Scientists found that *none* of these classical predictions are observed experimentally. No electrons are emitted if the frequency of the incoming light falls below a certain frequency, even if the intensity is very high. This frequency, known as the *threshold frequency* (f_t), differs from metal to metal.

If the light frequency exceeds the threshold frequency, the photoelectric effect is observed. The number of photoelectrons emitted is proportional to the light intensity, but the maximum kinetic energy of the photoelectrons is independent of the light intensity. Instead, the maximum kinetic energy of the photoelectrons increases with increasing frequency. Furthermore, electrons are emitted from the surface almost instantaneously, even at low intensities. See **Table 1.**

Einstein proposed that all electromagnetic waves are quantized

Albert Einstein resolved this conflict in his 1905 paper on the photoelectric effect, for which he received the Nobel Prize in 1921, by extending Planck's concept of quantization to electromagnetic waves. Einstein assumed that an electromagnetic wave can be viewed as a stream of particles, now called **photons.** Each photon has an energy, E, given by Planck's equation ($E = hf$). In this theory, each photon is absorbed as a unit by an electron. When a photon's energy is transferred to an electron in a metal, the energy acquired by the electron is equal to hf.

photon

a unit or quantum of light; a particle of electromagnetic radiation that has zero mass and carries a quantum of energy

Threshold frequency depends on the work function of the surface

In order to be ejected from a metal, an electron must overcome the force that binds it to the metal. The smallest amount of energy the electron must have to escape the surface of a metal is the **work function** of the metal. The work function is equal to hf_t, where f_t is the threshold frequency for the metal. Photons with energy greater than hf_t eject electrons from the surface of and from within the metal. Because energy must be conserved, the maximum kinetic energy (of photoelectrons ejected from the surface) is the difference between the photon energy and the work function of the metal. This relationship is expressed mathematically by the following equation:

work function

the minimum energy needed to remove an electron from a metal atom

MAXIMUM KINETIC ENERGY OF A PHOTOELECTRON

$$KE_{max} = hf - hf_t$$

maximum kinetic energy =
(Planck's constant × frequency of incoming photon) − work function

According to this equation, there should be a linear relationship between f and KE_{max} because h is a constant and the work function, hf_t, is constant for any given metal. Experiments have verified that this is indeed the case, as shown in **Figure 5,** and the slope of such a curve ($\Delta KE/\Delta f$) gives a value for h that corresponds to Planck's value.

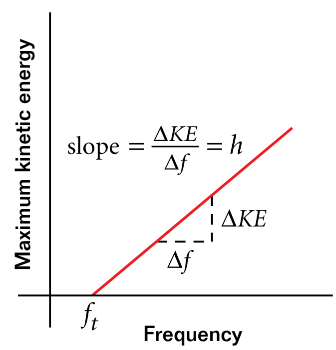

Figure 5
This graph shows a linear relationship between the maximum kinetic energy of emitted electrons and the frequency of incoming light. The intercept with the horizontal axis is the threshold frequency.