Quantum Phenomena

- Photons and the Photoelectric Effect
- The Momentum of a Photon and the Heisenberg Uncertainty Principle
- Matter Waves and the de Broglie Wavelength of a Particle

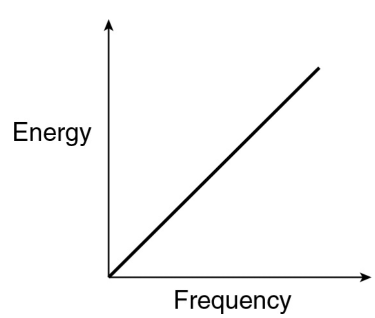
The word *quantum* simply means *the smallest piece of something*. The quantum of American money is one cent; the quantum of negative charge is the electron, since as far as we know there is no smaller negative charge that exists by itself. There are several quantities in physics that are *quantized*, that is, that occur in multiples of some smallest value. Light is one of these quantities.

A *quantum* is the smallest possible unit of a physical quantity.

Photons and the Photoelectric Effect

In chapters 15 through 17, we treated light as a wave. But there are circumstances when light behaves as though it is made up of individual bundles of energy, separate from each other but sharing a wavelength, frequency, and speed. The quantum of light is called the *photon*. In the late 19th century, an effect was discovered by Heinrich Hertz that could not be explained by the wave model of light. He shined ultraviolet light on a piece of zinc metal, and the metal became positively charged. Although he did not know it at the time, the light was causing the metal to emit electrons. The phenomenon of light causing electrons to be emitted from a metal is called the *photoelectric effect*. According to the theory of light at the time, light was considered a wave, and should not be able to "knock" electrons off of a metal surface. At the turn of the 20th century, Max Planck showed that light could be treated as tiny bundles of energy called photons, and the energy of a photon was proportional to its frequency. Thus, a graph of photon energy E vs. frequency f looks as follows.

The *photon* is the quantum of light.



The slope of this line is a constant called *Planck's constant* that appears many times in the study of quantum phenomena. Its symbol is *h*, and its value happens to be 6.63×10^{-34} J s. The equation for the energy of a photon is

$$E = hf,$$

$$\text{or, since } f = \frac{c}{\lambda},$$

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

So the energy of a photon is proportional to its frequency, but inversely proportional to its wavelength.

> The energy of a photon is proportional to its frequency.

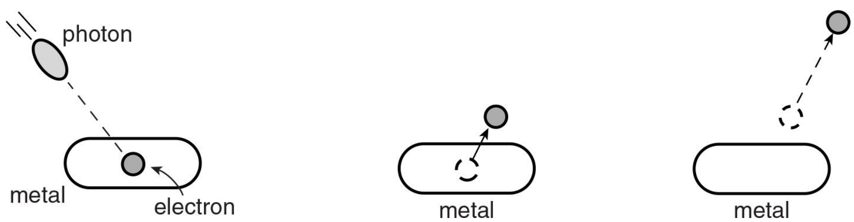
Example: List the following photons of light from lowest energy to highest energy:

1. (A) green
   (B) violet
   (C) yellow

Solution: Listing these photons from lowest to highest energy is the same as listing them from lowest to highest frequency, or, equivalently, from longest to shortest wavelength: yellow, green, violet.

In 1905, Albert Einstein used Planck's idea of the photon to explain the photoelectric effect: One photon is absorbed by one electron in the metal surface, giving the electron enough energy to be released from the metal. But not just any photon will knock an electron off of a metal surface. The photon must first have enough energy to "dig" the electron out of the metal, and then have some energy left over to give the electron some kinetic energy to escape completely.

The *photoelectric effect* results when light shined on a metal releases electrons from the surface of the metal.



Each metal that can exhibit the photoelectric effect has a minimum energy and frequency called the *threshold frequency* (f_o) that the incoming photon must meet to dig the electron out of the metal and must exceed to give it enough kinetic energy to escape. For example, the metal sodium has a threshold frequency that corresponds to yellow light. If yellow light is shined on a sodium surface, the yellow photons will be absorbed by electrons in the metal, causing them to be released, but there will be no energy left over for the electrons to have any kinetic energy. If we shine green light on the sodium metal, the electrons will be released and have some energy left over to use as kinetic energy, and the electrons will jump off the metal completely, since green light has a higher frequency and energy than yellow light.

The *threshold frequency* of a metal is the minimum frequency of incoming light necessary to release an electron from a metal surface.

Example: In the case of the yellow light and sodium metal described above, describe what would happen in the following instances:

1. (A) We shine orange light on the sodium metal.
   (B) We shine very bright red light on the sodium metal.
   (C) We shine blue light on the sodium metal.
   (D) We shine very bright blue light on the metal.
   (E) Sketch a graph of maximum kinetic energy of a photoelectron (an electron emitted in the photoelectric effect) vs. frequency of incident light for this metal.

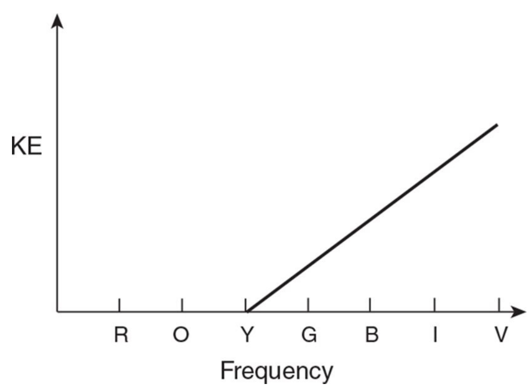
Solution:

1. (A) Since orange light is below the threshold frequency for sodium, no emission of electrons will take place.
   (B) The brightness of the light doesn't matter if the threshold frequency (minimum color) is not met, and red photons have less frequency than the necessary yellow photons, so no emission of electrons will occur.
   (C) Blue light has a higher frequency and energy than yellow, so electrons will be released from the sodium and will have kinetic energy left over to escape the metal.
   (D) We know that blue light will emit electrons from the sodium, and a brighter blue light means more blue photons. Since one photon

can be absorbed by one electron, more electrons will be emitted by a brighter light that exceeds the threshold frequency. If these electrons are funneled into a circuit, we can use them as current in an electrical device.

(E) The graph of maximum kinetic energy of a photoelectron vs. frequency of incident light would look as follows.

For light above the threshold frequency, a brighter light means more photons, and thus more electrons released from the metal.



Note that the electrons have no kinetic energy up to the threshold frequency (color), and then their kinetic energy is proportional to the frequency of the incoming light.

Auto-focus cameras use the photoelectric effect to measure light and adjust the lens to focus on the subject being photographed.