Photon-Photon Collision: Simultaneous Observation of Wave-Particle Characteristics of Light

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Abstract

The proposed paper presents the analysis of electromagnetic waves meeting at a point *in terms of their particle characteristics*. The observation that light beams moves un-deviated when encountered at a point, which is commonly justified on the wave characteristics of light, is now presented as momentum and wavelength exchange phenomenon of photon collision. Theoretical and mathematical justification of photon's inter-collision, on the basis of their *quasi-point particle* behavior is offered and the observation of the non-variation of wavelength of light beams is explained. Thus, the observation of light's non-deviation at the crossing point is explained as momentum exchange phenomenon on the basis of particle characteristics of light.

Keywords: Basic Quantum Mechanics, Bohr's Complementary Principle, Collision Mechanics

1. Introduction

The proposal of light as an electro-magnetic wave (Maxwell, 1865), explained its various wavy phenomena like interference and diffraction. However, in the beginning of the 20th century, particle type characteristics of light also came into picture, with many experimental supports (Einstein, 1905; Compton, 1923; Raman, 1929). According to the existing literature, light can show either wave characteristic or particle characteristic (Ghatak, *Quantum Mechanics*; Beiser, *Concepts of Modern Physics*; Feynman, *The Feynman Lectures of Physics*), however, the simultaneous observation of both the characteristics of light, in a single particular experiment, is not possible (Beiser, *Concepts of Modern Physics*), i.e. it is impossible to explain the behavior of light in an experiment, on the simultaneous basis of both particle and wave characteristics. Only one at a time can account for the situation. This is called Bohr's complementary principle. However, some of the physicists have demonstrated (even experimentally also) that it is possible to simultaneously observe both wave and particle properties of light (Afshar, 2007). The diffraction pattern of light, passing through a slit, is lost, if, the track of photons is monitored, in accordance with the limitations set by Bohr's Principle of Complementarity (Afshar, 2007). However, in Afshar's experiment, the presence of sharp interference was observed, while reliably maintaining the information about the particular pinhole through which each individual photon had passed (Afshar, 2007). Thus accounting the situation beyond the limits set by Bohr's Principle of Complementarity.

Being motivated by their work, we have presented simultaneous involvement of wave-particle characteristics of light in another well-know situation, concerning the meeting of two light beams at a common point. It is shown, theoretically, that both particle and wave type characteristics of light can explain the behavior of light in this situation. If two light beams are converged at a common point, the wave-fronts of light waves cross each other without deviating from their original direction. Moreover, no variation in the wavelength of light beams is observed. Figure 1 explains the observed situation. The two light beams originating from sources S_1 and S_2, converge at a point A making angle θ_1 and θ_2, with the vertical, at S_1 and S_2 respectively.

After passing un-deviated through A, the angle of light beams becomes $\phi_1 and \phi_2$, with the horizontal. Since the light beams propagate un-deviated, through each other, relation between θ_1, θ_2, $\phi_1 and \phi_2$ becomes:-

$$\theta_1 + \theta_2 + \phi_1 + \phi_2 = 180^0$$

$$\phi + \theta = 180^0 \qquad (1)$$

; where, $\theta=\theta_1+\theta_2$ and $\phi = \phi_1 + \phi_2$. This un-deviated propagation of light in such a situation is accountable by its wavy nature. The wave fronts of light beams passes through each other just like two ripple waves in a still pond. Thus, the wavelength of light beams remains unchanged and the waves propagate un-deviated through each other. *In the present paper, we have accounted this observation on the basis of the particle characteristics of light. This approach for explaining the non-variation of wavelength when the two light beams cross each other, on account of particle characteristics of light, is not familiar to the scientific community and literature yet, to the best of our knowledge*. It has been demonstrated that the un-deviated passage of light beams and its unchanged wavelengths are the results of light's particle-type behavior. It is shown that at the point of interaction photon collides and at a specific angle (given by equation 1) the photon's momentum and thus their wavelengths interchanges.

The idea of the simultaneous observation of the wave-particle character of light, in the same experiment, emerged on account of the following situations also:-

Polarization of photons: Polarization is generally accounted as a wavy phenomenon (Ghatak, *Optics*). However, photon which exhibits particle type nature undergoes polarization (Ghatak, *Optics*).

Frequency of light remains unaltered when light moves from one medium to another: - This observation is well accountable on the basis of the wave characteristics of light (Beiser, *Concepts of Modern Physics*), as the frequency of the oscillators of the medium remains equal to the frequency of incident radiation. However**, we have justified the same observation by taking into account the particle characteristics of light.** Suppose the energy of a photon in a medium is $h\nu_1$. On entering another medium, its energy remains invariant due to the non-availability of any energy dissipative mechanism for photon to loss some amount of its original energy. Therefore, the amount of photon's energy in the latter medium, say $h\nu_2$, is equal to its energy in the former medium $h\nu_1$, i.e.:-

$$h\nu_1 = h\nu_2$$

$$\Rightarrow \nu_1 = \nu_2$$

Therefore, on changing the medium of propagation, frequency of light remains unchanged and can be explained in terms of both wave and particle nature of light.

Convincingly, from these two observations it appears that the simultaneous observation of wave-particle nature of light in same experiments is theoretically possible.

In the upcoming sections the observation of non-deviation and non-variation of wavelengths of light beams converging at a point, which is justified by light's wavy behavior, is now being explained on the basis of the particle characteristics of light.

2. Photon-Collision in 2-D

If two light beams meet at a common point, the wave front of the light waves cross each other without being deviated from their original directions and thus, the wavelength of the individual light beams remain unaltered. This unaltered parametric passage of light beams across each other suggests that the particle characteristic of light is not significant in this situation. Therefore, photon does not appear to collide at the point of meeting and no change in momentum (and thus wavelength) or deviation in the angle of incoming light is observed. The wave fronts of light simply pass through each other, similar to ripple waves in a still pond. In this section, the participation of light's particle characteristic is presented i.e. the theoretical justification of the photon collision at the converging point, satisfying the observation of non-variation of wavelengths, is presented. The notion for the occurrence of photon collision in this situation emerged on the account of the symmetry in nature i.e., if two electrons can collide mutually and a photon can collide with an electron; then a photon should also be able to collide with another photon. Thus, the particle type behavior should be visualized when two light beams are encountered at a point.

The **fundamental postulation** is: *inter-collision of photons is possible at the converging point* and *they are quasi-point particles, with volume tending to zero.* Consequently, *the collision has to be elastic*, as expected from two point particles. This elastic collision, at a specific *interchange angle*, will be shown to become perfectly elastic, ensuing photon's momentum, and therefore wavelength, interchanges. This wavelength exchange actually gives the impression that light beams cross each other un-deviated. Working with the assumption adopted, we have derived the wavelength expression for the photon scattered from its original path, due to the collision with other photon.

Figure 2 shows two light beams of wavelengths λ_1 and λ_2 originating from the sources S_1 and S_2, respectively. The beams are converged at the point A such that the angle made by them is θ_1 and θ_2, with the vertical, at points, S_1 and S_2 respectively. The circular figure on the path S_1A shows the incoming photon from the source S_1 and is designated as photon-1. Similarly, the photon of the other source is designated as photon-2. Due to the collision of photons at point A, the beams get deviated from their original incident directions, such that, the angle of light beams becomes $\phi_1 and \phi_2$, with the horizontal. The photon-1 now propagates on the path AP and photon-2 on path AQ, with some varied wavelengths.

The collision of photons results to variation in their momentum and wavelengths. The wavelength of photons after collision are supposed to be λ_1' and λ_2' and the corresponding momentums as P_1' and P_2', respectively.

Since the collision is elastic, the momentum and energy would remain conserved during the process.

2.1. Conservation of Energy

The postulation of photon's elastic collision provides implementation of Energy Conservation Principle. The photons' energy (E) sum should be equal, before and after the collision. Mathematically:-

$$E_1 + E_2 = E'_1 + E'_2 \qquad (2)$$

The energy of a photon is related to its momentum as (Beiser, *Concepts of Modern Physics*)

$$E = Pc$$

Equation (2) therefore becomes:-

$$P_1 + P_2 = P'_1 + P'_2 \tag{3}$$

2.2. Conservation of Momentum

The occurrence of photon's elastic collision is achievable only when the sum of the linear momentum of photons before collision, along each individual axis, should be equal to the sum of the photon's linear momentum after collision. Applying this principle along both axes:-

Along y-axis:-

Taking the components of photon's momentum along x-axis, the conservation of momentum gives:

$$P_2 \cos\theta_2 - P_1 \cos\theta_1 = P'_2 \sin\phi_2 - P'_1 \sin\phi_1 \tag{4}$$

Similarly, *along x-axis:-*

$$P_1 \sin\theta_1 + P_2 \sin\theta_2 = P'_1 \cos\phi_1 + P'_2 \cos\phi_2 \tag{5}$$

Squaring and adding equation (4) and (5), gives:-

$$P_1^2 + P_2^2 + 2P_1P_2[\sin\theta_1 \sin\theta_2 - \cos\theta_1 \cos\theta_2] = (P'_1)^2 + (P'_2)^2 + 2P'_1 P'_2[\cos\phi_1 \cos\phi_2 - \sin\phi_1 \sin\phi_2] \tag{6}$$

Using the following trigonometric identity:-

$$\sin A \sin B - \cos A \cos B = -\cos(A+B)$$

Equation (6) becomes:-

$$P_1^2 + P_2^2 - 2P_1P_2 \cos(\theta_1 + \theta_2) = (P'_1)^2 + (P'_2)^2 + 2P_1'P_2'\cos(\phi_1 + \phi_2) \tag{7}$$

From equation (3):-

$$P'_1 = P_1 + P_2 - P'_2 \tag{8}$$

Substituting equation (8) in equation (7):-

$$(P'_2)^2[1-\cos\phi] + (P'_2)[(P_1+P_2)(\cos\phi - 1)] + P_1P_2[1+\cos\theta] = 0 \tag{9}$$

where, $\theta = \theta_1 + \theta_2$ and $\phi = \phi_1 + \phi_2$.

Let: $Z = P_2'; (1-\cos\phi) = l; [(P_1+P_2)(\cos\phi - 1)] = m;\ P_1P_2(1+\cos\theta) = n$

Therefore, equation (9) becomes quadratic in *Z*:-

$$(l)Z^2 + mZ + n = 0 \tag{10}$$

The solution of above equations is given by:-

$$Z = \frac{-m}{2l} \pm \frac{\sqrt{m^2 - 4(l)n}}{2l}$$

Substituting the values of *Z*, *l*, *m* and *n* in above equation:-

$$P'_2 = \frac{P_1 + P_2}{2} \pm \frac{\sqrt{(P_1+P_2)^2 - 4P_1P_2\dfrac{(1+\cos\theta)}{(1-\cos\phi)}}}{2} \tag{11}$$

Equation (11) provides the varied momentum expression for photon-2 after collision with photon-1. Substitution of equation (11) in equation (8) provides the momentum expression for the photons-1 as:-

$$P'_1 = \frac{P_1 + P_2}{2} \mp \frac{\sqrt{(P_1 + P_2)^2 - 4P_1P_2 \dfrac{(1+\cos\theta)}{(1-\cos\phi)}}}{2} \tag{12}$$

Thus, we obtain the expression for the momentum of photons after collision, in the form of equation (11) and equation (12). To determine the varied momentums (P_1' and P_2'), information regarding the angles is an essential requirement. Since, no equation relates θ and φ in terms of P_1 and P_2, they are declared as purely variables. The substitution of the particular values of θ and φ would provide the corresponding momentum of photons, after collision. It is observed that the rays of light, as shown in fig. 1, passes through each other without any deviation from the original incident direction and the wavelengths of light beams remains unaltered even after the passage of light beams. Therefore, we should verify that whether this observation of non-variation of wavelengths is satisfied by the momentum equation (11) and (12) or not. Therefore, substituting equation (1) in equation (11) and (12) gives:-

$$P'_2 = \frac{P_1 + P_2}{2} \pm \frac{\sqrt{(P_1 + P_2)^2 - 4P_1P_2}}{2} = \frac{P_1 + P_2}{2} \pm \frac{P_1 - P_2}{2} \quad \Rightarrow P'_2 = P_1, or, P'_2 = P_2$$

$$P'_1 = \frac{P_1 + P_2}{2} \mp \frac{\sqrt{(P_1 + P_2)^2 - 4P_1P_2}}{2} = \frac{P_1 + P_2}{2} \mp \frac{P_1 - P_2}{2} \quad \Rightarrow P'_1 = P_2, or, P'_1 = P_1$$

The second solutions of P_1' and P_2' are not acceptable, because they dictates non-variation in photon's momentum, which is against the postulation of the occurrence of photons collision. Therefore, only the first solutions of P_1' and P_2' are admissible. Thus, the momentum of photons after collision becomes:-

$$P'_2 = P_1 \ and \ P'_1 = P_2$$

The above expressions, for the momentum of photons after collision, shows that photons due to collision exchanges their momentums, which implies that the nature of collision is perfectly Elastic Collision (Verma, *Concepts Of Physics*).

The angle $\varphi=\pi-\theta$ (equation 1) is termed as *interchange angle,* because only at this particular angle, the momentum of photons get interchanged and is indeed the observed angle between the light beams (fig. 1). Since, for photons (Ghatak, *Quantum Mechanics*; Beiser, *Concepts of Modern Physics*; Feynman, *The Feynman Lectures of Physics*)

$$P = h/\lambda$$

Thus, the wavelength of light beams after passage from the intersection point '*A*' becomes:-

$$\lambda'_2 = \lambda_1 ; \ \lambda'_1 = \lambda_2$$

The above expressions show that the wavelength of light beams after collision gets interchanged. The photon-1, due to collision, acquires the wavelength of photon-2, and vice versa. Therefore, the photon collision results in the wavelength interchange of the light beams. Figure 3 illustrates how the wavelengths of the light beams get interchanged on meeting at point A. The red photon (of wavelength λ_1), due to collision with the green photon (of wavelength λ_2) at point A, becomes a green photon and follows path AP and vice versa for photon-2. Therefore, the red photon coming from S_1 follows path AP (after becoming a green photon) and gives an impression, as if, it has been originated from the source S_2 and moved un-deviatedly. Similarly, the photon-2 follows path *AQ* and appears, as if originated from the source S_2. The wavelengths of two light beams thus appear unaltered. This is in accordance with the observed wavelengths of light (figure 1) beams after crossing point 'A'. Thus fig. 3 (demonstrating the varied wavelengths) turns out to be exactly like fig. 1. *The observed (fig.1) unchanged wavelength is thus shown to be a result of photon's collision with each other.*

Consequently, the observation of non-variation of light beam's wavelengths after passing from the converging point is explained on the basis of particle characteristics of light; by the photon collision. Moreover, it has been observed, that although the photons after collision could have passed through any arbitrary angle φ between them, they have chosen only a specific angle termed interchange angle for which their collision is perfectly elastic; which is indeed the observed angle (equation 1).

3. Conclusion

The observation of light beam's unaltered wavelengths after passage from the crossing point is explained on the account of its particle characteristics. When two photons collide at the intersection point of two light beams, their momentum gets exchanged. Thus, the observation of non-variation of wavelengths and un-deviated passage of light beams meeting at a point is explained by taking into account the particle characteristics of light. Thus, the behavior of light, in this situation is explainable on the basis of both the particle and wave aspects of light. Conclusively, the explanation of behavior of light on account of its both wave and particle characteristics suggests that the behavior of light in other known situations may also be explainable on the basis of both wave type and particle type personality of light.

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Author's Summary

Himanshu Chauhan was born at Delhi, India in Nov., 1992 and completed his 10+2 studies in Non-Medical Science from C.B.S.E, Delhi. He is currently pursuing his Bachelor's degree in Technology in the field of Mechanical Engineering from Delhi Technological University (formerly DCE), Delhi. Past since 2.5 years he is pursuing research at the Applied Physics Department, TIFAC-CORE, Mission REACH program of Technology Vision-2020, Delhi Technological University, Delhi, and has authored two research articles for international conferences and one research article in Journal. He is also a member of Optical Society of America (OSA) and SPIE-The International Society for Optical Engineering. His current research areas include Quantum Mechanics, Tachyon Particles and Photonic Crystal Waveguides for MEOMS and NEOMS.

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Figures

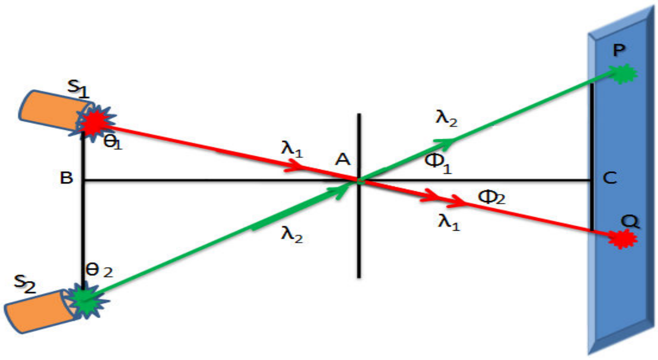

Figure 1 The observed non-deviation of light beams from their incident directions converging at a point.

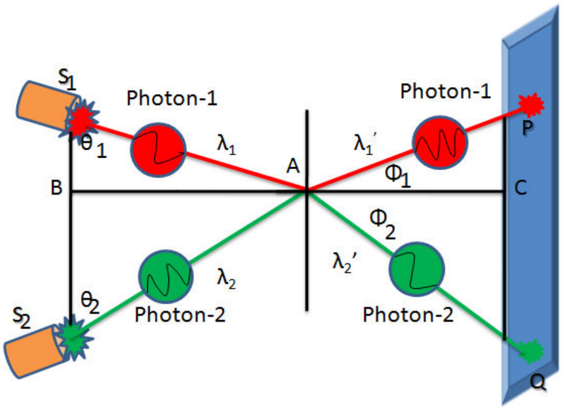

Figure 2 Assuming the occurrence of photon collision at the converging point of two light beams, resulting in their deviation and wavelength variation.

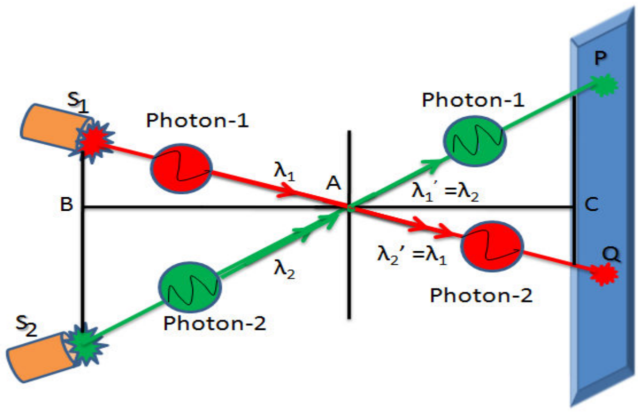

Figure 3 Photon collision at point A, resulting in the wavelength interchange of the two light beams