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Invited Paper

Developing causal interpretations for high and low level light used in quantum sensing

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ABSTRACT

We present observational and causality arguments to underscore that a better model for light is a "hybrid photon" wave packet. At the moment of quantum transitions, the electromagnetic energy is embedded in the transient quantum, hν. But, it immediately evolves into a diffractively spreading classical, quasi-exponential, EM wave packet. This hybrid photon accommodates both quantum and classical optics. The quantum formalism has demonstrated staggering successes in modeling the micro world of atoms. The Huygens-Fresnel diffraction integral and Maxwell's wave equation are also enjoying continued successes since early 1800's. In this paper, using the model of hybrid photon, we underscore that the photoelectron counting statistics should vary depending upon the relative phases, spacing and amplitudes of the superposed wave packets (hybrid photons) as they simultaneously arrive and stimulate the quantum mechanical dipole complexes on the surface of the photo detectors.

Keywords: Hybrid Photon; Photon statistics; Poissonian statistics; Non-Interaction of Waves, or NIW; Classical Superposition Effect; Quantum Superposition Effect; Eliminate duality of light; Detecting dipoles as quantum cups.

1. INTRODUCTION

1.1. Introducing the semi-classical model and questioning utility of wave-particle duality

The prevailing dominant assumption behind the mathematical modeling of photoelectron generation with extremely low light, whether for some optical sensing, or direct imaging or, say, LIDAR imaging through homodyne system, is the same – light consists of bullet-like "indivisible energy quanta", which is swapped for the "binding energy" of quantum mechanically bound electrons in different detecting materials and release them. This bullet-model is simply an extension of Einstein's energy-balancing photoelectric equation [1]. The physical model behind the initial stimulation of the dipole holding the electron is not explicitly considered. The basic assumption remains same whether the received signal is from a thermal source or a laser; or the signal has very high or very low levels of light. At high levels of light, we rarely worry about the "photon counting statistics"; but we do at very low levels of light. We experimentally find that there are dominantly three kinds of light sources with the following three kinds of photon statistics. "Coherent" laser light generates Poissonian statistics in the detected photoelectron-current pulses. "Incoherent" thermal light generates Super-Poissonian statistics. And laser induced nonlinearly generated, like down converted, "super-coherent" light gives Sub-Poissonian statistics [2]. These observations clearly underscore the importance of the engineering development and selection of the "right" kind of light generator as the illuminating sources, when the detected signal will be necessarily very low. Prevailing quantum optics generates analysis to validate these observations, while keeping the Einsteinian model effectively intact. In this paper, we underscore the importance of using the physical model of light as a hybrid-photon-wave-packet that has a time varying envelope. Further, we argue that a detector dipole-complex fills up its "quantum-cup" out of many superposed frequency-resonant wave packet amplitudes, which is a two-step physical process. First, it experiences a *linear sum* of joint amplitude stimulation induced by *multiple* E-vector amplitudes due to the multiple passing-by wave packets. Then the detecting dipole executes the *nonlinear square modulus* operation to absorb the required amount of energy out of all the passing by wave packets to fill up its "quantum cup". In fact, this is just an explicit physical visualization of the mathematics we use. With this approach, we can begin to recognize the physical origin behind the statistical variation in the rate of photocurrent pulse generation in our time-gated detection systems due to different types of light sources. The relative phases and the amplitudes between the randomly sampled multiple stimulating wave packets are discernably different for different kinds of sources when the stream of wave packets are highly thinned out at very low levels of light. Correspondingly, the temporal rate of quantum cup filling energy exchange should also be different for different kinds of light sources. The prevailing "bullet" model of light does

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not easily lend itself as to why their temporal distribution in space will be different for different light sources. However, the phases and amplitudes of different wave packets stimulating a detector at the same temporal moment would be different for different kinds of sources. For example, the wave packets emitted by a thermal source will have both random phases and random temporal spacing between them. In contrast, for a laser source, due to extremely fast-stimulated emission process, the in-phase wave packets will be necessarily "bunched" as the stimulated emission process continues from the beginning of the cavity to the output mirror. There will many such "bunched" coherent wave groups with random phase relations between them as they originate from independent spontaneous emissions. One can appreciate this from Fig.1 where we are showing a random set of "photon wave packets" and "photon bullets" as a case for low light snapshot.

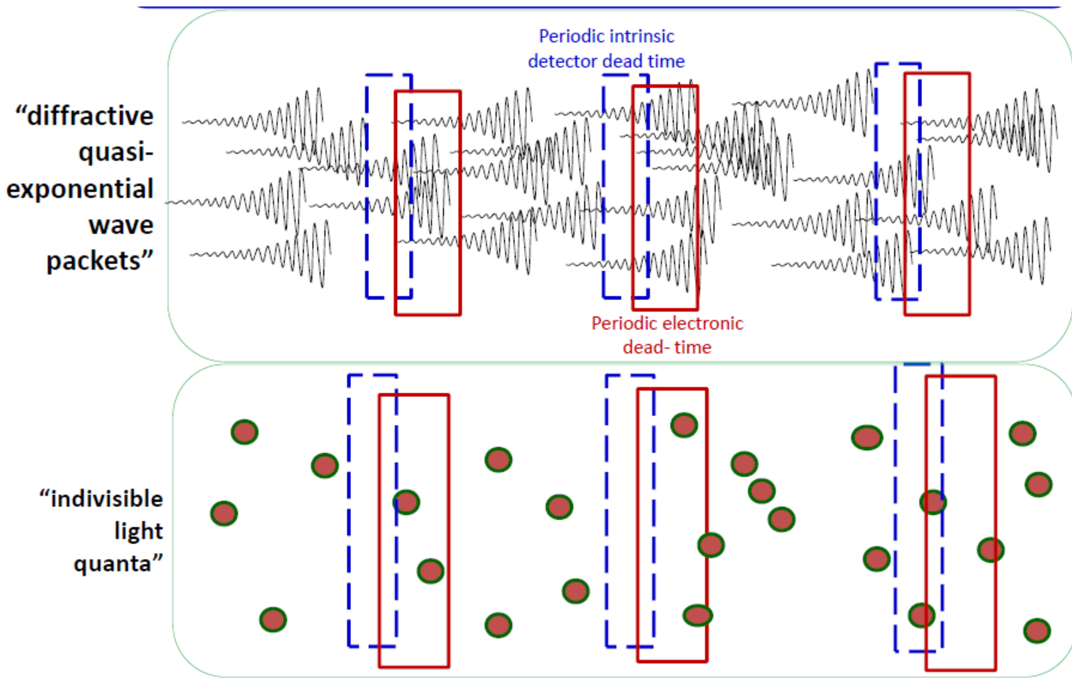


Figure 1. The above sketches, for a low light level case, represent an attempt to explore visually the origin of variations in the detected photocurrent-pulse statistics for incoherent thermal source, coherent laser source and super-coherent (entangled) nonlinear light generating source. Characteristic random variations in the phases and the amplitudes between simultaneously stimulating wave packets appears to be a more plausible physical model than random energetic "bullet' model. Readers should note that the emission of photoelectron happens through a two-step process – (i) linear amplitude simulations of the detecting dipole complexes by multiple frequency-resonant wave packets; followed by (ii) the nonlinear quadratic energy transfer step.

Our visualization of the light-matter interaction model with hybrid photon-wave-packet clearly implies that we definitely do not count indivisible "light quanta" through photodetectors. We count the rate of highly amplified current pulses generated out of the original photoelectron released while the detector interacts with multiple wave packets. Let us note that quantum formalism does not require that only quantum donors with the right amount of energy can trigger all quantum transitions. Our ancestors discovered the process of generating fire by striking two stones against each other. The generation of sparks and heat takes place through a cascade of quantum jumps of free electrons out of air on the levels of ionized silica molecules. The original quantum mechanical ionization energy is provided by the mechanical energy of fast moving hands. Our ancestors did not recognize that they had invented a fire-generating technique, which was inherently a quantum mechanical process. They had not yet invented mathematics and algebra; probably not even grammar driven language!

The key objective of this paper is to explore a physical model behind the photo-current-pulse statistics beyond the temporal distribution of "photon bullets". We intend to develop the necessary logical arguments, through simple logic, algebra and basic experiments, which naturally lead to the model of hybrid-photon-wave-packet, as is depicted in the upper sketch of Fig.1. This is in contrast to the prevailing "bullet" model, or "wave-particle duality". The latter concept effectively suppresses our desire to enquire deeper into the nature of waves and particles without providing any better and deeper knowledge of our micro world.

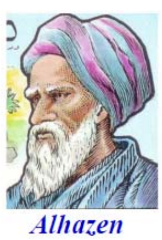
1.2. Flow of the paper

To justify the introduction of semi-classical approach of visualizing light as hybrid-photon wave packet, we need to explore the intrinsic nature of light and visualize the light-matter interaction processes. *In section 2*, we first underscore the physical processes behind light detection from the angle of light-matter interaction processes. This requires recognizing Non-Interaction of Waves (NIW), which can be expressed, as "light does not see light". However, the detectors do "see light" through mutual physical interaction or light-matter interaction, which must be modeled in equation by explicitly introducing the light-matter *interaction parameter*, the dipolar polarizability $\chi(\nu)$ of first and higher order, depending upon the conditions. We summarize this in the *section 3* and differentiate between observable (i) classical Superposition Effect (SE) due to classical energy re-direction by a beam splitter, and (ii) quantum mechanical SE where the energy of the superposed beam amplitudes can be absorbed by the quantum dipole only when the resultant E-vector stimulation is non-zero. Neither classical SE, nor quantum mechanical SE is due to *non-arrival* of photon quanta. They are always local and causal effects due to classical or quantum mechanical response characteristics of materials due to the presence of multiple wave amplitudes. In *section 4* we introduce the hybrid photon model using more rigorous arguments to support the pictorial upper sketch of Fig.1. In *section 5* we combine the hybrid photon model with the necessity of using the polarizability factor and model the upper sketch of Fig.1. *Section 6* summarizes the key conclusions of the paper.

2. NON-INTERACTION OF LIGHT WAVES (NIW)

2.1. Light does not "see" light

It is of critical importance to understand the fundamental nature of light and its interaction with itself and with materials before we can model the actual physically reasons behind varying statistics of photocurrent pulses released by different kinds of light sources. Light propagates as linearly oscillating harmonic wave amplitudes, not as intensity "bullets". At present, we do not explicitly acknowledge the mathematical property of linear wave amplitudes propagate through each other without re-organizing their energy distributions, which require a quadratic interaction process with materials. We call this, "Non-Interaction of Waves" (NIW). NIW is built into Huygens-Fresnel Diffraction integral [3] and Maxwell's wave equation [4]. These two equations are still the "staples" of optical scientists and engineers.



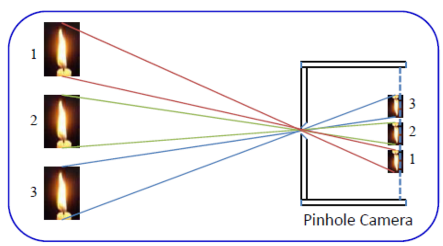


Figure 2. Light beams freely pass through each other! Unperturbed, inverted images are formed, even though different candle light are crossing through each other at the pinhole. [5]

There are no well-defined equation to propagate "indivisible light quanta" to design optical instruments and systems and model bulk light-matter interaction processes, including Nanophotonics. Whereas the necessity of quantum formalism become essential when we deal with emissions and absorptions of light through transitions between quantum levels or bands.

Figure 2 presents an experimental imaging of a set of candles by Alhazen using a pinhole camera, about a thousand years ago. Alhazen noted in his book about his experiment that light beams pass through each other unperturbed [5]. It was around 1080, or earlier! Then, in his 1690 book, Huygens explicitly mentioned [6] that his secondary wavelets, which is behind the diffractive propagation of light, keep evolving through each other unperturbed. Thus, NIW was experimentally and conceptually recognized long time ago.

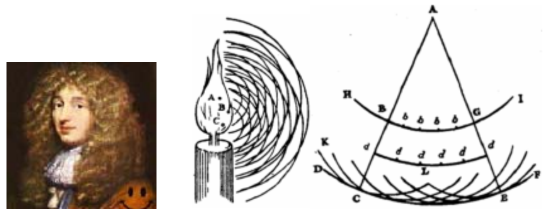


Figure 3. Huygens principle of secondary wavelets states that every point on the propagating wave front generates a secondary wavelet. These secondary wavelets keeps expanding and propagating as spherical wavelets through each other unperturbed, without any mutual interaction to re-organize mutual energy re-distribution [6].

Fresnel has captured this NIW in 1817 by formulating the equation for light wave propagation, now known as Huygens-Fresnel diffraction integral. All the secondary wavelets out of the aperture amplitude function $U(P_1)$ keep evolving to become the resultant *complex amplitude* $E(P_0)$ as the sum of the evolved spherical wavelets, $\exp(ikr_{01})/r_{01}$, at any forward plane [3] where ever the observer decides to insert his square-law detector. Note that Eq.1, representing the superposition principle for diffracted secondary wavelets, does not represent observable diffracted intensity pattern.

$$E(P_0) = \frac{-i}{\lambda}\iint_{\Sigma} U(P_1)\frac{\exp(ikr_{01})}{r_{01}}\cos\theta \, ds \tag{1}$$

Maxwell's wave equation of 1876 mathematically established that EM waves are *linear excitations* of the universal background field ("ether" of his time) with the electric and magnetic tensions, ε_0 and μ_0, always propagating with a velocity $c = (1/\varepsilon_0\mu_0)^{1/2}$ in "free space" [4]. *Linear waves* do not interact with each other to re-organize each other's energy in the linear domain and in the absence of some interacting medium. Planck has also underscored this point in his 1914 book [7] on how he derived the equation for blackbody radiation while explaining how the radiation inside the blackbody cavity become homogeneous by diffractive spreading through each other, unperturbed.

2.2. Only detectors "see" light. Necessity of the Interaction Process Mapping Epistemology (IPM-E).

Huygens was the first person who presented a visual model of secondary wavelets behind the perpetual propagation of waves, once generated in a parent tension field through perturbation by some appropriate stimulating external energy source. This visual model is valid for all forms of propagating linear waves. Sound waves leverage the pressure tension field of air. Water waves leverage surface tension field on the water surface. Mechanical string waves (Guitar, Piano, etc.) leverage the mechanical tension on some material strings. Once the parent tension field is influenced to generate a perturbation in its otherwise quiescent state and within its linear restoration capacity (Young's modulus) of the tension field, every point on the triggered perturbation generates its own harmonically oscillating secondary wavelets. The waves can propagate as far as the medium has the same and continuous physical tension field. Maxwell's model of EM waves is very similar. As mentioned already, EM waves are oscillations of a space-filling electromagnetic tension field with the electric and magnetic tensions, ε_0 and μ_0, as already mentioned above. {This tension field is related to the concept of old "ether". The modern version has been developed as a Complex Tension Field. [8]}

The only way to observe (register) the diffraction pattern of Eq.1 is to insert a detector array in any one of the forward plane from the aperture. Diffracted EM wave amplitudes will then collectively stimulate the assembly of detecting dipole molecules. If the molecules are frequency-resonant to the incident waves, they will be stimulated. The stimulated dipoles will then execute the square modulus operation to absorb energy out of all the fields.

We have not quite figured out how to visualize directly the physical interaction processes in nature. As mentioned above, the *complex amplitudes* of the evolving diffraction pattern in Eq.1 is neither directly detectable, nor physically observable. The acceptability of Eq.1, or any theoretical expression in science, depends upon quantitative validation through reproducible detection (measurement) process. This is what we call the evidence-based science. This approach of "evidence-based science" has been proven the best way to explore nature. Our current advancements in science and technology represent a resounding validation of this approach. We can re-phrase this approach as Measurable Data Modeling Epistemology (MDM-E). However, without our ability to visualize the actual physical details of the interaction processes that generate the data, we will always remain vulnerable to multiple possible interpretations of the same measurable data. We are all aware that diverse debates on the interpretations of the formalism of Quantum Mechanics (QM) is continuing for almost a century. "Single photon interference" and "wave-particle duality" are two specific examples, which we are attempting to resolve in this paper. Since direct visualization is still beyond our technological capacity, we are proposing to utilize our powerful and innate capacity of imagination guided by mathematical logic and the faithful assumption that nature is always causal. Let us call this thinking approach as the Interaction Process mapping Epistemology, or IPM-E. This is a logically valid approach based on the continued successes of our mathematical theories, which are always framed by equating observable *effect* with the hypothesized *cause*. Therefore, our proposal is to apply consistently IPM-E over and above the currently successful MDM-E.

We now apply this IPM-E to the HF diffraction Eq.1 representing evolution of un-observable wave amplitudes. We know that at the desired plane of observation, we must insert a detector array that is frequency-resonant to the diffracted waves. Then the dipole complexes of the detector will respond to the electric vector of the incident wave. This dipolar *amplitude* stimulation should be quantified as the qualified product $\chi(\nu)U(P_1)$. The real physics of the classical light-matter interaction process is embedded in the parameter $\chi(\nu)$. This interaction parameter guides the energy transfer process from the EM field to the detector as a square modulus step, standard in our math. Then the observable intensity of the diffraction pattern $D_{r_{01}}$ should have the expression as below.

$$D_{r_{01}} = \left|E\right|^2 = \left|\frac{-i}{\lambda}\iint_{\Sigma}\chi(\nu)U(P_1)\frac{\exp(ikr_{01})}{r_{01}}\cos\theta\, ds\right|^2 \tag{2}$$

Application of IPM-E to the above detectable (observable) generic diffraction integral implies that all registered diffraction effects are *local*, in the sense that the pattern can emerge as a local effect on a detector array only when placed in one of the forward diffraction-field plane [9,10]. This logic remains applicable when the aperture is set specifically as a double-slit. It is irrelevant to raise the debate like which slit the "photon" passed through. "Dark fringes" appear in those locations where the sum total E-vector stimulation is zero. Unstimulated detecting dipoles cannot absorb energy out of the EM waves. We should underscore that NIW is a generic property of all waves. An "indivisible light quanta" cannot execute self-destructive or self-regenerative operations at specific locations to create dark or bright fringes by themselves. Physical interaction processes are at the root of generating observable data in our instruments (detectors). The role of physics is to model these physical interaction processes, which are behind all registered data.

Attentive readers may note that because of the NIW property of waves, Fourier monochromatic modes cannot sum themselves in the absence of suitable interacting material. Further, the Fourier modes are not physical signals, as they exist over infinite space and infinite time. These have profound significance in all branches of physics wherever we use Fourier transform! [10].

3. NECESSITY OF TWO OR MORE EM WAVES TO GENERATE PHYSICAL SUPERPOSITION EFFECT. PHYSICAL REALITY OF THE TWO SIGNALS

To appreciate that the "bullet photon" model cannot fully explain the registered photocurrent statistics generated by two beam interferometers, we present here experiments that establishes the necessity of the simultaneous physical presence of the signals, just as we frame our superposition mathematics.

3.1. Two beam classical Superposition Effect (SE). Physical reality of each signal. Poynting vectors collinear

Here we present a simple two-beam Mach-Zehnder (MZ) interferometer experiment (Fig.4) to demonstrate that superposition effect could be completely classical without the need of invoking any quantum mechanical model [11]. A collimated He-Ne beam illuminates the MZ, which is aligned such that the Poynting vectors for the two pairs of outputs out of the beam combiner (BC) are perfectly collinear. One can obtain this by carefully by observing both the two output intensity fields blinking completely dark and bright while the mirror M1 is scanned very slowly. When the outputs are registered by detectors D1 and D2 and displayed on a dual beam scope, the two traces will show that when D1 receives all the energy of both incident beams on the BC from the opposite sides, D2 receives none, and vice versa. The two input beams must be set to equal intensity. The physical cause is purely classical. This has nothing to do with the concept of light as bullet-like "indivisible photons"; that the whole photon goes one way or the other. The physical cause is due to the π -phase shift in "external reflection", derived in most basic optics texts [12]. Fresnel derived this mathematically during early1800. Assume that the relative physical path difference between the two MZ arms has been set to zero. Then the upcoming bottom beam, from M2 to BC, on reflection from BC attempts to go to the detector D1 with a π -phase shift. Unfortunately, the right-going beam, from M2 to BC, on transmission to D1 has zero phase shift. Under these opposing phase conditions, the collective dipolar molecules of the outer layer of BC, fails to allow the radiation to go towards D1. This is a pure classical destructive "interference". Under this situation, both the beams (due to transmission and internal reflection) going towards D2, are in relative zero-phase delay. The boundary molecules of BC is now directing the energy due to both the beams towards the D2-port. This is a case of pure classical constructive interference.

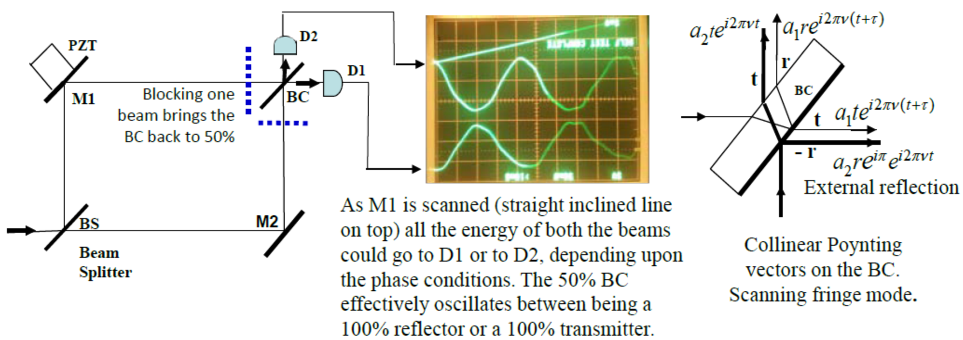


Figure 4. Pure classical superposition effect that can be demonstrated using a very simple two-beam Mach-Zehnder (MZ) interferometer. The MZ must be carefully aligned such that the pair of Poynting vectors belonging to each of the two pairs of output beams (right-D1 and up-D2) must be perfectly collinear to each other. Then, as the mirror M1 is scanned, all the energy belonging to both the beams could be directed to one or the other beam. This is a pure classical superposition effect engendered by the macro and classical beam combiner (BC). [11]

This experiment was carried out with ample beam energy (~ micro Watt). Had we reduced the beam energy and used a pair of photon counters at D1 and D2, set to sample the incident light one thousand time-windows per complete scanning cycle of the mirrorM1, we believe, we would have been able to plot very similar curves as shown in in the middle photo of Fig.4. However, at very photocurrent pulse counting rates, the plots would be noisier because of statistical variations in the relative phase differences between the overlapping wave packets (Fig.1, top sketch). Let us note that we have fundamental disagreement with multitudes of papers like Hong-Ou-Mandel (HOM), interferometer [13, 14], who claim that photon counting statistics prove photons as indivisible bullets when they arrive at a beam splitter or at a quantum detector. Under the condition of the collinearity of the Poynting vectors of both the output pair of beams, the classical energy *re-direction* is generated by the BC due to simultaneous and joint stimulation of the boundary layer dipole complexes from the two opposite sides. *The simultaneous presence of both the beams is of critical importance to generate this superposition effect.* We have verified this by simply blocking (dashed lines in Fig.4) one or the other beam traveling towards the BC while keeping M1 scanning. The output to D1 and D2 became steady and received standard 50% of the energy of the single incident beam. The BC now behaves as a standard 50% beam splitter as has been designed to function. When both the beams are present and M1 is scanning, the reflective and transmitive properties of the BC becomes *active and dynamic* under the simultaneous influence of the two beams. It's R and T values actively oscillate between 100% and 0% towards any one direction, and vice versa. When the Poynting vectors are collinear, classical E&M predicts the result automatically. Quantum formalism, using quantized photons, cannot not grasp this physical interaction process of a 50% beam splitter. Alternatively, at least, people have been missing the right quantum mathematical approach to predict the observed classical results we have presented here. The so-called "HOM dip" is a pure classical effect, indirectly predicted by Fresnel during early 1800 when he derived the π -phase shift for external reflection (see below). The reader may notice similar complementary dips in the middle scope-traces in Fig.4. There are two dips in the upper trace and one dip in the lower trace, representing energy conservation maintained by the beam splitter under the simultaneous influence of two phase-steady but out-of-phase beams from the opposite sides.

Let us now construct the necessary math to represent the amplitude superposition and the corresponding energy re-direction [10, 15]. We incorporate the linear polarizability parameter $\chi(\nu)$ to represent the bulk dipolar stimulation of the boundary layer of the beam splitter. The active polarizability of the boundary layer induced by the electric vector of EM waves is at the root of Brewster's Law, Malus' law and partial polarization of "un-polarized" light in reflection. In all these processes, the direction of propagation of EM waves, and hence that of the energy, are altered. This is also true for anisotropic crystals. EM waves always stimulate the material dipoles to oscillate along the direction of its E-vector while the wave propagates through any medium. The material dipole molecules in a boundary layer are constrained to oscillate *preferentially* along the surface as if they are embedded in an anisotropic medium.

Let us assume $A_{Rt.}(t,\tau)$ represents the sum of the two right-going amplitudes out of the BC and $A_{Up}(t,\tau)$ represents the two up-going amplitudes. In classical EM, values for $\chi(\nu)$ for a beam splitter is simply given by t and r, the amplitude transmittance and reflectance, respectively. However, for external reflection it assumes the structure $\chi(\nu)=re^{i\pi}$ to accommodate the π -phase shift. (This is also a classical boundary value problem.) In most cases, t and r are very slowly varying function of the frequency and we ignore using (ν) in parenthesis with t and r. This assumption would not be valid when we use beam splitters, or mirrors, with engineered narrow-band multilayer coatings. With the assumption of energy conservation that $T+R=1$ and the boundary layer of the BC is lossless (never strictly correct), we can now write the explicit expressions for $A_{Rt.}(t,\tau)$ and $A_{Up}(t,\tau)$ as:

$$\begin{aligned} A_{Rt.}(t,\tau) &\equiv \chi(\nu)E(t,\tau)=\chi(\nu)E_1(t+\tau)+\chi(\nu)E_2(t) \\ &= a_1te^{i2\pi\nu(t+\tau)}+a_2re^{i\pi}e^{i2\pi\nu t}=a_1te^{i2\pi\nu(t+\tau)}-a_2re^{i2\pi\nu t} \end{aligned} \quad (3)$$

$$A_{Up}(t,\tau)=a_1re^{i2\pi\nu(t+\tau)}+a_2te^{i2\pi\nu t} \quad (4)$$

The corresponding intensities are:

$$\begin{aligned} I_{Rt.}(\tau) &\equiv \left|A_{Rt.}(t,\tau)\right|^2=[(a_1^2t^2+a_2^2r^2)-2a_1a_2tr\cos 2\pi\nu\tau] \\ &= a^2[1-\cos 2\pi\nu\tau];\ \text{only if } r^2=t^2=0.5 \text{ and } a_1^2=a_2^2=a^2 \end{aligned} \quad (5)$$

$$\begin{aligned} I_{Up.}(\tau) &\equiv \left|A_{Up}(t,\tau)\right|^2=[(a_1^2r^2+a_2^2t^2)+2a_1a_2tr\cos 2\pi\nu\tau] \\ &= a^2[1+\cos 2\pi\nu\tau];\ \text{only if } r^2=t^2=0.5 \text{ and } a_1^2=a_2^2=a^2 \end{aligned} \quad (6)$$

Summing the first lines of the above two equation we can help us appreciate the generic law of conservation of energy for all values of, $\cos 2\pi\nu\tau$ as τ is scanned even when $a_1 \neq a_2$. The sum total energy of the two ports will always be $(a_1^2+a_2^2)$, even when part or all of this energy is being re-directed towards one or the other port. However, a careful analysis will show that the visibility of the fringes will be less than unity, under this condition of unequal beam energy incident on the BC. Here is another important logical point to appreciate that if we maintain honest trust in our "working" math, then the superposition effect is always due to more than one superposed amplitude signals, a_1 and a_2. It can never be due to a single photon, even if indivisible light quanta existed. The energy of a single photon is around $\sim 10^{-18}$ erg. Our current technological capability of direct measurement of the energy of a light beam is several orders of magnitude lower than this. Thus, strictly speaking, all MZ interferometry is carried out under the condition of $a_1 \neq a_2$. This is an especially important point to consider when one is claiming to carry out interferometry with only one photon at a time within the interferometer. We cannot count "photon". We count highly amplified current pulses out of our amplifying train of electronic instruments containing probably hundreds of millions of electrons, even though a single originally released electron has triggered it. We also know that photon-counting statistics tells us that when there are, say, on average100 photocurrent pulses within a preset time window, this count could increase to as high as 200 current pulses or more within the same allowed time slot opened at another time.

3.2. Two beam "quantum" Superposition Effect. Physical reality of each signal. Poynting vectors non-collinear

This section brings up the generic case of MZ interferometry when the Poynting vectors of the two pairs of output beams out of the final beam combiner (BC) are not collinear. As shown in Fig.5, the output beam pairs for the MZ are deliberately aligned to be non-collinear. Under this condition, the effective values of T and R remains unchanged as designed. For an ideal lossless 50% beam splitter, T=R=0.5. Unlike for the previous case (Fig.4), scanning of the mirror M1 would not re-direct all the energy of the two incident beams into one or the other direction. Half the energy of each of the two incident beams is directed through the outputs. Superpostion fringes will be visible only as spatial fringes when a detector array is placed in either of the two output ports. However, there will be a relative spatial shift in the fringe-position between the two sets of fringes due to the realtive pi-phase shift for the direction of external reflection. The mathematical expressions are essentially identical to those already shown in Eq.3 to 6. However, the relative path (or phase) variation is not induced by the scanning of M1, but due to position change along the X-axis, now given by $\tau = 2x\sin\theta / c$. The suitable sketch for the derivation of this relative spatial phase delay along the X-axis is shown as a wave front sketch in the middle of Fig.5. Now, scanning the mirror M1 will only shift the spatial fringes laterally. Unlike in the case of Poynting vector collinearity (in the last section), there will be no energy re-direction from one beam to the other. The total integrated energy in the overall wavefront of both the ports remain constant.

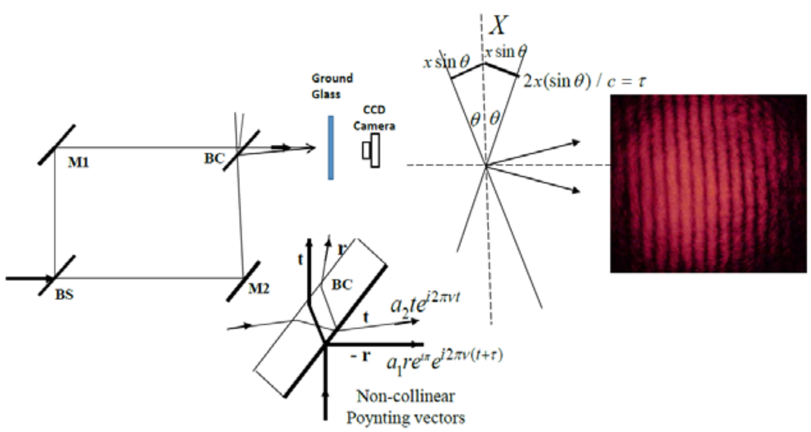


Figure 5. A Mach-Zehnder interferoemeter where the Poynting vectors for the two pairs of output beams are deliberately aligned to be non-collinear. Under this condition, the effective values of T and R remains unchanged and as designed. For an ideal lossless 50% beam splitter, T=R=0.5. Unlike for the previous case (Fig.4), scanning of the mirrorM1 would not re-direct all the energy of the two incident beams into one or the other direction. Superpostion fringes will be visible only as spatial fringes when a detector array is placed in either of the two ports. However, there will be a spatial fring-position shift between the two sets of fringes due to the realtive pi-phase shift for the direction of external reflection.

We can display these spatially varying superposition fringes by placing a CCD camera in either one of the two ports. One can "claim" that this is a quantum mechanical process because CCD function is quantum mechanical. However, even these fringes can be made observable by using classical physics by placing a scattering plate in either of the output ports. When the silica lumps in a ground glass is smaller than the incident wavelength of the light, each scattering element responds to the local resultant electric vector, very much like a quantum dipole complex. Wherever a silica lump is experiencing zero effective E-vector, they remain un-stimulated and they cannot scatter any light, effectively displaying the location as belonging to a dark fringe. Optical engineers have been using such fringes starting 1800's for various precision measurements [16].

4. HYBRID PHOTON MODEL TO BRIDGE CLASSICAL AND QUANTUM OPTICS. WAVE-PARTICLE DUALITY UNNECESSARY

Energy re-direction by a 50% beam splitter and the observability of superposition fringes by scatter plate clearly demonstrates that light does not have to consist of "indivisible light quanta". Then, it becomes useful to develop an improved model of light that accommodates both the successes of classical optics (HF diffraction integral and Maxwell's wave equation) and quantum optics for all cases of interaction of light with atoms and molecules. Einstein's photoelectric equation and reset it in the semi-classical model. Actually, Lamb and Scully, and many others have already done this [17, 18]. E. T. Jaynes has also been an early proponent of semi-classical approach light matter interactions [19]. Here we develop a complementary hybrid photon model that would lead to a better physical model for the derivation of photocurrent pulse statistics that would vary with the source characteristics.

4.1. Accommodating quantized emission

Quantum formalism has the validated demand that the energy content in a "photon" emitted due to a quantum downward transition must be $\Delta E_{mn} = h\nu_{mn}$. However, Maxwell's wave equation demands that the emitted photon diffractively photon wave propagate as a classical wave with a velocity $c = (1/\varepsilon_0\mu_0)^{1/2}$, while following Huygens-Fresnel diffraction integral. The velocity c is not imparted by the light emitter. It is the property of the medium through which it propagates. Measurement of the spectral linewidth of spontaneous emissions always appears to be of Lorentzian shape, which is, mathematically a Fourier transform of an exponential pulse. Modeling classical spectrometer by propagating an actual pulse generates this Fourier transform character [10]. These observations lead us to propose that photons are definitely a quantized packet at the moment of emission. However, it immediately evolves as a quasi-exponential classical wave packet.

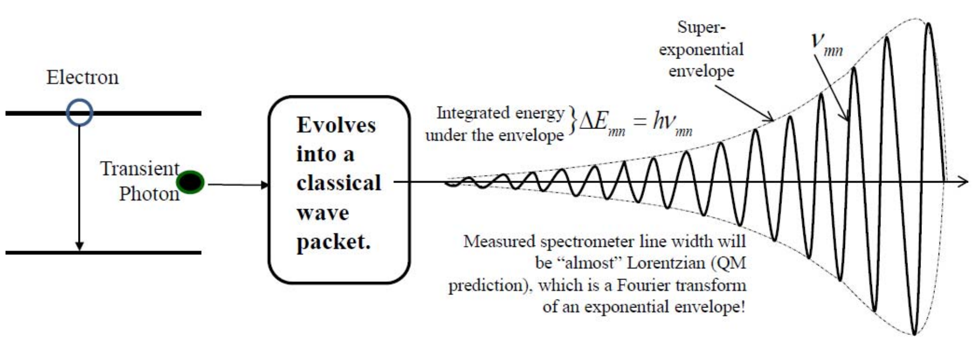


Figure 6. Pictorial presentation of the emergence of a hybrid photon. It is an energy quantum, as per QM formalism, at the moment of emission. However, it immediately evolves into a classical wave packet, still carrying the total energy as predicted by QM. The carrier frequency is also what is defined by QM. The envelope is quasi-exponential. This is to give the wave packet a causal envelope whose Fourier transform is Lorentzian, matching with the measured line width of spontaneous emissions [10, 20, 21].

4.2. Accommodating quantized absorption out of multiple classical wave packets

The demand of quantum mechanics is that a quantized entity absorbs a mathematically defined quantity of energy $\Delta E_{mn} = h\nu_{mn}$. However, a diffractively spread-out wave packet, usually orders of magnitude wider than an Angstrom-wide cross section of atoms, cannot provide $h\nu_{mn}$ quantity of energy within an atomic volume any more (exclude micro-cavity QED). To resolve this problem, we propose that all stimulate-able quantum entities are capable of absorbing energy out of multiple "thinned out" wave packets passing by it. It is also well known that the effective cross section of a resonetically stimulated dipole projects a wider cross-section [22] as a "quantum cup" [10]. This is depicted in the Fig.7. The readers should now be able to appreciate the rationale behind comparing multiple "photon wave packets" against multiple "bullet photons" in Fig.1 stimulating a photon counter at low-light level.

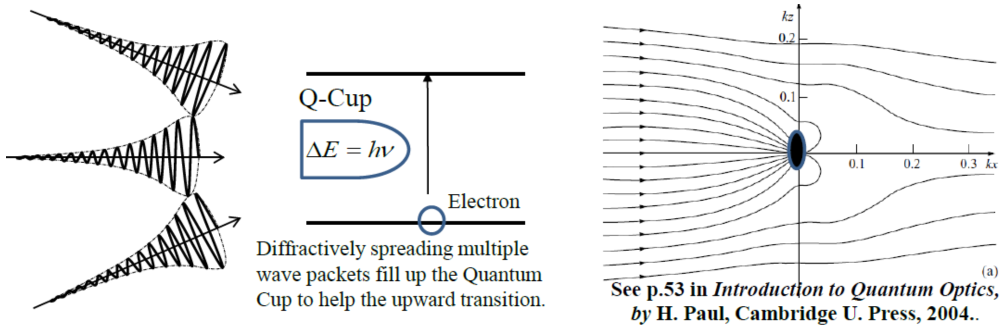


Figure 7. A single diffractively spreading out wave packet cannot deliver its full "quantum" of energy within an atomic volume of a cubic Angstrom. Therefore, we model atoms as large quantum cups when stimulated by frequency-resonant wave packets. Further, it is capable of accepting the necessary quantum of energy out of many classical wave packets [x].

5. INCORPORATING DIPOLAR STIMULATIONS OF DETECTING MOLECULES

Let us recall Einstein's original energy-balancing photoelectric equation [1]:

$$h\nu = \phi_{work\ fn.} + (1/2)mv_{el.}^2 \tag{7}$$

It represents the "bullet" model, a "photon bullet" ejecting out an "electron bullet'. It does not represent (incorporate) the Interaction Process Mapping Epistemology (IPM-E). At a minimum, Eq.7 should be reconstructed to represent the real experimental data as an ensemble average:

$$\left\langle h\nu_q \right\rangle_{Many\ QM\ Cups} = \left\langle \phi_{work\ fn.} + (1/2)mv_{el.}^2 \right\rangle \tag{8}$$

To incorporate the light-matter interaction process, we need to bring in the E-vector induced dipolar polarizability of detector's molecular complexes. Let us use the same symbol $\chi_Q(\nu)$ for polarizability as before. However, this time $\chi_Q(\nu)$ represents the quantum mechanical stimulation of the detector's polarizability, including the transition probability, from band to band, or level to level, as the case may be. The energy transfer equation, representing photocurrent-pulses, should be modeled as two-step process, first, E-vector-dipolar amplitude stimulation and then the square modulus step to collect the quantum-cupful of energy transfer out of the simultaneously stimulating multiple wave packets. It should look like Eq.9, where the subscript "q" denotes the presence of multiple wave packets with multiple carrier frequencies.

$$\left\langle |\psi_{reslt.}|^2 \right\rangle = \left\langle \left| \sum_q \chi_Q(\nu_q) E(t,\nu_q) \right|^2 \right\rangle \tag{9}$$

The right hand sides of Eq.8 and 9 are equivalent to each other, as far as reconciling with just the registered data is concerned. However, to incorporate our key point of detector's amplitude stimulation by a train of random time-finite wave packets, rather than "bullets", we need to introduce explicitly the amplitude envelope of the photon wave packets with random time delays $n\tau$ between individual wave packets, besides random phases (Fig.6 & 7) for thermal light.

$$E(t,\nu_q) = \sum_{n,q} a_q(t-n\tau)\ \exp[i2\pi\nu_q(t-n\tau) + \phi_q \tag{10}$$

However, for a single frequency coherent laser light, Eq.10 will be a lot more complex since they will constitute bunched groups of wave packets where ϕ_q would have the same value; but they would be different for different bunched groups.

Eq.9 and 10 represents the pictorial model presented in the top sketch of Fig.1; the “bullet” model of the bottom sketch of Fig.1 cannot fully explain the physical origin of statistical variations in the source-dependent photocurrent pulses.

Numerical computations of Eq.10 for different kinds of lights will now have multiple physical parameters and will help develop proper causal physical explanations behind the observed statistically varying data. Such computations will be presented in a future paper.

6. SUMMARY

(i) We have presented a model of light as classical wave packets triggered by a quantized energy packet released by atoms and molecules, whether spontaneous or stimulated emission. This model provides multiple variable physical parameters to explain better the observed statistical variations in the photocurrent pulse statistics compared to the “bullet” model of light. Compare sketches in Fig.1

(ii) Quantum excitation can be triggered by any kinds of sources of energy, classical, or quantum. Light wave induced release of electrons from atoms, molecules and molecular complexes is clearly a quantum phenomenon because all electrons are bound quantum mechanically in their host physical entities. However, this process does not validate that light consists of bullet-like indivisible quanta. Quantum energy transfer does not require another resonant quantum entity. In fact, Boltzmann’s classical statistical expression for thermal population density is equally useful in quantum mechanics, validating that thermal collisions do excite quantum levels.

(ii) One can register superposition effects due to classical EM waves by using either classical physical process or by quantum physical process. The beam splitter in the MZ interferometer of Fig.4 executes the re-direction of energy out of both the incident beams depending upon the relative phase of the two beams stimulating the boundary layers from the opposite sides. The beam Poynting vectors must be collinear. When the Poynting vectors are non-collinear, as in Fig.5, the superposition effect becomes manifest as spatial fringes. This can be observe either by using a quantum mechanical device like a CCD camera, or by a classical device like a ground glass. The beam combiner is now a passive beam splitter. Observation of superposition effect does not require a bullet-like model for light.

(iii) Experiments shown in Fig.4 and 5 clearly establishes that the physical causes behind the results observed by Hong-Ou-Mandel interferometers are classical superposition effects when the beams are properly aligned for Poynting vector collinearity.

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