Experimental study on Dual nature of light

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Abstract - Radiation has a dual nature: wave and particle. It is the nature of the experiment that decides whether a wave or particle description is best suited for understanding the experimental result. Dual nature of matter firstly proved by de-Broglie in 1924 by equation $\lambda = h/p$ because it contain a wave characteristics λ and a particle characteristics. After de-Broglie, Davisson and Germer in 1927 proves the existence of de-Broglie's waves by using the diffraction apparatus ($\lambda = 1.66\ A^0$). Again in 1928, Thomson proves that the electron beam behave like waves.

Key Words: **electron gun, thin foil, photographic plate, galvanometer, flat mirrors, young interferometer**

1. INTRODUCTION

Questions about the dual nature of light have been puzzling most physicists since more than one century, when M. Planck and A. Einstein were conducted to introduce the concept of "quantum of light", later called photon. The phenomena like interference, diffraction and polarization, etc, can be satisfactorily explained only on the basis of wave nature of light. On the other hand, the phenomena like photoelectric effect, Compton effect, etc, can be explained only in terms of quantum theory of light, i.e., by assuming particle nature of light. This show that light radiation has dual nature, i.e., it sometimes behaves like a wave and sometimes as a particle.

2. EXPERIMENTAL STUDY OF THEORIES

[A] De-Broglie wavelength of an electron: In 1924, the French physicist Louis Victor de-Broglie put forward the bold hypothesis that material particles in motion should display wave-like properties. His reasoning was based on the following two considerations:

1. The two physical quantities which govern all the forms of physical universe are mass and energy.
   The Einstein's mass-energy relationship:
   $$E = mc^2,$$
   Shows that there is a complete equivalence between matter (mass) and radiation (energy). There must be a mutual symmetry between matter (mass) and radiation.
2. Nature loves symmetry. Since radiation has dual nature therefore, from symmetry considerations, de-Broglie predicted that matter must also possess dual nature. Thus the particles like electrons, protons, neutrons, etc. should not behave like mass points but they should also exhibit wave nature when in motion.
   The waves associated with material particles in motion are called or de Broglie waves and their wavelength is called de Broglie wavelength.

   De-Broglie's wave equation: considering photon as a em wave of frequency ν, its energy from Planck's quantum theory is given by
   $$E = h\nu \qquad \text{(eq. 1)}$$
   Where h is Planck's constant. Considering photon as a particle of mass m, the energy associated with it is given by Einstein's mass- energy relationship as
   $$E = mc^2 \qquad \text{(eq. 2)}$$
   from equations (1) and (2), we get
   $$h\nu = mc^2$$
   we get lambda (λ) is equal to c/ν, then
   $$\text{Lambda } (\lambda) = h/mc = h/p$$
   Where, lambda (λ) is the wavelength of the radiation of frequency ν and $p = mc$, is the momentum of the photon. The above equation has been derived for a photon of radiation. According to de Broglie's hypothesis, it must be true for material particles like electrons, protons, neutrons, etc. Hence a particle of mass m moving with velocity v must be associated with a matter wave of wavelength given by
   $$\text{Lambda } (\lambda) = \frac{h}{p} \qquad \text{……….eq. (3)}$$

$$ƛ = \frac{h}{p} = \frac{h}{\sqrt{2mK}} = \frac{h}{\sqrt{2meV}} \qquad (K = \frac{p2}{2m} = eV)$$

$$ƛ = 6.63\times10^{-34}/\sqrt{2} \times 9.1\times 10^{-31} \times 1.6 \times 10^{-19}\ V$$

$$ƛ = \frac{12.3}{\sqrt{V}}\ A^0$$

This is de Broglie's wave equation for material particles. It explains the dual nature of matter.

From de-Broglie's equation, we find that

1. The wavelength of a moving particle is inversely proportional to its momentum.
2. If velocity v = 0 then lambda (ƛ) = ∞. This implies that waves are associated with material particles only associated with accelerated charged particles.

B] Experimental idea proves the de-Broglie waves by Davisson and Germer (1927):

They designed an experiment to study the wave properties of electron (fig.1). The electrons emitted by the hot filament of an electron gun are accelerated by applying a suitable potential difference V between the cathode and anode.

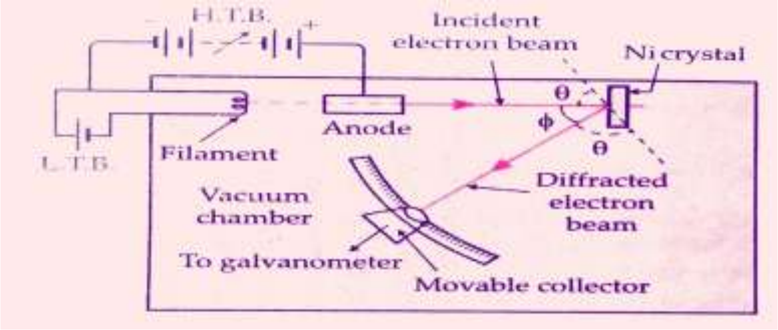

Fig:1. Davisson and Germer electron diffraction apparatus

The fine collimated beam of electrons from the electron gun is directed against the face of Ni crystal. The crystal is capable of rotation about an axis perpendicular to the plane of paper. The electrons, scattered in different directions by the atoms of Ni crystal, are received by a movable detector which is just an electron collector. Thus we measure scattered electron intensity as a function of the scattering angle Φ, the angle between the incidence and the scattered electron beam. The experiment is repeated for different accelerating potentials V. The results of Davisson and Germer experiment (fig.2) when the accelerating voltage was varied from 44 V to 68 V. clearly, there is a strong peak corresponding to a sharp diffraction maximum in the electron distribution at an accelerating voltage of 54 V and scattering angle 50^0. The maximum of intensity obtained in a particular direction is due to constructive interference of electrons scattered from different layers of the regularly spaced atoms of the crystal.

From fig.2, the angle Θ is given by

$$\Theta + \Phi + \Theta = 180^o$$

Or $\Theta = 90^o - \Phi = 90^o - 25^o = 65^o$

The interatomic separation for Ni crystal is

$$d = 0.914\ A^0$$

For the first order (n=1) diffraction maximum, the Bragg's law is

$$2d \sin\Theta = ƛ$$

$$ƛ = 2 \times 0.914 \times \sin 65^o \qquad (\sin 65^o = 0.906)$$

$$= 1.65\ A^0$$

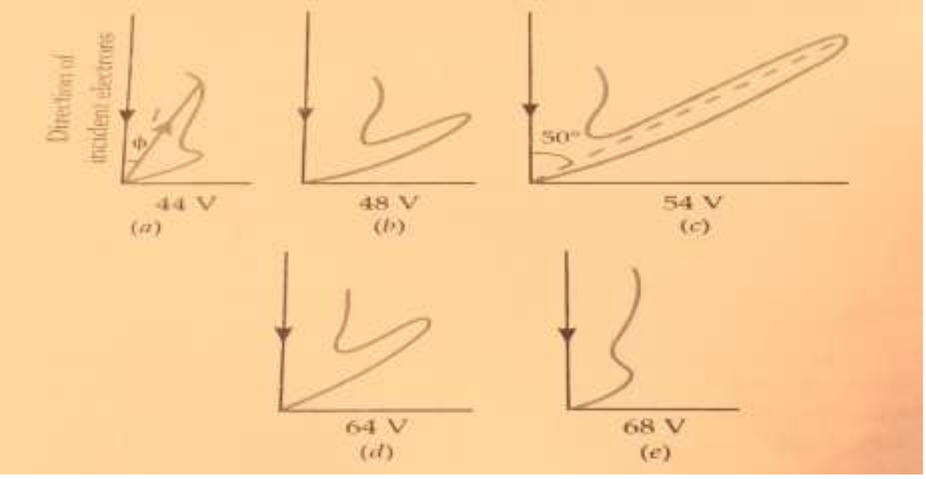

Fig:2. Polar graphs showing the intensities of electrons as a function of scattering angle

From de-Broglie's hypothesis, the wavelength associated with an electron beam accelerated through 54 V must be

$\lambda = h/mv = 12.3/\sqrt{V}\ A^0$

$= 12.3/\sqrt{54}$

$= 1.66\ A^0$

The experimentally measured wavelength is close to that estimated from de-Broglie hypothesis. This proves the existence of de-Broglie waves.

C] The wave nature of electrons by G. P. Thomson's experiment:

G.P. Thomson was able to obtain a diffraction pattern of an electron beam in 1928. The experimental set up is shown in fig 3. From an electron gun, a beam of electrons accelerated through a potential difference of 10 to 50 kV is incident on a thin platinum foil. The emergent beam is received on a photographic plate.

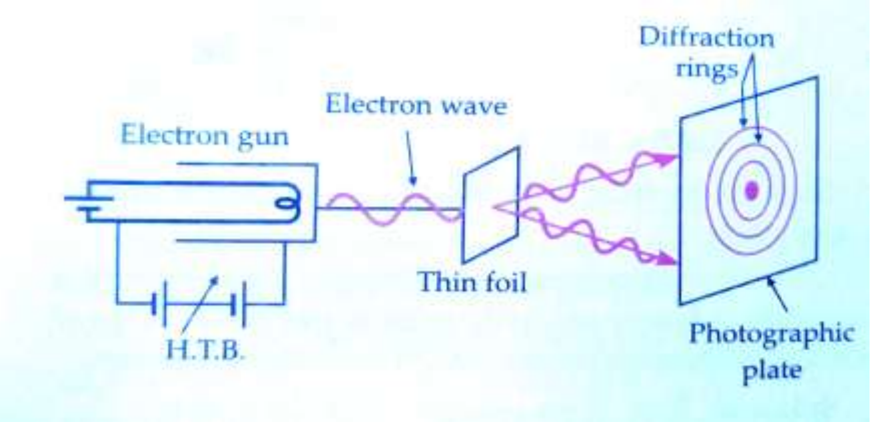

Fig:3. Thomson's experiment to study electron diffraction

The electron beam is diffracted at the spacing's between the randomly oriented crystals of the thin foil. On the photographic plate, we get a circular diffraction pattern similar to Laue's X- ray diffraction pattern. This conclusively proves that the electron beams behave like waves.

D] GEDANKEN EXPERIMENT

Although a model based upon hypotheses, simplistic and naïve, it might be possible to define a thought, or *Gedanken* experiment in order to verify or refute it. For that purpose the latter should incorporate one source of single-photons, using for instance the technique of spontaneous parametric down conversion, and also answer to two specific requirements, namely the division of the input beam by means of a dielectric plate in order to test assumptions , and a multi-axial light recombination as in Young's double slit experiment to assess assumptions. The proposed setup, somewhat inspired from Afshar et al., 2007 is therefore depicted in Figure 4. The entrance light quanta are first directed towards an air glass interface where they can be reflected under a high incidence angle *i*, or transmitted with comparable probabilities. The glass plate, which plays the role of the beam splitter, is actually a small prism whose angle is defined so as to reject parasitic internal reflections out of the interferometer. The reflected and transmitted beams are further recombined multi-axially by a concave mirror M focusing them near its focal point F (note that this monolithic mirror could be replaced by two separate flat mirrors). One of the beams (here the transmitted one) is slightly misaligned with respect to the other by means of the tip-tilt mirror M'. Finally, an optional reflective delay line can be added into the apparatus in order to equalize or modulate the optical path difference. The experiment is realizable for any state of polarization of the entrance light by simple readjustment of the angle *i* in order to equalize the amplitudes of both input beams.

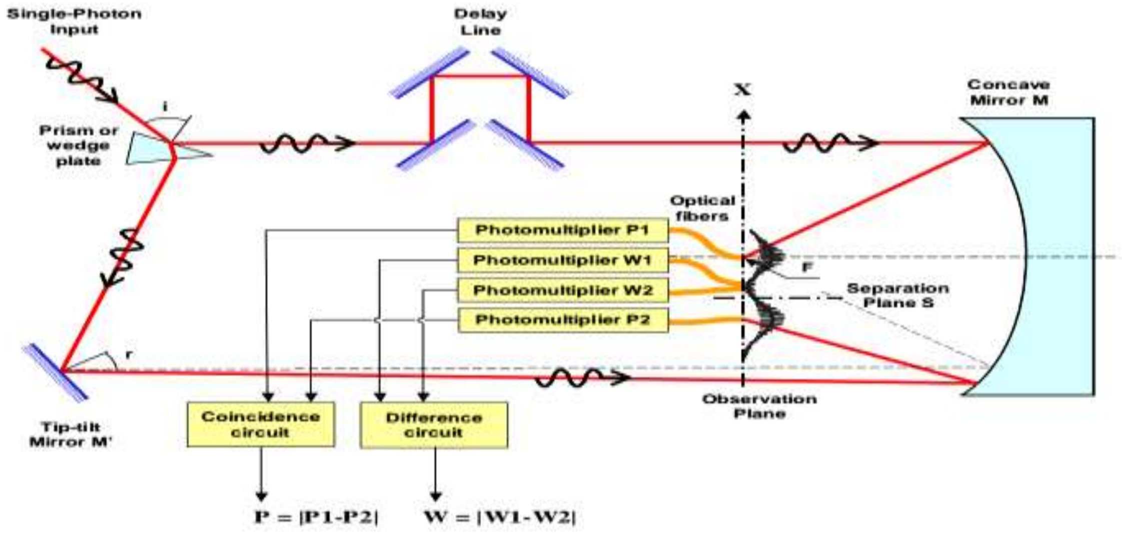

Fig:4. Principle of the proposed Gedanken experiment

One peculiarity of the proposed setup probably resides in its intrinsic asymmetry, because it starts as a Mach- Zehnder interferometer and ends up in a Young's double slit combining scheme, although most of the previously reported experiments are based on fully symmetric arrangements (either based on classical Mach-Zehnder or Young interferometers). Also, all photon-detecting devices can be installed in the same observation plane (i.e. the focal plane of mirror M).

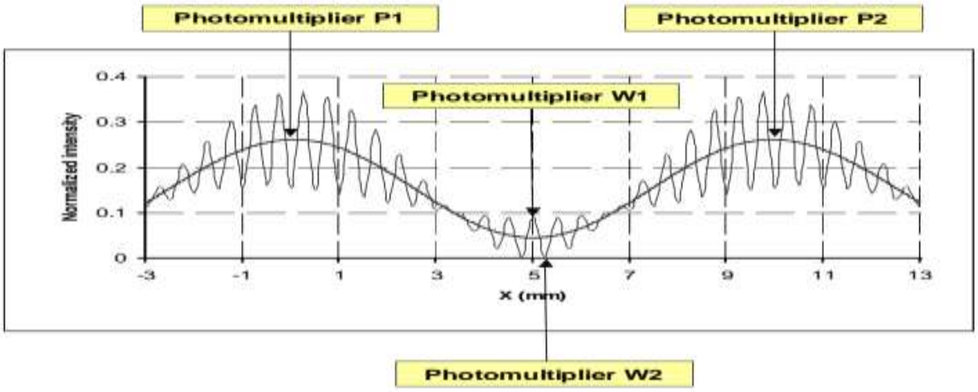

Fig:5. Four optical fiber haeds in then observation plane with repect to the intensity distributions revealing an interference pattern (thin line) or not (thick line)

The measurement apparatus itself essentially consists of four optical fibers located at accurate positions with respect to the expected intensity distributions when light is considered as either a particle or a wave (see Figure 5). The optical fibers are feeding two couples of photo-detectors denoted (P1,P2) and (W1,W2) where letters P and W respectively stand for "particle" and "wave" as in Greenberger et al., 1988. The correlations and anti-correlations between detectors P1 and P2 are measured by a coincidence circuit as in the first step of the Grangier, Roger and Aspect experiment. P1 and P2 are expected to provide a certain amount of "which-way" information that we note $P = |P1-P2|$. On the other hand, detectors W1 and W2 fed by the central fibers respectively located at two adjacent maxima and minima of the expected interferogram are measuring the fringe visibility $W = |W1-W2|$ (in practice, this interference counter may only "click" if W is superior to a certain threshold). The principle of the experiment suggests that we could in principle obtain a simultaneous measurement of both P and W – here the original principle of complementarily would not be respected (Bohr, 1928), but it has been shown in later publications that it can be re-expressed in a more general way as $P^2 + W^2 \leq 1$ [Greenberger and Englert].

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