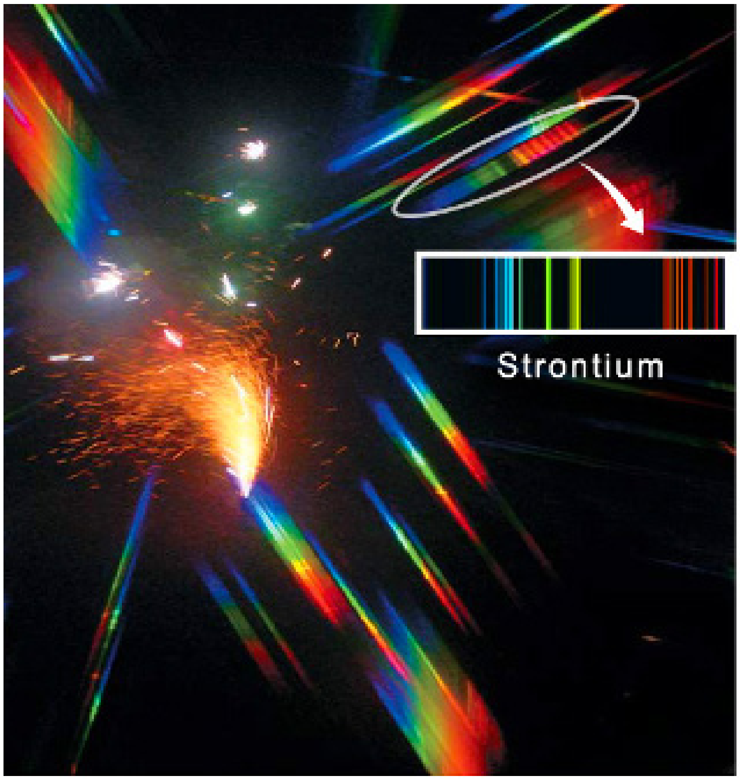


Chapter 4

Subatomic Particles

THE MAIN IDEA

Atoms are made of electrons, protons, and neutrons

4.7 Electrons Exhibit Wave Properties

If light has both wave properties and particle properties, why can't a material particle, such as an electron, also have both? This question was posed by the French physicist Louis de Broglie (1892–1987) while he was still a graduate student in 1924. His revolutionary answer was that every moving particle of matter—by virtue of its energy of motion—is endowed with the characteristics of a wave.

We now speak of waves as an essential feature of any bit of matter. An electron, or any particle, can show itself as a wave or as a particle, depending on how we examine it. This is called the wave–particle duality. Just a few years after de Broglie's suggestion, researchers in Great Britain and the United States confirmed the wave nature of electrons by observing diffraction and interference effects when electrons bounced from crystals. A practical application of the wave properties of electrons is the electron microscope, which focuses not visible-light waves but rather electron waves. Electron microscopes are able to show far greater detail than optical microscopes, as **Figure 4.23** shows.

An electron's wave nature can be used to explain why electrons in an atom are restricted to particular energy levels. Permitted energy levels are a natural consequence of the need for electron waves to form stable patterns around the atomic nucleus.

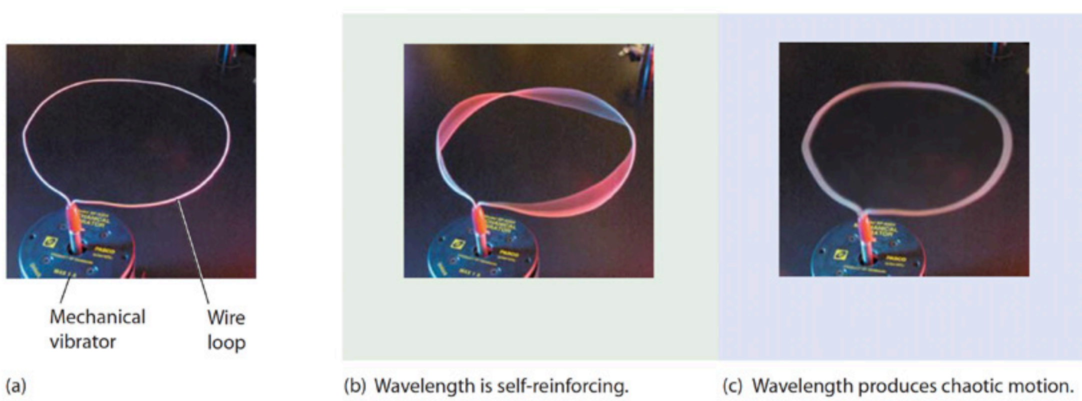
READING CHECK

What does the wave nature of an electron help to explain?

^ Figure 4.23

An electron microscope makes practical use of the wave nature of electrons. The wave- lengths of electron beams are typically thousands of times shorter than the wavelengths of visible light, so the electron microscope is able to distinguish detail not visible with optical microscopes. (b) Detail of an insect's head as seen with an electron microscope at a "low" magnification of 200 times. Note the remarkable resolution.

As an analogy, consider the wire loop shown in **Figure 4.24a**. This loop is affixed to a mechanical vibrator that can be adjusted to create a series of waves traveling through the wire. If the lengths of the waves are equal to the length of the wire (or some fraction thereof), then these waves form what is called a *standing wave*, as shown in **Figure 4.24b**. Within a standing wave, identically sized waves overlap one another, and they do so in a manner that creates regions of maximum intensity and other regions of minimum intensity. A region of maximum intensity occurs where crests are overlapping with crests and troughs are overlapping with troughs, as shown in **Figure 4.25**. (Note: a "crest" is the high point of a wave while a "trough" is the low point of a wave.) A region of minimum intensity occurs where crests and troughs overlap so as to cancel each other



^ Figure 4.24

A wire loop affixed to the post of a mechanical vibrator at rest. Waves are sent through the wire when the post vibrates. (b) Only waves of certain wavelengths are able to form standing waves. The one shown here is 2/3 the length of the loop. (c) Most other wavelengths result in chaotic motion with no specific regions of maximum and minimum intensities.

out. At the center of minimum intensity is a point of zero intensity, called a node.

For a given size of the wire loop, only certain wavelengths will give rise to a stable standing wave. Waves of any other wavelength are unable to align properly and the result is chaotic motion, as suggested in **Figure 4.24c**. These same ideas apply to electron waves within an atom. We find that only certain electron wavelengths form standing waves. Because of their stability, these particular electron wavelengths are favored.

But why does an electron have wavelike characteristics? Recall that according to de Broglie, the wavelength of an electron is a consequence of its energy. Significantly, if only certain wavelengths are favored, then it follows that only certain amounts of energy are favored. In other words, the energy of an electron confined to an atom is *quantized*. Consider what happens when whistling down a long tube. The whistler soon discovers that only certain frequencies can be generated. Interestingly, when a sound wave is confined to a tube, the consequence is a quantization of its frequencies. This is an important principle behind any wind instrument. Likewise, when an electron is confined to an atom, the consequence is a quantization of the electron's energy.

Each standing wave of an electron corresponds to one of the permitted energy levels seen in **Figures 4.21** and **4.22**. Only the frequencies of light that match the difference between any two of these permitted energy levels can be absorbed or emitted by an atom. The wave nature of electrons also explains why they do not spiral closer and closer to the positive nucleus that attracts them. By viewing each electron as a standing wave, we see that the circumference of the smallest orbit can be no smaller than a single wavelength.

In summary, the properties of electrons—and all atoms made of those electrons—arise from their quantum nature. In this sense, the quantum nature of the super-small is what makes our natural world possible.

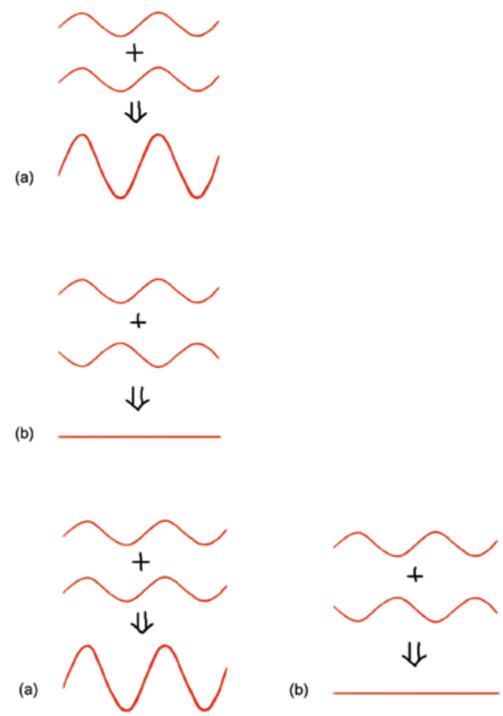


Figure 4.25
(a) Crests overlapping crests and troughs overlapping troughs results in a wave of maximum intensity. (b) Crests overlapping troughs results in a wave of zero intensity.

CONCEPT **CHECK**
What must an electron be doing in order to have wave properties?

CHECK YOUR ANSWER According to de Broglie, particles of matter behave like waves by virtue of their motion, which is a form of energy. An electron must therefore be moving in order to have wave properties.