Chapter. 3
Wave & Particles I

EM-“Waves” behaving like “Particles”

Outline:

• Blackbody Radiation (Plank; 1900; 1918*)
• The Photoelectric Effect (Einstein; 1905; 1921*)
• The Production of X-Rays (Rontgen; 1901; 1901*)
• The Compton Effect (Compton; 1927; 1927*)
• Pair Production (Anderson; 1932; 1936*)
• Is It a Wave or a Particle? Duality?
Historical Development

Newton (1704): light as a stream of particles.

Descartes (1637), Huygens, Young, Fresnel (1821), Maxwell: by mid-19th century, the wave nature of light was established (interference and diffraction, transverse nature of EM-waves).

Physics of the 19th century: mostly investigation of light waves
Physics of the 20th century: interaction of light with matter

One of the challenges – understanding the "black body spectrum" of thermal radiation

Black body:
In physics, a black body is an idealized object that absorbs all E&M radiation that falls on it. No E&M radiation passes through it and none is reflected. Because no light is reflected or transmitted, the object appears black when it is cold. However, a black body emits a temperature-dependent spectrum of light. (see Fig)

This thermal radiation from a black body is termed black-body radiation.

As the temperature decreases, the peak of the black-body radiation curve moves to lower intensities and longer wavelengths.

Black Body Radiation
(Max Planck 1900)

Experiment shows that as frequency increases, the blackbody spectral energy density reaches a max. then fall off. But, classical theory predicts a divergence!! Do we need a new theory?

In 1900, Planck suggested a solution based a revolutionary new idea: Emission and absorption of E&M radiation by matter has quantum nature: i.e. the energy of a quantum of E&M radiation emitted or absorbed by a harmonic oscillator with the frequency \( f \) is given by the famous Planck's formula

\[
E = h f
\]

where \( h \) is the Planck's constant

\[
h = 6.626 \times 10^{-34} J \cdot s
\]

- at odds with the "classical" tradition, where energy was always associated with amplitude, not frequency

Also, in terms of the angular frequency \( \omega = 2\pi f \)

\[
E = \hbar \omega \quad \text{where} \quad \hbar = \frac{h}{2\pi} \approx 1.05 \times 10^{-34} J \cdot s
\]
The Energy \((E)\) in the electromagnetic radiation at a given frequency \((f)\) may take on values restricted to

\[ E = n hf \]

where:
- \(n = \text{an integer}\)
- \(h = \text{a constant} \approx 6.626 \times 10^{-34} \text{ J} \cdot \text{s} \) ("Planck Constant")

Experimental Fact:

\[ E = n hf \]

BUT Why should the energy of an Electromagnetic wave be "Quantized"?

\(n = \text{integer}\)

No Explanation until 1905

Albert Einstein

The Photoelectric Effect

Blackbody Radiation: A New Fundamental Constant

Plank's spectral energy density is the critical link between temperature and EM radiation.

Interestingly, although the assumption \(E = n hf\) might suggest EM radiation behaving as an integral number of particles of energy \(hf\), he hesitated at the new frontier - others carried the revolution forward.

For the discovery, Plank was awarded the 1918 Nobel prize!!

The Photoelectric Effect

(Albert Einstein 1905)

Phenomenon observed long time before Einstein, and something very strange was observed:
Historical Note: The photoelectric effect was accidentally discovered by Heinrich Hertz in 1887 during the course of the experiment that discovered radio waves. Hertz died (at age 36) before the first Nobel Prize was awarded.

Observation: when a negatively charged body was illuminated with UV light, its charge was diminished.

J.J. Thomson and P. Lenard determined the ratio $e/m$ for the particles emitted by the body under illumination – the same as for electrons.

The effect remained unexplained until 1905 when Albert Einstein postulated the existence of quanta of light -- photons -- which, when absorbed by an electron near the surface of a material, could give the electron enough energy to escape from the material.

Robert Milliken carried out a careful set of experiments, extending over ten years, that verified the predictions of Einstein's photon theory of light. Einstein was awarded the 1921 Nobel Prize in physics: “For his services to Theoretical Physics, and especially for his discovery of the law of the photoelectric effect.” Milliken received the Prize in 1923 for his work on the elementary charge of electricity (the oil drop experiment) and on the photoelectric effect.