18.1 The Particle Nature of Light

SECTION OUTCOMES

- Explain how quantum physics evolved as new evidence came to light.
- Describe how the concept of quantum energy explains blackbody radiation and the photoelectric effect.
- Explain and apply the formula for the photoelectric effect.

KEY TERMS

- classical physics
- blackbody
- ultraviolet catastrophe
- empirical equation
- quantized
- quantum
- photoelectric effect
- stopping potential
- photon
- work function
- threshold frequency
- electron volt

In Unit 4, Waves, you studied light and electromagnetic radiation. You learned that Christiaan Huygens (1629–1695) revived the wave theory of light in 1678. In 1801, Thomas Young (1773–1829) demonstrated conclusively with his famous double-slit experiment that light consisted of waves.

For more than 200 years, physicists studied electromagnetism and accumulated evidence for the wave nature of light and all forms of electromagnetic radiation. In fact, in 1873, James Clerk Maxwell (1831–1879) published his *Treatise on Electricity and Magnetism*, in which he summarized in four equations everything that was known about electromagnetism and electromagnetic waves. Maxwell's equations form the basis of electromagnetism in much the same way that Newton's laws form the basis of mechanics.

These areas of study, Newtonian mechanics and electricity and magnetism, along with thermodynamics, constitute **classical physics**. By the late 1800s, classical physics was well established. Many years of experiments and observations supported the theories of Newton and Maxwell. However, the scientific community was about to be shaken by events to come with the turn of the century.

How could observations on something as seemingly simple as a blackbody expose a flaw in these well-established theories? What, exactly, is a blackbody?

Blackbody Radiation

Based on his studies on the emission and absorption spectra of gases, Gustav Kirchhoff (1824–1887) defined the properties of a blackbody. While working with Robert Bunsen (1811–1899), Kirchhoff observed that, when heated to incandescence, gases emit certain, characteristic frequencies of light. When white light shines through the gases, they absorb the same frequencies of light that they emit, so Kirchhoff proposed that all objects absorb the same frequencies of radiation that they emit. He further reasoned that since black objects absorb all frequencies of light, they should emit all frequencies when heated to incandescence. Thus, the term **blackbody** was defined as a "perfect radiator," a body that emits a complete spectrum of electromagnetic radiation.

Fortunately for experimenters, blackbodies are not difficult to simulate in the laboratory. Any cavity with the inner walls heated to a very high temperature and with a very small hole to allow radiation to escape (see Figure 18.1) will emit a spectrum of radiation nearly identical to that of a blackbody.

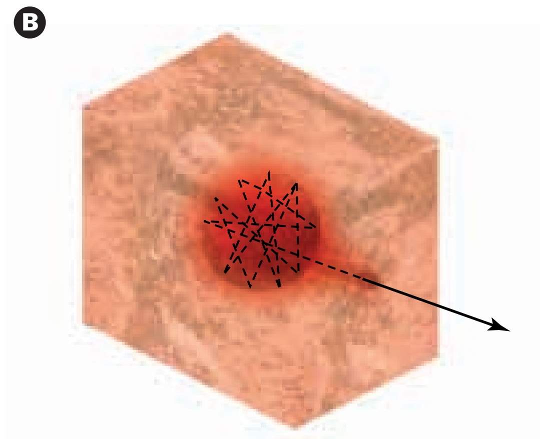

Figure 18.1 **(A)** When the temperature of a kiln surpasses 1000 K, the radiation is independent of the nature of the material in the kiln and depends only on the temperature. **(B)** A tiny hole in a very hot cavity "samples" the radiation that is being emitted and absorbed by the walls inside.

Figure 18.2 shows graphs of the blackbody radiation distribution at several different temperatures. The frequency of the radiation is plotted on the horizontal axis and the intensity of the radiation emitted at each frequency is plotted on the vertical axis. The area under the curve represents the total amount of energy emitted by a blackbody in a given time interval.

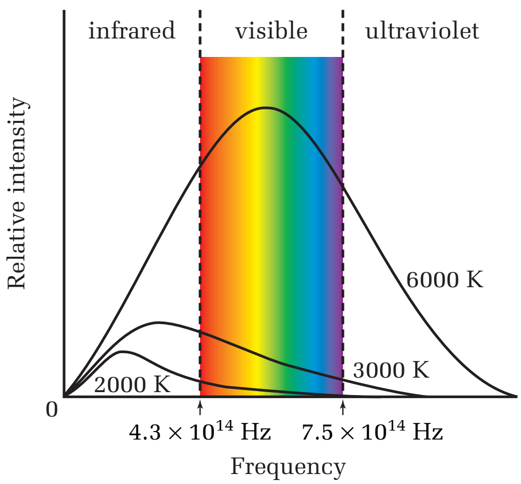

Figure 18.2 As the temperature of an incandescent body increases, the frequency that is emitted with the highest intensity (the peak of the curve) becomes higher.

Using data such as those in Figure 18.2, Kirchhoff was able to show that the power radiated by a blackbody depends on the blackbody's temperature. He also showed that the intensity of the radiation was related to the frequency in a complex way and that the distribution of intensities was different at different temperatures. Kirchhoff was unable to find the exact form of the mathematical relationships, so he challenged the scientific community to do so.

Figure 18.3 **(A)** While an object such as a crowbar emits no visible radiation at room temperature, it is actually emitting infrared radiation. **(B)** When a stove coil reaches 600 K, it emits mostly invisible, infrared radiation. The radiation appears to be red, because it emits a little visible radiation in the red end of the spectrum. **(C)** At 2000 K, a light bulb filament looks white, because it emits all frequencies in the visible range.

According to electromagnetic theory, accelerating charges emit electromagnetic radiation. Maxwell's equations describe the nature of these oscillations and the associated radiation. A blackbody therefore must have vibrating, or oscillating, charges on the surface that are emitting (or absorbing) electromagnetic energy.

Josef Stefan (1835–1893) showed experimentally in 1879 that the power (energy per unit time) emitted by a blackbody is related to the fourth power of the temperature ($P \propto T^4$). In other words, if the temperature of a blackbody doubles, the power emitted will increase by 2^4, or 16 times. Five years later, Ludwig Boltzmann (1844–1906) used Maxwell's electromagnetic theory, as well as methods Boltzmann himself had developed for thermodynamics, to provide a theoretical basis for the fourth-power relationship.

The exact mathematical relationship between frequency and intensity of radiation emitted by a blackbody is much more complex than the relationship between temperature and power. Nevertheless, Lord Rayleigh (John William Strutt, 1842–1919) and Sir James Hopwood Jeans (1877–1946) attempted to apply the same principles that Boltzmann had used for the energy-temperature relationship. When they applied these theories to blackbody radiation, they obtained the upper curve shown in Figure 18.4. The lower curve represents experimental data for the same temperature.

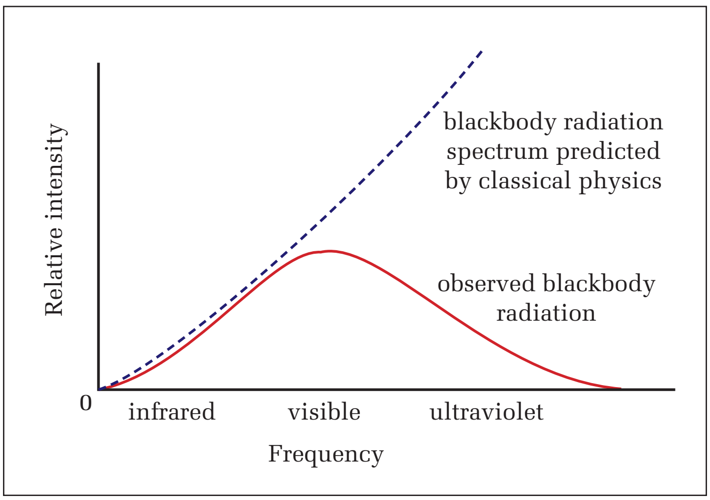

Figure 18.4 At low frequencies, predictions based on classical theory agree with observed data for the intensity of radiation from a blackbody. At high frequencies, however, theory and observation diverge quite drastically.

As you can see in Figure 18.4, classical theory applied to black-body radiation agrees with observed data at low frequencies, but predicts that energy radiated from incandescent objects should continue to increase as the frequency increases. This discrepancy between theory and observation shocked the physicists of the day so much that they called it the **ultraviolet catastrophe**. How could a theory that had explained all of the data collected for 200 years fail to predict the emission spectrum of a blackbody? Little did they realize what was in store.

The Birth of Quantum Theory

Max Planck (1858–1947), a student of Kirchhoff, developed an empirical mathematical relationship between intensity and frequency of blackbody radiation. (An **empirical equation** is one that fits the observed data but is not based on any theory.) To develop the theory behind his empirical relationship, Planck turned to a statistical technique that Boltzmann had developed to solve certain thermodynamic problems. Planck had to make a "minor adjustment" to apply this method to energies of oscillators in the walls of a blackbody, however.

Boltzmann's statistical method required the use of discrete units, such as individual molecules of a gas. Although the energies of oscillators had always been considered to be continuous, for the sake of the mathematical method, Planck assigned discrete energy levels to the oscillators. He set the value of the allowed energies of the oscillators equal to a constant times the frequency, or $E = hf$, where h is the proportionality constant.

According to this hypothetical system, an oscillator could exist with an energy of zero or any integral multiple of hf, but not at energy levels in between, as illustrated in Figure 18.5. When the blackbody emitted radiation, it had to drop down one or more levels and emit a unit of energy equal to the difference between the allowed energy levels of the oscillator. A system such as this is said to be **quantized**, meaning that there is a minimum amount of energy, or a **quantum** of energy, that can be exchanged in any interaction.

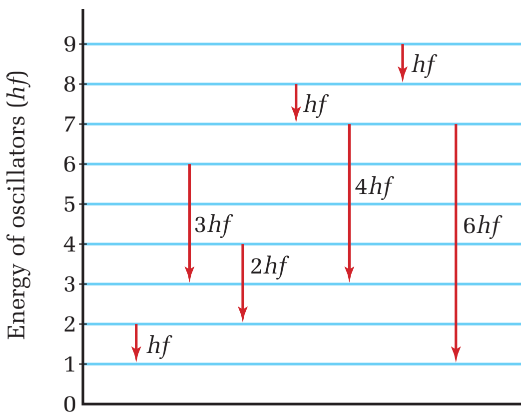

Figure 18.5 The "allowed" energy levels of the oscillators in the walls of a blackbody can be described as $E = nhf$, where n is any positive integer — 0, 1, 2, and up.

PHYSICS FILE

Shortly after Planck presented his paper on blackbody radiation, Einstein corrected one small error in the mathematics. He showed that the energy levels of the oscillators had to be $E = (n + \frac{1}{2})hf$. The addition of $\frac{1}{2}$ did not affect the *difference* between energy levels and thus did not change the prediction of the spectrum of blackbody radiation. However, it did show that the minimum possible energy of an oscillator is not zero, but $\frac{1}{2}hf$.

With discrete units of energy defined, Planck could now apply Boltzmann's statistical methods to his analysis of blackbodies. His plan was to develop an equation and then apply another mathematical technique that would allow the separation of energy levels to become smaller and smaller, until the energies were once again continuous. Planck developed the equation, but when he performed the mathematical operation to make oscillator energies continuous, the prediction reverted to the Rayleigh-Jeans curve. However, his equation fit the experimental data perfectly if the allowed energies of the oscillators remained discrete instead of continuous.

Planck was quite surprised, but he continued to analyze the equation. By matching his theoretical equation to experimental data, he was able to determine that the value of h, the proportionality constant, was approximately 6.55×10^{-34} J · s. Today, h is known as Planck's constant and its value is measured to be $6.626\,075\,5 \times 10^{-34}$ J · s.

With a theory in hand that could precisely predict the observed data for blackbody radiation, Planck presented his findings to the German Physical Society on December 14, 1900, and modern physics was born. Planck's revolutionary theory created quite a stir at the meeting, but the ideas were so new and radical that physicists — Planck included — could not readily accept them. More evidence would be needed before the scientific community would embrace the theory of the quantization of energy.

The Photoelectric Effect

The photoelectric effect, which would eventually confirm the theory of the quantization of energy, was discovered quite by accident. In 1887, Heinrich Hertz (1857–1894) was attempting to verify experimentally Maxwell's theories of electromagnetism. He assembled an electric circuit that generated an oscillating current, causing sparks to jump back and forth across a gap between electrodes, as illustrated in Figure 18.6. He showed that the sparks were generating electromagnetic waves by placing, on the far side of the room, a small coil or wire with a tiny gap. When the "transmitter" generated sparks, he observed that sparks were also forming in the gap of the "receiver" coil on the far side of the room. The electromagnetic energy had been transmitted across the room.

Hertz was able to show that these electromagnetic waves travelled with the speed of light and could be reflected and refracted, verifying Maxwell's theories. Ironically, however, Hertz made an observation that set the stage for experiments that would support the particle nature of electromagnetic radiation — the sparks were enhanced when the metal electrodes were exposed to ultraviolet light. At the time of Hertz's experiments, this phenomenon was difficult to explain.

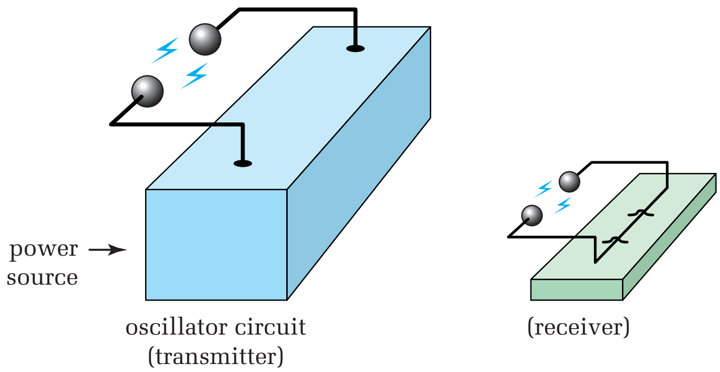

Figure 18.6 The electromagnetic waves that Hertz generated with his spark gap were in the frequency range that is now called "radio waves." Although Hertz's only intention was to verify Maxwell's theories, his experiments led to invention of the wireless telegraph, radio, television, microwave communications, and radar.

It was not until 10 years after Hertz carried out his experiments that Joseph John Thomson (1856–1940) discovered the electron. With this new knowledge, physicists suggested that the ultraviolet light had ejected electrons from Hertz's metal electrodes, thus creating a "conducting path" for the sparks to follow. The ejection of electrons by ultraviolet light became known as the **photoelectric effect**.

Early Photoelectric Effect Experiments

In 1902, physicist Philipp Lenard (1862–1947) performed more detailed experiments on the photoelectric effect. He designed an apparatus like the one shown in Figure 18.7. Electrodes are sealed in an evacuated glass tube that has a quartz window. (Ultraviolet light will not penetrate glass.) A very sensitive galvanometer detects any current passing through the circuit. Notice that the variable power supply can be connected so that it can make either electrode positive or negative.

To determine whether photoelectrons were, in fact, ejected from the "emitter," Lenard made the emitter negative and the collector positive. When he exposed the emitter to ultraviolet light, the galvanometer registered a current. The ultraviolet light had ejected electrons, which were attracted to the collector and then passed through the circuit. When Lenard increased the intensity of the ultraviolet light, he observed an increase in the current.

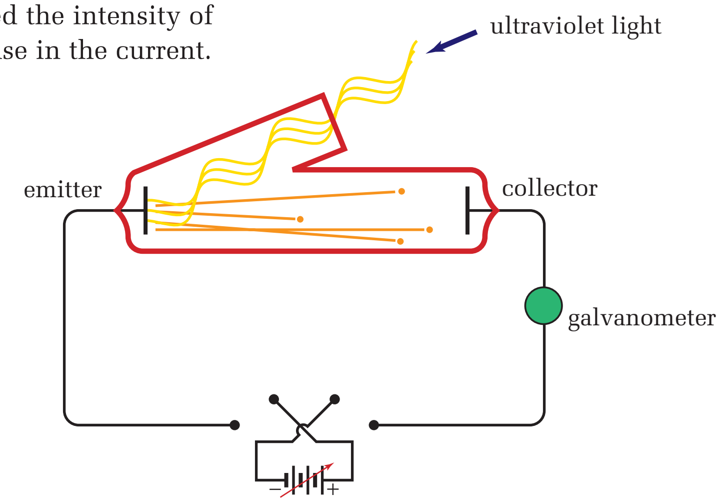

Figure 18.7 These glass tubes for experiments on the photoelectric effect had to be sealed in a vacuum so that the electrons would not collide with molecules of gas.

Web Link

www.mcgrawhill.ca/links/atlphysics

Many of the physicists who contributed to the development of quantum theory won the Nobel Prize in Physics. Find out who they were and learn more about their contributions to modern physics by going to the above Internet site and clicking on **Web Links**.

To learn more about the relative kinetic energies of photoelectrons, Lenard reversed the polarity of the power supply so that the electric field between the electrodes would oppose the motion of the photoelectrons. Starting each experiment with a very small potential difference opposing the motion of the electrons, he gradually increased the voltage and observed the effect on the current. The photoelectrons would leave the emitter with kinetic energy. He theorized that if the kinetic energy was great enough to overcome the potential difference between the plates, the electron would strike the collector. Any electrons that reached the collector would pass through the circuit, registering a current in the galvanometer. Electrons that did not have enough kinetic energy to overcome the potential difference would be forced back to the emitter.

Lenard discovered that as he increased the potential difference, the current gradually decreased until it finally stopped flowing entirely. The opposing potential had turned back even the most energetic electrons. The potential difference that stopped all photoelectrons is now called the **stopping potential**. Lenard's data indicated that ultraviolet light with a constant intensity ejected electrons with a variety of energies but that there was always a maximum kinetic energy.

In a critical study, Lenard used a prism to direct narrow ranges of frequencies of light onto the emitter. He observed that the stopping potential for higher frequencies of light was greater than it was for lower frequencies. This result means that, regardless of its intensity, light of higher frequency ejects electrons with greater kinetic energies than does light with lower frequencies. Once again, a greater *intensity* of any given frequency of light increased only the flowing current, or *number* of electrons, and had no effect on the electrons' stopping potential and, thus, no effect on their maximum kinetic energy. In summary, Lenard's investigations demonstrated the following.

- When the intensity of the light striking the emitter increases, the number of electrons ejected increases.
- The maximum kinetic energy of the electrons ejected from the metal emitter is determined *only* by the frequency of the light and is not affected by its intensity.

Lenard's first result is in agreement with the classical wave theory of light: As the intensity of the light increases, the amount of energy absorbed by the surface per unit time increases, so the number of photoelectrons should increase. However, classical theory also predicts that the kinetic energy of the photoelectrons should increase with an increase in the intensity of the light. Lenard's second finding — that the kinetic energy of the photoelectrons is determined *only* by the frequency of the light — cannot be explained by the classical wave theory of light.

Einstein and the Photoelectric Effect

Just a few years after Planck's quantum theory raised questions about the nature of electromagnetic radiation, the photoelectric effect raised even more questions. After publication, Planck's theory had been, for the most part, neglected. Now, however, because of the new evidence pointing to a flaw in the wave theory of light, Planck's ideas were revisited.

It was Albert Einstein (1879–1955) who saw the link between Planck's quantum of energy and the photoelectric effect. In 1905, Einstein published a paper in which he proposed that light must not only be emitted as quanta, or packets of energy, but it must also be absorbed as quanta. By treating light as quanta or **photons**, as they were named later, Einstein could explain Lenard's results for the photoelectric effect.

Einstein suggested that Planck's unit of energy, $E = hf$, is the energy of a photon. He proposed that when a photon strikes a metal surface, all of its energy is absorbed by one electron in one event. Since the energy of a photon is related to the frequency of the light, a photon with a higher frequency would have more energy to give an electron than would a photon with a lower frequency. This concept immediately explains why the maximum kinetic energy of photoelectrons depends only on frequency. Increasing the intensity of light of a given frequency increases only the *number* of photons and has no effect on the energy of a single photon.

Since the kinetic energy of the photoelectrons varied, some of the energy of the photons was being converted into a form of energy other than kinetic. Einstein proposed that some energy must be used to overcome the attractive forces that hold the electron onto the surface of the metal. Since some electrons are buried "deeper" in the metal, a larger amount of energy is needed to eject them from the surface. These electrons leave the emitter with less kinetic energy. The electrons with maximum kinetic energy must be the most loosely bound. Einstein gave the name **work function** (W) to this minimum amount of energy necessary to remove an electron from the metal surface. He predicted that the value would depend on the type of metal. The following mathematical expression describes the division of photon energy into the work function of the metal and the kinetic energy of the photoelectron.

$$hf = W + E_{k(max)}$$

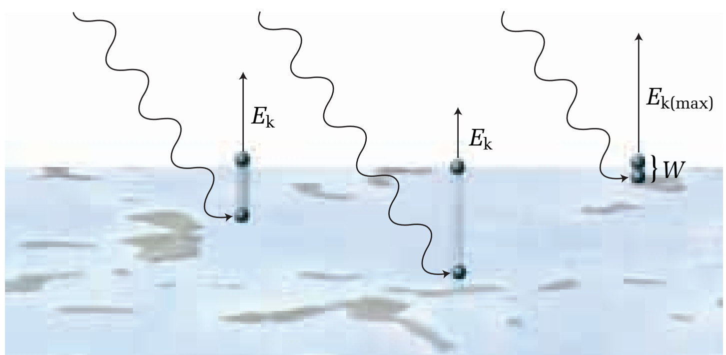

Figure 18.8 The energy of the photon must first extract the electron from the metal surface. The remainder of the energy becomes the kinetic energy of the electron.

ELECTRONIC LEARNING PARTNER

To enhance your understanding of the photoelectric effect, go to your Electronic Learning Partner.

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Albert Einstein never actually carried out any laboratory experiments. He was a genius, however, at interpreting and explaining the results of others. In addition, the technology needed to test many of his theories did not exist until many years after he published them. Einstein was truly a theoretical physicist.

While Einstein's explanation could account for all of the observations of the photoelectric effect, very few physicists, including Planck, accepted Einstein's arguments regarding the quantum (or particle) nature of light. It was very difficult to put aside the 200 years of observations that supported the wave theory. Unfortunately, when Einstein wrote his paper on the photoelectric effect, the charge on the electron was not yet known, so there was no way to prove him right or wrong.

Millikan and the Photoelectric Effect

By 1916, Robert Millikan (1868–1953) had established that the magnitude of the charge on an electron was 1.60×10^{-19} C. With this "ammunition" in hand, Millikan set out to prove that Einstein's assumptions regarding the quantum nature of light were incorrect. Like others, Millikan felt that the evidence for the wave nature of light was overwhelming.

Millikan improved on Lenard's design and built photoelectric tubes with emitters composed of various metals. For each metal, he measured the stopping potential for a variety of frequencies. Using his experimentally determined value for the charge on an electron, he calculated the values for the maximum kinetic energy for each frequency, using the familiar relation $E = qV$. In this application, E is the energy of a charge, q, that has fallen through a potential difference, V. In Millikan's case, E was the maximum kinetic energy of the photoelectrons and q was the charge on an electron. The equation becomes $E_{\text{k(max)}} = eV_{\text{stop}}$. Millikan then plotted graphs of kinetic energy versus frequency for each type of metal emitter.

To relate graphs of $E_{\text{k(max)}}$ versus f to Einstein's equation, it is convenient to solve for $E_{\text{k(max)}}$, resulting in the following equation.

$$E_{\text{k(max)}} = hf - W$$

$E_{\text{k(max)}}$ is the dependent variable, f is the independent variable, and h and W are constants for a given experiment. Notice that the equation has the form of the slope-intercept equation of a straight line.

$$y = mx + b$$

Comparing the equations, you can see that Planck's constant (h) is the slope (m), and the negative of the work function ($-W$) is the y-intercept (b).

When Millikan plotted his data, they resulted in straight lines, as shown in Figure 18.9. The slopes of the lines from all experiments were the same and were equal to Planck's constant. When Millikan extrapolated the lines to cross the vertical axis, the value gave the negative of the work function of the metal. Much to Millikan's disappointment, he had proven that Einstein's equations perfectly predicted all of his results. He begrudgingly had to concede that Einstein's assumptions about the quantum nature of light were probably correct.

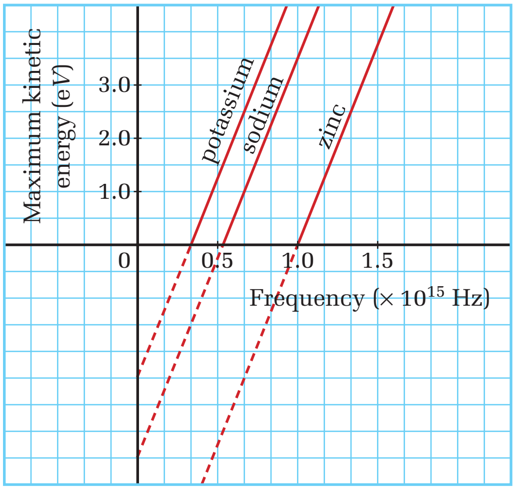

Figure 18.9 The graphs of Millikan's data were straight lines with equal slopes. The only differences were the points at which the extrapolated lines crossed the axes.

PHOTOELECTRIC EFFECT

The maximum kinetic energy of a photoelectron is the difference of the energy of the photon and the work function of the metal emitter.

$$E_{k(max)} = hf - W$$

Quantity	Symbol	SI unit
maximum kinetic energy of a photoelectron	$E_{k(max)}$	J (joules)
Planck's constant	h	J · s (joule · seconds)
frequency of electromagnetic radiation	f	Hz (hertz: equivalent to s^{-1})
work function of metal	W	J (joules)

Unit Analysis

(joule · second)(hertz) – joule = (J · s)(s^{-1}) = J

Another critical feature of a graph of maximum kinetic energy versus frequency is the point at which each line intersects the horizontal axis. On this axis, the maximum kinetic energy of the photoelectrons is zero. The frequency at this horizontal intercept is called **threshold frequency** (f_o), because it is the lowest frequency (smallest photon energy) that can eject a photoelectron from the metal. When photons with threshold frequency strike the emitter, they have just enough energy to raise the most loosely bound electrons to the surface of the emitter, but they have no energy left with which to give the photoelectrons kinetic energy. These photoelectrons are drawn back into the emitter.

Conceptual Problem

- At threshold frequency (f_o), the maximum kinetic energy of the photoelectrons is zero ($E_{k(max)} = 0$). Substitute these terms (f_o and 0) into Einstein's equation for the photoelectric effect and solve for the work function (W). Explain the meaning of the relationship that you found and how you can use it to find the work function of a metal.

You might have noticed that the unit for energy on the vertical axis in Figure 18.9 was symbolized as "eV," which in this case stands for "electron volt." The need for this new unit will become apparent when you start to use the photoelectric equation. You will find that the kinetic energy of even the most energetic electrons is an extremely small fraction of a joule. Since working with numbers such as 1.23×10^{-17} J becomes tedious and it is difficult to compare values, physicists working with subatomic particles developed the electron volt as the energy unit suitable for such particles and for photons. The **electron volt** is defined as the energy gained by one electron as it falls through the potential difference of one volt. The following calculation shows the relationship between electron volts and joules.

$$E = qV$$
$$1\text{ eV} = (1\text{ e})(1\text{ V})$$
$$1\text{ eV} = (1.60 \times 10^{-19}\text{ C})(1\text{ V})$$
$$1\text{ eV} = 1.60 \times 10^{-19}\text{ J}$$

Table 18.1 lists the work functions, in units of electron volts, of several common metals that have been studied as emitters in photoelectric experiments.

Like many other theoretical developments in physics, scientists soon found some practical applications for the photoelectric effect. The first light meters used the photoelectric effect to measure the intensity of light. Light meters have specialized metal emitters that are sensitive to visible light. When light strikes the metal, electrons are released and then collected by a positive electrode. The amount of current produced is proportional to the intensity of the light. The photon that physicists once had difficulty accepting is now almost a household word.

MODEL PROBLEM

Light with a wavelength of 581 nm strikes a cesium metal surface inside a vacuum tube.
(a) What is the maximum kinetic energy of the electrons emitted from the surface?
(b) What is the stopping potential for these electrons?
(c) What is the threshold frequency for cesium metal?

Frame the Problem

- When the light *photon* strikes the surface of the cesium, some of its energy will be used to *remove an electron* from the surface and the remainder of the energy will become *kinetic energy* of the electron.
- The *energy of photons* is often expressed in terms of the *frequency* of the light rather than *wavelength* so convert wavelength to frequency.
- *Stopping potential* is the *potential difference* that would convert all of the *kinetic energy* of the electron to *electric potential energy*.
- *Threshold frequency* is the frequency of a photon that has an amount of energy identical to the *work function* of the metal.

Identify the Goal

(a) maximum kinetic energy, $E_{k(max)}$ of the electron emitted from cesium metal

(b) stopping potential energy, V_s, for the electrons

(c) threshold frequency, f_0, for cesium metal

Variables and Constants

Known	Implied	Unknown	
$\lambda = 571$ nm	$W = 2.14$ eV	f	$E_{k(max)}$
	$h = 6.626 \times 10^{-34}$ J·s	f_0	V_s

Strategy

Use the wave equation to find the frequency of the photon.

Calculations

$$v = \lambda f$$
$$f = \frac{v}{\lambda}$$
$$f = \frac{2.998 \times 10^8 \frac{\cancel{m}}{s}}{571 \times 10^{-9} \cancel{m}}$$
$$f = 5.2504 \times 10^{14}\ s^{-1}$$

Use Einstein's equation for the photoelectric effect to find the maximum kinetic energy of the electrons.

$$E_{k(max)} = hf - W$$
$$E_{k(max)} = (6.626 \times 10^{-34}\ J \cdot \cancel{s})(5.2504 \times 10^{14}\ \cancel{s^{-1}}) - (2.14\ \cancel{eV})\left(1.602 \times 10^{-19} \frac{1}{\cancel{eV}}\right)$$
$$E_{k(max)} = 3.4789 \times 10^{-19}\ J - 3.4283 \times 10^{-19}\ J$$
$$E_{k(max)} = 5.066 \times 10^{-21}\ J$$
$$E_{k(max)} \cong 5.07 \times 10^{-21}\ J$$

(a) The maximum kinetic energy of the electrons emitted from cesium is 5.07×10^{-21} J (or 3.16×10^{-2} eV)

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Find the stopping potential from the relationship between electric potential energy, potential difference, and charge.

$$E_Q = qV$$
$$V_s = \frac{E_Q}{q}$$
$$V_s = \frac{5.066 \times 10^{-21}\ \text{J}}{1.602 \times 10^{-19}\ \text{C}}$$
$$V_s = 3.1623 \times 10^{-2}\ \frac{\text{J}}{\text{C}}$$
$$V_s \cong 0.0316\ \text{V}$$

(b) The stopping potential for the electrons is 0.0316 V.

Find the threshold frequency by setting the energy of a photon equal to the work function.

$$hf_0 = W$$
$$f_0 = \frac{W}{h}$$
$$f_0 = \frac{(2.14\ \cancel{\text{eV}})\left(1.602 \times 10^{-19}\ \frac{\cancel{\text{J}}}{\cancel{\text{eV}}}\right)}{6.626 \times 10^{-34}\ \cancel{\text{J}}\cdot\text{s}}$$
$$f_0 = 5.174 \times 10^{14}\ \text{s}^{-1}$$
$$f_0 = 5.17 \times 10^{14}\ \text{Hz}$$

(c) The threshold frequency for cesium is 5.17×10^{14} Hz.

Validate

All units cancelled to give the expected unit. The values of frequency are all near the frequencies of light. Energies are reasonable for individual electrons.

PRACTICE PROBLEMS

1. Photons with a frequency of 4.86×10^{15} Hz are directed toward a nickel surface in a vacuum tube.
   - **(a)** What will be the maximum kinetic energy of the electrons emitted from the nickel surface?
   - **(b)** What is the threshold frequency for nickel?
   - **(c)** Within what range of the electromagnetic spectrum do these photons lie?
2. The stopping potential for electrons emitted from the surface of sodium metal in a vacuum tube is 2.93 V. What is the frequency of the photons that are striking the metal surface?
3. The maximum kinetic energy of electrons emitted from a metal surface is 3.65×10^{-19} J when photons with a frequency 1.25×10^{15} Hz strike the surface. What is the most likely type of metal surface that the photons are striking?
4. Light of the same wavelength causes electrons to be emitted from a lithium surface but cannot eject electrons from an iron surface. Give the range of wavelengths within which this light must lie.

Table 18.1 Work Functions of Some Common Metals

Metal	Work function (eV)
aluminum	4.28
calcium	2.87
cesium	2.14
copper	4.65
iron	4.50
lead	4.25
lithium	2.90
nickel	5.15
platinum	5.65
potassium	2.30
tin	4.42
tungsten	4.55
zinc	4.33

18.1 Section Review

1. K/U Explain how a very hot oven can simulate a blackbody.

2. K/U Why was Planck's theory of blackbody radiation considered to be revolutionary?

3. C **(a)** Describe how the Hertz experiment, in which he used spark gaps to transmit and receive electromagnetic radiation, also provided early evidence for the photoelectric effect.
   (b) Name one modern technology that has its origin in the Hertz experiment. Briefly describe how it is related to this experiment.

4. C Describe how Einstein used Planck's concept of quanta of energy to explain the photoelectric effect.

5. K/U Define the terms "work function" and "threshold frequency."

6. C Describe how the quantum (photon) model for light better explains the photoelectric effect than does the classical wave theory.

7. MC What instruments have you used that rely on the photoelectric effect?

8. I Plot a graph of the following data from a photoelectric effect experiment and use the graph to determine Planck's constant, the threshold frequency, and the work function of the metal. Consult Table 18.1 and determine what metal was probably used as the target for electrons in the phototube.

Stopping potential (V)	Frequency of light (Hz)
0.91	9.0×10^{14}
1.62	10.7×10^{14}
2.35	12.4×10^{14}
3.50	15.0×10^{14}
4.21	16.5×10^{14}