OPTICS

PHYS 311

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INTRODUCTION

Are not the rays of light very small bodies emitted from shining substances?

Isaac Newton

All these 50 years of conscious brooding have brought me no nearer to the answer to the question ‘what are light quanta?’. Nowadays every Tom, Dick and Harry thinks he knows it, but he is mistaken.

Albert Einstein

How wonderful that we have met with a paradox. Now we have some chance of making progress.

Niels Bohr

Light is an electromagnetic wave: light is also a stream of photons, discrete particles carrying packets of energy and momentum.

How can these two statements be reconciled?

Can we use these descriptions of waves and photons interchangeably, and how should we choose between them?

THE NATURE OF LIGHT

- Newton described light as a stream of particles or corpuscles.
- This helped in:
  - explaining rectilinear propagation
  - Developing theories of reflection and refraction. (splitting of sunlight by a prism)
- Particles in rays of different colors have different qualities (mass, size or velocity).
- White light is a compound of colored rays.
- Colors of transparent materials are due to selective absorption.

THE NATURE OF LIGHT

- Newton couldn't explain:
  - Colored interference patterns in thin films (Newton rings)
  - Partial reflection of light at glass surface.
- He tried also to explain the double refraction in calcite crystals ← polarization.

THE NATURE OF LIGHT

- Newton argued against the WAVE THEORY!!
  - Waves would spread in angles rather than travel as rays.
  - No medium to carry light waves from distant celestial bodies.

- But where did the WAVE THEORY COME FROM ?!!!

THE NATURE OF LIGHT

- WAVE THEORY:
  - Descartes thought of it as a pressure wave in an elastic medium.
  - Huygens developed the wave theory:
    - ‘Huygens construction’ ← rectilinear propagation
    - Refraction ← lower velocity in a denser medium
  - 100 years after Newton the wave theory was firmly established
  - Young’s double slit experiment could only be explained in terms of waves.
  - Fresnel showed that the waves must be transverse.
  - Fresnel also developed the theories of partial reflection and transmission and the of diffraction at shadow edges.
  - Finally Maxwell, working on E & M, deduced that an electromagnetic wave would propagate at a speed that EQUALLED that of light. ← hmmm light IS an EM wave!! ☺

THE NATURE OF LIGHT

- By the end of the nineteenth century the wave theory was on unassailable foundation.
- Did the wave theory show failure?
  - Couldn’t explain the interaction of light with matter. ☹
  - Couldn’t explain the black body spectrum. ☹
- So WHAT IS LIGHT?!! ☹

THE NATURE OF LIGHT

- The corpuscular theory came back to life ☺ + ☹ = !!!
- Max Planck explained the black body spectrum by postulating that the walls of the body consisted of harmonic oscillators with a range of frequencies, and that the energies of those with frequency ν were restricted to integral multiples of the quantity $h\,\nu$.
- Each oscillator had a FUNDAMENTAL ENERGY QUANTUM!!

$$E = h\,\nu \qquad (1.1)$$

- Einstein explained the photoelectric effect ← electrons are emitted from a metal surface when radiation is absorbed in discrete quanta.

THE NATURE OF LIGHT

Newton was right after all!!!!

Light is understood as a stream of particles

$\Downarrow$

PHOTONS

THE NATURE OF LIGHT

- De Broglie asked: "If light is a WAVE that has properties usually associated with PARTICLES, could PARTICLES correspondingly have WAVE-LIKE properties?"
- Three years later it was experimentally confirmed by Thomson, Davisson and Germer.← a beam of particles, like light ray encountering an obstacle, could be diffracted, behaving as a wave rather than a geometric ray.
- The wavelength λ involved was related to the momentum p of the electron by

$$\lambda = h / p \qquad (1.2)$$

THE NATURE OF LIGHT

- A general wave theory of the behavior of matter, wave mechanics, was developed by Schrödinger following de Broglie's ideas.
- Wave mechanics revolutionized our understanding of how microscopic particles were described and placed limitations on the extent of information we can have about such systems ← Heisenberg uncertainty principle.

THE NATURE OF LIGHT

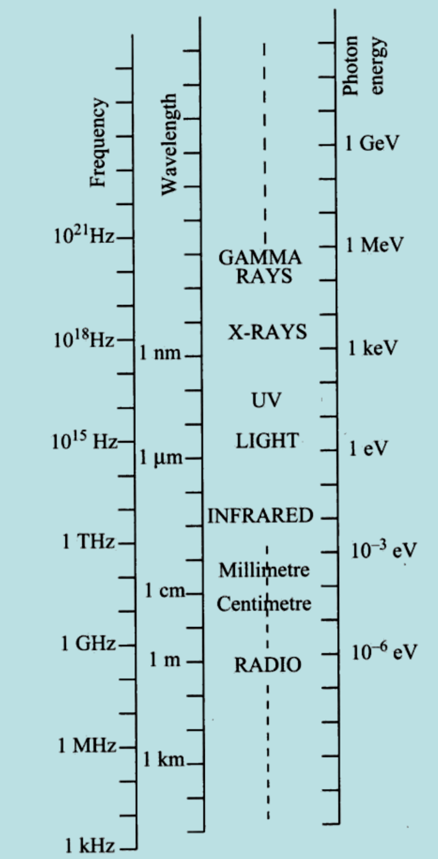
- Photons and electrons behave as particles and as waves.
- The description that best describes their behavior depends on the circumstances.
- Photons and electrons are different:
  - No two electrons can be in the same state ←→ no restriction on photons.

ELECTROMAGNETIC WAVES

- Faraday developed qualitatively the idea that light was propagated as a combination of electric and magnetic fields.
- Maxwell placed the mathematical formulation which made it clearly understood.

THE ELECTROMAGNETIC SPECTRUM

- The EM spectrum covers a vast range:
  - Visible light from 400 nm to 800 nm.
  - Difference in behaviour across the EM spectrum is large.
  - ν & λ are related by $c = \nu\lambda$.
  - Wave aspects dominate the behaviour of the longest λ.
  - Photon aspects dominate the behaviour of the short λ.
  - In optical range ← we encounter the ‘wave-particle duality’
    - Propagation → wave nature
    - Interaction with matter → quantum physics
    - Photon energy range 1.5 – 3 eV.
    - Quantum effects: emission, absorption or detection.
    - Line spectrum (emission or absorption) or continuum (emission).



The electromagnetic spectrum.

WAVES AND PHOTONS

- Beginning of the twentieth century:
  - the wave nature of light was fully understood.
  - Young, Fresnel and Michelson experiments
  - Maxwell's EM theory.
- Twentieth century:
  - Planck's quantized oscillator
  - Einstein's photoelectric effects and the reality of photons.
- Einstein's photon theory cleared up the mystery about the interchange of energy between matter and EM waves.← also helped in the invention of LASER.