are ejected from the top metal and move to the metal plate below. The smallest electric potential difference able to eject electrons gives the value of the work function, W:

$$W = e\Delta V$$

where ΔV is the electric potential difference at which electrons begin to jump across the vacuum gap in Figure 2, and e is the elementary charge, 1.6×10^{-19} C.

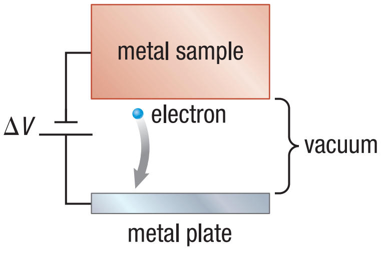

Figure 2 Electrons will leave a metal sample and will move into a metal plate when the applied voltage is above a certain level. That voltage times the elementary charge equals the work function.

Table 1 lists the values of the work functions for common materials in both joules and electron-volts.

Table 1 Work Functions of Several Metals

Metal	Work function (J)	Work function (eV)
aluminum (Al)	6.73×10^{-19}	4.20
calcium (Ca)	4.60×10^{-19}	2.87
cesium (Cs)	3.12×10^{-19}	1.95
copper (Cu)	8.17×10^{-19}	5.10
iron (Fe)	7.48×10^{-19}	4.67
lead (Pb)	6.81×10^{-19}	4.25
platinum (Pt)	9.04×10^{-19}	5.64
potassium (K)	3.67×10^{-19}	2.29
silver (Ag)	7.43×10^{-19}	4.64
sodium (Na)	3.78×10^{-19}	2.36

The Photoelectric Effect

Another way to extract electrons from a metal is by shining light onto it. Light striking a metal surface is absorbed by the electrons. If an electron absorbs an amount of light energy above the metal's work function, it ejects from the metal in a phenomenon called the **photoelectric effect**. **Figure 3(a)** shows the photoelectric effect. Experimental studies of the photoelectric effect carried out around 1900 revealed that no electrons are emitted unless the light's frequency is greater than the **threshold frequency**, f_0, which is the minimum frequency at which electrons are ejected from a material. When the frequency is above f_0, the kinetic energy of the emitted electrons varies linearly with frequency f, as shown in **Figure 3(b)**. Physicists tried to explain these results using the classical wave theory of light, but two difficulties existed with the classical explanations.

photoelectric effect the phenomenon of electrons being ejected from a material when exposed to electromagnetic radiation

threshold frequency (f_0) the minimum frequency at which electrons are ejected from a metal

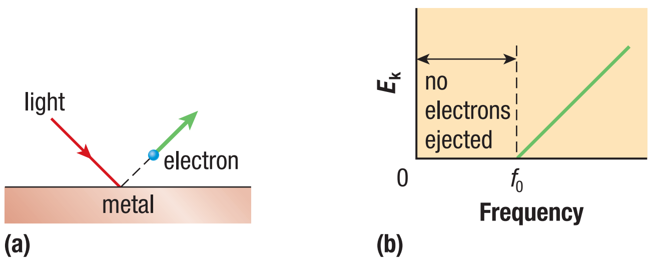

Figure 3 (a) In the photoelectric effect, electrons are ejected from a metal when light at or above a certain frequency strikes it. (b) Experiments show that the kinetic energy of the ejected electrons, E_k, depends on the frequency of the light. When the frequency is below the threshold frequency, no electrons are ejected.

First, experiments show that the threshold frequency is independent of the intensity of the light. Recall the discussion from Section 12.1 in which we compared the differences between particles and waves: According to classical wave theory, the energy carried by a light wave is proportional to the intensity of the light. It should always be possible to eject electrons by increasing the intensity to a sufficiently high value. Experiments found that when the frequency is below the threshold frequency, however, no electrons are ejected, no matter how great the light intensity.

Second, the kinetic energy of an ejected electron is independent of the light intensity. Classical theory predicts that increasing the intensity will increase the kinetic energy of the electrons, but experiments do not show this.

Many scientists refused to abandon the classical wave theory and continued to look for complicated ways to explain the photoelectric effect. Some scientists looked for interference from other sources of electromagnetic noise, and some considered errors from preparing the metallic samples. Quantum theory eventually prevailed as the accepted explanation.

Einstein's Quantum Theory of Light

photon a discrete bundle of energy carried by light

In 1905, Albert Einstein proposed that light should be thought of as a collection of particles, now called **photons**. Photons have two important properties that are quite different from classical particles. Photons do not have any mass, and they exhibit interference effects, as electrons do in double-slit interference experiments. Photons are unlike any other particle in classical physics.

According to Einstein, each photon carries a parcel of maximum kinetic energy (quantum) according to the following equation:

$$E_{\text{photon}} = hf$$

Planck's constant (*h*) a constant with the value 6.63×10^{-34} J·s; represents the ratio of the energy of a single quantum to its frequency

where f is the frequency of the light and h is a constant of nature called **Planck's constant**, which has the value 6.63×10^{-34} J·s. Planck's constant had been introduced a few years earlier by Max Planck to explain another unexpected property of electromagnetic radiation, the blackbody radiation spectrum, discussed later in this section.

Einstein's photon, or quantum, theory explains the two puzzles associated with photoelectric experiments. In fact, Einstein won the Nobel Prize for Physics in 1921 for his contributions regarding the photoelectric effect. First, the absorption of light by an electron is just like a collision between two particles, a photon and an electron. The photon carries energy hf, which the electron absorbs. When this energy is less than the work function, the electron is not able to escape from the metal. For monochromatic light, increasing the light intensity increases the number of photons that arrive each second. However, if the photon energy is less than the work function, even a high-intensity light will not eject electrons. The energy of a single photon—and hence the energy gained by any particular electron—depends on the frequency but not on the light intensity. Electrons can be ejected with varying speeds and, therefore, varying kinetic energies. However, in our discussion of the photoelectric effect, we are concerned with the electron's maximum kinetic energy.

Second, Einstein's quantum theory also explains why the kinetic energy of ejected electrons depends on light frequency but not intensity. The threshold frequency in the photoelectric effect (Figure 3(b)) corresponds to photons whose energy is equal to the work function, W:

$$hf_0 = W$$

Such a photon has barely enough energy to eject an electron from the metal, but the ejected electron then has no kinetic energy. If a photon has a higher frequency and thus a greater energy, the extra energy above the work function goes into the kinetic energy of the electron. So

$$E_{\text{k}} = hf - hf_0$$
$$E_{\text{k}} = hf - W$$

This is the equation of a straight line. Hence, the kinetic energy of an ejected electron should be linearly proportional to f. This linear behaviour is precisely what is found in experiments (**Figure 4** on the next page). The slope of this line is the factor that is multiplied by f, which is Planck's constant, h.

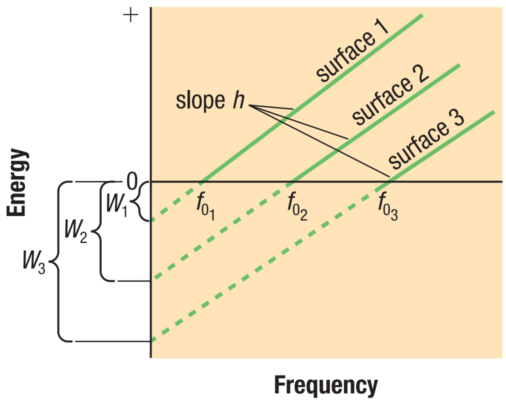

Figure 4 The slope of the energy of ejected electrons versus the frequency of incident light does not change for the three surfaces, even though they each have a different work function. The slope equals *h*.

Investigation 12.2.1

The Photoelectric Effect (page 654)
This investigation will give you an opportunity to simulate the photoelectric effect and work with the work function equation.

Photoelectric experiments give a way to measure *h*, and the values found agree with the value known prior to Einstein's quantum theory. Tutorial 1 models how to solve problems involving the photoelectric effect.

Tutorial 1 Solving Problems Involving the Photoelectric Effect

This Sample Problem models how to apply Einstein's theory of the photoelectric effect to determine the lowest photon energy that light must have to cause emission of electrons from a given metal.

Sample Problem 1: Determining Photon Energy

Aluminum is being used in a photoelectric effect experiment. According to Table 1 on page 621, the work function of aluminum is 6.73×10^{-19} J.

(a) Calculate the minimum photon energy and frequency needed to emit electrons.

(b) Incident blue light of wavelength 450 nm is used in the experiment. Determine whether any electrons are emitted, and if they are, determine their maximum kinetic energy.

Solution

(a) **Given:** $W = 6.73 \times 10^{-19}$ J; $h = 6.63 \times 10^{-34}$ J·s

Required: the lowest energy, E_{photon}, that photons must have to cause emission of electrons; frequency, f_0

Analysis: The lowest photon energy must satisfy the equation $E_{\text{photon}} = W$, and the frequency this corresponds to is f_0 in the equation $E_{\text{photon}} = hf_0$.

$$f_0 = \frac{E_{\text{photon}}}{h}$$

Solution: $E_{\text{photon}} = W$

$$E_{\text{photon}} = 6.73 \times 10^{-19}\ \text{J}$$

$$f_0 = \frac{E_{\text{photon}}}{h} = \frac{6.73 \times 10^{-19}\ \cancel{\text{J}}}{6.63 \times 10^{-34}\ \cancel{\text{J}}\cdot\text{s}}$$

$$f_0 = 1.02 \times 10^{15}\ \text{Hz}$$

Statement: The minimum energy needed to emit electrons is 6.73×10^{-19} J, corresponding to using incident light with a frequency of 1.02×10^{15} Hz.

(b) **Given:** $\lambda = 450$ nm $= 4.50 \times 10^{-7}$ m; $W = 6.73 \times 10^{-19}$ J; $h = 6.63 \times 10^{-34}$ J·s; $c = 3.0 \times 10^8$ m/s

Required: E_k

Analysis: The energy of the photon is $E_{\text{photon}} = hf$, and the frequency is related to the wavelength by $\lambda f = c$. Therefore,

$$\lambda f = c$$

$$f = \frac{c}{\lambda}$$

$$E_{\text{photon}} = hf$$

$$E_{\text{photon}} = \frac{hc}{\lambda}$$

If E_{photon} is greater than W, then electrons can be emitted by the incident photon. If that happens, then the maximum kinetic energy an ejected electron can have is the incident photon energy minus the work function W:

$$E_k = E_{\text{photon}} - W$$

Solution: $E_{\text{photon}} = \dfrac{hc}{\lambda}$

$$= \frac{(6.63 \times 10^{-34}\ \text{J}\cdot\cancel{\text{s}})\left(3.0 \times 10^8\ \frac{\cancel{\text{m}}}{\cancel{\text{s}}}\right)}{4.50 \times 10^{-7}\ \cancel{\text{m}}}$$

$$E_{\text{photon}} = 4.4 \times 10^{-19}\ \text{J}$$

This energy is less than W. No electrons are ejected.

Statement: The frequency of the 450 nm wavelength light is too low and the photon energy is too low for electrons to be emitted from aluminum by means of the photoelectric effect.

Practice

1. A photoelectric effect experiment uses calcium instead of aluminum. Determine the lowest photon energy that can cause emission of electrons by means of the photoelectric effect. Refer to Table 1 on page 621. T/I A [ans: 4.60×10^{-19} J]
2. The wavelength of light incident on a clean metal surface is slowly decreased. The emission of electrons from the metal first occurs at a wavelength of 268 nm. Determine the work function of the metal. Then use Table 1 to determine whether the metal is silver or lead. T/I A [ans: 7.42×10^{-19} J; silver]

Photons Possess Energy and Momentum

Einstein's quantum theory states that light energy can only be absorbed or emitted in discrete parcels, that is, as single photons. Each photon carries an energy, E_{photon}, equal to hf. The classical theory of electromagnetic waves predicts that a light wave with energy E also carries a certain amount of momentum,

$$p = \frac{E}{c}$$

You can also derive this formula (as Einstein did) from the formulas for the relativistic energy and momentum for an object with zero mass.

Identifying the energy E with E_{photon}, Einstein's quantum theory predicts that the momentum of a single photon is

$$p_{\text{photon}} = \frac{hf}{c}$$

The wavelength of a light wave is related to its frequency as

$$f\lambda = c$$

So, substituting $f\lambda$ for c in the photon momentum equation gives

$$p_{\text{photon}} = \frac{hf}{c}$$

$$= \frac{h\cancel{f}}{\cancel{f}\lambda}$$

$$p_{\text{photon}} = \frac{h}{\lambda}$$

Evidence of Photon Momentum

In 1923, American physicist A.H. Compton (1892–1962) discovered a phenomenon that provided experimental evidence of the momentum carried by individual photons. Instead of using visible light, Compton directed a beam of high-energy X-ray photons at a thin metal foil. The foil ejected both electrons and lower-energy X-ray photons. This effect, in which incident X-ray photons lose energy and scatter off a metal foil along with free electrons, is called the **Compton effect**.

Compton effect the elastic scattering of photons by high-energy photons

Compton conducted a series of experiments using different metal foils and different beams of X-rays. X-rays have higher-energy photons, and the electron is able to absorb only some of this energy. In contrast, in a typical photoelectric experiment, lower-energy photons are used, and the electron is able to absorb all the energy, leaving none left over for a residual photon. Each test produced similar results that could not be explained using electromagnetic wave theory. The results suggested to Compton that each incident X-ray photon acts like a particle in an elastic collision with an electron in the metal. The photon emerges from the collision with lower energy and a different momentum. The electron deflects with the kinetic energy and momentum lost by the photon (**Figure 5**).

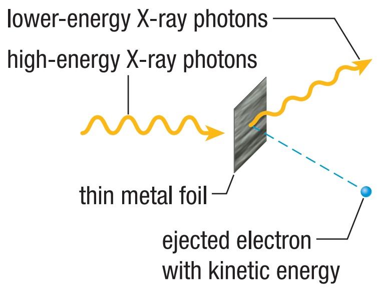

Figure 5 The Compton effect results when X-ray radiation scatters from a metal and ejects an electron. The effect can be explained as an elastic collision between a photon and an electron in the metal.

Compton's data indicated that the effect conserves both energy and momentum. Compton had to use equations of special relativity to analyze the collisions, including the equations for relativistic momentum that you learned about in Section 11.3. He would not have obtained the correct results without using special relativity. In this way, Einstein's ideas on relativity and the speed of light influenced work that confirmed Einstein's ideas about the behaviour and characteristics of photons.

Photon Energy

We can use the equation $E_{\text{photon}} = hf$ to calculate the energy carried by a single photon. For example, a green laser pointer with a wavelength of about 530 nm has a frequency of 5.7×10^{14} Hz. This frequency corresponds to an energy of 3.8×10^{-19} J, which is quite a small amount of energy. This is much smaller than what you might encounter in the everyday world. In most applications, you can detect the presence or absence of light (the presence or absence of one or more photons) through the energy carried by the light. If each photon of light has so little energy, you can infer that a laser beam must contain a huge number of photons.

In the following Tutorial, you will solve problems related to the momentum and energy of a photon.

Tutorial 2 Analyzing Photon Energy and Momentum

In the following Sample Problem, you will examine how the momentum and energy of a photon depend on the photon's frequency.

Sample Problem 1: Analyzing the Momentum and Energy of a Photon

A certain AM radio station has a frequency near 1.0 MHz, and a certain FM station has a frequency near 110 MHz. Radio waves are electromagnetic waves, so the radio waves produce photons.

(a) Compare the momentum of the photons from the AM station with the momentum of the photons from the FM station.

(b) Compare the energy of the photons from the AM and the FM stations.

Solution

(a) **Given:** $f_{\text{AM}} = 1.0 \text{ MHz} = 1.0 \times 10^6 \text{ Hz}$; $f_{\text{FM}} = 110 \text{ MHz} = 1.10 \times 10^8 \text{ Hz}$; $h = 6.63 \times 10^{-34} \text{ J}\cdot\text{s}$; $c = 3.0 \times 10^8 \text{ m/s}$

Required: p_{photon}, the momentum of the photon at each given frequency

Analysis:

$$p_{\text{photon}} = \frac{h}{\lambda} = \frac{hf}{c}$$

Solution: For the AM station:

$$p_{\text{photon AM}} = \frac{hf}{c}$$

$$= \frac{(6.63 \times 10^{-34} \text{ J}\cdot\cancel{\text{s}})\left(1.0 \times 10^6 \frac{1}{\cancel{\text{s}}}\right)}{3.0 \times 10^8 \text{ m/s}}$$

$$p_{\text{photon AM}} = 2.2 \times 10^{-36} \text{ kg}\cdot\text{m/s}$$

For the FM station:

$$p_{\text{photon FM}} = \frac{(6.63 \times 10^{-34}\ \text{J}\cdot\cancel{\text{s}})\left(1.10 \times 10^{8}\ \frac{1}{\cancel{\text{s}}}\right)}{3.0 \times 10^{8}\ \text{m/s}}$$

$$p_{\text{photon FM}} = 2.4 \times 10^{-34}\ \text{kg}\cdot\text{m/s}$$

Statement: The photons from the FM station have the greater momentum.

(b) **Given:** $f_{\text{AM}} = 1.0\ \text{MHz} = 1.0 \times 10^{6}\ \text{Hz}$; $f_{\text{FM}} = 110\ \text{MHz} = 1.10 \times 10^{8}\ \text{Hz}$; $h = 6.63 \times 10^{-34}\ \text{J}\cdot\text{s}$

Required: E_{photon}, the energy of the photon at each given frequency

Analysis: $E_{\text{photon}} = hf$

Solution: For the AM station:

$$E_{\text{photon AM}} = hf$$

$$= (6.63 \times 10^{-34}\ \text{J}\cdot\cancel{\text{s}})\left(1.0 \times 10^{6}\ \frac{1}{\cancel{\text{s}}}\right)$$

$$E_{\text{photon AM}} = 6.6 \times 10^{-28}\ \text{J}$$

For the FM station:

$$E_{\text{photon FM}} = (6.63 \times 10^{-34}\ \text{J}\cdot\cancel{\text{s}})\left(1.10 \times 10^{8}\ \frac{1}{\cancel{\text{s}}}\right)$$

$$E_{\text{photon FM}} = 7.3 \times 10^{-26}\ \text{J}$$

Statement: The higher-frequency FM photons have higher energy.

Practice

1. Calculate the momentum of a photon with a wavelength of 450 nm. T/I A [ans: 1.5×10^{-27} kg·m/s]
2. A hand-held laser pointer emits photons with a wavelength of 630 nm. Determine the energy of these photons. T/I A [ans: 3.2×10^{-19} J]
3. Suppose an atomic nucleus at rest emits a gamma ray with energy 140 keV (which is 2.2×10^{-14} J). Calculate the momentum of the gamma ray. T/I A [ans: 7.3×10^{-23} kg·m/s]

Photon Interactions

In both the photoelectric effect and the Compton effect, when a photon comes into contact with matter, an interaction takes place. Five main interactions can occur:

1. A photon may simply reflect, as when photons of visible light undergo perfectly elastic collisions with a mirror.
2. A photon may free an electron and be absorbed in the process, as in the photoelectric effect.
3. A photon may emerge with less energy and momentum after freeing an electron. After this interaction with matter, the photon still travels at the speed of light but with less energy and a lower frequency. This is the Compton effect.
4. A photon may be absorbed by an individual atom and elevate an electron to a higher energy level within the atom. (You will read more about energy levels in Section 12.6.) The electron remains within the atom but is in what is called an *excited* state.
5. A photon can undergo **pair creation**, where it becomes converted into two particles with mass. This process conserves energy and momentum because all the energy of the photon becomes converted into the kinetic energy of the new particles and their rest mass energy.

pair creation the transformation of a photon into two particles with mass

Blackbody Radiation

blackbody an object that absorbs all radiation reaching it

blackbody radiation radiation emitted by an ideal blackbody

In 1901, Max Planck was studying blackbodies and blackbody radiation. A **blackbody** is an object that absorbs all radiation reaching it, and **blackbody radiation** is radiation emitted by a blackbody. The specific problem that puzzled Planck is represented by the glowing oven in **Figure 6(a)**. This oven emits radiation over a range of wavelengths and frequencies, as shown in **Figure 6(b)**. To the eye, the colour of the oven is determined by the wavelength of the largest radiation intensity.

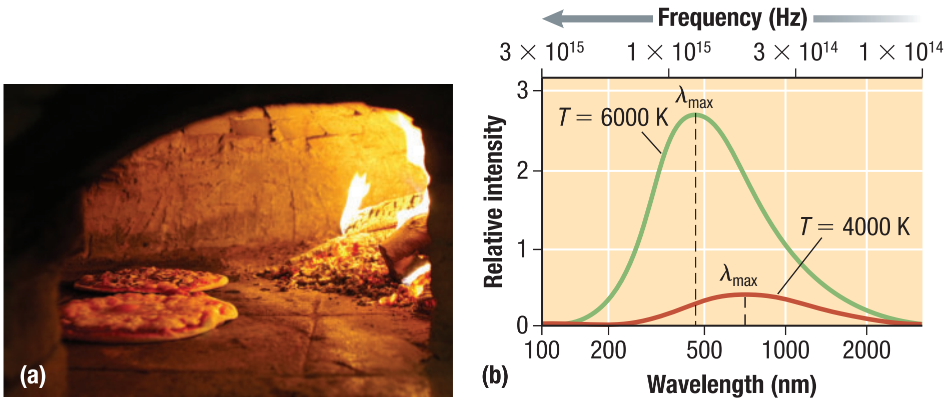

Figure 6 (a) This pizza oven is an approximate blackbody. (b) Light emitted from an ideal blackbody follows the blackbody spectrum shown here. The wavelength, λ_{max}, at which the radiation intensity is largest depends on the temperature of the blackbody.

Experiments prior to Planck's work showed that the intensity curve in Figure 6(b) has the same shape for a wide variety of objects. The blackbody intensity falls to zero at both long and short wavelengths, corresponding to low and high frequencies, respectively, with a peak in the middle. Planck tried to explain this behaviour.

At that time, physicists knew that electromagnetic waves form standing waves as they reflect back and forth inside an oven. These standing waves are just like the standing waves on a string. Standing waves on a string have frequencies that follow the pattern $f_n = nf_0$, where f_0 is the fundamental frequency and $n = 1, 2, 3, \ldots$ (**Figure 7**).

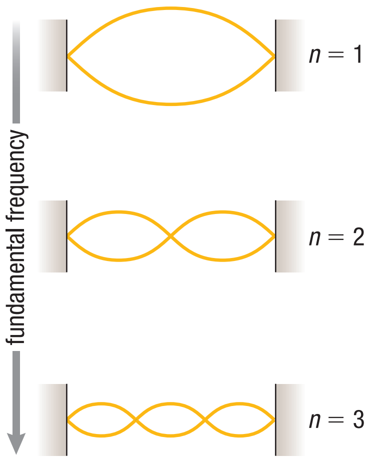

Figure 7 Standing waves form on a string fixed at both ends. The frequency increases as a multiple of the fundamental frequency, f_0.

Standing electromagnetic waves in an oven follow the same mathematical pattern. There is no limit to the value of n (as long as it is a whole number), so the frequency, f_n, of a standing electromagnetic wave in a blackbody can be infinitely large. According to classical physics, each of these standing waves carries energy, and as their frequency increases, so does the total energy. As a result, the classical theory predicts that the blackbody intensity should become infinite as the frequency approaches infinite values.

Investigation 12.2.2

Determining Planck's Constant (page 656)

In this investigation, you will measure Planck's constant in a simple circuit using LEDs.

LEARNING **TIP**

Kelvin Temperature Scale

The kelvin (K) temperature scale is an extension of the degree Celsius scale down to absolute zero, a hypothetical temperature characterized by a complete absence of thermal energy. To convert from a Celsius temperature to a kelvin temperature, simply add 273. Subtract 273 to convert from kelvins to degrees Celsius. For example, absolute zero is 0 K and –273 °C. Temperatures expressed in kelvins do not take the degree symbol.

Planck's Hypothesis

Planck and other physicists of the time thought that any theory that predicts that the intensity of radiation is infinite could not possibly be correct. Such a theory would also be in conflict with the experimental intensity curves in Figure 6(b) because the true intensity falls to zero at high frequencies. Furthermore, nearly all objects act as approximate blackbodies. It is quite difficult to imagine how all objects could emit an infinite amount of energy and still be consistent with our ideas about conservation of energy.

This disagreement between theory and experiment is called the ultraviolet catastrophe. It is called the ultraviolet catastrophe because the predicted infinite intensity is found at high frequencies, and high-frequency visible light falls at the ultraviolet end of the electromagnetic spectrum.

Despite much effort, physicists were not able to connect classical theory with the observed blackbody behaviour. Many researchers had different ideas about how they might solve the problem. Until Planck offered an explanation that fit all the details, multiple theories existed.

Planck resolved this disagreement by hypothesizing that the energy in a blackbody comes in discrete parcels (quanta). He believed that each parcel has energy equal to hf_n, where f_n is one of the standing-wave frequencies and h is a universal constant. Planck showed that this hypothesis supports the theory of blackbody radiation so that it correctly produces the blackbody spectrum in Figure 6(b). However, he could give no reason or justification for his assumption about standing-wave quanta.

His theory of blackbody radiation could fit the experiments perfectly, but no one (including Planck) knew why it worked. Einstein answered that question in part. The standing electromagnetic waves in a blackbody consist of photons. These photons have quantized energies given by Planck's expression, hf_n. While Einstein's photon theory supported Planck's result, physicists would still need several decades of study before they fully worked out and understood the photon concept.

Wien's Law

In Figure 6(b) on page 627, the wavelength at which the radiation intensity of a blackbody is largest is denoted by λ_{max} and is determined by the temperature, T, of the blackbody through an expression called Wien's law:

$$\lambda_{max} = \frac{2.90 \times 10^{-3}\ \text{m}\cdot\text{K}}{T}$$

Here, T is measured in the kelvin temperature scale. According to Wien's law, the value of λ_{max}, and hence the colour of the blackbody, depends on the temperature. A hotter object (higher T) has a smaller value of λ_{max}, and the entire blackbody curve in Figure 6(b) shifts to shorter wavelengths when the temperature is increased. A flame that appears blue (shorter wavelength) is therefore hotter than one that is red (longer wavelength).

One technology that applies Wien's law is an ear thermometer (**Figure 8**), which detects the radiation from inside your ear. According to Wien's law, the wavelength at which the radiation intensity is largest depends on temperature. This thermometer measures λ_{max} and then uses Wien's law to calculate your body temperature. In Tutorial 3, you will use Wien's law to solve blackbody problems.

Figure 8 Ear thermometers use blackbody radiation to calculate body temperature.

Tutorial 3 Solving Problems Related to Blackbody Radiation

This Tutorial models how to use Wien's law to solve problems related to blackbody radiation.

Sample Problem 1: Analyzing Blackbody Radiation

A blackbody would appear to our eye to have a colour determined by the wavelength at which the radiation is most intense. Use **Table 2** to determine the colour of a blackbody that radiates at 4143 K and a blackbody that radiates at 6444 K.

Table 2 Wavelengths of Visible Light

Colour	Wavelength range (m)
red	6.25×10^{-7} to 7.40×10^{-7}
orange	5.90×10^{-7} to 6.25×10^{-7}
yellow	5.65×10^{-7} to 5.90×10^{-7}
green	5.20×10^{-7} to 5.65×10^{-7}
cyan	5.00×10^{-7} to 5.20×10^{-7}
blue	4.35×10^{-7} to 5.00×10^{-7}
violet	3.80×10^{-7} to 4.35×10^{-7}

Given: $T_1 = 4143$ K; $T_2 = 6444$ K

Required: λ_1; λ_2

Analysis: $\lambda_{max} = \dfrac{2.90 \times 10^{-3}\ \text{m·K}}{T}$

Solution:

$$\lambda_{max} = \frac{2.90 \times 10^{-3}\ \text{m·K}}{T}$$

$$\lambda_1 = \frac{2.90 \times 10^{-3}\ \text{m·K}}{T_1}$$

$$= \frac{2.90 \times 10^{-3}\ \text{m·}\cancel{\text{K}}}{4143\ \cancel{\text{K}}}$$

$$\lambda_1 = 7.00 \times 10^{-7}\ \text{m}$$

$$\lambda_2 = \frac{2.90 \times 10^{-3}\ \text{m·K}}{T_2}$$

$$= \frac{2.90 \times 10^{-3}\ \text{m·}\cancel{\text{K}}}{6444\ \cancel{\text{K}}}$$

$$\lambda_2 = 4.50 \times 10^{-7}\ \text{m}$$

Statement: The 4143 K blackbody has a peak wavelength of 7.00×10^{-7} m, which is red light. The 6444 K blackbody has a peak wavelength of 4.50×10^{-7} m, which is blue light.

Practice

1. Determine the colour of a blackbody that radiates at 5100 K. Refer to Table 2. [ans: yellow] T/I
2. A certain blackbody appears to have an aqua colour. The wavelength of the emitted radiation is 510 nm. Determine the temperature of the blackbody. T/I A [ans: 5700 K]
3. The human body emits electromagnetic radiation according to the body's temperature (37 °C). Estimate λ_{max} for the human body. Can you see this electromagnetic radiation? Explain your answer. T/I A [ans: 9.4×10^{-6} m]

Wave–Particle Nature of Light

The photoelectric effect and blackbody radiation can only be understood in terms of the particle nature of light. While light has some properties like those of a classical particle, it also has wave properties such as interference.

In Section 12.1, you read about a double-slit experiment with electrons and observed how the electrons arrive one at a time at the screen. Light behaves in precisely the same way. Consider a double-slit experiment performed with light with a very low intensity. Suppose the screen responds to the arrival of individual photons by emitting light from the spot where the photon strikes. The results would then appear just as in **Figure 9** on the next page. The full interference pattern at the far right becomes visible only after many photons have reached the screen. As with electrons, this experiment shows both the particle nature of light (the arrival of individual photons) and the wave nature of light (interference) at the same time.

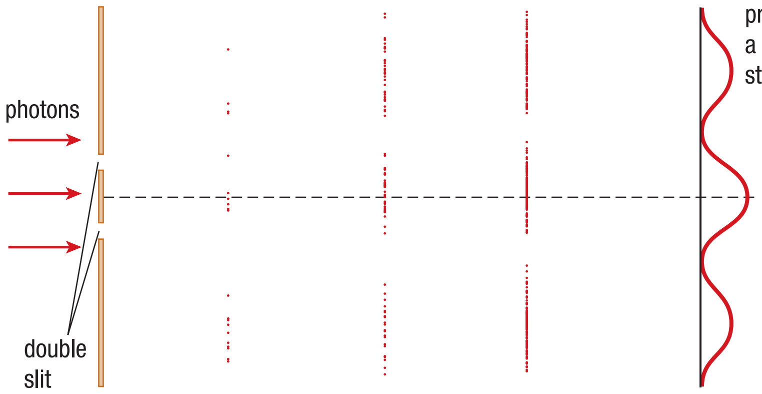

Figure 9 Light with a very low intensity produces an interference pattern of photons.

Research This

Exploring Photonics

Skills: Researching, Analyzing, Evaluating, Communicating SKILLS HANDBOOK A4.1

The particle nature of light forms the basis for the development of photonics technology. Photonics technology uses light in different functions in various fields of electronics. In this activity, you will research a specific photonics technology that works because of the particle nature of light.

1. Choose a technology or process that uses the particle nature of light, such as lasers (light production), light sensors, photocells (**Figure 10**), or photosynthesis.

Figure 10 A photocell

2. Research your choice, and find out how the particle nature of light is applied.
3. Determine how quantum theory led to the development of the technology or process that you chose.
4. Investigate any new advances in the field of photonics related to your choice.
5. Research the economic, environmental, and social impacts of your chosen technology or process, if applicable. Include both positive and negative impacts in your research.
6. Research the Canadian Photonics Consortium.

A. How does the particle nature of light make the technology or process work? K/U A

B. How is the technology or concept made possible through the understanding of quantum theory? K/U T/I

C. What are some examples of other related emerging technologies? T/I A

D. How many Canadian companies are part of the Canadian Photonics Consortium? Approximately how many people are employed by photonics companies in the consortium?

WEB LINK

12.2 Review

Summary

- The work function, W, is the minimum energy needed to remove an electron bound to a metal surface. The work function equation is $W = eV$.
- A photon is a quantum of electromagnetic energy. The quantum theory of light says that photons have both energy and momentum.
- The energy of a photon is given by $E = hf$.
- The momentum of a photon is given by $p = \frac{hf}{c} = \frac{h}{\lambda}$.
- Planck's constant, h, is a universal constant with a value of 6.63×10^{-34} J·s.
- In the photoelectric effect, electrons are ejected when light with a certain minimum frequency strikes a metal. Energy is conserved during this process.
- In the Compton effect, electrons are ejected when X-rays strike a metal. Energy and momentum are conserved during this process.
- Planck explained the observed spectrum of blackbody radiation by hypothesizing that the energy in a blackbody comes in discrete parcels called quanta.
- The photoelectric effect and blackbody radiation demonstrate that photons exhibit both wave-like and particle-like properties.

Questions

1. The work function for a metal is 5.0 eV. Determine the minimum photon frequency that can just eject an electron from the metal. T/I
2. A photocell is a light sensor that affects the flow of current in a circuit based on the amount of light falling on the cell. When light strikes the cell, the photoelectric effect causes electrons to eject from a metal piece in the cell and flow through the circuit. You are designing a photocell to work with visible light and are considering the use of either aluminum or cesium. Aluminum has a work function of 4.20 eV, and cesium has a work function of 1.95 eV. K/U T/I A
   (a) Which one is the better choice? Explain your answer.
   (b) Calculate the lowest photon frequency that can be measured with your photocell.
   (c) Determine where this frequency falls in the electromagnetic spectrum. Refer to **Table 3**.

Table 3 Frequencies of Electromagnetic Waves

Wave	Frequency (Hz)
radio	$< 3.0 \times 10^9$
microwave	3.0×10^9 to 3.0×10^{12}
infrared	3.0×10^{12} to 4.3×10^{14}
visible light	4.3×10^{14} to 7.5×10^{14}
ultraviolet	7.5×10^{14} to 3.0×10^{17}
X-ray	3.0×10^{17} to 3.0×10^{19}
gamma	$> 3.0 \times 10^{19}$

3. A wavelength of dim red light ejects no electrons. Suppose you increase the intensity by a factor of 1000. Explain whether the red light can now eject electrons according to the photoelectric effect. T/I C
4. Calculate the photon energy and momentum for each of the following. T/I A
   (a) FM radio with a frequency of 100 MHz
   (b) red light with a wavelength of 633 nm
   (c) X-ray radiation with a wavelength of 0.070 nm
5. Determine which has greater energy, an ultraviolet photon or an X-ray photon. Refer to Table 3. Explain your answer. K/U C
6. The highest-energy photons emitted by a hydrogen atom have been measured to have an energy of 13.6 eV. K/U A
   (a) Express this energy in joules.
   (b) Calculate the frequency and wavelength of these photons. What type of electromagnetic radiation do they correspond to? (Use Table 3.)
7. The most common method for converting solar energy into electrical energy uses solar cells. Research the technology of solar cells, and describe to a classmate how they use quantum mechanics to produce electricity. K/U T/I C A

WEB LINK