

## Planck's Quantum Hypothesis

In the year 1900, Max Planck (1858–1947) proposed a theory that was able to reproduce the graphs of Fig. 27–4. His theory, still accepted today, made a new and radical assumption: that the energy of the oscillations of atoms within molecules cannot have just any value; instead each has energy which is a multiple of a minimum value related to the frequency of oscillation by

$$E = hf.$$

Here  $h$  is a new constant, now called **Planck's constant**, whose value was estimated by Planck by fitting his formula for the blackbody radiation curve to experiment. The value accepted today is

$$h = 6.626 \times 10^{-34} \text{ J}\cdot\text{s}.$$

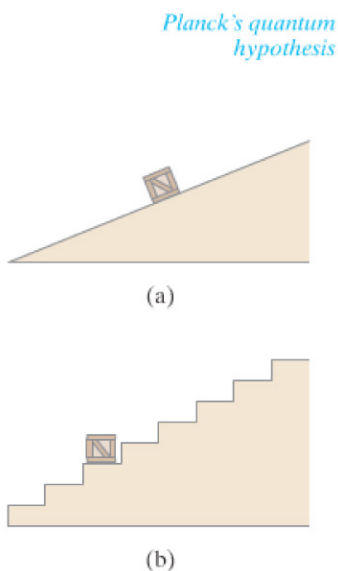
Planck's assumption suggests that the energy of any molecular vibration could be only some whole number multiple of  $hf$ :

$$E = nhf, \quad n = 1, 2, 3, \dots, \quad (27-3)$$

where  $n$  is called a **quantum number** (“quantum” means “discrete amount” as opposed to “continuous”). This idea is often called **Planck's quantum hypothesis**, although little attention was brought to this point at the time. In fact, it appears that Planck considered it more as a mathematical device to get the “right answer” rather than as a discovery comparable to those of Newton. Planck himself continued to seek a classical explanation for the introduction of  $h$ . The recognition that this was an important and radical innovation did not come until later, after about 1905 when others, particularly Einstein, entered the field.

The quantum hypothesis, Eq. 27–3, states that the energy of an oscillator can be  $E = hf$ , or  $2hf$ , or  $3hf$ , and so on, but there cannot be vibrations with energies between these values. That is, energy would not be a continuous quantity as had been believed for centuries; rather it is **quantized**—it exists only in discrete amounts. The smallest amount of energy possible ( $hf$ ) is called the **quantum of energy**. Recall from Chapter 11 that the energy of an oscillation is proportional to the amplitude squared. Thus another way of expressing the quantum hypothesis is that not just any amplitude of vibration is possible. The possible values for the amplitude are related to the frequency  $f$ .

A simple analogy may help. A stringed instrument such as a violin or guitar can be played over a continuous range of frequencies by moving your finger along the string. A flute or piano, on the other hand, is “quantized” in the sense that only certain frequencies (notes) can be played. Or compare a ramp, on which a box can be placed at any height, to a flight of stairs on which the box can have only certain discrete amounts of potential energy, as shown in Fig. 27–5.



**FIGURE 27–5** Ramp versus stair analogy. (a) On a ramp, a box can have continuous values of potential energy. (b) But on stairs, the box can have only discrete (quantized) values of energy.

## 27–3 Photon Theory of Light and the Photoelectric Effect

In 1905, the same year that he introduced the special theory of relativity, Einstein made a bold extension of the quantum idea by proposing a new theory of light. Planck's work had suggested that the vibrational energy of molecules in a radiating object is quantized with energy  $E = nhf$ , where  $n$  is an integer and  $f$  is the frequency of molecular vibration. Einstein argued that when light is emitted by a molecular oscillator, the molecule's vibrational energy of  $nhf$  must decrease by an amount  $hf$  (or by  $2hf$ , etc.) to another integer times  $hf$ , such as  $(n - 1)hf$ . Then to conserve energy, the light ought to be emitted in packets, or *quanta*, each with an energy

$$E = hf, \quad (27-4)$$

where  $f$  is here the frequency of the emitted light.

Photon energy