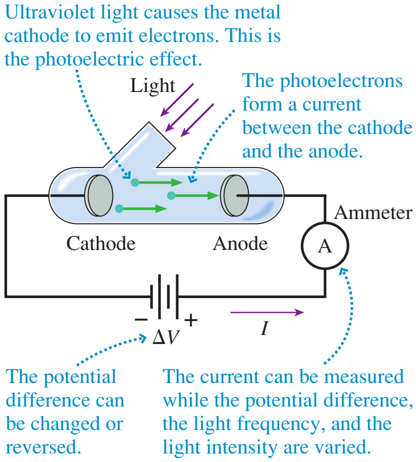
38.1 The Photoelectric Effect

FIGURE 38.1 Lenard's experimental device to study the photoelectric effect.



In 1886, Heinrich Hertz, who was the first to demonstrate that electromagnetic waves can be artificially generated, noticed that a negatively charged electroscope could be discharged by shining ultraviolet light on it. Hertz's observation caught the attention of J. J. Thomson, who inferred that the ultraviolet light was causing the electrode to emit electrons, thus restoring itself to electric neutrality. The emission of electrons from a substance due to light striking its surface came to be called the **photoelectric effect.** The emitted electrons are often called *photoelectrons* to indicate their origin, but they are identical in every respect to all other electrons.

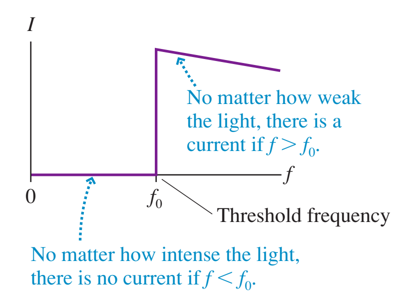
Although this discovery might seem to be a minor footnote in the history of science, it soon became a, or maybe *the,* pivotal event that opened the door to new ideas.

Characteristics of the Photoelectric Effect

It was not the discovery itself that dealt the fatal blow to classical physics, but the specific characteristics of the photoelectric effect found around 1900 by one of Hertz's students, Phillip Lenard. Lenard built a glass tube, shown in FIGURE 38.1, with two facing electrodes and a window. After removing the air from the tube, he allowed light to shine on the cathode.

Lenard found a counterclockwise current (clockwise flow of electrons) through the ammeter whenever ultraviolet light was shining on the cathode. There are no junctions in this circuit, so the current must be the same all the way around the loop. The current in the space between the cathode and the anode consists of electrons moving freely through the evacuated space between the electrodes (i.e., not inside a wire) at the *same rate* (same number of electrons per second) as the current in the wire. There is no current if the electrodes are in the dark, so electrons don't spontaneously leap off the cathode. Instead, the light causes electrons to be ejected from the cathode at a steady rate.

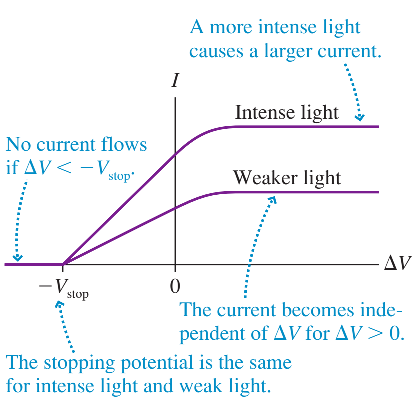
FIGURE 38.2 The photoelectric current as a function of the light frequency f for light of constant intensity.



Lenard used a battery to establish an adjustable potential difference ΔV between the two electrodes. He then studied how the current I varied as the potential difference and the light's frequency and intensity were changed. Lenard made the following observations:

1. The current I is directly proportional to the light intensity. If the light intensity is doubled, the current also doubles.
2. The current appears without delay when the light is applied. To Lenard, this meant within the ≈ 0.1 s with which his equipment could respond. Later experiments showed that the current begins in less than 1 ns.
3. Photoelectrons are emitted *only* if the light frequency f exceeds a **threshold frequency** f_0. This is shown in the graph of FIGURE 38.2.
4. The value of the threshold frequency f_0 depends on the type of metal from which the cathode is made.
5. If the potential difference ΔV is more than about 1 V positive (anode positive with respect to the cathode), the current does not change as ΔV is increased. If ΔV is made negative (anode negative with respect to the cathode), by reversing the battery, the current decreases until, at some voltage $\Delta V = -V_{stop}$ the current reaches zero. The value of V_{stop} is called the **stopping potential.** This behavior is shown in FIGURE 38.3.
6. The value of V_{stop} is the same for both weak light and intense light. A more intense light causes a larger current, as Figure 38.3 shows, but in both cases the current ceases when $\Delta V = -V_{stop}$.

FIGURE 38.3 The photoelectric current as a function of the battery potential.



NOTE ▶ We're defining V_{stop} to be a *positive* number. The potential difference that stops the electrons is $\Delta V = -V_{stop}$, with an explicit minus sign. ◀

Classical Interpretation of the Photoelectric Effect

The mere existence of the photoelectric effect is not, as is sometimes assumed, a difficulty for classical physics. You learned in Chapter 25 that electrons are the charge carriers in a metal. The electrons move freely but are bound inside the metal and do not spontaneously spill out of an electrode at room temperature. But a piece of metal heated to a sufficiently high temperature *does* emit electrons in a process called **thermal emission.** The electron gun in an older television or computer display terminal starts with the thermal emission of electrons from a hot tungsten filament.

A useful analogy, shown in FIGURE 38.4, is the water in a swimming pool. Water molecules do not spontaneously leap out of the pool if the water is calm. To remove a water molecule, you must do *work* on it to lift it upward, against the force of gravity. A minimum energy is needed to extract a water molecule, namely the energy needed to lift a molecule that is right at the surface. Removing a water molecule that is deeper requires more than the minimum energy. People playing in the pool add energy to the water, causing waves. If sufficient energy is added, a few water molecules will gain enough energy to splash over the edge and leave the pool.

Similarly, a *minimum* energy is needed to free an electron from a metal. To extract an electron, you would need to exert a force on it and pull it (i.e., do *work* on it) until its speed is large enough to escape. The minimum energy E_0 needed to free an electron is called the **work function** of the metal. Some electrons, like the deeper water molecules, may require more energy than E_0 to escape, but all will require *at least* E_0. Different metals have different work functions; Table 38.1 provides a short list. Notice that work functions are given in electron volts.

Heating a metal, like splashing in the pool, increases the thermal energy of the electrons. At a sufficiently high temperature, the kinetic energy of a small percentage of the electrons may exceed the work function. These electrons can "make it out of the pool" and leave the metal. In practice, there are only a few elements, such as tungsten, for which thermal emission can become significant before the metal melts!

Suppose we could raise the temperature of only the electrons, not the crystal lattice. One possible way to do this is to shine a light wave on the surface. Because electromagnetic waves are absorbed by the conduction electrons, not by the positive ions, the light wave heats only the electrons. Eventually the electrons' energy is transferred to the crystal lattice, via collisions, but if the light is sufficiently intense, the *electron temperature* may be significantly higher than the temperature of the metal. In 1900, it was plausible to think that an intense light source could cause the thermal emission of electrons without melting the metal.

The Stopping Potential

Photoelectrons leave the cathode with kinetic energy. An electron with energy E_{elec} inside the metal loses energy ΔE as it escapes, so it emerges as a photoelectron with $K = E_{elec} - \Delta E$. The work function energy E_0 is the *minimum* energy needed to remove an electron, so the *maximum* possible kinetic energy of a photoelectron is

$$K_{max} = E_{elec} - E_0 \tag{38.1}$$

Some photoelectrons reach the anode, creating a measurable current, but many do not. However, as FIGURE 38.5 shows:

- A positive anode attracts the photoelectrons. Once all electrons reach the anode, which happens for ΔV greater than about 1 V, a further increase in ΔV does not cause any further increase in the current I. That is why the graph lines become horizontal on the right side of Figure 38.3.
- A negative anode repels the electrons. However, photoelectrons leaving the cathode with sufficient kinetic energy can still reach the anode. The current steadily decreases as the anode voltage becomes increasingly negative until, at the stopping potential, *all* electrons are turned back and the current ceases. This was the behavior observed on the left side of Figure 38.3.

FIGURE 38.4 A swimming pool analogy of electrons in a metal.

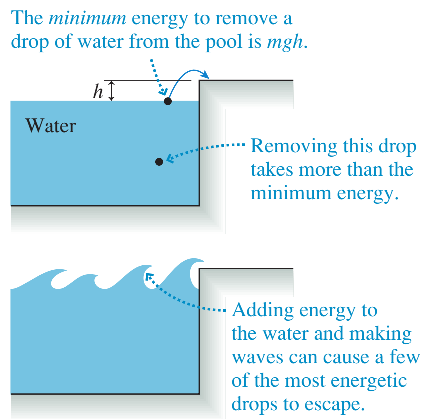


TABLE 38.1 The work function for some of the elements

Element	E_0 (eV)
Potassium	2.30
Sodium	2.75
Aluminum	4.28
Tungsten	4.55
Copper	4.65
Iron	4.70
Gold	5.10

FIGURE 38.5 The photoelectron current depends on the anode potential.

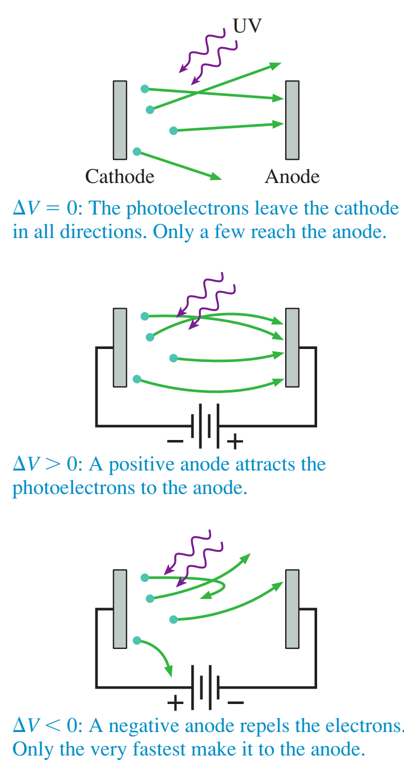
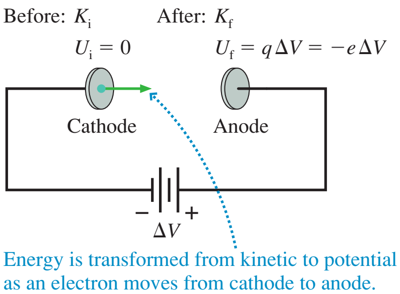


FIGURE 38.6 Energy is conserved.



Let the cathode be the point of zero potential energy, as shown in FIGURE 38.6. An electron emitted from the cathode with kinetic energy K_i has initial total energy

$$E_i = K_i + U_i = K_i + 0 = K_i$$

When the electron reaches the anode, which is at potential ΔV relative to the cathode, it has potential energy $U = q\,\Delta V = -e\,\Delta V$ and final total energy

$$E_f = K_f + U_f = K_f - e\,\Delta V$$

From conservation of energy, $E_f = E_i$, the electron's final kinetic energy is

$$K_f = K_i + e\,\Delta V \qquad (38.2)$$

The electron speeds up ($K_f > K_i$) if ΔV is positive. The electron slows down if ΔV is negative, but it still reaches the anode ($K_f > 0$) if K_i is large enough.

An electron with initial kinetic energy K_i will stop just as it reaches the anode if the potential difference is $\Delta V = -K_i/e$. The potential difference that turns back the very fastest electrons, those with $K = K_{max}$, and thus stops the current is

$$\Delta V_{\text{stop fastest electrons}} = -\frac{K_{max}}{e}$$

By definition, the potential difference that causes the electron current to cease is $\Delta V = -V_{stop}$, where V_{stop} is the stopping potential. The stopping potential is

$$V_{stop} = \frac{K_{max}}{e} \qquad (38.3)$$

Thus the stopping potential tells us the maximum kinetic energy of the photoelectrons.

EXAMPLE 38.1 The classical photoelectric effect

A photoelectric-effect experiment is performed with an aluminum cathode. An electron inside the cathode has a speed of 1.5×10^6 m/s. If the potential difference between the anode and cathode is -2.00 V, what is the highest possible speed with which this electron could reach the anode?

MODEL Energy is conserved.

SOLVE If the electron escapes with the maximum possible kinetic energy, its kinetic energy at the anode will be given by Equation 38.2 with $\Delta V = -2.00$ V. The electron's initial kinetic energy is

$$E_{elec} = \frac{1}{2}mv^2 = \frac{1}{2}(9.11 \times 10^{-31}\ \text{kg})(1.5 \times 10^6\ \text{m/s})^2$$
$$= 1.025 \times 10^{-18}\ \text{J} = 6.41\ \text{eV}$$

Its maximum possible kinetic energy as it leaves the cathode is

$$K_i = K_{max} = E_{elec} - E_0 = 2.13\ \text{eV}$$

where $E_0 = 4.28$ eV is the work function of aluminum. Thus the kinetic energy at the anode, given by Equation 38.2, is

$$K_f = K_i + e\,\Delta V = 2.13\ \text{eV} - (e)(2.00\ \text{V}) = 0.13\ \text{eV}$$

Notice that the electron loses 2.00 eV of *energy* as it moves through the *potential* difference of -2.00 V, so we can compute the final kinetic energy in eV without having to convert to joules. However, we must convert K_f to joules to find the final speed:

$$K_f = \frac{1}{2}mv_f^2 = 0.13\ \text{eV} = 2.1 \times 10^{-20}\ \text{J}$$

$$v_f = \sqrt{\frac{2K_f}{m}} = 2.1 \times 10^5\ \text{m/s}$$

Limits of the Classical Interpretation

A classical analysis has provided a possible explanation of observations 1 and 5 above. But nothing in this explanation suggests that there should be a threshold frequency, as Lenard found. If a weak intensity at a frequency just slightly above f_0 can generate a current, why can't a strong intensity at a frequency just slightly below f_0 do so?

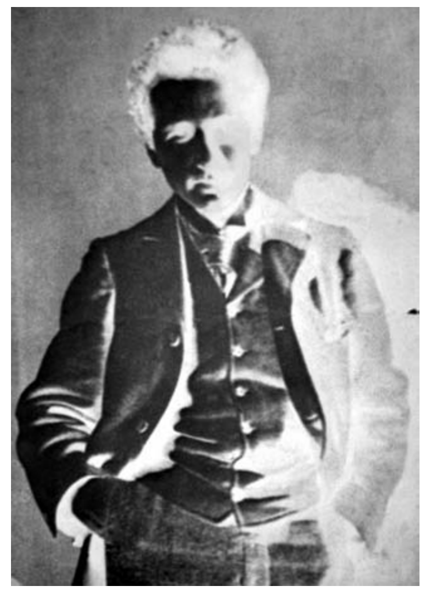
What about Lenard's observation that the current starts instantly? If the photoelectrons are due to thermal emission, it should take some time for the light to raise the electron temperature sufficiently high for some to escape. The experimental evidence was in sharp disagreement. And more intense light would be expected to heat the electrons to a higher temperature. Doing so should increase the maximum kinetic energy of the photoelectrons and thus should increase the stopping potential V_{stop}. But as Lenard found, the stopping potential is the same for strong light as it is for weak light.

Although the mere presence of photoelectrons did not seem surprising, classical physics was unable to explain the observed behavior of the photoelectrons. The threshold frequency and the instant current seemed particularly anomalous.

38.2 Einstein's Explanation

Albert Einstein, seen in **FIGURE 38.7**, was a little-known young man of 26 in 1905. He had recently graduated from the Polytechnic Institute in Zurich, Switzerland, with the Swiss equivalent of a Ph.D. in physics. Although his mathematical brilliance was recognized, his overall academic record was mediocre. Rather than pursue an academic career, Einstein took a job with the Swiss Patent Office in Bern. This was a fortuitous choice because it provided him with plenty of spare time to think about physics.

FIGURE 38.7 A young Einstein.



In 1905, Einstein published his initial paper on the theory of relativity, the subject for which he is most well known to the general public. He also published another paper, on the nature of light. In it Einstein offered an exceedingly simple but amazingly bold idea to explain Lenard's photoelectric-effect data.

A few years earlier, in 1900, the German physicist Max Planck had been trying to understand the details of the rainbow-like blackbody spectrum of light emitted by a glowing hot object. As we noted in the preceding chapter, this problem didn't yield to a classical physics analysis, but Planck found that he could calculate the spectrum perfectly if he made an unusual assumption. The atoms in a solid vibrate back and forth around their equilibrium positions with frequency f. You learned in Chapter 14 that the energy of a simple harmonic oscillator depends on its amplitude and can have *any* possible value. But to predict the spectrum correctly, Planck had to assume that the oscillating atoms are *not* free to have any possible energy. Instead, the energy of an atom vibrating with frequency f has to be one of the specific energies $E = 0, hf, 2hf, 3hf, \ldots$, where h is a constant. That is, the vibration energies are *quantized.*

Planck was able to determine the value of the constant h by comparing his calculations of the spectrum to experimental measurements. The constant that he introduced into physics is now called **Planck's constant.** Its contemporary value is

$$h = 6.63 \times 10^{-34}\ \mathrm{J\,s} = 4.14 \times 10^{-15}\ \mathrm{eV\,s}$$

The first value, with SI units, is the proper one for most calculations, but you will find the second to be useful when energies are expressed in eV.

Einstein was the first to take Planck's quantization idea seriously. He went even further and suggested that **electromagnetic radiation itself is quantized!** That is, light is not really a continuous wave but, instead, arrives in small packets or bundles of energy. Einstein called each packet of energy a **light quantum,** and he postulated that the energy of one light quantum is directly proportional to the frequency of the light. That is, each quantum of light has energy

$$E = hf \tag{38.4}$$

where h is Planck's constant and f is the frequency of the light.

The idea of light quanta is subtle, so let's look at an analogy with raindrops. A downpour has a torrent of raindrops, but in a light shower the drops are few. The difference between "intense" rain and "weak" rain is the *rate* at which the drops arrive. An intense rain makes a continuous noise on the roof, so you are not aware of the individual drops, but the individual drops become apparent during a light rain.

Similarly, intense light has so many quanta arriving per second that the light seems continuous, but very weak light consists of only a few quanta per second. And just as raindrops come in different sizes, with larger-mass drops having larger kinetic energy, higher-frequency light quanta have a larger amount of energy. Although this analogy is not perfect, it does provide a useful mental picture of light quanta arriving at a surface.

EXAMPLE 38.2 Light quanta

The retina of your eye has three types of color photoreceptors, called *cones*, with maximum sensitivities at 437 nm, 533 nm, and 575 nm. For each, what is the energy of one quantum of light having that wavelength?

MODEL The energy of light is quantized.

SOLVE Light with wavelength λ has frequency $f = c/\lambda$. The energy of one quantum of light at this wavelength is

$$E = hf = \frac{hc}{\lambda}$$

The calculation requires λ to be in m, but it is useful to have Planck's constant in eV s. At 437 nm, we have

$$E = \frac{(4.14 \times 10^{-15}\ \text{eV s})(3.00 \times 10^{8}\ \text{m/s})}{437 \times 10^{-9}\ \text{m}} = 2.84\ \text{eV}$$

Carrying out the same calculation for the other two wavelengths gives $E = 2.33$ eV at 533 nm and $E = 2.16$ eV at 575 nm.

ASSESS The electron volt turns out to be more convenient than the joule for describing the energy of light quanta. Because these wavelengths span a good fraction of the visible spectrum of 400–700 nm, you can see that visible light corresponds to light quanta having energy of roughly 2–3 eV.

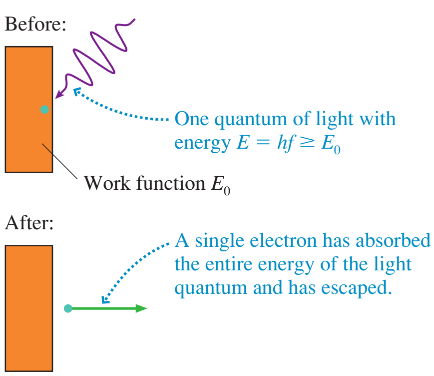
Einstein's Postulates

Einstein framed three postulates about light quanta and their interaction with matter:

1. Light of frequency f consists of discrete quanta, each of energy $E = hf$. Each photon travels at the speed of light c.
2. Light quanta are emitted or absorbed on an all-or-nothing basis. A substance can emit 1 or 2 or 3 quanta, but not 1.5. Similarly, an electron in a metal cannot absorb half a quantum but, instead, only an integer number.
3. A light quantum, when absorbed by a metal, delivers its entire energy to *one* electron.

NOTE ▶ These three postulates—that light comes in chunks, that the chunks cannot be divided, and that the energy of one chunk is delivered to one electron—are crucial for understanding the new ideas that will lead to quantum physics. They are completely at odds with the concepts of classical physics, where energy can be continuously divided and shared, so they deserve careful thought. ◀

FIGURE 38.8 The creation of a photoelectron.



Let's look at how Einstein's postulates apply to the photoelectric effect. If Einstein is correct, the light of frequency f shining on the metal is a flow of light quanta, each of energy hf. Each quantum is absorbed by *one* electron, giving that electron an energy $E_{elec} = hf$. This leads us to several interesting conclusions:

1. An electron that has just absorbed a quantum of light energy has $E_{elec} = hf$. (The electron's thermal energy at room temperature is so much less than hf that we can neglect it.) **FIGURE 38.8** shows that this electron can escape from the metal, becoming a photoelectron, if

$$E_{elec} = hf \geq E_0 \tag{38.5}$$

where, you will recall, the work function E_0 is the minimum energy needed to free an electron from the metal. As a result, there is a *threshold frequency*

$$f_0 = \frac{E_0}{h} \tag{38.6}$$

for the ejection of photoelectrons. If f is less than f_0, even by just a small amount, none of the electrons will have sufficient energy to escape no matter how intense the light. But even very weak light with $f \geq f_0$ will give a few electrons sufficient energy to escape **because each light quantum delivers all of its energy to one electron.** This threshold behavior is exactly what Lenard observed.

NOTE ▶ The threshold frequency is directly proportional to the work function. Metals with large work functions, such as iron, copper, and gold, exhibit the photoelectric effect only when illuminated by high-frequency ultraviolet light. Photoemission occurs with lower-frequency visible light for metals with smaller values of E_0, such as sodium and potassium. ◀

2. A more intense light means *more quanta* of the same energy, not more energetic quanta. These quanta eject a larger number of photoelectrons and cause a larger current, exactly as observed.
3. There is a distribution of kinetic energies, because different photoelectrons require different amounts of energy to escape, but the *maximum* kinetic energy is

$$K_{max} = E_{elec} - E_0 = hf - E_0 \tag{38.7}$$

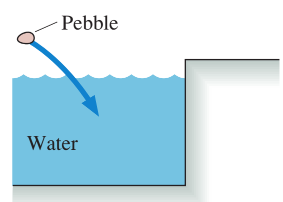
As we noted in Equation 38.3, the stopping potential V_{stop} is directly proportional to K_{max}. Einstein's theory predicts that the stopping potential is related to the light frequency by

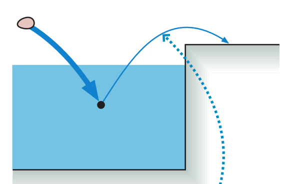
$$V_{stop} = \frac{K_{max}}{e} = \frac{hf - E_0}{e} \tag{38.8}$$

The stopping potential does *not* depend on the intensity of the light. Both weak light and intense light will have the same stopping potential, which Lenard had observed but which could not previously be explained.

4. If each light quantum transfers its energy hf to just one electron, that electron *immediately* has enough energy to escape. The current should begin instantly, with no delay, exactly as Lenard had observed.

FIGURE 38.9 A pebble transfers energy to the water.





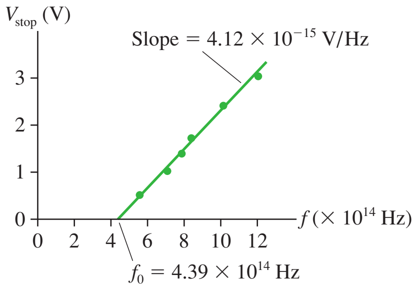
Using the swimming pool analogy again, **FIGURE 38.9** shows a pebble being thrown into the pool. The pebble increases the energy of the water, but the increase is shared among all the molecules in the pool. The increase in the water's energy is barely enough to make ripples, not nearly enough to splash water out of the pool. But suppose *all* the pebble's energy could go to *one drop* of water that didn't have to share it. That one drop of water could easily have enough energy to leap out of the pool. Einstein's hypothesis that a light quantum transfers all its energy to one electron is equivalent to the pebble transferring all its energy to one drop of water.

A Prediction

Not only do Einstein's hypotheses explain all of Lenard's observations, they also make a new prediction. According to Equation 38.8, the stopping potential should be a linearly increasing function of the light's frequency f. We can rewrite Equation 38.8 in terms of the threshold frequency $f_0 = E_0/h$ as

$$V_{stop} = \frac{h}{e}(f - f_0) \tag{38.9}$$

FIGURE 38.10 A graph of Millikan's data for the stopping potential as the light frequency is varied.



A graph of the stopping potential V_{stop} versus the light frequency f should start from zero at $f = f_0$, then rise linearly with a slope of h/e. In fact, the slope of the graph provides a way to measure Planck's constant h.

Lenard had not measured the stopping potential for different frequencies, so Einstein offered this as an untested prediction of his postulates. Robert Millikan, known for his oil-drop experiment to measure e, took up the challenge. Some of Millikan's data for a cesium cathode are shown in **FIGURE 38.10**. As you can see, Einstein's prediction of a linear relationship between f and V_{stop} was confirmed.

Millikan measured the slope of his graph and multiplied it by the value of e (which he had measured a few years earlier in the oil-drop experiment) to find h. His value agreed with the value that Planck had determined in 1900 from an entirely different experiment. Light quanta, whether physicists liked the idea or not, were real.

EXAMPLE 38.3 The photoelectric threshold frequency

What are the threshold frequencies and wavelengths for photoemission from sodium and from aluminum?

SOLVE Table 38.1 gives the sodium work function as $E_0 = 2.75$ eV. Aluminum has $E_0 = 4.28$ eV. We can use Equation 38.6, with h in units of eV s, to calculate

$$f_0 = \frac{E_0}{h} = \begin{cases} 6.64 \times 10^{14}\ \text{Hz} & \text{sodium} \\ 10.34 \times 10^{14}\ \text{Hz} & \text{aluminum} \end{cases}$$

These frequencies are converted to wavelengths with $\lambda = c/f$, giving

$$\lambda = \begin{cases} 452\ \text{nm} & \text{sodium} \\ 290\ \text{nm} & \text{aluminum} \end{cases}$$

ASSESS The photoelectric effect can be observed with sodium for $\lambda < 452$ nm. This includes blue and violet visible light but not red, orange, yellow, or green. Aluminum, with a larger work function, needs ultraviolet wavelengths $\lambda < 290$ nm.

EXAMPLE 38.4 Maximum photoelectron speed

What is the maximum photoelectron speed if sodium is illuminated with light of 300 nm?

SOLVE The light frequency is $f = c/\lambda = 1.00 \times 10^{15}$ Hz, so each light quantum has energy $hf = 4.14$ eV. The maximum kinetic energy of a photoelectron is

$$K_{max} = hf - E_0 = 4.14\ \text{eV} - 2.75\ \text{eV} = 1.39\ \text{eV}$$
$$= 2.22 \times 10^{-19}\ \text{J}$$

Because $K = \frac{1}{2}mv^2$, where m is the electron's mass, not the mass of the sodium atom, the maximum speed of a photoelectron leaving the cathode is

$$v_{max} = \sqrt{\frac{2K_{max}}{m}} = 6.99 \times 10^5\ \text{m/s}$$

Note that we had to convert K_{max} to SI units of J before calculating a speed in m/s.

STOP TO THINK 38.1 The work function of metal A is 3.0 eV. Metals B and C have work functions of 4.0 eV and 5.0 eV, respectively. Ultraviolet light shines on all three metals, creating photoelectrons. Rank in order, from largest to smallest, the stopping potentials for A, B, and C.

38.3 Photons

Einstein was awarded the Nobel Prize in 1921 not for his theory of relativity, as many suppose, but for his explanation of the photoelectric effect. Although Planck had made the first suggestion, it was Einstein who showed convincingly that energy is quantized. Quanta of light energy were later given the name **photons.**

But just what are photons? To begin our explanation, let's return to the experiment that showed most dramatically the wave nature of light—Young's double-slit interference experiment. We will make a change, though: We will dramatically lower the light