Photodetectors

Modern photodetectors are descendants of the photoelectric effect. These range from simple "electric eyes" to the detector array in a video camera. Most detectors use what is called a *photodiode* in which the photoelectrons are emitted internally in a semiconductor. Even so, they still have a threshold frequency, a stopping potential, and other attributes of the photoelectric effect.

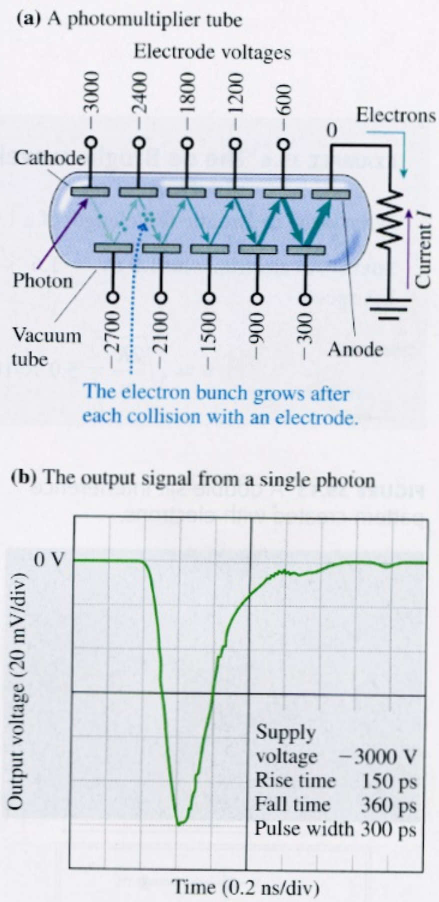
Very low light levels can be detected photon by photon with a device called a *photomultiplier tube,* or PMT. **FIGURE 39.12a** shows that a PMT consists of a cathode, an anode, and a number of intermediate electrodes sealed inside an evacuated glass tube. The cathode is coated with a low-work-function material, allowing it to respond to most visible wavelengths of light. The cathode is at a fairly high negative voltage and the anode, at the other end, is at essentially zero volts. Steadily descending potentials are applied to the intermediate electrodes.

A photon of light ejects a photoelectron from the cathode. The electric field between the cathode and the first intermediate electrode accelerates that electron through a potential difference of about 300 V, and it then strikes this electrode at high speed. When a fast electron collides with a metal surface, it can kick out two or three other electrons called *secondary electrons.* The secondary electrons of the first electrode are accelerated to the second electrode, where they kick out more electrons. These are accelerated to the third electrode, where they kick out yet more electrons, and so on. There is a chain-reaction *multiplication* of electrons—1, 2, 4, 8, 16, . . . —as they move from the cathode toward the anode. For a typical PMT, a single photon at the cathode causes an electron bunch with 10^6 or 10^7 electrons to arrive at the anode.

The electrons are collected by the anode and flow through a resistor. Because these are negative charge carriers, we would say that a current pulse I travels upward through the resistor. This creates a *negative* voltage across the resistor, $\Delta V = IR$, for the length of time that the current lasts. **FIGURE 39.12b**, an actual measurement, shows a pulse generated by a single photon. The horizontal scale is 0.2 ns/division and the vertical scale is 20 millivolts (mV)/division. You can see that the width of the pulse is $\approx$0.3 ns and its height (measured downward from the baseline) is $\approx$120 mV = 0.12 V. This is not a large voltage, even after the multiplication, but it is a voltage easily detected with modern electronics.

NOTE ► The 0.3 ns pulse duration is *not* an indication of the duration of a photon. The photon absorption is instantaneous, but as the electron bunch grows in size, the electron-electron repulsion causes the bunch to spread out some. The observed pulse width is an artifact of the PMT, not a characteristic of the photon. ◄

FIGURE 39.12 A photomultiplier tube can detect individual photons.



STOP TO THINK 39.2 The intensity of a beam of light is increased but the light's frequency is unchanged. Which one (or perhaps more than one) of the following is true?

a. The photons travel faster.
b. Each photon has more energy.
c. The photons are larger.
d. There are more photons per second.

39.4 Matter Waves and Energy Quantization

Prince Louis-Victor de Broglie was a French graduate student in 1924. It had been 19 years since Einstein had shaken the world of physics by blurring the distinction between a particle and a wave. As de Broglie thought about these issues, it seemed that nature should have some kind of symmetry. If light waves could have a particle-like nature, why shouldn't material particles have some kind of wave-like nature? In other words, could **matter waves** exist?

With no experimental evidence to go on, de Broglie reasoned by analogy with Einstein's equation $E = hf$ for the photon and with some of the ideas of his theory of relativity. The details need not concern us, but they led de Broglie to postulate that *if* a material particle of momentum $p = mv$ has a wave-like nature, then its wavelength must be given by

$$\lambda = \frac{h}{p} = \frac{h}{mv} \tag{39.11}$$

where h is Planck's constant. This is called the **de Broglie wavelength.**

EXAMPLE 39.6 The de Broglie wavelength of an electron

What is the de Broglie wavelength of a 1.0 eV electron?

SOLVE An electron with $1.0 \text{ eV} = 1.6 \times 10^{-19}$ J of kinetic energy has speed

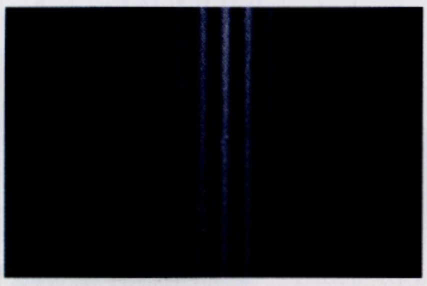
$$v = \sqrt{\frac{2K}{m}} = 5.9 \times 10^5 \text{ m/s}$$

Although fast by macroscopic standards, this is a slow electron because it gains this speed by accelerating through a potential difference of a mere 1 V. Its de Broglie wavelength is

$$\lambda = \frac{h}{mv} = 1.2 \times 10^{-9} \text{ m} = 1.2 \text{ nm}$$

ASSESS The electron's wavelength is small, but it is larger than the wavelengths of x rays and larger than the approximately 10^{-10} m spacing of atoms in a crystal.

FIGURE 39.13 A double-slit interference pattern created with electrons.

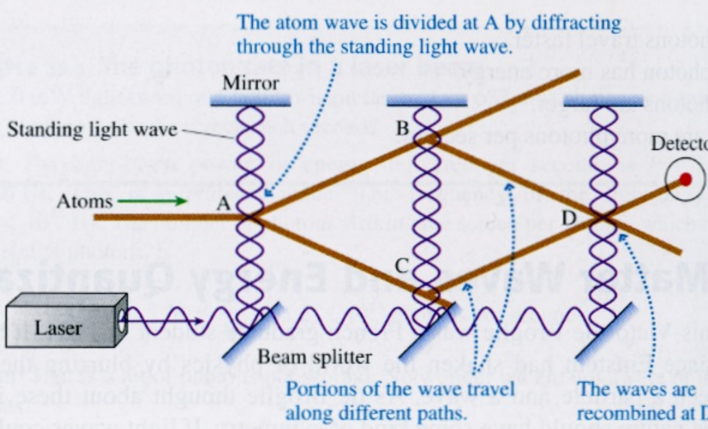


What would it mean for matter—an electron or a proton or a baseball—to have a wavelength? Would it obey the principle of superposition? Would it exhibit interference and diffraction? These are questions we examined in Chapter 25, where we found that, indeed, matter *does* exhibit interference. For example, **FIGURE 39.13** shows the intensity pattern recorded after 50 keV electrons passed through two slits separated by 1.0 μm. The pattern is clearly a double-slit interference pattern, and the spacing of the fringes is exactly as predicted for a wavelength given by de Broglie's formula. Because the electron beam was weak, with one electron at a time passing through the apparatus, it would appear that each electron somehow went through both slits, then recombined to interfere with itself!

Electrons are fundamental subatomic particles. Perhaps subatomic particles have wave-like aspects, but what about entire atoms, aggregates of many fundamental particles? Amazing as it seems, research during the 1980s demonstrated that whole atoms, and even molecules, can produce interference patterns.

FIGURE 39.14 shows an *atom interferometer*. You learned in Chapter 22 that an interferometer, such as the Michelson interferometer, works by dividing a wave front into

FIGURE 39.14 An atom interferometer.



two waves, sending the two waves along separate paths, then recombining them. For light waves, wave division can be accomplished by sending light through the *periodic* slits in a diffraction grating. In an atom interferometer, the atom's matter wave is divided by sending atoms through the *periodic* intensity of a standing light wave.

You can see in the figure that a laser creates three parallel *standing waves* of light, each with nodes spaced a distance $\lambda/2$ apart. The wavelength is chosen so that the light waves exert small forces on an atom in the laser beam. Because the intensity along a standing wave alternates between maximum at the antinodes and zero intensity at the nodes, an atom crossing the laser beam experiences a *periodic* force field. A particle-like atom would be deflected by this periodic force, but a wave is *diffracted.* After being diffracted by the first standing wave at A, an atom is, in some sense, traveling toward both point B *and* point C.

The second standing wave diffracts the atom waves again at points B and C, directing them toward D where, with a third diffraction, they are recombined after having traveled along different paths. Depending on the phases of the waves as they recombine, the detector sometimes records atoms (constructive interference) but at other times does not (destructive interference). Altering one of the paths, such as by applying an electric field in the region around B but not around C, shifts the phases of the atom waves and causes the detector to record interference fringes.

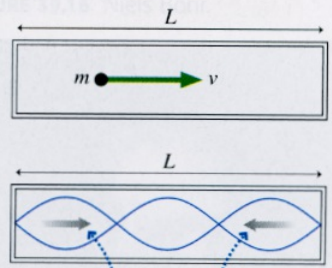
The atom interferometer is fascinating because it completely inverts everything we previously learned about interference and diffraction. The scientists who studied the wave nature of light during the 19th century aimed light (a wave) at a diffraction grating (a periodic structure of matter) and found that it diffracted. Now we aim atoms (matter) at a standing wave (a periodic structure of light) and find that the atoms diffract. The roles of light and matter have been reversed!

Quantization of Energy

De Broglie considered a matter wave to be a traveling wave. But suppose that a "particle" of matter is *confined* to a small region of space and cannot travel? How do the wave-like properties manifest themselves?

This is the problem of "a particle in a box" that we looked at in Chapter 25. We will briefly summarize that discussion. **FIGURE 39.15** shows a particle of mass m moving in one dimension as it bounces back and forth with speed v between the ends of a box of length L. We'll call this a *one-dimensional box;* its width isn't relevant.

FIGURE 39.15 A particle in a box creates a standing de Broglie wave as it reflects back and forth.



A wave, if it reflects back and forth between two fixed points, sets up a standing wave. You learned in Chapter 21 that a standing wave of length L *must* have a wavelength given by

$$\lambda_n = \frac{2L}{n} \qquad n = 1, 2, 3, 4, \ldots \tag{39.12}$$

If the confined particle has wave-like properties, it should satisfy both Equation 39.12 *and* the de Broglie relationship $\lambda = h/mv$. That is, a particle in a box should obey the relationship

$$\lambda = \frac{h}{mv} = \frac{2L}{n}$$

This can be true only if the particle's speed is

$$v_n = n\left(\frac{h}{2Lm}\right) \qquad n = 1, 2, 3, \ldots \tag{39.13}$$

In other words, the particle cannot bounce back and forth with just any speed. Rather, it can have *only* those specific speeds v_n, given by Equation 39.13, for which the de Broglie wavelength creates a standing wave in the box.

Thus the particle's energy, which is purely kinetic energy, is

$$E_n = \frac{1}{2}mv_n^2 = n^2\frac{h^2}{8mL^2} \qquad n = 1, 2, 3, \ldots \tag{39.14}$$

De Broglie's hypothesis about the wave-like properties of matter leads us to the remarkable conclusion that **the energy of a confined particle is quantized.** The energy of the particle in the box can be $1(h^2/8mL^2)$, or $4(h^2/8mL^2)$, or $9(h^2/8mL^2)$, but it *cannot* have an energy between these values.

The possible values of the particle's energy are called **energy levels,** and the integer n that characterizes the energy levels is called the **quantum number.** The quantum number can be found by counting the antinodes, just as you learned to do for standing waves on a string. The standing wave shown in Figure 39.15 is $n = 3$, thus its energy is E_3.

We can rewrite Equation 39.14 in the useful form

$$E_n = n^2E_1 \tag{39.15}$$

where

$$E_1 = \frac{h^2}{8mL^2} \tag{39.16}$$

is the **fundamental quantum of energy** for a particle in a one-dimentional box. It is analogous to the fundamental frequency f_1 of a standing wave on a string.

EXAMPLE 39.7 The energy levels of an oil droplet

What is the fundamental quantum of energy for one of Millikan's 1.0-μm-diameter oil droplets confined in a box of length 10 μm? The density of the oil is 900 kg/m^3.

SOLVE The mass of a droplet is $m = \rho V$, where the volume is $\frac{4}{3}\pi r^3$. A quick calculation shows that a 1.0-μm-diameter droplet has mass $m = 4.7 \times 10^{-16}$ kg. The confinement length is $L = 1.0 \times 10^{-5}$ m. From Equation 39.16, the fundamental quantum of energy is

$$E_1 = \frac{h^2}{8mL^2} = \frac{(6.63 \times 10^{-34}\ \text{J s})^2}{8(4.7 \times 10^{-16}\ \text{kg})(1.0 \times 10^{-5}\ \text{m})^2}$$
$$= 1.2 \times 10^{-42}\ \text{J} = 7.3 \times 10^{-24}\ \text{eV}$$

ASSESS This is such an incredibly small amount of energy that there is no hope of distinguishing between energies of E_1 or $4E_1$ or $9E_1$. For any macroscopic particle, even one this tiny, the allowed energies will *seem* to be perfectly continuous. We will not observe the quantization.

EXAMPLE 39.8 The energy levels of an electron

What are the first three allowed energies for an electron confined in a one-dimensional box of length 0.10 nm, about the size of an atom?

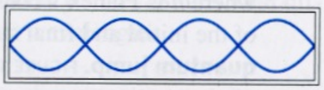
SOLVE We can use Equation 39.16, with $m_{elec} = 9.11 \times 10^{-31}$ kg and $L = 1.0 \times 10^{-10}$ m to find that the fundamental quantum of energy is $E_1 = 6.0 \times 10^{-18}$ J = 38 eV. Thus the first three allowed energies of an electron in a 0.10 nm box are

$$E_1 = 38\ \text{eV}$$
$$E_2 = 4E_1 = 152\ \text{eV}$$
$$E_3 = 9E_1 = 342\ \text{eV}$$

We see that confining a wave-like particle creates a standing de Broglie wave, and we know that a standing wave has only certain discrete wavelengths. Thus we find that a confined particle can have only certain discrete energies. In other words, the **confinement of a particle leads directly to the quantization of its energy.** The particle in a box, although not a realistic model of an atom, is a simple example to illustrate these ideas. An electron confined in a real atom will need to be a much more complex three-dimensional standing wave. But, just like the simple particle in a box, it will have quantized energies. Furthermore, we expect a typical energy difference between adjacent energy levels will be a few electron volts.

Now, this is an intriguing result. We found that visible and ultraviolet photons of light have energies of a few electron volts. We also know that atoms emit *discrete* wavelengths of visible and ultraviolet light, with photon energies of a few electron volts. Now we see that an electron confined in an atomic-size box has energy levels spaced a few electron volts apart. Might there be a connection between these phenomena? We will explore this topic in the next section.

STOP TO THINK 39.3 What is the quantum number of this particle confined in a box?



39.5 Bohr's Model of Atomic Quantization

Thomson's electron and Rutherford's nucleus made it clear that the atom has a *structure* of some sort. The challenge at the beginning of the 20th century was to deduce, from experimental evidence, the correct structure. The difficulty of this task cannot be exaggerated. The evidence about atoms, such as observations of atomic spectra, was very indirect, and experiments were carried out with only the simplest measuring devices. Using observations as a guide, physicists were attempting to construct a *model* of the atom that could successfully explain the various experiments.

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Rutherford's nuclear model was the most successful of various proposals, but Rutherford's model failed to explain why atoms are stable or why their spectra are discrete. A missing piece of the puzzle, although not recognized as such for a few years, was Einstein's 1905 introduction of light quanta. If light comes in discrete packets of energy, which we now call photons, and if atoms emit and absorb light, what does that imply about the structure of the atoms?

This was the question posed by Niels Bohr. Bohr, shown as young man in **FIGURE 39.16**, was born, educated, and spent most of his life in Denmark. He later established an institute in Copenhagen that, for many decades, was the leading center for the development of quantum physics. Although few discoveries bear Bohr's name, he was the intellectual driving force behind the development of quantum mechanics and the mentor of many of the young physicists who reshaped physics in the 1920s and 1930s.

FIGURE 39.16 Niels Bohr.

After receiving his doctoral degree in physics in 1911, Bohr went to England to work in Rutherford's laboratory. Rutherford had just, within the previous year, completed his development of the nuclear model of the atom. Rutherford's model certainly contained a kernel of truth, but Bohr wanted to understand how a solar-system-like atom could be stable and not radiate away all its energy. He soon recognized that Einstein's light quanta had profound implications for the structure of atoms. In 1913, Bohr proposed a radically new model of the atom in which he added quantization to Rutherford's nuclear atom.

The basic assumptions of the **Bohr model of the atom** are as follows:

1. An atom consists of negative electrons orbiting a very small positive nucleus, as in the Rutherford model.
2. Atoms can exist only in certain **stationary states.** Each stationary state corresponds to a particular set of electron orbits around the nucleus. These states are distinct and can be numbered $n = 1, 2, 3, 4, \ldots$, where n is the *quantum number.*