The Photoelectric Effect

The quantum nature of light and the quantization of energy were suggested by Albert Einstein in 1905 in his explanation of the photoelectric effect. Einstein's work marked the beginning of quantum theory, and for his work, Einstein received the Nobel Prize for physics. Figure 34-2 shows a schematic diagram of the basic apparatus for studying the photoelectric effect. Light of a single frequency enters an evacuated chamber and falls on a clean metal surface C (C for cathode), causing electrons to be emitted. Some of these electrons strike the second metal plate A (A for anode), constituting an electric current between the plates. Plate A is negatively charged, so the electrons are repelled by it, with only the most energetic electrons reaching the plate. The maximum kinetic energy of the emitted electrons is measured by slowly increasing the voltage until the current becomes zero. Experiments give the surprising result that the maximum kinetic energy of the emitted electrons is *independent of the intensity* of the incident light. Classically, we would expect that increasing the rate at which light energy falls on the metal surface would increase the energy absorbed by individual electrons and, therefore, would increase the maximum kinetic energy of the electrons emitted. Experimentally, this is not what happens. The maximum kinetic energy of the emitted electrons is the same for a given wavelength of incident light, no matter how intense the light. Einstein demonstrated that this experimental result can be explained if light energy is quantized in small bundles called **photons.** The energy E of each photon is given by

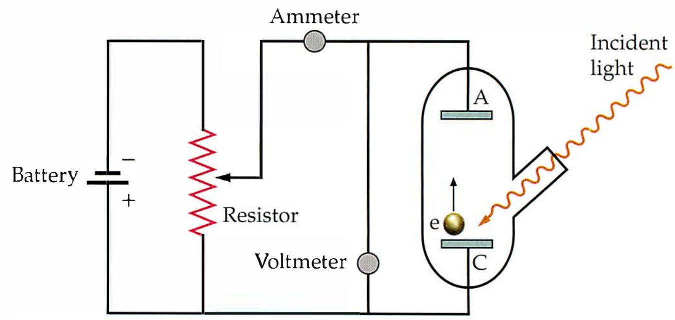

FIGURE 34-2 A schematic drawing of the apparatus for studying the photoelectric effect. Light of a single frequency enters an evacuated chamber and strikes the cathode C, which then ejects electrons. The current in the ammeter measures the number of these electrons that reach the anode A per unit time. The anode is made electrically negative with respect to the cathode to repel the electrons. Only those electrons with enough initial kinetic energy to overcome the repulsion can reach the anode. The voltage between the two plates is slowly increased until the current becomes zero, which happens when even the most energetic electrons do not make it to plate A.

$$E = hf = \frac{hc}{\lambda} \qquad 34\text{-}1$$

EINSTEIN EQUATION FOR PHOTON ENERGY

where f is the frequency, and h is a constant now known as **Planck's constant.**†
The measured value of this constant is

$$h = 6.626 \times 10^{-34}\ \text{J·s} = 4.136 \times 10^{-15}\ \text{eV·s} \qquad 34\text{-}2$$

PLANCK'S CONSTANT

Equation 34-1 is sometimes called the **Einstein equation.**

At the fundamental level, a light beam consists of a beam of particles—photons—each with energy hf. The intensity (power per unit area) of a monochromatic light beam is the number of photons per unit area per unit of time, times the energy per photon. The interaction of the light beam with the metal surface consists of collisions between photons and electrons. In these collisions, the photons disappear, with each photon giving all its energy to an electron, and the electron emitted from the surface thus receives its energy from a single photon. If the intensity of light is increased, more photons fall on the surface per unit time, and more electrons are emitted. However, each photon still has the same energy hf, so the energy absorbed by each electron is unchanged.

If ϕ is the minimum energy necessary to remove an electron from a metal surface, the maximum kinetic energy of the electrons emitted is given by

$$K_{\text{max}} = (\tfrac{1}{2}mv^2)_{\text{max}} = hf - \phi \qquad 34\text{-}3$$

EINSTEIN'S PHOTOELECTRIC EQUATION

The quantity ϕ, called the **work function,** is a characteristic of the particular metal. (Some electrons will have kinetic energies less than $hf - \phi$, because of the loss of energy from traveling through the metal.)

† In 1900, the German physicist Max Planck introduced this constant to explain discrepancies between the theoretical curves and experimental data on the spectrum of blackbody radiation. Planck also assumed that the radiation was emitted and absorbed by a blackbody in quanta of energy hf, but he considered his assumption to be just a calculational device rather than a fundamental property of electromagnetic radiation. Blackbody radiation was discussed in Chapter 20.