Wave-Particle Duality

Unit: Quantum and Particle Physics

NGSS Standards/MA Curriculum Frameworks (2016): HS-PS4-3

AP® Physics 2 Learning Objectives/Essential Knowledge (2024): 15.1.A, 15.1.A.2, 15.1.A.2.i, 15.1.A.2.ii, 15.1.A.4, 15.1.A.4.i, 15.1.A.4.ii

Mastery Objective(s): (Students will be able to…)

- Explain the de Broglie model of the atom.
- Calculate the de Broglie wavelength of a moving particle such as an electron.

Success Criteria:

- Descriptions & explanations are accurate and account for observed behavior.

Language Objectives:

- Explain the important features of each model of the atom.

Tier 2 Vocabulary: model, quantum

Notes:

In 1924, French physicist Louis de Broglie determined that quanta of light could be considered to be particles with very small mass moving at relativistic speeds (*i.e.,* close to the speed of light.)

de Broglie proposed the idea that particles are actually bundles of waves that move with a group velocity and have an effective mass. He concluded that any moving particle or object must therefore be able to be characterized with some periodic frequency, $f=\frac{E}{h}$, from Planck's equation. This means that the wavelength of any moving object is therefore:

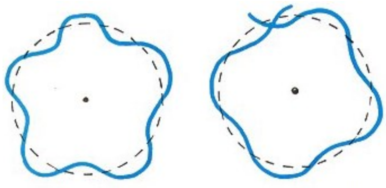
$$\lambda=\frac{h}{p}=\frac{h}{mv}$$

where:

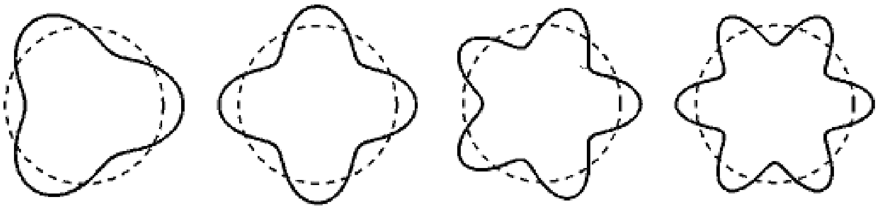
λ = de Broglie wavelength (m)
h = Planck's constant = $6.626\times10^{-34}\ \text{J}\cdot\text{s}$
p = momentum (N·s)
m = mass (kg)
v = velocity $\left(\frac{\text{m}}{\text{s}}\right)$

Although every moving object has a de Broglie wavelength, wavelengths of macroscopic objects are far too small to be detectable.

de Broglie theorized that if electrons behaved as waves as well as particles, then the reason that only certain wavelengths were possible was because the wave produced by an electron would only be stable if it were a standing wave, meaning that its path length as it orbited the nucleus must be an integer multiple of the wavelength.



Different quantum amounts of energy were possible with de Broglie's theory, but were restricted to amounts that produced an integer number of wavelengths.



Photons

photon: a particle of light. Photons have no mass and are electrically neutral.

Photons move at a constant velocity, called the "speed of light". The speed of light, denoted by the variable *c* (because it is constant) depends on the medium that the photons are traveling through.

In a vacuum, the speed of light is $c = 3.00\times10^{8}\ \frac{\text{m}}{\text{s}}$. As described in the topic *Refraction*, starting on page 385, the speed of photons through other media is proportional to the index of refraction of the medium:

$$n = \frac{c}{v}$$

Note that the idea that photons exhibit wave-like behavior did not originate with de Broglie. Recall that Thomas Young's double-slit experiment in 1801 demonstrated that light exhibited wave-like properties. (See *Wave Interactions* starting on page 323.)

Homework Problems

1. **(M)** What is the de Broglie wavelength associated with an electron moving at 0.5*c*? (You will need to look up the mass of the electron and the speed of light in a vacuum in *Table FF. Constants Used in Nuclear Physics* on page 512 of your Physics Reference Tables.)

   Answer: $4.8\times10^{-12}\,\text{m} = 0.0048\,\text{nm}$

2. **(M)** How fast would that same electron need to be moving in order to produce a wavelength of visible light of 500 nm (which equals 5×10^{-7} m)?

   Answer: $1450\,\frac{\text{m}}{\text{s}}$