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Interaction of a Photon with a Particle with Rest Mass

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Abstract: *The interaction of a photon with a particle with rest mass is analyzed based on following principles:(i) elastic collision (ii) electron excitation for jumping to a higher energy orbital, then falling back by emitting a photon (iii) photon energy convert to thermal energy or vice-verse(iv) bond between electron and the atom broken (v) photon speed changes in different medium (vi) photon propagation direction change when collide with a corner of a slit. The reader shall find how those principles contribute to phenomena such as the Compton effect, diffraction, Mie Scattering, Rayleigh Scattering, etc.*

Keywords: Compton effect, scattering, reflection, refraction, diffraction, elastic collision

INTRODUCTION

The paper aims to study the interaction between a photon and a particle with rest mass, particularly the electron. The motivation of the paper is the postulate of "A quantum at rest is a (one) wave, repeatedly fluctuating within the wavelength, λ" **[1].** With this postulate, a particle with rest mass, such as an electron no longer treated as a point particle with no size. The interaction of a photon and an electron can then be studied as an elastic collision between the two. F=ma or Rectified Newton's Third Law shall be applied in the collision based on whether the electron is free or restricted to move [**2].** The article shall also explore other cases such as the electron loses the bond with the molecule, or is excited to higher orbital or thermal energy is involved in the collision, using a well-structured method.

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LITERATURE REVIEW

Those phenomena observed in the interaction between photon and electron are traditionally described as
(i) Campton effect
(ii) Photoelectric effect
(iii) Scattering
(iv) Reflection,
(v) Deflection
(vi) Refraction
The principles or approaches used among (i)~(vi) are often minimally related.

METHODOLOGY

This paper acknowledges the principle that the physical law governs phenomenon in the macroscopic world manifests a similar, and higher-level physical law in the microscopic world **[1].** The analysis also recognized our primary interest on principle in interaction between a photon and an electron, shall be the elastic collision between them; only a photon or a single quantum shall interact with the electron at the instant of the collision, regardless of the intensity of the light /total number of quanta. The freedom of the electron within the molecule is the crucial factor to determine F=ma or Rectified Newton's Third law, to be utilized in the elastic collision analysis **[2].** For those cases not fall in the elastic collision, other principles shall apply in the analysis.

Campton Effect

The Compton effect is the effect of the interaction of a photon with a free electron at rest. The electron is not restricted to move, thus F=ma is applicable in the elastic collision. As the photon is rebounded after the collision, the equation of force is as follows:
Action force=Force on electron + Force on photon **[2]**

Action force, $-\frac{dp_p}{dt} = \frac{dp_e}{dt} + \frac{d(p_{p'})}{dt}$

In which action force is simply reduced in momentum of the photon.
Take instant of Δt are same,

$$-(m_{Pf}\,c - m_{Pi}\,c) = (m_{ef}v_{ef} - m_0 v_0) + (m_{PRf}c - m_{PRi}c)$$

Since $m_{Pf} = m_{PRi}$

$$-m_{Pf}\,c + m_{Pi}\,c = m_{ef}v_{ef} + m_{PRf}c - m_{Pf}c$$

$m_{Pi}\,c = m_{ef}v_{ef} + m_{PRf}c$ (equation of law of conservation of linear momentum) (1)

In which,
c = *velocity of light*

p_p= *momentum of photon*
p_e= *momentum of electron*
m_{Pi} =*initial mass of photon during action*
m_{Pf} =*final mass of photon during action*
m_{PRi} =*initial mass of photon after action*
m_{PRf} =*final mass of photon after action*
m_0 =*rest mass of electron*
m_{ef} =*final mass of electron*
v_0 =*initial velocity of electron is equal to zero*
v_{ef} =*final velocity of electron*

The mechanism as described below:
"A quantum at rest is a (one) wave, repeatedly fluctuating within the wavelength, λ"**[1]**, such quantum/electron is free to move in Compton effect.

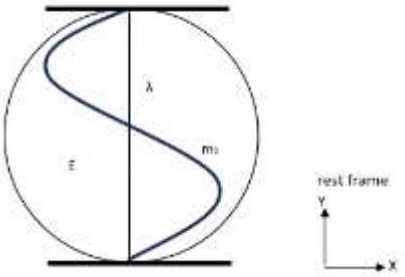

Figure 1: A quantum at rest from the paper "Intrinsic Properties of a Quantum"**[1]**

As photon move in constant speed of light, c; but the momentum of photon is changed after the collision; thus, the change is due to wavelength increases or mass decreases of that photon, indicating the photon has transferred energy to the electron.

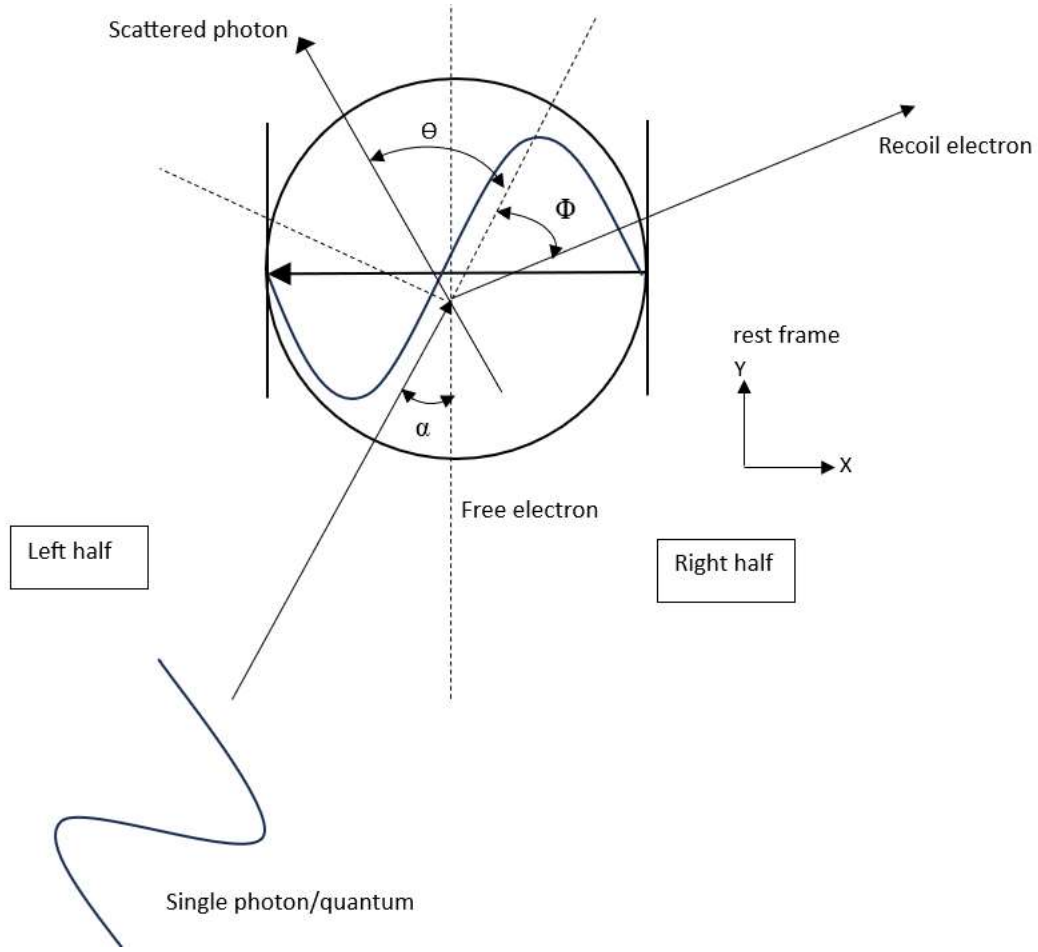

Figure 2: Collision of a photon with a free electron

The equation of collision is equivalent to the Compton equation, as the equation is derived from the principle of conservation of energy **[3]**:

$photon\ wavelength\ shift, (\Delta\lambda), \lambda_f - \lambda_i = \lambda_0(1 - cos\Theta)$ (2)

λ_f = wavelength of photon after the collision

λ_i = wavelength of photon before the collision

λ_0 =wavelength of free electron at rest before the collision

Θ =scattering angle

Once incident photon wavelength, λ_i , scattered photon wavelength, λ_f obtained from experiment; the scattering angle of photon, Θ could be calculated from equation (2), and the energy transferred to the electron then be derived by following steps.

The energy relates to wavelength, λ by the following

$$\lambda = \frac{hc}{m\,c^2}$$

$$E = m\,c^2 = \frac{hc}{\lambda}$$

Hence, energy lost of photon,

$Energy\ lost\ of\ photon\ , \Delta E = \frac{hc}{\lambda_f} - \frac{hc}{\lambda_i}$ (3)

To find the velocity of electron:

$Energy\ lost\ of\ photon\ is\ equal\ to\ energy\ transfered\ to\ electron\ , \Delta E = m_{ef}\,c^2 - m_0\,c^2$

$\frac{hc}{\lambda_f} - \frac{hc}{\lambda_i} = \frac{m_o c^2}{\sqrt{1-\frac{v^2}{c^2}}} - m_0\,c^2$ (4)

In which,

v=velocity of electron

m_{ef} *=mass of electron in motion*

c=speed of light

m_0 *= the rest mass of electron which is equal to* $\frac{h}{\lambda_0 c}$

Electron wavelength at rest, λ_0 equals to 2.43X10^{--12}m.

To find the recoil angle, ϕ of the electron, apply conservation of momentum in the direction X&Y of the initial photon direction.

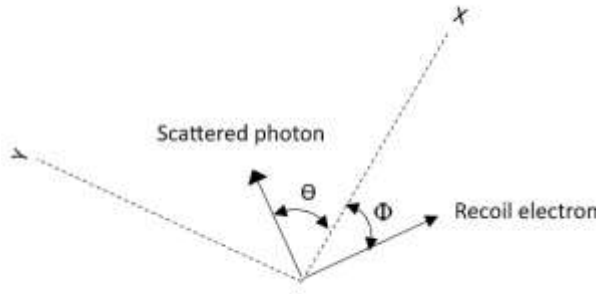

Figure 3:X&Y direction of the collision

$0 = m_{PRf}c\ sin\Theta - m_{ef}v_{ef}sin\phi$ (Apply conservation of momentum in Y direction)

$m_{PRf}c\ sin\Theta = m_{ef}v_{ef}c\ sin\phi$ (5)

$m_{Pi}c = m_{PRf}c\ cos\Theta + m_{ef}v_{ef}cos\phi$ (Apply conservation of momentum in X direction)

$m_{Pi}c - m_{PRf}c\ cos\Theta = m_{ef}v_{ef}cos\phi$ (6)

$tan\ \phi = \frac{m_{PRf}\ sin\Theta}{m_{Pi} - m_{PRf}cos\Theta}$ Divide (5) by (6)

$cot\phi = \frac{m_{Pi} - m_{PRf}cos\Theta}{m_{PRf}\ sin\Theta}$

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Factor determines the scattering angle, Θ

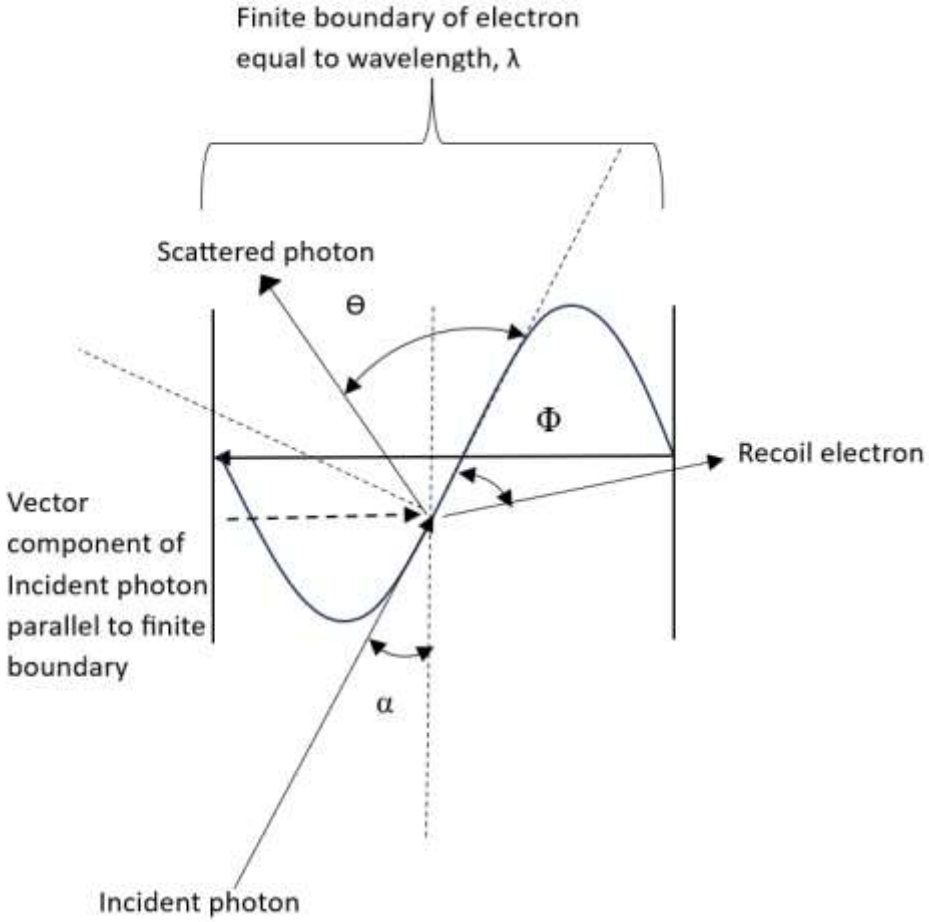

Figure 4: Vector component of incident photon interacting with electron is in the direction parallels to finite boundary

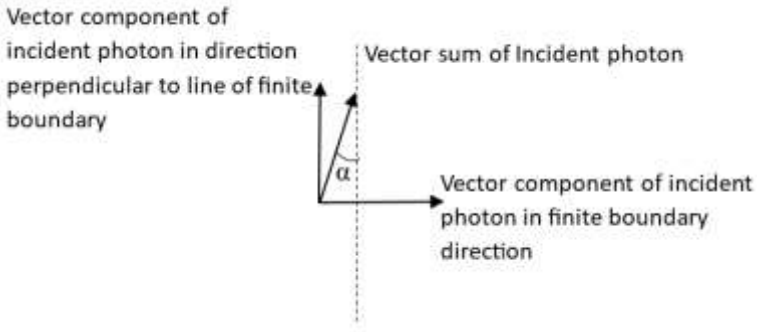

Figure 5: Decompose vector of incident photon

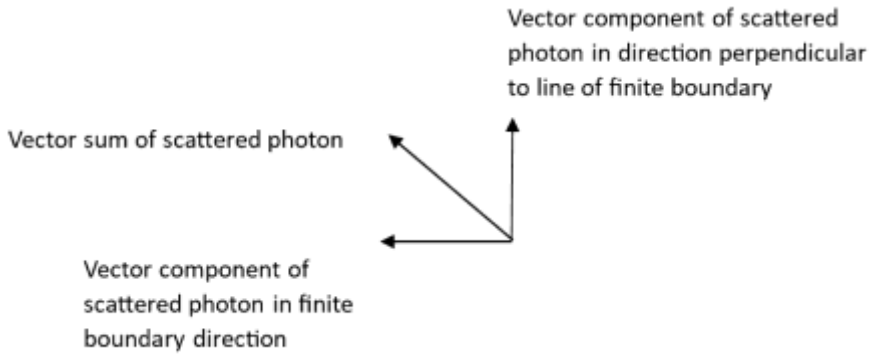

Figure 6: Decompose vector of scattered photon

From Figure (4), (5) & (6)
The energy of vector component of the incoming photon in direction parallel to the finite boundary of electron, Esin□ contributed to the elastic collision between them. The energy of vector component of incoming photon in direction perpendicular to the finite boundary, Ecos□ is not interacting with electron, it shall then combine with the rebounded component of photon in the direction of the finite boundary to form the vector sum of scattered photon.

Scenarios after the collision
Θ=0 degree,□=0 degree; no energy transfer from photon to electron, the incident photon moves straight through the electron
Θ<90 degree; forward scattering, the scattered photon moves forward relative to its initial direction.
Θ=90 degree; the scattered photon moves perpendicular to its initial direction.
Θ>90 degree; backward scattering, the scattered photon moves backward relative to its initial direction.
Θ=180 degree, □=90 degree; maximum energy transferred from photon to electron, the scattered photon is reflected backward directly from the initial direction.
The incident path, scattered path of the photon, and the path of the recoil electron are mirrored against (i) the line of finite boundary (ii) the line perpendicular to the finite boundary.
The Compton effect indeed is the verification of the definition of charge: "the charge of a quantum (one wave) is the fluctuation of the quantum (one wave) in a specific pattern within a finite boundary of length equal to wavelength, λ" in the paper titled "Intrinsic Properties of a Quantum" **[1]**.

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Elastic Collision between Photon and Molecule

Reflection

Reflection is the elastic collision between a photon and molecules in a fixed position. Thus, Rectified Newton's Third Law is applied.

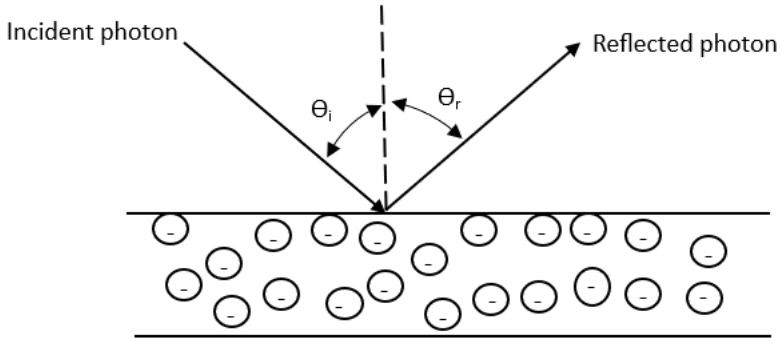

Figure 7: Reflection (I)

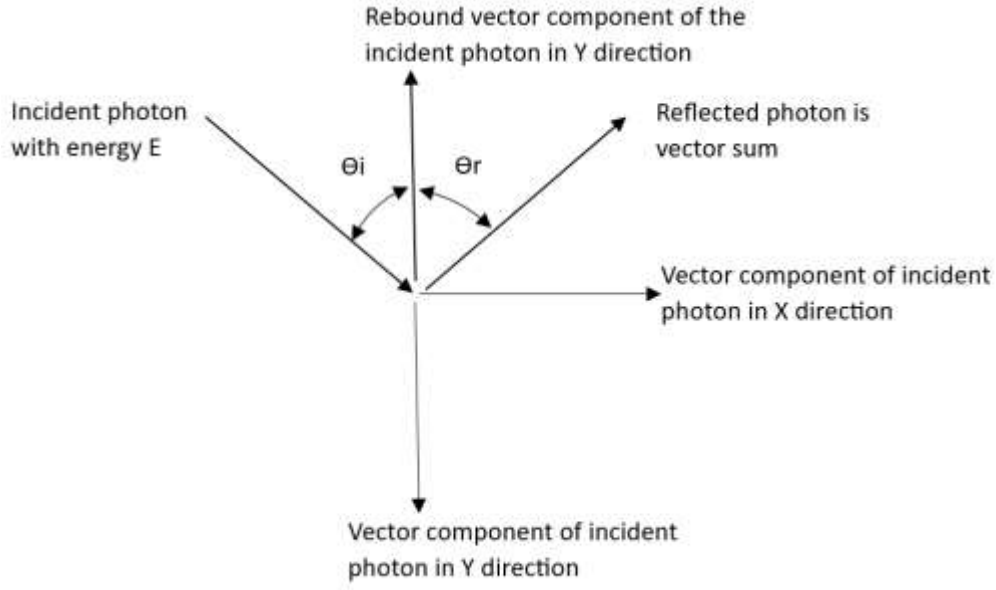

Figure 8: Reflection (II)

Action force on the target mass is due to the loss of energy of the incident photon in direction normal to surface of fixed molecules, which is equal to EcosΘ, and then it rebounds according to the Rectified Newton's Third law. The vector sum of the rebounded vector & vector component in the X direction is the reflected photon, having the reflection angle, Θ_r, equal to the incident angle, Θ_i.

Mie Scattering
The water droplet or dust in sky is not restricted to move, hence F=ma is applied by considering the collision system as an elastic collision between a photon and molecule of water or dust. This is the scenario of a projectile mass (a photon) much smaller than the target mass (a molecule of water droplet or dust). All wavelengths of visible light shall rebound uniformly with minimal energy transferred to molecules of water droplet or dust after the collision.

Absorption of the Entire Photon
Absorption of the entire photon is the phenomenon in which the entire photon energy is absorbed by the electron bound in the molecule. No uninteracted photon energy passes through the electron compared to the Compton effect.

Scattering (photon emission)
The electron absorbs an entire incident photon energy which is precisely matches the energy gap between the two atomic orbitals, the electron is excited to jump to the outer, higher orbital level. The excited electron wouldn't be stable, it then falls back to the inner, lower orbital by releasing a photon with a wavelength equal to the incident photon wavelength.

Rayleigh Scattering
The electron absorbs only high energy photon of sunlight for excitation to a higher energy orbital, and then falls back to the original orbital by emitting the equal wavelength of photon in random direction. All other wavelength photons collide with the free gas molecule. Hence F=ma is applied by considering the elastic collision as a projectile mass (a photon) much smaller than the target mass (gas molecule); these photons are less deviated from their original paths.

Photothermal Conversion
The electron absorbs entire photon energy, and this energy then transfers as heat to latice ion to raised temperature of the material.

Photoelectric Effect
The electron increases kinetic energy by absorption of entire photon energy; if the photon energy absorbed is large enough to overcome the binding energy of the electron to the ion, the electron is ejected from the metal. If the photon energy absorbed is lower than the binding energy then no electron being eject, but the temperature of the metal shall increases by photothermal conversion.
Formula derived by Einstein:
$E = hf = \phi + K_{max}$ (7)

E=hf is equal to a single photon energy(where h is Planck's constant & f is frequency of photon)
Φ is equal to the binding energy or work function
$K_{max} = \frac{1}{2} mv^2$ is equal to the maximum kinetic energy of the ejected electron (where m is electron mass, v is velocity).
The binding energy or work function, Φ is independent on the temperature of metal.

Blackbody Radiation
It is the electrons of a blackbody that gain kinetic energy via heating up, followed by emitting photons. The photons emitted is having wavelength across a continuous range; the intensity of the photons emitted and the wavelength at which radiation is the most intense is temperature dependent.

What is Color of an Object
The color of an object is due to the absorption & emission of a photon under the following conditions:
(i) A photon excites an electron to jump to the next higher orbital, followed by emitting a photon by scattering.The excitation band is limited to a very narrow wavelength range of visible light.
(ii) Wavelengths of photons other than the excitation range are all absorbed by electrons as photothermal conversion.

Refraction
Refraction is the phenomenon opposite to absorption of a photon by an electron bound to the molecule. There is no photon energy absorbed by the electron; instead, the photon passes through the electron at a reduced speed. Shorter wavelength of photon reduces more in speed.

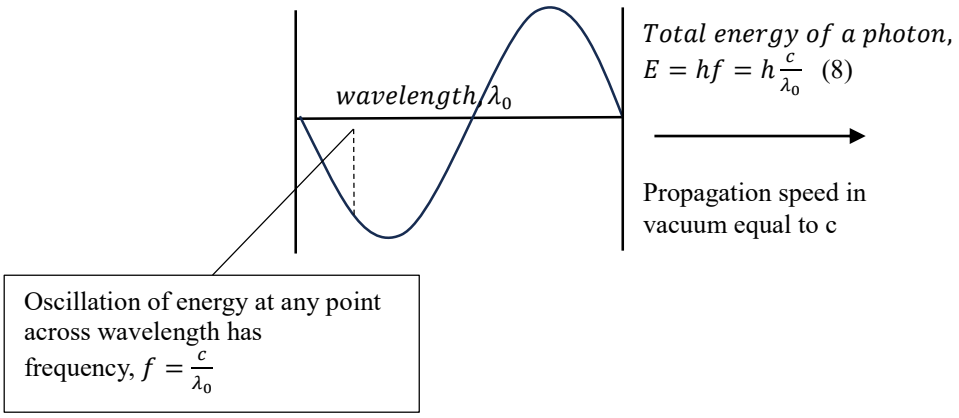

Figure 9: Propagation speed & wavelength of photon in vacuum

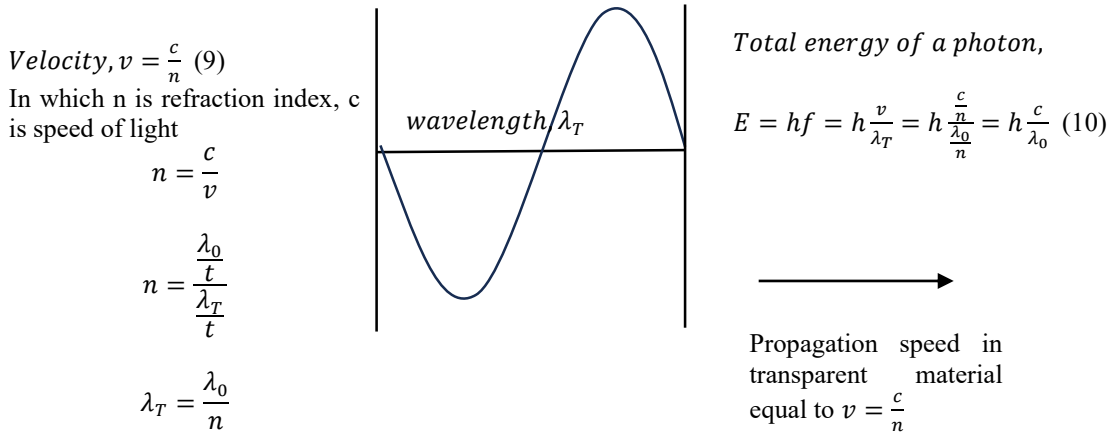

Figure 10: Propagation speed & wavelength of photon in transparent material

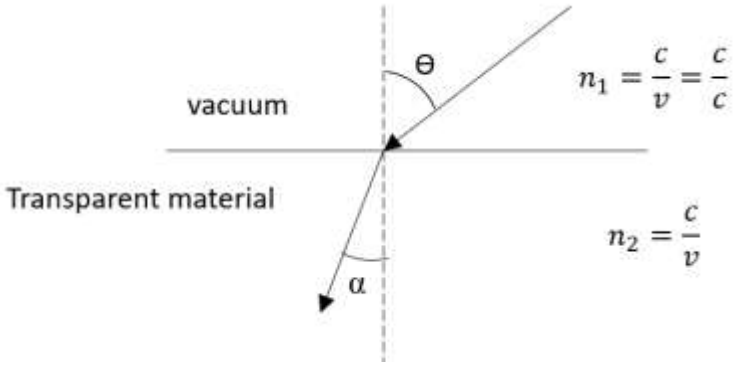

Figure 11: Refraction index in vacuum & transparent material

The law of refraction,
Snell law: $n_1 sin\emptyset = n_2 sin\alpha$ (11)
the derivation is by the geometry method with recognition of photon speed is varied in different medium.

Diffraction
Diffraction is somewhat similar to refraction; the photons interact with electrons at the edge of wall, then the photons bend in a wide variety of angles, with no loss of energy.

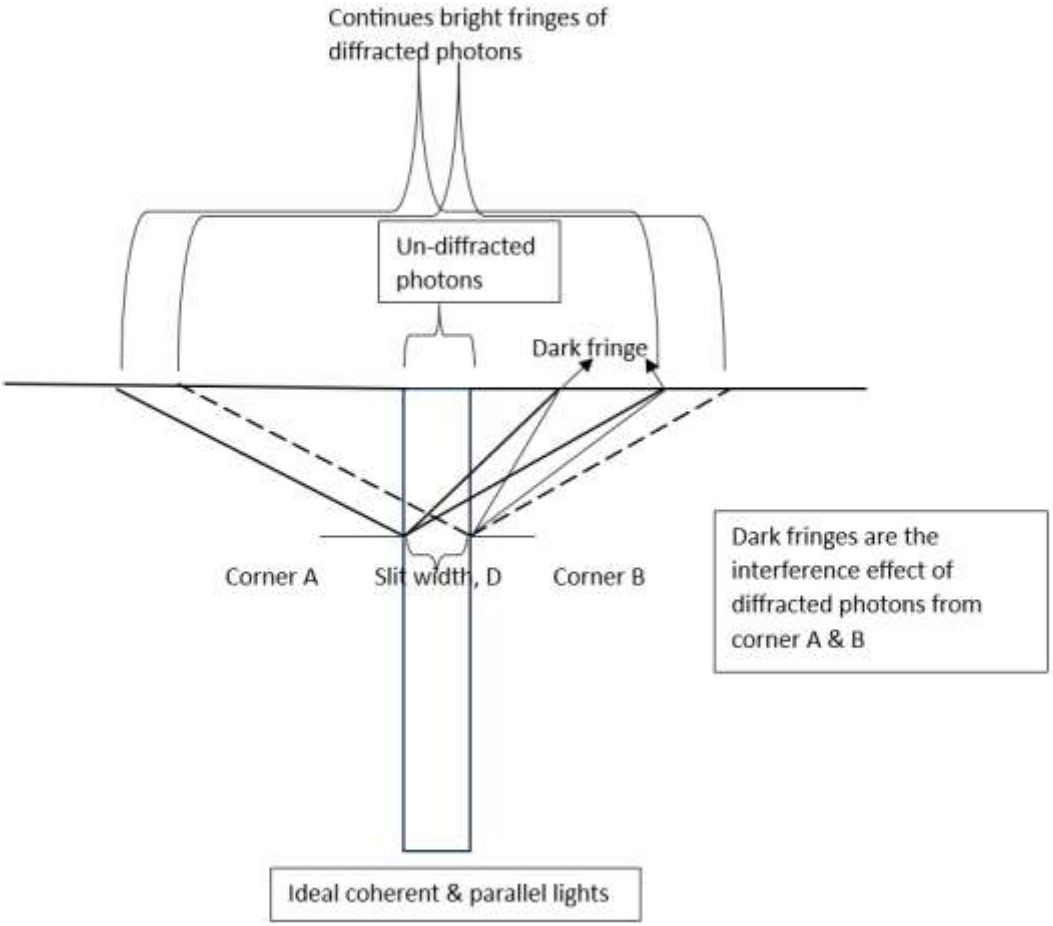

Figure 12: Diffraction of single slit

The dark fringes on the screen are the interference effect of diffracted photons from corners A & B.

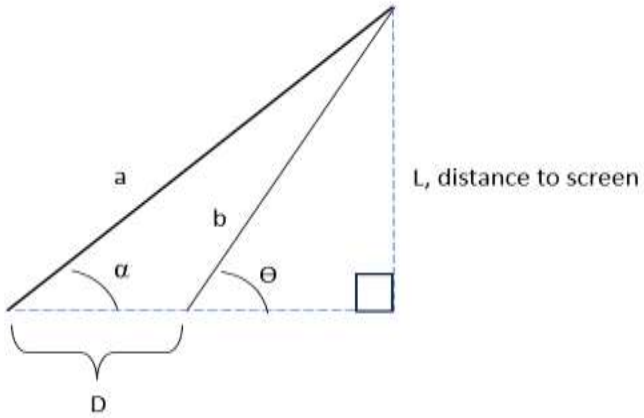

Figure 13: Interference due to path length different

Dark fringes governing equation: $a - b = (m + \frac{1}{2})\,\lambda$ (12)
a-b is the path length difference (Δlength)
m is a positive integer
λ is the wavelength of photon

CONCLUSION

The interaction of a photon with a particle with rest mass can be seen in multiple scenarios. The underlying principle are
(i) elastic collision
(ii) electron excitation for jumping to a higher energy orbital, then falling back by emitting a photon
(iii) photon energy convert to thermal energy or vice-verse
(iv) bond between electron and the atom broken
(v) photon speed changes in different medium
(vi) photon propagation direction change when collide with a corner of a slit.
Phenomena of Compton effect, reflection, and Mie Scattering fall in category (i) elastic collision. Rayleigh Scattering is the phenomenon of principle (i) & (ii). Phtoelectric effect is the phenomenon of principles (iv). Photothermal conversion & blackbody radiation are phenomena of principle (iii). Color of an object is the phenomenon of principles (ii) & (iii). Refraction is the phenomenon of principle (v). Diffraction is the phenomenon of principle (vi).

Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this paper.

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