WPM02 WAVE-PARTICLE DUALITY

SPH4U

CH 12 (KEY IDEAS)

- define and describe the concepts and units related to the present-day understanding of the nature of the atom
- describe the photoelectric effect in terms of the quantum energy concept
- outline evidence that supports a photon model of light
- describe and explain the Bohr model of the hydrogen atom
- collect or interpret experimental data involving the photoelectric effect and the emission spectrum of hydrogen
- outline the historical development of models of matter and energy from 1890 to 1925
- describe how the development of quantum theory has led to scientific and technological advances
- describe some Canadian contributions to modern physics

EQUATIONS

- de Broglie Wavelength

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

THE PARTICLE NATURE OF ELECTROMAGNETIC WAVES

- Electromagnetic waves are "guides" that predict the probable behaviour of a photon
- Constructive interference increases the probability of a photon being in that location, while destructive interference decreases the probability
- Photons arrive individually, but their distribution on a detecting screen is predicted by their wave properties

THE PARTICLE NATURE OF ELECTROMAGNETIC WAVES – CONT.

- **Wave–Particle Duality:** the property of electromagnetic radiation that defines its dual nature of displaying both wave-like and particle-like characteristics
- **Principle of Complementarity:** to understand a specific experiment, one must use either the wave theory or the photon theory but not both.

THE WAVE NATURE OF MATTER

- Since the momentum of a photon is $p = \frac{h}{\lambda}$, de Broglie suggested that any particle with non-zero mass would have an associated wavelength
- **de Broglie Wavelength:** the wavelength associated with the motion of a particle possessing momentum of magnitude p:

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

- The de Broglie wavelengths are known as <u>matter waves</u>
  - **Matter Waves:** the name given to wave properties associated with matter

PROBLEM 1

What de Broglie wavelength is associated with a 0.10 kg ball moving at 19.0 m/s?

PROBLEM 1 – SOLUTIONS

$m = 0.10$ kg

$v = 19.0$ m/s

$\lambda = ?$

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

$$= \frac{6.63 \times 10^{-34}\ \text{J·s}}{(0.10\ \text{kg})(19.0\ \text{m/s})}$$

$$\lambda = 3.5 \times 10^{-34}\ \text{m}$$

The de Broglie wavelength of the ball is 3.5×10^{-34} m.

We see from this example that for macroscopic objects the wavelength is extremely small, even by subatomic standards (being a million-billion-billionth the approximate diameter of a typical atom).

PROBLEM 2

What de Broglie wavelength is associated with an electron that has been accelerated from rest through a potential difference of 52.0 V?

PROBLEM 2 – SOLUTIONS

$m = 9.11 \times 10^{-31}$ kg

$\Delta V = 52.0$ V

$\lambda = ?$

$$\Delta V = \frac{\Delta E_e}{q}$$

$$\Delta E_e = q\Delta V$$

The loss of electric potential energy is equivalent to the gain in the electron's kinetic energy.

$$\Delta E_K = \Delta E_e$$

For an electron

$$E_K = e\Delta V$$

$$= (1.60 \times 10^{-19}\ \text{C})(52.0\ \text{J/C})$$

$$E_K = 8.32 \times 10^{-18}\ \text{J}$$

PROBLEM 2 – SOLUTIONS

But $E_K = \frac{1}{2}mv^2$

$$v = \sqrt{\frac{2E_K}{m}}$$

$$= \sqrt{\frac{2(8.32 \times 10^{-18}\ \text{J})}{9.11 \times 10^{-31}\ \text{kg}}}$$

$$v = 4.27 \times 10^{6}\ \text{m/s}$$

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

$$= \frac{6.63 \times 10^{-34}\ \text{J·s}}{(9.11 \times 10^{-31}\ \text{kg})(4.27 \times 10^{6}\ \text{m/s})}$$

$$\lambda = 1.70 \times 10^{-10}\ \text{m}$$

The de Broglie wavelength of the electron is 1.70×10^{-10} m.

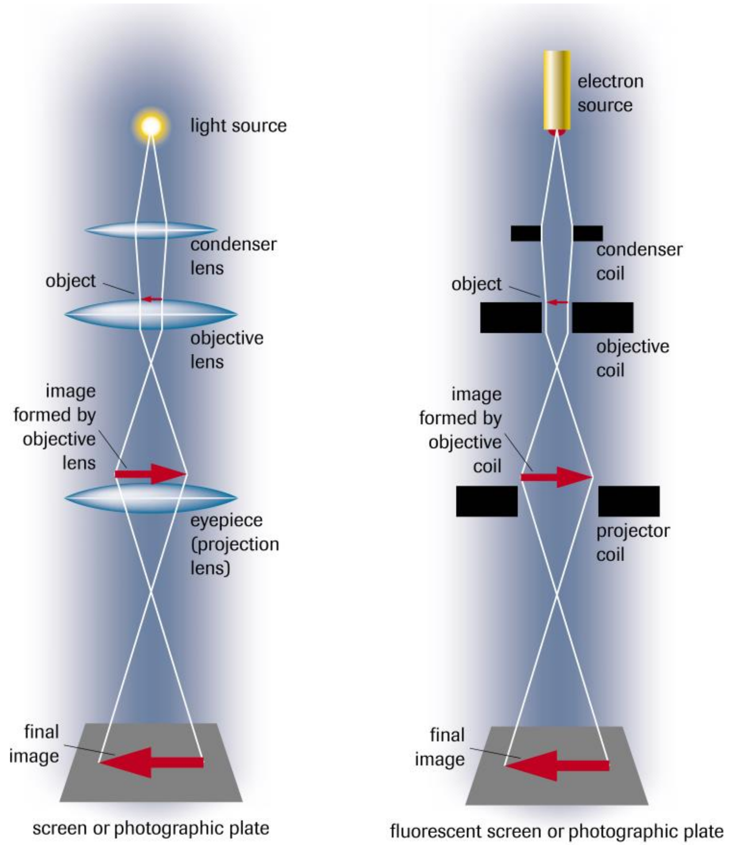
We see from this example that while for a low-momentum subatomic particle such as an electron the de Broglie wavelength is still small, it is no longer very small. For example, the diameter of a hydrogen atom is approximately 1.0×10^{-10} m, that is, *less* than the de Broglie wavelength associated with an electron. This is an issue of great importance, to which we will return in Section 12.5.

MATTER WAVES

- **Quantum Mechanics:** mathematical interpretation of the composition and behaviour of matter, based on the wave nature of particles
- Ordinary objects have extremely small wavelengths
  - They act like particles, concealing their wave nature
- Subatomic particles have wavelengths of similar size to the matter with which they interact
  - diffraction patterns are observable
- Matter waves do not carry energy; they only predict behaviour
  - The particle carries the energy

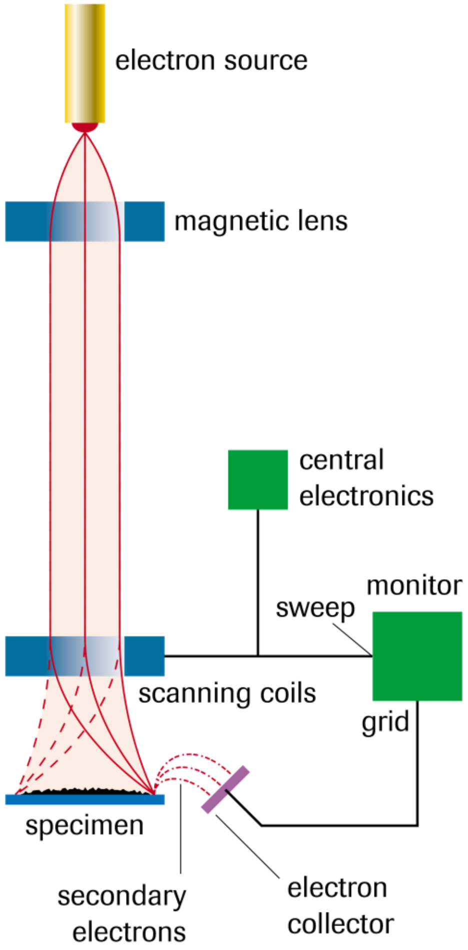
ELECTRON MICROSCOPES

- **Transmission Electron Microscope:** a type of microscope that uses magnetic lenses fashioned from circular electromagnetic coils creating strong magnetic fields
  - Similar in design to the compound microscope



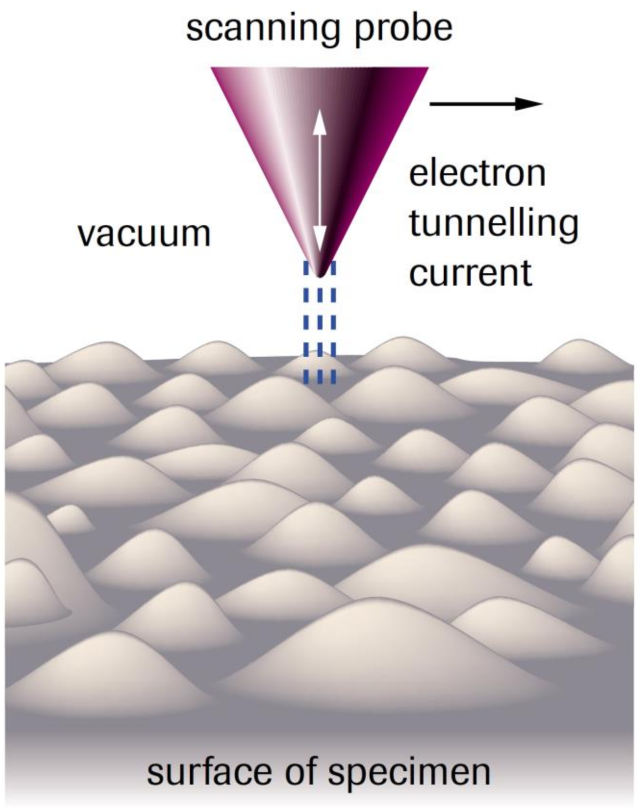
ELECTRON MICROSCOPES – CONT.

- **Scanning Electron Microscope:** a type of microscope in which a beam of electrons is scanned across a specimen
  - Three-dimensional, coloured images are possible
  - Specimens are coated with a thin layer of gold to prevent accumulation of negative charges, which would repel the sweeping electrons and cause image distortion



ELECTRON MICROSCOPES – CONT.

- **Scanning Tunnelling Electron Microscope:** a type of microscope in which a probe is held close to the surface of the sample; electrons "tunnel" between the sample and the probe, creating a current
  - Three-dimensional images are possible
  - Can scan the surface at the atomic level, even showing electron distribution



SUMMARY – WAVE-PARTICLE DUALITY

- The behaviour of a single photon was predicted by the wave theory. The electromagnetic wave predicts the probability that a photon will register at a certain position on a detecting surface at a given instant.
- Light is not just a wave and not just a particle but exhibits a "wave–particle duality."
- Understanding both the wave and the particle properties of light is essential for a complete understanding of light; the two aspects of light complement each other.
- When light passes through space or through a medium, its behaviour is best explained using its wave properties; when light interacts with matter, its behaviour is more like that of a particle.
- The wave–particle model of light has superseded Newton's particle theory and Maxwell's electromagnetic theory, incorporating elements of both.
- A particle of nonzero mass has a wavelike nature, including a wavelength λ, found by de Broglie to equal $\frac{h}{mv}$.
- Matter wavelengths of most ordinary objects are very small and thus unnoticeable.
- Matter waves predict the probability that a particle will follow a particular path through space. The diffraction of electrons revealed these wave characteristics.
- Electron microscopes use the principles of quantum mechanics and matter waves to achieve very high magnifications, in some cases exceeding 2 million times.

PRACTICE

Readings

- Section 12.2 (pg 610)

Questions

- pg 620 #1,4,7