Journal of St. Xavier's Physics Council

Particle nature of light and it's interaction with matter

Arjun Dahal, Tribhuvan University

arjundahalard.thereason@gmail.com

ABSTRACT

Following the Einstein's 1905 paper on photoelectric effect, the concept of particle nature of light took birth in the physics community, which stated that light is composed of many small particles known as photons. When the light or any electromagnetic radiation with high frequency strikes on the metal surface, it emits photoelectrons from the metals. Similarly when X-rays are incident on elements with low atomic number, elastic interaction takes place resulting in change in the wavelength of scattered beam along with the change in direction. Further, when γ-rays interact with matter, then it gets disappeared and converts itself into electron-positron pair known as pair production. Through this article we have attempted to study the particle nature of light and how it interacts with matter under the certain conditions to form new physical phenomena, and their applications to determine the crystal structures, Gravitational Red shift, Information on Black Holes and for Medical purposes.

Introduction:

Einstein with his 1905 paper on photoelectric effect erected the cornerstone on the particle nature of light, by describing the light as a series of packets known as photon or quanta. It is an effect observed in metals, first discovered by Heinrich Hertz in 1887, and later on Einstein provided a satisfactory explanation for it on the basis of quantum theory, which later earned him the Noble Prize. Similarly, two other basic phenomenon are Compton effect /Compton scattering, named after physicist Sir Arthur Compton, who in 1924 showed that when a high frequency light/radiation incidents on the electron, it transfers some of its energy partially to the electron in the process of elastic scattering. And pair-production came shortly after it, which not only provided us the existence of anti-matter particles, but also satisfied the Einstein's mass energy relationships, proving that matter could be

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

converted into energy and vice-versa. Hence, these three phenomenons are the basic ones that show the particle behavior of the matter and deals with the question, what happens, when the particle interacts with the matter under different conditions.

Photoelectric Effect:

As light/radiation spreads out from its source in the form of concentrated photons each having energy hν in the form of concentrated photons each having energy hν and incidents on a metal surface, it transfers its entire energy to a single electron it interacts with. As a result, some part of the energy is used to eject the photoelectrons from the metal surface whereas the remaining energy is used in providing K.E to the electron.
The minimum amount of energy required to eject the electron out from the metal is known as work function of metal (φ), and the minimum frequency of the photon required to eject the photoelectron (with zero velocity) is known as threshold frequency.
Hence at threshold frequency,

$$\phi = h\,\nu_0 \qquad \text{(Eqn 1)}$$

where, h is the Planck's constant, and ν is the frequency of radiation, and ν_0 is the threshold frequency.

Energy difference (hν – ϕ) appears on the K.E of the electron if the energy imparted by the incident photon on the electron is greater than the work function of the metal.
If m and v be the mass and velocity of the electron, then

$$(h\nu - \phi) = \frac{1}{2} mv^2$$

or, $$h\nu = \phi + \frac{1}{2} mv^2 \qquad \text{(Eqn 2)}$$

This eqn 2) is known as Einstein's Photoelectric Equation.
From eqn 1) and 2)

$$h\nu = h\,\nu_0 + \frac{1}{2} mv^2$$

or $$\frac{1}{2} mv^2 = h(\nu - \nu_0)$$

or $$\frac{1}{2} mv^2 = hc\left(\frac{1}{\lambda} - \frac{1}{\lambda_0}\right)$$

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

Where λ and λ_0 are the wavelength of the incident photon, and wavelength at threshold frequency, and c is the velocity of light.
Thus photoelectric effect provides us with a deep insight on the particle nature of metals, their work functions as well as other properties.
The photoelectric current emitted by a metal surface is directly proportional to the number of photoelectrons incident on them. In the process of photoelectric effect, only those electrons are ejected which have threshold frequency and wavelength less than that of incident photon and the velocity, thus the K.E. of emitted photoelectrons is independent of the light incident on the metal surface, as well as the temperature of the photoelectric materials. It is an instantaneous process and the time lag is never greater than $3 * 10^{-9}$ s.
If wave nature of light is assumed then it will take a very long time for the photoelectron to come out of the surface. Alkali metals are best suited for photoelectric effect.

Pair Production:

When a light/radiation interacts with a photon, it disappears and is converted into electron-positron pair. This process is known as pair production. Positron is antiparticle of electron, having same mass but opposite charge (i.e Positive). It is a process of conversion of energy into matter as predicted by the Special Theory of Relativity ($E = mc^2$), since a photon of sufficient energy gets materialized into an electron and a positron.
Pair production does not violates any conservation principles, since the sum of charge of electron and positron is zero, as well as the total energy including the most mass energy too is equal to that of photon. Momentum is conserved by the help of nucleus by carrying away the necessary photon, for the phenomena to happen.

It takes only in the presence of nuclear field because energy and momentum cannot be conserved in vacuum. Also, for this process to occur, γ-ray photons having energy greater than $2m_0c^2$ (1.2 MeV) is required, which is same to the sum of rest mass energy of electron and positron.
The inverse of this phenomenon happens when positron is brought closer to the electron and due to the nature of opposite charges, both of the particles vanishes

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

simultaneously resulting in the formation of 2 γ-ray photon. Since each photon has energy of 0.54 MeV, the total energy of γ-ray photon is same as 1.02 MeV, and the direction of the emitted photons are also in the way such as to conserve the both energy and momentum.

Compton Effect:

When monochromatic radiation of light wavelength is incident on atoms having low atomic number, then some part of energy or γ-ray is transferred to the electron during the course of elastic interaction. This phenomenon is known as Compton Effect or Compton Scattering.

Since photon not only carries the quantity of energy $h\nu$, but also momentum and hence during the course of interaction with electron, both energy and momentum are conserved. When a γ-ray photon of energy $h\nu$ and momentum $\frac{h\nu}{c}$ collides with an electron of rest mass m_0, then some part of energy is transmitted to the electron at the expense of energy of the photon, and is given by,

$$\lambda' - \lambda = \frac{h}{m_0}(1 - \cos\theta)$$

where, θ is the angle made by the scattered photon with the horizontal, λ is the wavelength of incident photon, and λ' is the wavelength of scattered photon.

Thus, the change in the wavelength is given by,

$$\Delta\lambda = \lambda_c (1 - \cos \theta)$$

$$\therefore\ \Delta\lambda = 2\lambda_c sin^2\frac{\theta}{2} \qquad \text{(Eqn 4)}$$

where, $\lambda_c = \frac{h}{m_0 c} = 0.234\ A^0$ is the universal constant known as Compton wavelength of the electron.

(Eqn 4) shows that Δλ depends only on the angle of scattering 'θ' and is independent of the wavelength of the incident radiation as well as the nature of the incident particle.

When the incident photon incidents at 0^0, then there is no change in wavelength, whereas the photon incident at 180^0 has the maximum value for change in

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

wavelength. This means that Compton effect can be detected only for three radiations where wavelength is not greater than few angstroms as the maximum value of Δλ is 0.0484 A^0 at 180^0. For visible light (λ = 5000 A^0), the value of $(\Delta\lambda)_{max}$ is only about 0.001% of the initial wavelength which cannot be detected.

Applications:

Gravitational Redshift and Information on Black Holes

The potential energy of the photon on the surface of the star is given by $\frac{-GM}{R^2}\frac{h\nu}{c^2}$.
Here, - sign indicates that the force is attractive.
Hence the total energy of the photon is
E = Quantum Energy + Potential Energy

$$= h\nu - \frac{GM}{R^2}\frac{h\nu}{c^2}$$

$$= h\nu\,(1 - \frac{GM}{Rc^2})$$

For any distance further from the star or any celestial body, the photon becomes free from gravitational field, and becomes completely electromagnetic with the energy hν', where ν' is the frequency of the arriving photon. P.E. of the photon in the earth's field is almost negligible in compared to that of of the star's field is,

$$h\nu' = h\nu\,(1 - \frac{GM}{Rc^2})$$

or, $\frac{\nu}{\nu'} = 1 - \frac{GM}{Rc^2}$

This relative change in frequency in the presence of gravitational field is called Gravitational Redshift, and is given by,

$$\frac{\Delta\nu}{\nu} = \frac{GM}{Rc^2}$$

Since, the photon loses its energy, as it leaves the gravitational field of star, so the photon in the visible region of spectrum shifts towards the red end, and the phenomenon is known as gravitational redshift.

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

Journal of St. Xavier's Physics Council

When $\frac{GM}{Rc^2} \geq 1$, it immediately follows that, no any photon can escape out of the star. To escape out, it needs more energy than the initial energy hν, which stretches the photon's wavelength to infinity. Hence, the star is not able to radiate and becomes invisible in the space, which we commonly known as black hole.
On applying the general relativity for a photon in a black hole, the exact criterion for a star in order to be black hole becomes, $\frac{GM}{Rc^2} \geq \frac{1}{2}$.

The Schwarzschild radius or the radius of event horizon, from which nothing can escape out is given by $r_s = \frac{2GM}{c^2}$. Thus studying the nature of photons and gravitational redshift provides us valuable information regarding the black holes and the universe.

Crystal Structures:
When monochromatic light (X-rays) are made incident on the atoms of a crystal lattice, then each atoms of the cystal acts as a source of scattering radiation of the same wavelength. The intensity of those reflected beams at certain angles becomes maximum. If the path differences between two reflected waves from two different planes is integral multiple of wavelength, and is governed by the eqn called Bragg's law, and mathematically given by,
$n\lambda = 2d\sin\theta$
Where, d is the interatomic distance, θ is the glancing angle, and λ is the wavelength of the light.

Medical and Research:
Radiations (Light) are highly used for medical purposes. X-rays are used in radiotherapy for detecting fractures, tumors and presence of foreign matters, as X-rays, are absorbed, between bones, tissues, and metals. Similarly different tumor cells are also destroyed by using X-rays. In industrial purposes too X-rays are used to detect the crack and flaws in the finished products, as well as provides valuable information regarding the molecular gaping of different materials. Radiations are further used for research purposes mostly for analyzing the number of facts, concerning the alloys, crystals as well as different atoms and molecules.

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

Conclusion:
For the photons with low energies, photoelectric effect is the chief mechanism of the energy loss. The importance of photoelectric effect decreases with increasing energy, to be overcome Compton scattering. Photoelectric effect remains significant for the absorber, with greater atomic structure. Pair Production is the immediate implication of conversion of matter into energy and vice-versa. All three phenomena, i.e. Photoelectric effect, Pair Production, and Compton Effect are the fundamental properties of the particle nature of light, and on studying these phenomena, several other secrets and mysteries of the physics can be resolved.

REFERENCES

[1] Young, H.D. and Freedman, R.A. (2003) University Physics with Modern Physics. 11th Edition, Addison Wesley, Boston.

[2] Nelkon, M. and Parker, P. (1982), Advanced Level Physics, 5th Edition, Arnold – Heinemann Publication, London.

[3] Adhikari, P.B, Chhatkuli, D.N. and Koirala, I.P. (2014) A Text Book of Physics Vol-II, Sukunda Pustak Bhawan, Kathmandu

[4] Murugeshan, R, Prasad, K.S., Modern Physics, S.Chand and Company, Ramnagar, New Delhi

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

[5] Dahal, A. and Adhikari N., An Overview of Black Holes, Journal of St.Xavier's Physics Council, http://www.sxpc.ga/2018/04/17/an-overview-of-black-holes/?i=1

[6] Dahal, A. "A Glimpse of Special Theory of Relativity", Journal of St.Xavier's Physics Council, http://www.sxpc.ga/2017/10/29/sr-dahal/

Footnotes: if any! (Replace "Footnotes: if any!" by your footnotes or to whom you want to thanks!)

