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Characteristics of a Photon / what Exactly is a Photon? / Is Photon Chargeless? / A Concise Description of the Photon.

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Abstract:

The Photon which is a fundamental entity of electromagnetic radiations is a boson. According to Maxwell equations, it is nothing but an electric field which propagates through space with the speed of light and produce orthogonal magnetic field during its movement. Photoelectric effect and Compton effect suggested its particle nature. In this review paper, it is tried to build a comprehensive and concise description of photon. Various theories and results are indicated to generalize specific properties of the photon. Quantum entanglement, bunching effect, comparison of photon with hypothetical particle Graviton, pair production, Schwinger effect, photon-photon collision and polarization of photons are some remarkable phenomena that are related to photon; these terms are concisely explained in this review article. These phenomena are not only vital for future technology but also will have the central key for our understanding of the sub-atomic world.

Introduction:

Photon is a fundamental particle. It can also be termed as the quantum of electromagnetic radiations. According to Standard Model of Elementary Particle photon is a chargeless particle and it falls in gauge boson family. Boson is the particle whose spin quantum number is an integral number (0,1,2…). Photon has a spin of 1 with spin states of $+1h/2\pi$ or $-1h/2\pi$. The color charge of this particle is zero. It is a massless particle ($< 1\times10^{-18}$ev/c^2 experimental limit of mass calculation) having very stable mean lifetime. In contrast, it is also believed that this particle has some non-zero rest mass. Such an effect of non-zero rest mass of photon can be explained with the help of electromagnetism. For dealing the non-zero rest mass of photon the proca equations are used. These equations are generalization of Maxwell's equations[1]. It moves with the speed of light ($c = 3\times 10^8$ m/s) and it is denoted by gamma(γ)[2]. Maxwell's equations give significant information about the nature of photons. These fundamental equations explain the nature of oscillating electric and magnetic field of photon during its motions. Furthermore, it explains the nature and propagation of photon. According to his theory, photon is nothing but an electrical field moving with speed of light. When such an electrical field change it produces magnetic field and vice versa[3]. The contribution of electric field component is higher than magnetic field component, when there are some interactions of photons with matters, and it is probably the electric field component which interact with matter. There are numerous examples in nature when photon in the form particle encountered with particles. Spectroscopy is a branch combinedly of chemistry and physics which is solely based on the interaction of photon with matters. For example, high energy x-rays photons are used in structure determination of different ionic crystals. UV/Visible light is particularly helpful in determining the presence of alternative double and single bond in various molecules. Similarly, radio waves are very particular during its interaction with the spin-active nucleus of an atom[4]. According to Plank quantum theory, electromagnetic radiations are not continuous but contain large numbers of tiny photon. These photons have quantized energy which are directly related to the frequency of radiation and independent of the wavelength of photons[5]. Higgs Boson theory has many significant applications in understanding the nature of fundamental particles like photon. According to this theory, there exist a field termed as Higgs boson field which is always present in all the places. All fundamental particles like electron, quarks and bosons interact with this field to some extent. More the extent of interaction of these particles with Higgs field higher will be the mass of the particle. In short, this field is responsible for all masses which various fundamental particles possess. Photon which is a massless particle suggests that its interaction with Higgs field is almost negligible and that is the reason photon has zero rest mass[6]. The gravitational force which is one of the fundamental forces has strange effect on photons. Gravitational force attracts both mass and light toward itself. There exists a common term called space-time curvature. Near all the massive body the nature of space-time is curved. So massive bodies try to curve the space-time fabric. Photon near massive body bends its path due to its gravity. In general, gravity without any distinction attracts both electromagnetic radiation and mass[7]. Blackholes are entity that have very large gravitational pull on both light and mass due to its giant massive structure. It is believed that photon cannot pass through these black holes and nature of light near and inside black hole has been testified via general relativity[8].

According to the Einstein's theory of special relativity photon that mediates electromagnetic radiation is independent of frame of reference. It propagates with constant velocity through space-time. Any object which possesses mass can never attain the speed of light according to this theory. Therefore, it is difficult to find the rest mass of photon. Experimental efforts are trying to improve the possibilities of finding the rest mass of photon based on classical Maxwellian electromagnetism. In this context, the Proca equations have seemed to be the most reliable tool in calculating the nonzero rest mass of photon[1].

Theory:

Particle nature of Photon:

In classical concepts, it was believed that electromagnetic radiations have a continuous spectrum and without any particle nature. Modern experiments have visualized the solid background for its particle nature. Photoelectric effect is one of the phenomena which proof the particle nature of photon. When a UV/Visible light with a suitable frequency fall on metal surface electrons are emitted. Photons need a threshold hitting frequency without which electrons are not emitted from metal surface. Photons interaction with the electrons are like hitting of billiard balls with each other. This phenomenon can be understood with the Einstein equation for Photoelectric effect. It can be expressed as.

$$E_K = hf - \emptyset \qquad (1)$$

Where E_k is the kinetic energy of emitted electron h is the Plank constant f is frequency of incident photon and $\emptyset$ is work function amount of energy required to remove an electron from a photocathode surface.

However, it may assume here that photon which is considered as a chargeless entity may interact with electrons in charge like fashion. In recent research a breakthrough happened when there was an unusual photoemission using $SrTiO_3$. In this experiment, when photon of energy near 10ev are focused on strontium titanate secondary photoemission is observed. Additionally, there is no mechanism which can explain this phenomenon. Authors termed these photocathode quantum materials. It is believed that primary electron before its emission from photocathode surface interact with another secondary electron and a coherent intense beam of secondary electron is emitted. Theory is still needed to explain how photon can result in emission of a secondary electron. Photon may either interact with its propagational charged fields or primary electron stimulate secondary electron to emit[9].

Pair Production

Quantum electrodynamics theory allow the conversion of pure light into matter. Pair production is a phenomenon in which the particle and antiparticle can be created using a neutral Boson. Usually high energy photon (gamma ray) can be transformed into matter. The most common example of pair production is creation of electron and positron from gamma radiation. The Breit Wheeler (BW) process proposed the conversion of two photons into electron and positron. This concept can be illustrated as:

$$\gamma + \gamma' \rightarrow e^{+} + e^{-} \qquad (2)$$

It is a simple proposed mechanism by which light can be changed into matter. The BW process for two photons seems straightforward has never observed in any laboratory until now. Via this process it is lucid that somehow it is possible to convert a chargeless gamma photon into equivalent number of well-balanced charges fulfilling the law of conversation of charge on both sides of the above equation[10].

Schwinger Effect

It is a phenomenon in which high energy electric field can result in pair production (emission of electron and positron). That means matter can be created by a strong electric field. It is a well-known prediction in the field of quantum electrodynamics. There exists a false vacuum which can be termed as metastable state. Such a false vacuum can exist for a long time. When such a false vacuum interacts with a very strong electric field a process called false vacuum decay occurs. To compensate the energy when such a false vacuum is converted to the true vacuum pair production occurs. A Schwinger limit for electric field exist whose value is equal to 1.38×10^{18} V/m. Above this limit pair production phenomenon increasingly occurs. The magnetic field at Schwinger limit is very high and it is approximately equal to 4×10^{9} Tesla. At this limit Maxwell equations and theory of electromagnetic radiations do not hold good and becomes nonlinear. In short, photons show nonlinearity above this threshold limit. Such a pair production mechanism in term of Schwinger equation can be given by this equation in term of production rate per unit volume as:

$$\Gamma = \frac{(eE)^2}{4\pi^3\hbar c}\sum_{n=1}^{\infty}\frac{1}{n^2}\, exp\left\{-\frac{\pi m^2 c^3 n}{\hbar e E}\right\} \qquad (3)$$

In this equation h is Planck constant c is speed of light e is elementary charge E is electric field strength and m is the mass of electrons[11]. In recent research the Schwinger effect was observed in graphene. One dimension Schwinger conductance was observed on a graphene transistor[12].

Graviton and Photon

Graviton is a hypothetical elementary particle which is the forces carrier of gravitational field. It is much like the photon which is the force carrier of electromagnetic radiation. It is symbolized by G. It has spin of 2 and having approximately zero supposed mass. It is electrically neutral just like consideration for the photon. Both photon and graviton are long range fields. Both are stable. Graviton is expected to travel with the speed of light. Both particles are Boson. In contrast, both have different spin. The Photon has the spin of 1 whereas the graviton has the spin of 2. Both are in different space. For example, the graviton is a tensor particle as gravitational field is explained by using tensor Einstein's equation. Photon is a vector particle as electromagnetic field is estimated by vector Maxwell's equation. Graviton has a tensor whereas photon has a vector character. Spin of the photon is equal to $\pm\hbar$. It means that the photon possesses two helicities in term of circular polarization. One term is for left-polarized and other for right-polarized. It is possible to calculate the interaction of a mass particle with graviton precisely in Riemann's space-time. In contrast, the interaction of a mass particle with photon cannot precisely be calculated in Euclidian space. Therefore, Richard Feynman diagram method is implied for such calculations[13].

Spin of Photons:

Spin is one of the ways to distinguish between elementary particles. Fermion particles possess half spin integer and Boson particles have integer spins. Photon being a boson particle has a spin of one. Polarization of light is related to spin-based degree of freedom of a photon. There are two possible traverse polarizations in free space. The photon spin is connected to two circular polarizations. The circular polarization of electromagnetic radiations is the phenomenon in which electric and magnetic fields continuously rotate around axis of propagating beam of light. Such polarization may either Left (L) or Right (R) depending on direction of rotation along axis. In a circularly polarized light photon has spin angular momentum. This spin angular momentum has two possible values of $\pm\hbar$. The positive sign indicates for left polarization whereas the negative sign is for right side polarization. Spin angular momentum is always positioned along the beam axis. The spin and angular operator of light originated from quantum field theory is used to explain various properties of a photon. The spin angular momentum (SAM) of a photon can be expressed by given equation:

$$S_M = (\frac{1}{C}) \int d^3x \, \pi \times A \qquad (4)$$

The orbital angular momentum (OAM) of a photon can be expressed by given equation:

$$L_M = (-\frac{1}{C}) \int d^3x \, \pi^\mu \times \nabla A_\mu \qquad (5)$$

Where c is speed of light, π is conjugate canonical momentum, A is a vector potential and μ is four indices of spacetime[14]. Stokes parameters is implied to study the polarization state of the photon. General consideration about the angular momentum of a photon is that the total angular momentum of the photon cannot be split into the spin and angular momentum in a specific gauge. The spin of the photon is the inherent property of the photon. It possesses the quantized degree of freedom which is inherent to the photon. Additionally, the spin angular momentum of a photon is independent of its frequency[15].

Photon-Photon Reaction/Collision:

In classical electrodynamics, (from linear maxwell equations) it was impossible to study the light-light scattering. It is because, light becomes sum of each light wave when added (interference). Although, in quantum mechanics, there are many possible intermediate states energy of a photon which can be denoted by E_γ. This photon having energy E_γ can have quantum fluctuation into pair of charged particles. The estimated lifetime (Δt) of such an intermediate particles state having some mass (m_{pair}) can be calculated using Heisenberg uncertainty principal as:

$$\Delta t = 2E_\gamma / m_{pair}^2 \qquad (6)$$

According to this equation for infinite photon's energy E_γ the lifetime of intermediate state becomes significant and photon-photon scattering is possible. Photon during his reaction may create virtual pairs. There are two possible types of scattering in photon: elastic and inelastic collision. Elastic collision mechanism of two photons is explained with the box diagram first explained by Richard Feynman. The phenomena of inelastic collision of photon can occur for high energy collisions of photon. In such collision may produce many possibilities of the following pairs like electron positron pair, leptons pair, hadrons, weak vector bosons, neutral Higgs boson. The inelastic collision of photons is symbolized with many other possibilities of production of other fundamental particles as:

$$\gamma + \gamma \rightarrow e^+ + e^- \quad (7)$$
$$\gamma + \gamma \rightarrow l^+ + l^- \quad (8)$$
$$\gamma + \gamma \rightarrow hadrons \quad (9)$$
$$\gamma + \gamma \rightarrow Z^0 \quad (10)$$
$$\gamma + \gamma \rightarrow W^+ + W^- \quad (11)$$
$$\gamma + \gamma \rightarrow H^0 \quad (12)$$

Additionally, beam of photon shows coupling with the beam of electron. During such coupling it is possible to evaluate the structure and function of the photon and its transition and reactions like conversion to hadron and many virtual reactions $\gamma\gamma^*$ of photons. Photons collision has led a paradigm to seek new pieces of information about collisions of gauge fields gluons. Moreover, photon interacts and couples with particles like quarks, leptons and bosons. The most important application of the 2-photons collision is the production of $W^{\pm}$ pairs. Such a conversion can help to understand the helicities of both photon and W particles[16, 17].

Low Energy Photon-Photon Collision:

Quantum chromodynamics (QCD) theory is developed to study the strong interactions between quarks that are strongly bound by gluons. Chiral perturbation theory (ChPT) is used to study low energy quantum chromodynamics (QCD) based on chiral symmetry (particle having spin of either left-handedness or right-handedness)[18]. The double equivalent photon approximation is used to describe the phenomena of the quasi-photon beams production in a collider. It produces a wider bremsstrahlung spectrum for the consideration of energies possess by virtual photons. Photons phenomena of elastic scattering is feasible wide energies ranges using the method of light-by-light scattering $\gamma\gamma \rightarrow \gamma\gamma.$. In quantum electrodynamics phenomena $e^+e^- \rightarrow e^+e^-\mu^+\mu^-$,the muon pair invariant mass had been studied in range of 3 Gev to 40 Gev in past. The mechanism of $\gamma\gamma \rightarrow \pi^+\pi^-$ is generated by using the tree diagrams of photon. The scattering amplitude of photon is measured in one-loop and two-loop expression by using the chiral perturbation theory. Virtual photons are used for the reactions $\gamma\gamma \rightarrow \pi^+\pi^-$ occurrence. The mass range for such reactions may lie in the range of 0.5-1.5 Gev or more depending on detection limit implied. The $\pi^+\pi^-$ mass spectrum can be divided into various regions to study the resonance phenomena. The cross-section is approximated with comparison of results with the born term predictions[16-19].

High Energy Photon-Photon Collision:

The production of photons during the hadronic collisions are gluttonous. This copiously production of photons from hydrons at large transverse momentum p_t indicated that hydrons possessed some point charge inside them. There is a sound consistency of the photon signal with the prediction of quantum chromodynamics (QCD). A hard-gluon interaction and distribution is generally required to observe the direct signal of photon. The coherent back-scattered laser beam for the phenomena of $e^{\pm}e^-$ collision can result in the conversion of major portion of lepton's energy into high energy photons. When the polarized electron beam is scattered by the polarized laser beam via Compton-scattering mechanism then each electron with a definite amount of energy is converted into polarized photon. These photons carry the major share of energy obtain from the polarized electron. The high energy and polarized back-scattered laser beam will allow to study the high energy collisions phenomena of photon-photon and photon-electron collisions. High energy photons collisions can be classified into following classes:

(1) The photons during annihilation converted into charged particles like pairs of either leptons or charged Higgs.

$$\gamma\gamma \rightarrow W^{+} + W^{-} or\ q^{+} + q^{-} \quad (13)$$

(2) Photons may produce neutral particles like gluons and neutral bosons.

$$\gamma\gamma \rightarrow Z^{0} + Z^{0} or\ \gamma Z^{0} \quad (14)$$

$$\gamma\gamma \rightarrow gg \quad (15)$$

(3) Photons have an option to couple separately to other charged pairs. Such coupling may scatter via a gauge particle exchange.

$$\gamma\gamma \rightarrow q_1\bar{q}_2 q_2\bar{q}_2 \quad (16)$$

(4) Photon can merge to produce a single resonance state like C = + resonance. It is a neutral Higgs for example $\chi_b\ or\ \eta_b$. It is the higher orbital state in photons collisions[16, 20]. (17,23).

The cross section of Higgs particle production can be calculated by the following relations:

$$\sigma(\gamma\gamma \rightarrow H^{0}) = \frac{8\pi^{2}\Gamma(H\rightarrow\gamma\gamma)}{M_H} \frac{m_H \frac{\Gamma_{total}}{\pi}}{(s-m_H^2)^2 + (m_H\Gamma_{total})^2} \quad (17)$$

Photon bunching and Antibuncing effect:

Photon bunching effect:

Bunching effect is commonly observed for an ordinary light source. It means when an ordinary light source is detected via detector photons have appeared in clusters. In photomultiplier tube (PMT), photons are collected in clusters or bunches. When coincidence counting rate was plotted against delayed time, a peak was appeared at delayed time equal to zero. This peak suggested that photons were coming in the pairs. This effect is term as bunching effect of photons. This effect was first investigated by Hanbury Brown and Twiss in 1950s.This effect is the property of incoherent light source. The conventional source of light emits chaotic light which give birth to the bunching effect. Bunching effect is explained with the help of classical theory of light. The intensity of such a chaotic light due to various source atoms cause fluctuations. A crust or trough may observe in cycle-average intensity graph for such a conventional light source. According to quantum mechanics, photon is a boson particle. Therefore, it is possible for large number of photons to occupy the same quantum state as a set of bunches. If N photons bunch together than their cluster can be indicated with N-photon cluster. It is quite difficult to quantify photon bunching effect. In a recent experiment, using quantum Fourier transform spectrometer, N-photon cluster ranging up to N =12 was observed. The light source implied in the experiment was a halogen lamp[21, 22]. (25,26)

Photon antibunching effect:

Antibunching was introduce by Rondey Louden. Antibunching is an effect in which light beam has more equally spaced photon than the classical light source. When laser light has a stable amplitude, then the counting rate of photon by detector is likely to depend on delay time. In case of single emitter like quantum dots, when they are present in excited state, cannot be re-excited, unless their ground state is achieved. Consequently, the emission of photons is dependent on the lifetime for which single emitter is present in excited state. The smaller the excited-state lifetime of such an emitter, the more prominent the antibunching effect will be and vice versa. Antibunching effect can be quantitatively measured by Time-Correlated Single Photon Counting (TCSPC) using Hanbury-Brown-Twiss experiment[21, 23].

Quantum entanglement of photon:

EPR Paradox/Paper

Einstein Podolsky and Rosen introduced the term of entanglement via their EPR paper in 1935. Einstein called this phenomenon spooky action at a distance. According to their mathematical formulation, a physical quantity is only real when there is sufficient chance of it to be measured with reliability. Additionally, in quantum mechanics when two physical quantities are described by a non-commuting operator: information of one physical quantity contains the information of other physical quantity. In simple words, when two objects interact with each other then they are entangled to each other irrespective of their distance. Two possibilities may be possible for such situation in quantum mechanics: firstly, the reality provided by quantum mechanics is not complete; secondly, description of reality and quantum mechanics cannot be true simultaneously. Reality of a system is defined with the reference to system's prediction with certainty. In their paper they argued that quantum theory for the formulation of all the properties of a wave function may not be sufficient to explain the particles that are entangled with one another. Mathematically, this paper had represented the following equations.

$$\Psi' \equiv A\Psi = a\Psi \quad (18)$$

For an observable quantity, if A is an operator, Ψ is the eigenfunction, and a is a number. Particle state of the system can be given by Ψ. To meet reality criteria particle state can be modified as:

$$\Psi = e^{(2\pi i/h)p_0 x} \quad (19)$$

In given equation, p_0 is a constant number, x is an independent variable, and h is Planck's constant. Equation is useful for calculation of real momentum of a particle. Momentum associated with particle in term of quantum operator is as follow:

$$p = (h/2\pi i)\partial/\partial x \quad (20)$$

Similarly, Ψ' can be modified as:

$$\Psi' = p\Psi = (h/2\pi i)\partial\Psi/\partial x = p_0 x \quad (21)$$

The momentum calculated from Eq. (19) will be real and equal to p_0 whereas equation (18), if does not hold than the quantitative value of A becomes ambiguous.

If q indicates the operator of multiplication for some independent variables of a particle than mathematically it can be written that:

$$q\Psi = \mathrm{x}\Psi \neq \mathrm{a}\Psi \quad (21)$$

According to quantum mechanics, there is only a relative possibility that can be measured, and absolute value cannot be predicted. In example:

$$\mathrm{P(a,b)} = \int_a^b \Psi'\Psi\mathrm{dx} = \int_a^b dx = b - a \quad (22)$$

According to Eq. (22), probability is independent of limits (a) and (b). The quantum mechanics can only predict the difference (b-a) and does not predict the absolute values. In this regard, direct measurement of value of coordinate is impossible to measure as given by Eq. 19, unless direct measurement is taken. After the measurements of coordinate values Eq. 19 is not applicable as particle state is not described by this equation.

In a net shell, this paper argued that either quantum mechanical approach of wave function is not complete or operators that are operating on two physical quantities, when do not commute then two quantities do not possess reality at the same time. It concluded that for complete description there must exist some theory/ local hidden variables which was not known till date, and they left the discussion with open end question. Furthermore, this paper sets the criterion of reality, locality and hidden variables[24]. Later in 1978, theoretical calculations which had done for positron's spin in a paper suggested that density-matric approach can possibly solve this inconsistency raised by EPR paper. In simple words non-locality was unacceptable for Einstein due to his relativity term. According to EPR paradox, no influence is able enough to move faster than speed of light[25].

Bohm EPR paradox and Bell Inequality

In 1957, a paper had come forward by Bohm and other scientists to discuss the experimental proof of EPR paper. In this paper, authors had explained that to study the paradox argued in EPR paper needed a source of particles. The ideal source, according to this paper, was the study of polarization of a pair of photons produce during electron-positron annihilation. The other source may include the spin of electrons. The EPR paradox is difficult to explain only for the case when particles are separated to a very large distance. Suppose a pair of electron and positron is formed by the decay of neutral pi meson. If meson is at rest the electron and positron pair will move in opposite direction after such production.

$$\pi^0 \rightarrow e^+ + e^-$$

As, meson has zero spin, therefore, obeying the law of conservation of angular momentum both particles should exist in the singlet configuration. If the electron has possessed the spin up configuration, then positron must have the spin down configuration and vice versa.

$$\frac{1}{\sqrt{2}}(\uparrow_-\downarrow_+ - \downarrow_-\uparrow_+)$$

Quantum mechanics cannot predict which combination of these two pairs will be preferrable. However, it provides information that such measurement will be correlated to each particle and average of these combination will be observed in result. If such particles are flown away to a very large distance and one particle has measured having spin up, then other will be spin down. The orthodox point of view opposes this fact that without measurement neither have any spin. Measurement of positron's spin generates the spin of electron at a distance[26].

If a molecule has zero total spin consisting of two atoms, then wave function of this system can be given as:

$$\Psi = \frac{1}{\sqrt{2}}[\Psi_+(1)\Psi_-(2) - \Psi_-(1)\Psi_+(2)]$$

(BOHM paper on epr)

Bell inequality is about any local hidden variable which can be applied in real world. Bell tried to test whether local realism exist in real world or not. He showed that physical systems do not show consistency with the assumption of local hidden variables. In other words, no local hidden variable theory could satisfactorily explain the prediction that is done by quantum mechanics. By advocating Bohm's idea of electron-positron pair produced by meon; he added that the detectors (Stern-Gerlach) which were allowed to orient in the same direction for particle's spin measurement could also be rotated independently. Suppose the measurements of electron's spin by a detector is indicated by 'a' and positron's measurements by 'b'. The product of the spins of those pair is dependent on the orientation of detectors. Average value of their detection can be represented by P(a,b).

If detectors are parallel (a = b), then the following relation holds.

$$P(a, a) = -1$$

If detectors are anti-parallel (b = -a), then the result would be different.

$$P(a, -a) = +1$$

For any arbitrary orientations of detectors, quantum mechanics predicts the following relation:

$$P(a, b) = -a.b$$

Quantum mechanics results were incompatible EPR paradox. This means that complete description of the state of electron/positron is impossible to explain without some hidden variable (λ). Suppose this hidden variable (λ) is ambiguous (unknown) for all results. To support locality assumption, it is further assumed that measurement of each particle is independent of orientation of detector that is applied to measure the opposite paired particle placed at a large distance. Then, for the measurements of orientation of both electron and positron two function will exist in example A (a, λ) and B (b, λ). These functions have only one possibility of either +1 or -1.

$$A(a, \lambda) = \pm 1 \quad B(b, \lambda) = \pm 1$$

When detectors are anti-correlated the functions can be related as:

$$A(a, \lambda) = -B(b, \lambda)$$

The product of two components (paired particles) can be represented with the help of probability distribution as:

$$P(\mathbf{a}, \mathbf{b}) = \int \rho(\lambda)\, A(\mathbf{a}, \lambda)\, B(\mathbf{b}, \lambda)\, d\lambda$$

Where ρ (λ) is related to hidden variable and termed as probability density. This relation will change sign an when detectors will be oriented in opposite direction with respect to each other.

$$P(\mathbf{a}, \mathbf{b}) = -\int \rho(\lambda)\, A(\mathbf{a}, \lambda)\, A(\mathbf{b}, \lambda)\, d\lambda$$

If there is any other unit vector **c** is present than equation will further modified as:

$P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c}) = -\int \rho(\lambda)\, [\, A(\mathbf{a}, \lambda)\, A(\mathbf{b}, \lambda) - A(\mathbf{a}, \lambda) A(\mathbf{c}, \lambda)] d\lambda$

Since $[A(b, \lambda)]^2 = 1$

Therefore,

$|P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c})| = -\int \rho(\lambda)\, [\, 1 - A(\mathbf{a}, \lambda) A(\mathbf{c}, \lambda)] A(\mathbf{a}, \lambda) A(\mathbf{b}, \lambda) d\lambda$

From

$$A(a, \lambda) = \pm 1 \quad B(b, \lambda) = \pm 1$$

It can be concluded that:

$-1 \leq [A(\mathbf{a}, \lambda) A(\mathbf{b}, \lambda) \leq = +1$

Moreover,

$$\rho(\lambda)[1 - A(\mathbf{a}, \lambda) A(\mathbf{c}, \lambda)] \geq 0$$

The simplest version of bell inequality for all hidden variables term can be given as:

$$|P(\mathbf{a}, \mathbf{b}) - P(\mathbf{a}, \mathbf{c})| \leq 1 + P(\boldsymbol{b}, \boldsymbol{c})$$

If a third vector **c** makes an angle of 45^0 between these two-measuring vector **a** and **b**, then quantum mechanics predicts it measurement as:

P (**a**, **b**) = 0, P (**a**, **c**) = P (b, c) = -0.707.

Whereas Bell's inequality violates such result as:

$$0.707 \neq 1 - 0.707 = 0.293$$

Hence, local realism is untenable. (That cannot be proved). Local realism was contradicted by quantum mechanics[27]. (QM).

Quantum Entanglement/ Breakthrough in bell's inequality:

A system is said to be entangled when quantum state of that system cannot be written as product of its states in its local constituents. More precisely, if a composite system cannot be formulated as its product of the states of constitutional subunits/subsystems, it is called quantum entangled system[24].

(EPR paper). In an experiment by Clauser and other researcher showed that it was quantum mechanics whose result was in complete agreement with entangled particles. His research proved that Bell's inequality was wrong. In his experiment two entangled proton was produced from a calcium atom. During the excitation and deexcitation of electron two entangled photons were emitted and their linear polarization were measured for various fixed angled. There results violated the Bell's inequality. These results were in great agreement with the predications of quantum mechanics for various angles of measurement[28]. The main problem with the Clauser's experiment was that the polarizers used to sense/detect the photons were immobilized and fixed at some orientations. 'Is there any effect of orientation of polarizer on the photons?' was the new burning question. In this sense, it was possible for the photons to have some preferred orientation with respect to fixed polarizers. Furthermore, Bell's locality conditions were not considerable for static experiment. Therefore, such polarizers were unable to measure for wide ranges of angle's measurement of photons. Consequently, it was desirable to design an experimental setup that can be able to use the movable polarizer for such an experiment. This problem was solved in another experiment. In this experiment, having a very similar experimental structure like Clauser, Alain Aspect and his team were able to reproduce the results with variable polarizers which had favored the predictions of Quantum Mechanics against Bell's inequality. In his experiment, he used polarizers which were connected to an optical switching device. Two such switches were unrelated with each other to fulfil the requirement of Bell' inequality. The switching between two channels were very fast (10 nano second). During their measurement, the results showed a complete agreement with the Quantum Mechanics' predictions[29].

Conclusion:

The Photon is one of the unique particles that exist in nature. Due to its relatively high speed (speed of light) and its interaction with fundamental sub-atomic particles makes it highly useful for studying sub-atomic inside the atom. Additionally, Quantum Mechanics has opened the new mysterious outlook of particles in term of quantum entanglement. Such applications will lead to further development in the field of IT and Quantum based technologies. Photon- photon collision has resulted in the productions of many sub-atomic particles whose nature were not well explained before the existence of such high energy particle colliders. It is expected that further exploration of photon will open new Pandora's box in near future that will revolutionize the existing world.

References:

L.-C. Tu, J. Luo and G. T. Gillies, Reports on Progress in Physics **68** (1), 77 (2004).

R. Oerter, *The theory of almost everything: The standard model, the unsung triumph of modern physics*. (Penguin, 2006).

D. P. Hampshire, Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences **376** (2134), 20170447 (2018).

D. L. Pavia, G. M. Lampman, G. S. Kriz and J. A. Vyvyan, *Introduction to spectroscopy*. (Cengage learning, 2014).

M. Planck and N. Bohr, *Quantum Theory*. (Flame Tree Publishing., 2019).
Nature **607** (7917), 52-59 (2022).
A. I. Miller, *Albert Einstein's Special Theory of Relativity: emergence (1905) and early interpretation (1905-1911)*. (Springer, 1981).
K. Yagi and L. C. Stein, Classical and Quantum Gravity **33** (5), 054001 (2016).
C. Hong, W. Zou, P. Ran, K. Tanaka, M. Matzelle, W.-C. Chiu, R. Markiewicz, B. Barbiellini, C. Zheng and S. Li, Nature **617** (7961), 493-498 (2023).
S. H. Dhobi, M. J. Rangrej and S. K. Verma.
J. Schwinger, Physical Review **82** (5), 664 (1951).
A. Schmitt, P. Vallet, D. Mele, M. Rosticher, T. Taniguchi, K. Watanabe, E. Bocquillon, G. Feve, J.-M. Berroir and C. Voisin, Nature Physics, 1-6 (2023).
A. N. Volobuev, Journal of High Energy Physics, Gravitation and Cosmology **8** (4), 1110-1126 (2022).
L.-P. Yang, F. Khosravi and Z. Jacob, Physical Review Research **4** (2), 023165 (2022).
S. Saito, arXiv preprint arXiv:2303.17112 (2023).
S. J. Brodsky, Acta Physica Polonica B **37** (3), 619 (2006).
M. M. Velasco, arXiv preprint hep-ex/0111055 (2001).
R. N. Mohapatra and J. C. Pati, Physical Review D **11** (9), 2558 (1975).
G. Mennessier and T. N. Truong, Physics Letters B **177** (2), 195-196 (1986).
T. Ferbel and W. Molzon, Reviews of Modern Physics **56** (2), 181 (1984).
H. Paul, Reviews of Modern Physics **54** (4), 1061 (1982).
D. Zhang, arXiv preprint arXiv:2103.03419 (2021).
R. H. Brown and R. Q. Twiss, Nature **177** (4497), 27-29 (1956).
A. Einstein, B. Podolsky and N. Rosen, Physical review **47** (10), 777 (1935).
C. D. Cantrell and M. O. Scully, Physics Reports **43** (13), 499-508 (1978).
D. Bohm and Y. Aharonov, Physical Review **108** (4), 1070 (1957).
D. J. Griffiths and D. F. Schroeter, *Introduction to quantum mechanics*. (Cambridge university press, 2018).
S. J. Freedman and J. F. Clauser, Physical review letters **28** (14), 938 (1972).
A. Aspect, J. Dalibard and G. Roger, Physical review letters **49** (25), 1804 (1982).