21.2 Einstein and the Photoelectric Effect

Section Learning Objectives

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

- Describe Einstein's explanation of the photoelectric effect
- Describe how the photoelectric effect could not be explained by classical physics
- Calculate the energy of a photoelectron under given conditions
- Describe use of the photoelectric effect in biological applications, photoelectric devices and movie soundtracks

Section Key Terms

electric eye	photoelectric effect	photoelectron	photon

The Photoelectric Effect

Teacher Support
[EL]Ask the students what they think the term *photoelectric* means. How does the term relate to its definition?

When light strikes certain materials, it can eject electrons from them. This is called the **photoelectric effect**, meaning that light (*photo*) produces electricity. One common use of the photoelectric effect is in light meters, such as those that adjust the automatic iris in various types of cameras. Another use is in solar cells, as you probably have in your calculator or have seen on a rooftop or a roadside sign. These make use of the photoelectric effect to convert light into electricity for running different devices.

Figure 21.5 The photoelectric effect can be observed by allowing light to fall on the metal plate in this evacuated tube. Electrons ejected by the light are collected on the collector wire and measured as a current. A retarding voltage between the collector wire and plate can then be adjusted so as to determine the energy of the ejected electrons. (credit: P. P. Urone)

Revolutionary Properties of the Photoelectric Effect

When Max Planck theorized that energy was quantized in a blackbody radiator, it is unlikely that he would have recognized just how revolutionary his idea was. Using tools similar to the light meter in Figure 21.5, it would take a scientist of Albert Einstein's stature to fully discover the implications of Max Planck's radical concept.

Through careful observations of the photoelectric effect, Albert Einstein realized that there were several characteristics that could be explained only if *EM radiation is itself quantized*. While these characteristics will be explained a bit later in this section, you can already begin to appreciate why Einstein's idea is very important. It means that the apparently continuous stream of energy in an EM wave is actually not a continuous stream at all. In fact, the EM wave itself is actually composed of tiny quantum packets of energy called **photons**.

In equation form, Einstein found the energy of a photon or **photoelectron** to be

$$E = h\mathrm{f},$$

where E is the energy of a photon of frequency f and h is Planck's constant. A beam from a flashlight, which to this point had been considered a wave, instead could now be viewed as a series of photons, each providing a specific amount of energy see Figure 21.6. Furthermore, the amount of energy within each individual photon is based upon its individual frequency, as dictated by $E = hf$. As a result, the total amount of energy provided by the beam could now be viewed as the sum of all frequency-dependent photon energies added together.

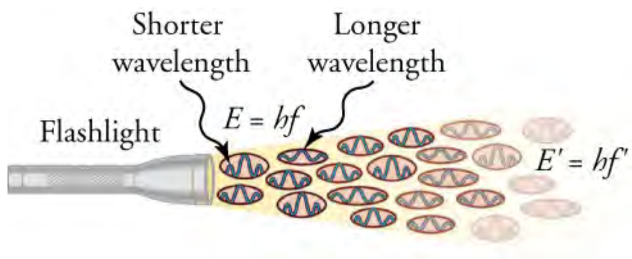

Figure 21.6 An EM wave of frequency *f* is composed of photons, or individual quanta of EM radiation. The energy of each photon is $E = hf$, where *h* is Planck's constant and *f* is the frequency of the EM radiation. Higher intensity means more photons per unit area per second. The flashlight emits large numbers of photons of many different frequencies, hence others have energy $E' = hf'$, and so on.

Just as with Planck's blackbody radiation, Einstein's concept of the photon could take hold in the scientific community only if it could succeed where classical physics failed. The photoelectric effect would be a key to demonstrating Einstein's brilliance.

Consider the following five properties of the photoelectric effect. All of these properties are consistent with the idea that individual photons of EM radiation are absorbed by individual electrons in a material, with the electron gaining the photon's energy. Some of these properties are inconsistent with the idea that EM radiation is a simple wave. For simplicity, let us consider what happens with monochromatic EM radiation in which all photons have the same energy *hf*.

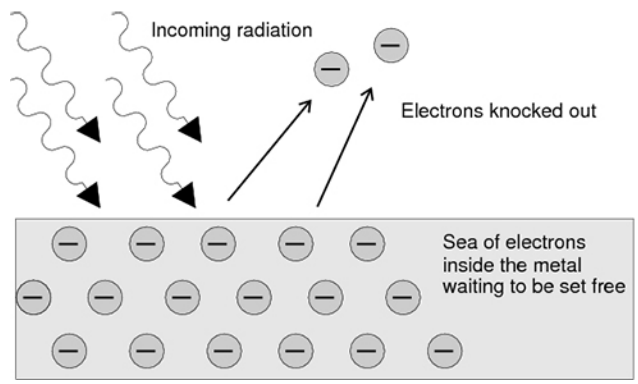

Figure 21.7 Incident radiation strikes a clean metal surface, ejecting multiple electrons from it. The manner in which the frequency and intensity of the incoming radiation affect the ejected electrons strongly suggests that electromagnetic radiation is quantized. This event, called the photoelectric effect, is strong evidence for the existence of photons.

1. If we vary the frequency of the EM radiation falling on a clean metal surface, we find the following: For a given material, there is a threshold frequency f_0 for the EM radiation below which no electrons are ejected, regardless of intensity. Using the photon model, the explanation for this is clear. Individual photons interact with individual electrons. Thus if the energy of an individual photon is too low to break an electron away, no electrons will be ejected. However, if EM radiation were a simple wave, sufficient energy could be obtained simply by increasing the intensity.
2. *Once EM radiation falls on a material, electrons are ejected without delay*. As soon as an individual photon of sufficiently high frequency is absorbed by an individual electron, the electron is ejected. If the EM radiation were a simple wave, several minutes would be required for sufficient energy to be deposited at the metal surface in order to eject an electron.
3. The number of electrons ejected per unit time is proportional to the intensity of the EM radiation and to no other characteristic. High-intensity EM radiation consists of large numbers of photons per unit area, with all photons having the same characteristic energy, *hf*. The increased number of photons per unit area results in an increased number of electrons per unit area ejected.
4. If we vary the intensity of the EM radiation and measure the energy of ejected electrons, we find the following: *The maximum kinetic energy of ejected electrons is independent of the intensity of the EM radiation*. Instead, as noted in point 3 above, increased intensity results in more electrons of the same energy being ejected. If EM radiation were a simple wave, a higher intensity could transfer more energy, and higher-energy electrons would be ejected.
5. The kinetic energy KE of an ejected electron equals the photon energy minus the binding energy BE of the electron in the

specific material. An individual photon can give all of its energy to an electron. The photon's energy is partly used to break the electron away from the material. The remainder goes into the ejected electron's kinetic energy. In equation form, this is given by

$$KE_e = hf - BE, \tag{21.6}$$

where KE_e is the maximum kinetic energy of the ejected electron, hf is the photon's energy, and BE is the binding energy of the electron to the particular material. This equation explains the properties of the photoelectric effect quantitatively and demonstrates that BE is the minimum amount of energy necessary to eject an electron. If the energy supplied is less than BE, the electron cannot be ejected. The binding energy can also be written as $BE = hf_0$, where f_0 is the threshold frequency for the particular material. Figure 21.8 shows a graph of maximum KE_e versus the frequency of incident EM radiation falling on a particular material.

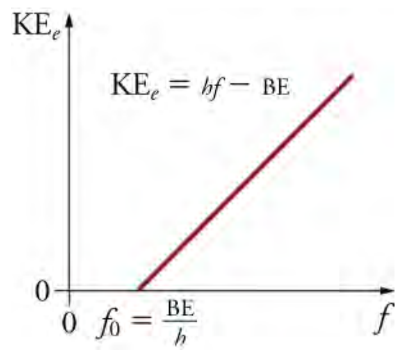

Figure 21.8 A graph of the kinetic energy of an ejected electron, KE_e, versus the frequency of EM radiation impinging on a certain material. There is a threshold frequency below which no electrons are ejected, because the individual photon interacting with an individual electron has insufficient energy to break it away. Above the threshold energy, KE_e increases linearly with f, consistent with $KE_e = hf - BE$. The slope of this line is h, so the data can be used to determine Planck's constant experimentally.

TIPS FOR SUCCESS

The following five pieces of information can be difficult to follow without some organization. It may be useful to create a table of expected results of each of the five properties, with one column showing the classical wave model result and one column showing the modern photon model result.
The table may look something like Table 21.1

	Classical Wave Model	Modern Photon Model
Threshold Frequency		
Electron Ejection Delay		
Intensity of EM Radiation		
Speed of Ejected Electrons		
Relationship between Kinetic Energy and Binding Energy		

Table 21.1 Table of Expected Results

Virtual Physics

Photoelectric Effect

Click to view content (http://www.openstax.org/l/28photoelectric)

In this demonstration, see how light knocks electrons off a metal target, and recreate the experiment that spawned the field of quantum mechanics.

GRASP CHECK

In the circuit provided, what are the three ways to increase the current?

a. decrease the intensity, decrease the frequency, alter the target
b. decrease the intensity, decrease the frequency, don't alter the target
c. increase the intensity, increase the frequency, alter the target
d. increase the intensity, increase the frequency, alter the target

WORKED EXAMPLE

Photon Energy and the Photoelectric Effect: A Violet Light

(a) What is the energy in joules and electron volts of a photon of 420-nm violet light? (b) What is the maximum kinetic energy of electrons ejected from calcium by 420 nm violet light, given that the binding energy of electrons for calcium metal is 2.71 eV?

Strategy

To solve part (a), note that the energy of a photon is given by $E = hf$. For part (b), once the energy of the photon is calculated, it is a straightforward application of $KE_e = hf - BE$ to find the ejected electron's maximum kinetic energy, since BE is given.

Solution for (a)

Photon energy is given by

$$E = hf.$$

Since we are given the wavelength rather than the frequency, we solve the familiar relationship $c = f\lambda$ for the frequency, yielding

$$f = \frac{c}{\lambda} \tag{21.7}$$

Combining these two equations gives the useful relationship

$$E = \frac{hc}{\lambda}. \tag{21.8}$$

Now substituting known values yields

$$E = \frac{\left(6.63 \times 10^{-34}\,\mathrm{J \cdot s}\right)\left(3.00 \times 10^{8}\,m/s\right)}{4.20 \times 10^{-7}\,m} = 4.74 \times 10^{-19}\,\mathrm{J}. \tag{21.9}$$

Converting to eV, the energy of the photon is

$$E = (4.74 \times 10^{-19}\,\mathrm{J \cdot s})\frac{1\ \mathrm{eV}}{1.60 \times 10^{-19}\,\mathrm{J}} = 2.96\ \mathrm{eV}. \tag{21.10}$$

Solution for (b)

Finding the kinetic energy of the ejected electron is now a simple application of the equation $KE_e = hf - BE$. Substituting the photon energy and binding energy yields

$$KE_e = hf - BE = 2.96\ \mathrm{eV} - 2.71\ \mathrm{eV} = 0.25\ \mathrm{eV}. \tag{21.11}$$

Discussion

The energy of this 420 nm photon of violet light is a tiny fraction of a joule, and so it is no wonder that a single photon would be difficult for us to sense directly—humans are more attuned to energies on the order of joules. But looking at the energy in electron volts, we can see that this photon has enough energy to affect atoms and molecules. A DNA molecule can be broken with about 1 eV of energy, for example, and typical atomic and molecular energies are on the order of eV, so that the photon in this example could have biological effects, such as sunburn. The ejected electron has rather low energy, and it would not travel far, except in a vacuum. The electron would be stopped by a retarding potential of only 0.26 eV, a slightly larger KE than calculated above. In fact, if the photon wavelength were longer and its energy less than 2.71 eV, then the formula would give a negative kinetic energy, an impossibility. This simply means that the 420 nm photons with their 2.96 eV energy are not much above the frequency threshold. You can see for yourself that the threshold wavelength is 458 nm (blue light). This means that if calcium metal were used in a light meter, the meter would be insensitive to wavelengths longer than those of blue light. Such a light meter would be completely insensitive to red light, for example.

Practice Problems

10. What is the longest-wavelength EM radiation that can eject a photoelectron from silver, given that the bonding energy is 4.73 eV ? Is this radiation in the visible range?

a. 2.63×10^{-7} m; No, the radiation is in microwave region.
b. 2.63×10^{-7} m; No, the radiation is in visible region.
c. 2.63×10^{-7} m; No, the radiation is in infrared region.
d. 2.63×10^{-7} m; No, the radiation is in ultraviolet region.

11. What is the maximum kinetic energy in eV of electrons ejected from sodium metal by 450-nm EM radiation, given that the binding energy is 2.28 eV?

a. 0.48 V
b. 0.82 eV
c. 1.21 eV
d. 0.48 eV

Technological Applications of the Photoelectric Effect

While Einstein's understanding of the photoelectric effect was a transformative discovery in the early 1900s, its presence is ubiquitous today. If you have watched streetlights turn on automatically in response to the setting sun, stopped elevator doors from closing simply by putting your hands between them, or turned on a water faucet by sliding your hands near it, you are familiar with the **electric eye**, a name given to a group of devices that use the photoelectric effect for detection.

All these devices rely on photoconductive cells. These cells are activated when light is absorbed by a semi-conductive material, knocking off a free electron. When this happens, an electron void is left behind, which attracts a nearby electron. The movement of this electron, and the resultant chain of electron movements, produces a current. If electron ejection continues, further holes are created, thereby increasing the electrical conductivity of the cell. This current can turn switches on and off and activate various familiar mechanisms.

One such mechanism takes place where you may not expect it. Next time you are at the movie theater, pay close attention to the sound coming out of the speakers. This sound is actually created using the photoelectric effect! The audiotape in the projector booth is a transparent piece of film of varying width. This film is fed between a photocell and a bright light produced by an exciter lamp. As the transparent portion of the film varies in width, the amount of light that strikes the photocell varies as well. As a result, the current in the photoconductive circuit changes with the width of the filmstrip. This changing current is converted to a changing frequency, which creates the soundtrack commonly heard in the theater.

WORK IN PHYSICS

Solar Energy Physicist

According to the U.S. Department of Energy, Earth receives enough sunlight each hour to power the entire globe for a year. While converting all of this energy is impossible, the job of the solar energy physicist is to explore and improve upon solar energy conversion technologies so that we may harness more of this abundant resource.

The field of solar energy is not a new one. For over half a century, satellites and spacecraft have utilized photovoltaic cells to create current and power their operations. As time has gone on, scientists have worked to adapt this process so that it may be used in homes, businesses, and full-scale power stations using solar cells like the one shown in Figure 21.9.

Figure 21.9 A solar cell is an example of a photovoltaic cell. As light strikes the cell, the cell absorbs the energy of the photons. If this energy exceeds the binding energy of the electrons, then electrons will be forced to move in the cell, thereby producing a current. This current may be used for a variety of purposes. (credit: U.S. Department of Energy)

Solar energy is converted to electrical energy in one of two manners: direct transfer through photovoltaic cells or thermal conversion through the use of a CSP, concentrating solar power, system. Unlike electric eyes, which trip a mechanism when current is lost, photovoltaic cells utilize semiconductors to directly transfer the electrons released through the photoelectric effect into a directed current. The energy from this current can then be converted for storage, or immediately used in an electric process. A CSP system is an indirect method of energy conversion. In this process, light from the Sun is channeled using parabolic mirrors. The light from these mirrors strikes a thermally conductive material, which then heats a pool of water. This water, in turn, is converted to steam, which turns a turbine and creates electricity. While indirect, this method has long been the traditional means of large-scale power generation.

There are, of course, limitations to the efficacy of solar power. Cloud cover, nightfall, and incident angle strike at high altitudes are all factors that directly influence the amount of light energy available. Additionally, the creation of photovoltaic cells requires rare-earth minerals that can be difficult to obtain. However, the major role of a solar energy physicist is to find ways to improve the efficiency of the solar energy conversion process. Currently, this is done by experimenting with new semi conductive materials, by refining current energy transfer methods, and by determining new ways of incorporating solar structures into the current power grid.

Additionally, many solar physicists are looking into ways to allow for increased solar use in impoverished, more remote locations. Because solar energy conversion does not require a connection to a large-scale power grid, research into thinner, more mobile materials will permit remote cultures to use solar cells to convert sunlight collected during the day into stored energy that can then be used at night.

Regardless of the application, solar energy physicists are an important part of the future in responsible energy growth. While a doctoral degree is often necessary for advanced research applications, a bachelor's or master's degree in a related science or engineering field is typically enough to gain access into the industry. Computer skills are very important for energy modeling, including knowledge of CAD software for design purposes. In addition, the ability to collaborate and communicate with others is critical to becoming a solar energy physicist.

GRASP CHECK

What role does the photoelectric effect play in the research of a solar energy physicist?

a. The understanding of photoelectric effect allows the physicist to understand the generation of light energy when using photovoltaic cells.
b. The understanding of photoelectric effect allows the physicist to understand the generation of electrical energy when using photovoltaic cells.
c. The understanding of photoelectric effect allows the physicist to understand the generation of electromagnetic energy when using photovoltaic cells.
d. The understanding of photoelectric effect allows the physicist to understand the generation of magnetic energy when using photovoltaic cells.

Check Your Understanding

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

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

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

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

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

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

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

21.3 The Dual Nature of Light

Section Learning Objectives

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

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

Section Key Terms

Compton effect	particle-wave duality	photon momentum

Photon Momentum

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

Despite the odd nature of photons, scientists prior to Einstein had long suspected that the fundamental particle of