Is light a particle or a wave?

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An excerpt taken from "The Gateway to understanding: Electrons to waves and beyond," 2005

(Pages 197-202)

3.7 Particle and Wave Duality

Before we solve the dilemma of whether something behaves like a "wave" or a "particle" we need to define precisely what we mean by them.

DEFINITION-PARTICLE: *Any infinitesimal subdivision of matter, which is ranging in diameter from a fraction of an Angstrom (such as an electron, an atom or a molecule, etc.) to a few millimeters (such as a raindrop, etc.). This concept is shown in Figure 3.13.*

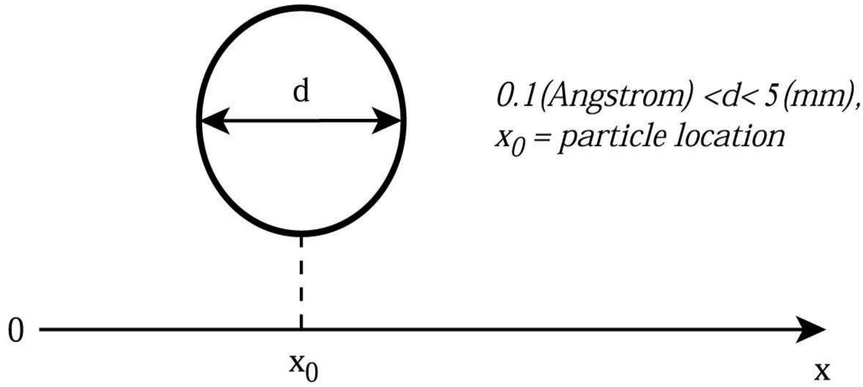

FIGURE 3.13 Definition of a particle.

DEFINITION-WAVE: *A disturbance or vibration which propagates from one point in a medium to other points without giving the medium as a whole any permanent displacement. Waves follow certain specific phenomena such as reflection, refraction, and diffraction. A simple wave is shown in Figure 3.14.*

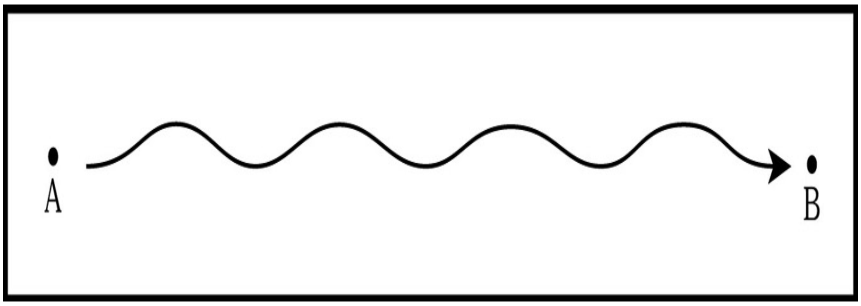

FIGURE 3.14 A simple wave.

Having defined these two concepts, we now turn to the concept of duality. This concept was under the heading of "The duality principle", which was discussed in Chapter 1.

The duality principle is widely used in all aspects of physics and electrical engineering since it is a fundamental property of all of the constituents of the physical universe. It has applications here, since waves and particles form a duality pair, which can be stated as follows:

WAVE-PARTICLE DUALITY: *Is the principle, which states that both matter and energy particles exhibit some phenomena in which they behave opposite to their usual nature,* *that is, there are cases in which electromagnetic waves (such as lightwaves, etc.) behave as localized particles (photons) and other cases, where localized particles (such as electrons) behave as electromagnetic waves. The two aspects are being related by the de Broglie's relation.*

de Broglie's relation is contained in the de Broglie's theory, which states that particles of matter have wavelike properties, which can give rise to interference effects. The wavelength (λ) associated with a moving particle, which has a mass (m) and a velocity (v) is given by:

$$\lambda=h/mv \qquad (3.1a)$$

where "h" is the Planck's constant ($h=6.62x10^{-34}$ Js) and λ is the associated wave's wavelength in free space propagation given by:

$$\lambda=c/f=300/f(MHz) \text{ meters,} \qquad (3.1b)$$

Where "c" is the speed of light in free space or vacuum, and is approximately given by:

$$c=3x10^8 \text{ m/s} \qquad (3.1c)$$

The frequency of oscillation (f) of a quantum particle is related to the energy of the particle (E) by:

$$E=hf \qquad (3.2)$$

Furthermore, since an electron in an atom is not flowing rather orbiting, thus it is a locked up form of energy. Therefore we are dealing with a standing wave. The de Broglie's theory shows that electrons in an atom are associated with standing waves on a Bohr orbit.

NOTE: *By Bohr orbit we mean one of the electron paths about the nucleus in Bohr's model of the hydrogen atom.*

3.7.1 Motivation for the Development of the Wave-Particle Theory

When beams of electrons were passed through crystals of matter, diffraction patterns could be observed. This was much similar to diffraction of light waves passing through a diffraction grating.

With this preamble, let us define diffraction as:

DEFINITION-DIFFRACTION: *Is the redistribution of intensity of waves in space, which results from the presence of an object (such as a grating, consisting of narrow slits or grooves) in the path of beam of light waves. This shall split up the beam into several beams in the short range, causing interference and thus producing patterns of dark and light bands downstream (i.e., regions with variations of wave amplitude and phase). This concept is shown in Figure 3.15.*

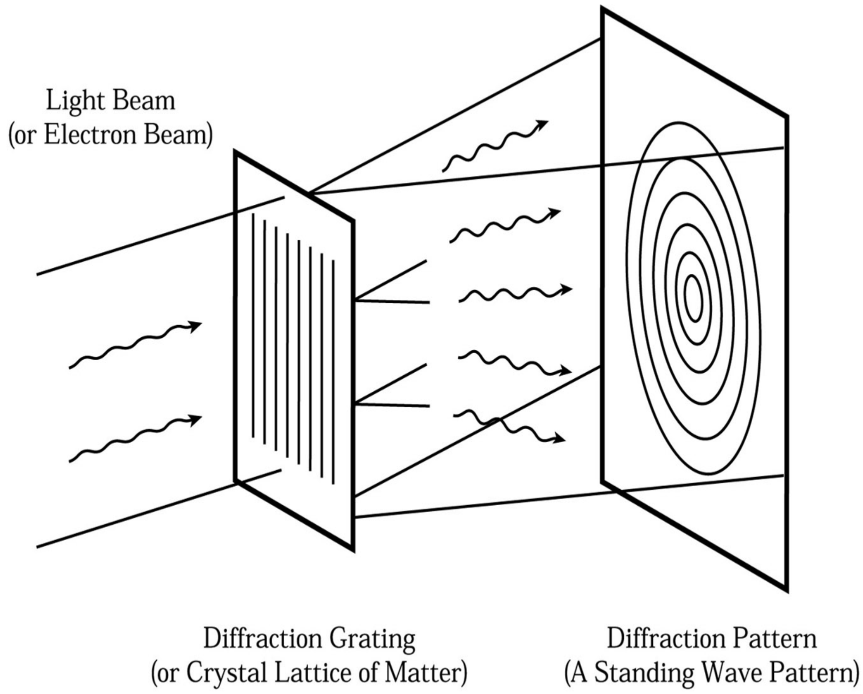

FIGURE 3.15 A diffraction pattern.

NOTE: *In the long range and far away from the diffraction grating, the original light beam is split up into several beams traveling at different angles, where each is separated from the next by a fixed angular increment.*

That a particle has wavelike properties follows from electron diffraction experiments, which show that electron beams behave like light beams and thus obey the same wave relations as light. These observations indicated that electrons have characteristics similar to EM waves and thus should obey the wave motion equations.

The foundation for this subject was solidly laid by de Broglie. He formulated a relationship between dynamic properties of motion of an electron, which are its momentum and its wave properties in terms of wavelength. Thus for the first time the particle and wave properties were related.

In 1924, using relativity theory, de Broglie predicted that an electron with mass (m), moving with velocity (v) should have a wave associated with its motion as shown in Figure 3.16.

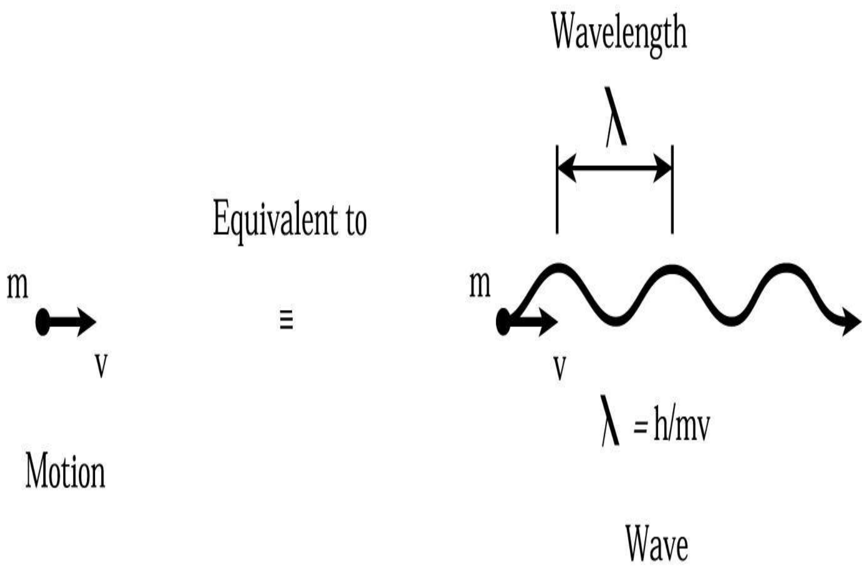

FIGURE 3.16 Physical motion and the associated wavelength.

He presented a relation called the de Broglie's relation which states that the wave associated with a free particle of matter has:

a) A wavelength (λ) which is equal to Planck's constant divided by particles momentum (mv):

$\lambda = h/mv$ (3.3)

b) A frequency (f) equal to the particle's energy (E) divided by Planck's constant (h):

$f = E/h$ (3.4)

Thus the waves, which accompany a moving particle, such as an electron or an atom, are called the de Broglie waves. According to this theory a hypothetical wave is associated with any particle in motion. The motion of the particle is describable in probability terms rather the in terms of accurate laws of classical mechanics. The probability in the motion of a particle is due to the uncertainties inherent in the physical universe.

The uncertainty in the physical universe is stated elegantly in the Heisenberg uncertainty principle derived purely from rigorous mathematics, which reflect the general indeterministic nature of the physical universe in which we live.