MODERN PHYSICS
Chapter 10. Quantum Physics (5 Hours)

Content
10.1 Particle Theory of Light
10.2 Quantization of light
10.3 The Photoelectric Effect
10.4 Wave Properties of particle (matter)
10.5 The de Broglie Wavelength
10.6 Electron Diffraction

Learning Outcome
Students should be able to
(a) explain the particulate nature of light
(b) apply the equation $E = hf$ for a photon
(c) describe the photoelectric effect experiment
(d) identify features in the photoelectric emission that cannot be explained by wave theory
(e) explain features in (d) using the concept of quantization of light
(f) define and explain work function and cut-off frequency and stopping potential (apply $eV = \frac{1}{2}mv^2$)
(g) apply Einstein’s equation for the photoelectric effect as $hf = KE_{\text{max}} + \phi$
(h) explain why the photoelectric energy is independent of intensity whereas the photoelectric current is proportional to intensity
(i) explain how the photoelectric effect provides evidence for the particulate nature of electromagnetic radiation while interference and diffraction provides evidence for its wave nature
(j) state and apply the formulae for wave particle duality of de Broglie (use $\lambda = \frac{h}{p}$ to calculate the de Broglie wavelength)
(k) describe observations in the electron diffraction experiment that acts as evidence to the wave nature of particles
Notes:

• Light has a dual nature.
  – Particle
  – Wave

• Wave characteristics will be discussed in this chapter.
  – Reflection
  – Refraction
  – These characteristics can be used to understand mirrors and lenses.

• Early models of light
  – It was proposed that light consisted of tiny particles.

• Newton
  – Used this particle model to explain reflection and refraction

• Huygens (1678)
  – Explained many properties of light by proposing light was wave-like

• Young (1801)
  – Strong support for wave theory by showing interference

• Maxwell (1865)
  – Electromagnetic waves travel at the speed of light.

• Einstein (Published in 1905, Nobel Prize in 1921)
  – Particle nature of light
  – Explained the photoelectric effect
  – Used Planck’s ideas

• “Particles” of light are called photons.

• Each photon has a particular energy.
  – \( E = hf \)
  – \( h \) is Planck’s constant
• \( h = 6.63 \times 10^{-34} \text{ J s} \)
  – Encompasses both natures of light
    • Interacts like a particle
    • Has a given frequency like a wave
• In some experiments light acts as a wave and in others it acts as a particle.
  – Classical electromagnetic wave theory provides explanations of light propagation and interference.
  – Experiments involving the interaction of light with matter are best explained by assuming light is a particle.
• Light has a number of physical properties, some associated with waves and others with particles.

**Photoelectric Effect**
• When light is incident on certain metallic surfaces, electrons are emitted from the surface.
  – This is called the *photoelectric effect*.
  – The emitted electrons are called *photoelectrons*.
• The effect was first discovered by Hertz.
• The successful explanation of the effect was given by Einstein in 1905.
  – Received Nobel Prize in 1921 for paper on electromagnetic radiation, of which the photoelectric effect was a part
Fig. 10.1 Photoelectric Effect Schematic

- When light strikes E, photoelectrons are emitted.
- Electrons collected at C and passing through the ammeter create a current in the circuit.
- C is maintained at a positive potential by the power supply.

![Diagram of Photoelectric Effect Schematic]

Fig. 10.2 Photoelectric Current/Voltage Graph

- The current increases with intensity, but reaches a saturation level for large ΔV’s.
- No current flows for voltages less than or equal to –ΔV_s, the stopping potential.
- The stopping potential is independent of the radiation intensity.
- The maximum kinetic energy of the photoelectrons is related to the stopping potential:
  \[ KE_{\text{max}} = e\Delta V_s \]
- No electrons are emitted if the incident light frequency is below some cutoff frequency that is characteristic of the material being illuminated.
- The maximum kinetic energy of the photoelectrons is independent of the light intensity.
- The maximum kinetic energy of the photoelectrons increases with increasing light frequency.
- Electrons are emitted from the surface almost instantaneously, even at low intensities.

Einstein’s Explanation
• A tiny packet of light energy, called a photon, would be emitted when a quantized oscillator jumped from one energy level to the next lower one.
  – Extended Planck’s idea of quantization to electromagnetic radiation

• The photon’s energy would be $E = hf$

• Each photon can give all its energy to an electron in the metal.

• The maximum kinetic energy of the liberated photoelectron is $KE_{\text{max}} = hf - \phi$

• $\phi$ is called the work function of the metal

**Explanation of Classical “Problems”**

• The effect is not observed below a certain cutoff frequency since the photon energy must be greater than or equal to the work function.
  – Without this, electrons are not emitted, regardless of the intensity of the light

• The maximum KE depends only on the frequency and the work function, not on the intensity.
  – The absorption of a single photon is responsible for the electron’s kinetic energy.

• The maximum KE increases with increasing frequency.

• The effect is instantaneous since there is a one-to-one interaction between the photon and the electron.

**Verification of Einstein’s Theory**
• Experimental observations of a linear relationship between KE and frequency confirm Einstein’s theory.

• The x-intercept is the cutoff frequency.

Cutoff Wavelength

• The cutoff wavelength is related to the work function.

\[ \lambda_c = \frac{hc}{\phi} \]

• Wavelengths greater than \( \lambda_c \) incident on a material with a work function \( \phi \) don’t result in the emission of photoelectrons.

Photons and Electromagnetic Waves

• Light has a dual nature. It exhibits both wave and particle characteristics.
  – Applies to all electromagnetic radiation
  – Different frequencies allow one or the other characteristic to be more easily observed.

• The photoelectric effect and Compton scattering offer evidence for the particle nature of light.
  – When light and matter interact, light behaves as if it were composed of particles.
• Interference and diffraction offer evidence of the wave nature of light.

**Louis de Broglie**

• 1892 – 1987
• Discovered the wave nature of electrons
• Awarded Nobel Prize in 1929

**Wave Properties of Particles**

• In 1924, Louis de Broglie postulated that because photons have wave and particle characteristics, perhaps all forms of matter have both properties.
• Furthermore, the frequency and wavelength of matter waves can be determined.

**de Broglie Wavelength and Frequency**

• The *de Broglie wavelength* of a particle is

\[
\lambda = \frac{h}{p} = \frac{h}{m \nu}
\]

• The frequency of matter waves is

\[
f = \frac{E}{h}
\]

**Dual Nature of Matter**

• The de Broglie equations show the dual nature of matter.
• Each contains matter concepts.
  – Energy and momentum
• Each contains wave concepts.
  – Wavelength and frequency