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Contrasting quantum sensing light source properties, which generate different photocurrent pulse-statistics

C. Roychoudhuri*[a], G. Fernando[b], N. Tirfessa[c] and N. Prasad[d]
[a,b]Physics Department, University of Connecticut, Storrs, CT 06269, USA
[c]Department of Physical Sciences, Manchester Comm. College, Manchester, CT, USA
[d]N. Prasad, NASA Langley Research Center, MS 468, Hampton, VA 23681
*Chandra.Roychoudhuri@uconn.edu [contact author]

Abstract

We are developing a semi-classical model to explain the physical processes behind the origin of the statistical variations in the photoelectron current pulses that we register for different kinds of light. They are: super-Poissonian thermal light, Poissonian laser light and sub-Poissonian nonlinearly generated light. Einstein's photoelectron equation is an energy balancing equation. It does not incorporate the E-vector stimulation process before the quantum mechanically bound electrons can be released, which constitutes a key objective of physics. To introduce physics, we postulate that the photons are hybrid entities. They are discrete packets of energy $h\nu_{mn}$ at the moment of emission. Then they immediately evolve into spatially spreading diffractive wave packets to accommodate Huygens-Fresnel principle. HF principle has been behind the sustained progress in classical optics and photonics engineering. Thus a spatially spread out single wave-packet cannot any more deliver the necessary quantum cupful of energy $h\nu_{mn}$ to Angstrom-size detecting atoms. We need simultaneous stimulation of the same quantum entity by multiple wave packets. This model of physical interaction process naturally brings into play the significance of the degree of mutual coherence between different photon wave packets, along with their time varying amplitudes that are simultaneously stimulating the detecting quantum entities during any time-interval selected for the detection system. The *superposition effects* on the detector due to these phase and amplitude fluctuations are the physics-reasons behind the generation of different statistical variations in the photoelectron counts due to different kinds of sources even though the original photons are released randomly by all quantum sources.

Keywords: Non-Interaction of Waves, or NIW; Hybrid Photon; Detectors as Quantum Cups; Eliminate duality of light; Quasi-Exponential photon wave packet; Statistical phase variation between wave packets in spontaneous emissions; Statistical phase variation between wave packets in a stimulated emission source; Statistical phase variation between wave packets in a stimulated emission source.

1. INTRODUCTION

This paper is a modest attempt to trigger new discussions as to whether we can go beyond "wave-particle duality" (WPD) and encourage new paths of thinking towards developing deeper physical models behind the emergence of electromagnetic waves out of atomic and radio oscillators, which move perpetually with a fixed velocity in free space; and particles, which must be nudged by some force to move. The debate around WPD started during late 1600's by Newton and Huygens. However, they were in agreement that the debate arose because neither of them could really explain the emergence of perpetually moving light waves. In our modern times, in spite of the fact that both the theories behind classical wave optics and quantum mechanics are immensely successful, we still have not really succeeded in modeling in details the physical processes behind the emergence of EM waves and particles. *Our successful theories can only predict the measurable data; not the physical processes that give rise to the measurable data*. The theories are still failing to give us recipes to visualize the physical causes behind the emergence of distinct but diverse properties during diverse light-matter interactions. Assigning the characteristics of "duality" to light and particles has not given us any significantly deeper understanding of the nature of waves and particles. Therefore, we must learn to develop deeper enquiring questions, which will guide us to develop the next generations of deeper level theories. Observed or perceived

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data are generated by our engineered sensors or bodily sensors. We are not observers. Our human minds are interpreters only. With our genetic diversity, we are bound to make different interpretations of the same data, even when they are re-producible.

Does the released quantum packet of energy $h\nu_{mn}$ keep traveling as a bullet photon? Or, does it quickly evolve into a diffractively propagating classical wave packet obeying classical electromagnetism? Our belief in WPD does not really give us a causal, scientific answer. Therefore, further enquiry is a rational scientific approach.

Specifically, consider the prevailing model of bullet photon. A bullet-photon individually knocks out one quantum mechanically bound electron at a time. Implication is that the electron release in not influenced by the presence of other photons. Does that imply that, during individual photoelectric-current-pulse counting, the presence of other photons are irrelevant? The superposition principle is irrelevant to the detector? Here, we propose to develop Einstein's photoelectric equation starting with the superposition principle as applied directly on the detector, utilizing the semi-classical model and explore the physical processes behind the emergence photo-current-pulse statics within the detection electronics.

Einstein had published his paper [1] in 1905 on the photoelectric phenomenon to explain the experimental curves obtained by various people plotting the kinetic energy of photo-electrons against the optical frequency of the incident light. Below a threshold frequency, no electrons are released. Einstein's brilliance was that he recognized some buried "quantum-ness" behind the photoelectron emission curve. Einstein chose to assign the quantum-ness to EM radiation rather than to electrons. We now know that all electrons in materials are bound quantum mechanically with binding energies $h\nu_{mn}$, where m & n represents sharp levels or wide bands, as the case may be. We should note that Einstein's work was done some 20 years before the formalism of quantum mechanics was developed by Heisenberg and Schrodinger. However, by about 1900, Planck presented the analytical equation that perfectly matches the experimental Blackbody radiation curve, which required the molecules of the blackbody surface to emit and absorb electromagnetic radiation in discrete amounts of $h\nu$. Planck always underscored [2] that the discrete emissions in the blackbody cavity evolved quickly into diffractively spreading classical wave packets to create the intra-cavity homogeneous energy density. The quantum-ness of the surface molecules allowed them to absorb only a discrete amount of energy out of the field, as if they hold out frequency-sensitive discrete-energy cups of various sizes. Planck's model, of course, is congruent with the continuing success of Huygens-Fresnel diffraction integral and Maxwell's wave equation. We follow Planck's model, with some modifications where the discrete energy emitted by atoms and molecules are assumed to immediately evolve into classical quasi-exponential pulses to accommodate the Lorentzian spectral line-shape for spontaneous emissions [3].

Note that the sustained advancement in optical science and engineering, to this day, depend upon these above-mentioned two basic mathematical formalisms [4, 5], without any quantization of the EM waves. Therefore, the correctness of the formalism of Quantum Mechanics (QM) should not force us to accept the "wave-particle duality" (WPD) as the only way out to bridge the apparent differences between classical and quantum physics. This ad hoc concept of WPD debate actually was introduced as early as late 1600's by Newton ("corpuscular") and Huygens ("multitudes of secondary wavelets"). Newton and Huygens were also of the agreement that the debate arose because of their limitations in understanding the deeper and fundamental nature of light at that time. In modern days, we are accepting WPD as the confirmed new knowledge even though we have not really developed the foundational physical models behind the emergence of perpetually propagating EM waves without the need of any other force while discrete particles requiring different forces to alter their positions. One of the authors (CR) have been trying to revive the debate to underscore that WPD does not represent our final ontological knowledge about EM waves and particles [6-8]. There are many new physics to be explored and understood and many new applications to be invented by exploring the fundamental nature of light and particles while freshly re-building physics starting from the bottom up [9-11]. We strongly recommend ref.11 for serious readers.

In this paper, we attempt to develop a semi-classical analytical model to capture the *physical interaction processes* that a detector experiences under the influence of the incident light, which can generate the observed photo-current-pulse (PCP) statistics in our complex and multi-stage electronic system. The semi-classical approach is already well accepted [12-15]. However, the origin of the statistical fluctuations in the photo-current-pulse (PCP) statistics at low light level have not yet been derived explicitly out of the superposition of multiple quasi-exponential light pulses stimulating the detector with random times of arrival [16]. Thus, the $h\nu$ quantity of deliverable energy to a detector by such ensembles of pulses with random amplitudes and phases will naturally fluctuate in time. *The Superposition Principle of physics plays* *a critical role here, which has not been explicitly incorporated in Einstein's energy-balancing photo electric equation.* For a thermal source, the fluctuations will be maximum since the spontaneously emitted pulses are independent of each other. For a laser, with strong phase coherence between the consecutive pulses through stimulated emission, the fluctuations will be much less. When the light level is ample, thermal or laser, the number of random pulses are extremely dense and the deliverable energy by them to the detector will be essentially uniform. However, for a weak second harmonic light, the fluctuations should be less than that for a laser since this light is generated through the quadratic process (intensity driven) by a *steady high intensity* laser light. Since, both the spontaneous and stimulated emissions are completely random in time within the source, their arrival as "energy bullet" photons at the detector should maintain the same randomness. We underscore that it is the square-modulus operation, carried out *locally* [17] by the detectors on the simultaneously present quasi-exponential pulses, which determine the PCP statistics generated through the time-gated electronic systems. We should note that we count individual PCP's, and not "photons", even if "indivisible light quanta" existed. Thus, exploring the physical processes behind the release of individual photo-electron and post-amplifications, will help us explore further and deeper into the nature of light [3, 16, 18].

2. HYBRID PHOTON MODEL

2.1 The Need for the Hybrid Photon Model

Sustained and broad successes of both the classical optical formalisms (Huygens-Fresnel, Maxwell, et al) and the QM formalism (Heisenberg; Schrodinger, et al) clearly indicate that these theories have captured some fundamental realities of nature, even though, we know that no theories represent the final human knowledge of the intended fields [see Ch.12 of ref. 8]. However, their sustained successes imply that we must explore the foundational postulates behind these theories and try to improve upon them *iteratively towards higher level of integration*. As already underscored, the postulate of wave-particle duality (WPD) still represents our ignorance, and not new deeper knowledge about the waves and particles.

2.2 Accommodating Quantized Emission

Accordingly, we have proposed the postulate [3, Ch.10 in ref. 8] that atoms and molecules do release a discrete packet of energy $\Delta E_{mn} = h\nu_{mn}$, which immediately triggers the evolution of a quasi-exponentially decaying classical EM wave packet carrying the QM predicted total energy ΔE_{mn} with a carrier E-vector frequency ν_{mn} [Fig.1]. We still do not have any well-developed model for the dashed square box in Fig.1

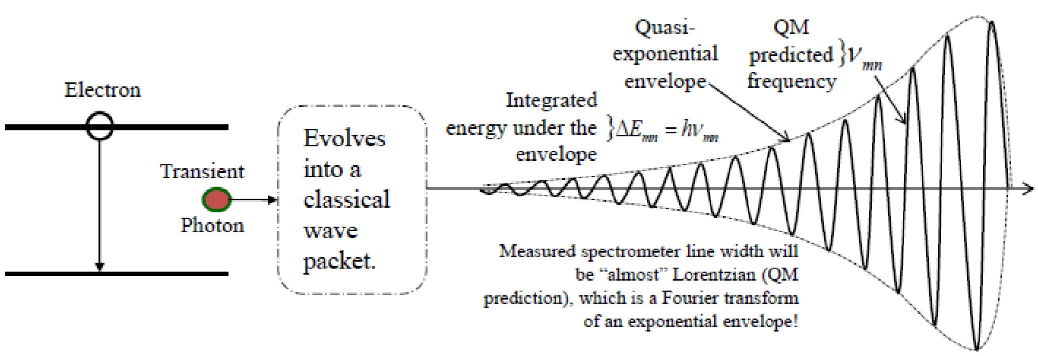


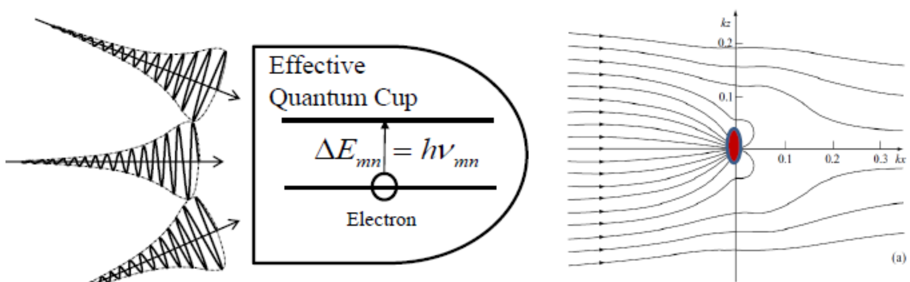
Figure 1. A pictorial definition of the Hybrid Photon. A quantum of energy gets released when a downward transition takes place in an atom or a molecule (left cartoon). This quantum immediately triggers the generation of a Maxwellian electromagnetic wave packet, which propagates out following Huygens-Fresnel diffraction principle. The key predictions of the quantum transition, the total energy and the carrier frequency, are preserved. This is very much like the kinetic energy of a dropped stone in water, which generates a diffractively spreading water-wave packet. The dashed box in the middle indicates new physics that need to be explored.

2.3 Defining the Quantum Cup to Accommodate Quantized Absorption

Experimental resonance fluorescence spectroscopy indicates that the light emission takes place extremely fast even when the “photon density” within an atomic volume of A^3 [19-21] is extremely low. Consider a 780nm, 1mW laser beam of diameter 1mm, passing through a low pressure vapor tube of resonant Rb. One can visually observe immediately a strong visible and glowing 1mm cylindrical trajectory of spontaneous emission within the Rb-tube. Simple calculation will show that the number of photons of energy $h\nu$ passing through a cylinder of diameter 1A and a length of 1A, is on the order of ~10^{-18} photons. The probability of almost instantaneous stimulated absorption of one photon by a Rb-atom out of ~10^{-18} photons, would have extremely low probability, because the EM field energy density is unusually low, in view of “A and B” coefficients of Einstein. Both the processes of resonance absorption-emission and photodetector stimulation and electron release, are unusually fast, on the order of a femto second. From the standpoint of energy density, neither the number of the bullet photons, nor the classical energy flux, passing through a miniscule target atom or molecule, can explain the availability of energy travelling at the speed of c. Then the $h\nu$ amount of energy has to be collected out of a very much larger volume of the EM field. This is the reason why we need to postulate that a resonetically stimulated 1-cubic-A dipole must project an energy-absorbing *quantum cup* of volume of at least on the order of ~10^{18} cubic-A, extended towards the oncoming stimulating resonant field to intercept one-photon-equivalent energy. This could be imagined as a box of three sides of $10^6 A$ each. For a resonant Rb-atom at $\lambda \sim 7800A$, the projected (stimulated) Rb-quantum cup should be a cube of at least a cube of sides ~128, if not an order or more magnitude larger to accommodate sufficient available to trigger the stimulated absorption. These are just hand-waving order of magnitude arguments. More rigorous modeling is required taking the leads from the advancements in the field of Nano photonics dealing with Nano-optical antennas [22].

We further postulate that in the semi-classical model, the resonantly excited dipole experiences a “push-pull” effect during energy absorption process. The “push” by the EM wave packet, possibly, to neutralize itself by delivering any amount of energy it can to a resonant quantum mechanical energy sink. And “pull” by the dipole, once the frequency resonance is established, to absorb the necessary quantum of energy out of the field to undergo the allowed upward transition [see section 10.2.3 in ref.8]. The idea is to causally accommodate the extremely high speed, albeit finite, at which the quantum mechanical stimulated processes take place. The postulate of “wave function collapse” is not a causal postulate, which can eventually be experimentally validated.

The left cartoon in Figure 2 helps us visualize this quantum cup concept. The cartoon on the right is a classical analytical model on how a large volume of field lines converge on a resonant dipole. Our cellphones, resonant to the designated microwave frequency, present an excellent example of such a model, even though RF oscillators are really classical. The physical cross-section of the cellphone antennas are unusually small compared to the energy it is able to pick up to maintain the sustained communications.



Frequency-resonant diffractively spreading multiple wave packets fill up the Quantum Cup to help the upward transition.

Convergence of field lines to resonantly excited dipole
See p.53 in *Introduction to Quantum Optics*, *by* H. Paul, Cambridge U. Press, 2004.

Figure 2. A resonant dipole functions like a quantum cup of large physical volume (left cartoon) to very quickly fill itself up. The right cartoon shows a classical quantitative model of field lines converging on to a small dipole out of a large spatial volume.

2.4 Recasting Einstein's Photoelectric Equation in Terms of Detector's Amplitude Stimulation

2.4.1. The generic background: When an EM wave is incident on some material, whether individual atoms, or molecules or their assembly in solid or in liquid states, the harmonically oscillating electric vector tries to induce a generic dipolar oscillation. The generic strength of the amplitude stimulation in the material is given by the induced polarizability, which has been successfully modeled as a sum of linear and non-linear terms [23].

$$d(t) = [\chi_1 E(t) + \chi_2 E^2(t) + \chi_3 E^3(t) + ...] \tag{1}$$

Here, $E(t) = a(t)\cos(2\pi\nu t + \phi)$ is the incident EM wave and χ_n's are the light-matter interaction parameter, or the polarizability of various orders and its value is unique for different atoms or materials and also is frequency dependent. χ_n's are quantum mechanical parameters when the energy transfer takes place through transitions between allowed quantum levels or quantum bands. In pure classical bulk-material phenomena, the *conversion efficiency of fundamental signal to higher harmonic signals depend upon the length and the volume of interaction, while requiring phase matching conditions between the two waves*. The readers should note that the experimental validation of the physics behind the terms χ_n's require that the EM waves be represented by real function representation, and not complex representation. This is an important point to remember to appreciate that for the physical processes behind light-matter interactions, the material dipoles literally executes a forced oscillation induced by the E-vector of the classical incident light before energy of the field can be transferred in the material in different forms, whether internal quantum transitions, or interaction length-dependent higher order harmonic wave generations. The strength of χ_1 is usually much stronger than $\chi_{n>1}$. This is why, in general, EM wave generation through nonlinear processes require the use of very strong fundamental waves. Traditional photoelectric phenomenon usually belongs to χ_1-process with quantum band transitions.

2.4.2. Setting the equation for photoelectron emission: Photoelectron release from atoms or compound molecules happens through two-step physical interaction process. First, the E-vector of the EM wave packet induces a linear dipolar oscillation on the target if the frequency matches the resonant quantum level or band of the detector. In the second step, the detector executes the square modulus operation on all the superposed waves to absorb the necessary quantum of energy to fill up its quantum cup and release a bound electron. The Energy exchange requires this quadratic step. This has been known both in classical and in quantum mechanics. The simplest resultant dipolar stimulation process, $d_{res.}(t)$, can be represented as the product of the time-finite hybrid photon wave packets $E_q(t,\nu)$ and the interaction parameter (the linear dipolar polarizability factor), $\chi_1(\nu)$, summed over all the simultaneously stimulating wave packets passing through the detecting entity. This is shown in Eq.2, with the assumption that the strength of $\chi_{n>1}(\nu)$ are negligible at moderate light levels. Note that atoms and molecules, being entities holding finite amount of energy, they can only emit time and space finite packets of EM energy. Thus the summation presented in Eq.2 is the best causal approach to model light-matter interactions. We must not use space and time infinite Fourier monochromatic mode as the starting platform. Fourier monochromatic mode is a non-causal signal in the universe that strictly follows energy conservation.

$$d_{res.}(t) = \sum_q \chi_1(\nu) E_q(t,\nu) \tag{2}$$

We also know from our historical experience that the detected signal, or the energy transfer equation, is simply the square modulus of Eq.2:

$$D(t) \equiv |d_{res.}|^2 = \left|\sum_q \chi_1(\nu) E_q(t,\nu)\right|^2 \tag{3}$$

If the incident light is from a very narrow line laser, the value of χ_1 becomes a fixed number. Then, according to the allowed mathematical rules, χ_1^2 can be taken out of two consecutive mathematical operations of summation and the square modulus:

$$D(t) \equiv \left|d_{res.}(t)\right|^2 = \chi_1^2 \left|\sum_q E_q(t,\nu)\right|^2 \tag{3a}$$

A single data point cannot validate a proposed theory. We must take the average o f a large ensemble of data.

$$\left\langle D \right\rangle = \left\langle \left|\sum_q \chi(\nu) E_q(\nu)\right|^2 \right\rangle \tag{4}$$

We can now discover the equivalence of Eq.4 with that of Einstein's original photoelectric equation as an ensemble averaged phenomenon:

$$\left\langle \left|d_{res.}\right|^2 \right\rangle = \left\langle \left|\sum_q \chi(\nu) E_q(\nu)\right|^2 \right\rangle \Rightarrow \left\langle h\nu \right\rangle = \left\langle \phi_{work\ fn.} + (1/2)m\mathrm{v}_{el.}^2 \right\rangle \tag{5}$$

We can clearly see that Einstein's core photoelectric equation represents only an energy-balancing data-modeling relation, since his equation did not address the initial step of actual light-matter interaction processes, which is the real physics behind this phenomenon. While the total energy exchanged $h\nu$ is quantized, the frequency ν of the EM wave has to match with the internal quantum dipole resonance frequency of the detecting entity. This physical interaction process model was missing from Einstein's original paper on photo electricity. From the stand point of interaction process mapping thinking, *the bound electrons in materials have to be first quantized to be in resonance with the incident wave frequency* ν , irrespective of whether the EM waves are actually quantized or not. Further, we already know that to trigger a quantum transition, it is not a required criterion that one must pair up quantum entities having the same discrete amount of energy to donate and accept. Thus, the photo electric phenomenon does not dictate us to quantize the EM wave.

The kinetic thermal energy of any entity is "continuous" and is classical. During thermal collisions, quantum entities routinely acquire quantum transitions while accepting/donating the discrete amount of energy necessary for the quantum transitions. This is why the classical Boltzmann expression for the statistical thermal population density plays such an integral in Quantum Mechanics. It is interesting to note that the discovery of fire by hitting two stones against each other to generate sparks is an example of classical-to-quantum energy transfer process. Our ancient predecessors discovered this quantum process, playing such a crucial role in human evolution, without having any access to quantum formalism.

Let us briefly digress to the Eq.3a. Let us explore the implication of this data-wise correct mathematical rule from Eq.3a. The implication is that the EM wave amplitudes can now sum themselves and can also take square modulus of their superposed amplitudes. This has been a major and continuing confusion in interpreting many optical phenomena, both classical and quantum physics [8]. Let us note that in the linear domain, different wave amplitudes by themselves cannot interfere (interact) with each other to re-organize their energy distributions, either in time domain or in the space domain. Only interacting materials, classical and quantum, can facilitate the field-matter energy exchange and/or energy re-distribution (observed fringes due to superposition effects on detectors). We call this as Non-Interaction of Waves or NIW [8, 24]. Although NIW is not openly discussed in modern literature, it was articulated about a thousand years ago by Alhazen [25, see p.53] and was formally postulated over three hundred years ago by Huygens [26]. The Huygens-Fresnel diffraction integral, framed in 1817, embodies NIW in its mathematical structure since all the summed secondary wavelets evolve independent of each other. Diffracted energy pattern at any forward plane can be observed only after a detector array executes the square modulus operation on the resultant diffracted amplitudes. Further, we know that Maxwell's equation accepts any linear combinations of its individual solutions, which implies that all the individual waves can coexist and co-propagate through the same volume, unperturbed by each other as long as the medium is linear Fig.3 depicts a simple model of two photons as wave packets propagating through the space preserving their individual characteristics unperturbed. Benign neglect of NIW has necessitated the construction of many postulates in physics, which would not have been necessary had we been explicitly employing NIW in formulating light-matter interaction processes. The concept of "indivisible light quanta" and "wave-particle duality" are two of them, as mentioned earlier [27].

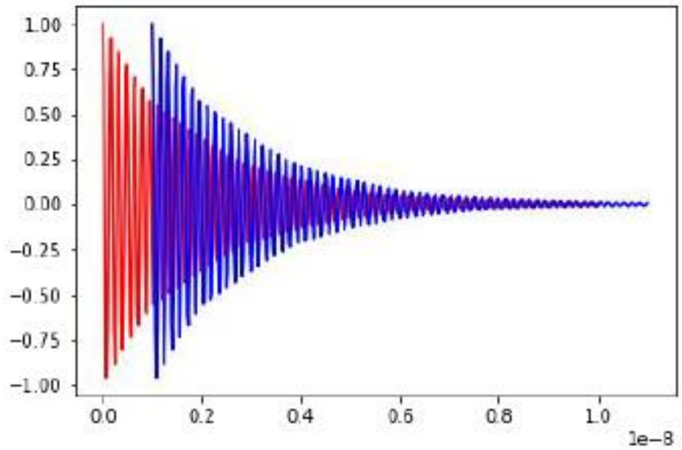


Figure 3. Two classical photon wave packets, $a_1 e^{-(t_0-t_n)/\tau} e^{i(2\pi\nu t+\phi)}$ *with relative displacement* t_n*, are co-propagating through the same non-interacting homogeneous medium without interacting with each other, or modifying each other's basic characteristics. Linear wave excitations follow Non-Interaction of Waves (NIW) in the linear domain.*

If light amplitudes cannot re-organize their energy in the absence of interacting material, as dictated by NIW, then a single photon-amplitude cannot also make itself appear or disappear to generate dark and bright fringes, built up one at a time. Our mathematical superposition equation implies physical superposition of more than one different physical signals carrying physically different values of the parameters involved. Thus, single photon interference experiments should be re-visited by first reducing the intensity literally to single-photon-equivalent energy flux by using a thick stack of calibrated neutral density filters. If we want a flow of only one photon per second from a 780nm CW laser beam, we need to bring down the energy flow to an unmeasurable quantity of $2.55\times10^{-19} J/\sec$ (Watts). We have not yet discovered any technique to directly measure such extremely low EM wave energy. We cannot conclude from individual clicks in our detecting system that the light beam literally contained only a single photon. Further, we really do not count "photon". Our complex electronic photo-electron counting systems counts highly amplified individual current pulses containing, perhaps, 100 million or more amplified electrons as a bunch. Such electrical pulses cannot validate with *certainty* that the light beam consisted definitely of "bullet photons". We will discuss this point again when considering the variation of statistical properties of photo-current pulses (PCP) generated by different kinds of light sources.

3. SEMICLASSICAL MODELING OF PHOTO-CURRENT-PULSE (PCP) STATISTICS

3.1 The Basic Approach

We want to model the statistical distribution of the availability of single or multiple packets of $h\nu$ amount of energy within a set of time bins using our semi-classical model as depicted in the top box of Fig.4, out of the statistically random flow of a large number of quasi-exponential EM wave groups. For comparison, the lower box of Fig.4 depicts the equivalent bullet photon model. Rational behind this exploratory model derives from the following brief discussions.

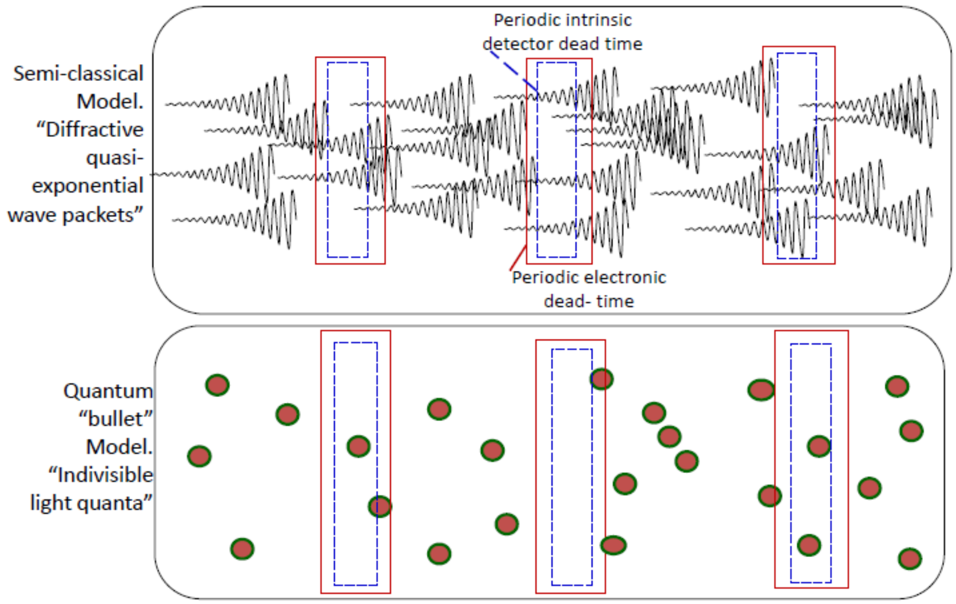


Figure 4. Pictorial comparison of a stream of classical wave packets vs. a stream of bullet photon traveling to a detector on the right. The dashed rectangular boxes imply the detector dead-time between two consecutive emissions of single photo-electrons. The solid rectangles indicate the adjustable electronic gating normally imposed on the counting system to count the number of photo-current-pulses (PCP) during a set time-bin. The top box depicts random propagation of quasi-exponential classical pulses of EM waves. The lower box depicts propagation of equivalent photon bullets.

3.1.1 **Rationales behind exploring a semi-classical physical model:** In general, all quantum transitions have finite exponential decay time, whether this "life time" is long or very very short. Accordingly, the core characteristics of the temporal statistical distribution of the emitted energy packets from lasers and thermal sources should not be significantly different. For the statistical ***temporal*** distribution of bullet photons to be different (lower cartoon of Fig.4) for different sources, effectively ignores the effects of mutual phase coherence or incoherence between the bullet photons. Our model is focused on building up the PCP statistics as the outcome of classical degree of coherence existing between the assembly of quasi-exponential pulses arriving on the detector for the cases of lasers, thermal sources and nonlinear second order sources excited by high power CW lasers. This degree of coherence is due to multitudes of random wave packets; it is not two-beam coherence, although they can be shown to be mathematically related [28]. Readers should note that the final algebraic expression for the quantum coherence derived by Glauber [29] is equivalent to the expression derived by the theory of classical coherence, as has been shown by Sudarshan [28]. To derive the instantaneous intensities, we will simply use the classical superposition principle and then integrate the intensity curve over a time interval that contains $h\nu_{mn}$ amount of energy.

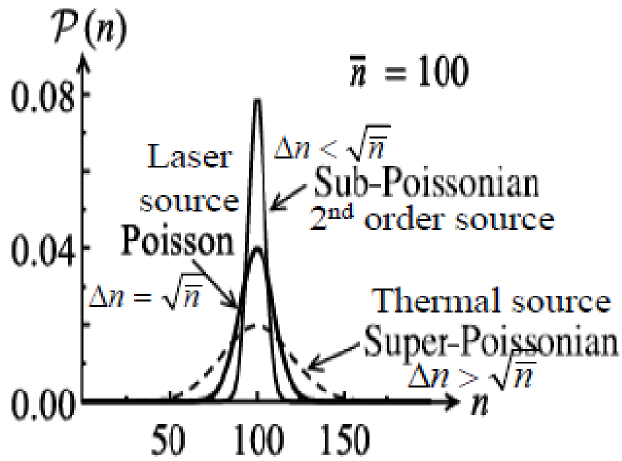


Figure 5. Variation of photo-current-pulse (PCP) count around the mean of 100counts/time-bean (i) for lasers sources (Poissonian), (ii) for thermal sources (super-Poissonian) and (iii) for non-linear second order sources (Sub-Poissonian) [30].

It is also important for us to carefully underscore the conceptual problems behind the prevailing assumption of detected "single photons" using the statistical distribution curves constructed out of the actual PCP counts over a large number of identical time-bins. Fig.5 has been copied from a recent introductory book [30] with minor additions. Consider the case for the mean PCP count as $\bar{n} = 100$ for a given repeated fixed time-window. There is a wide fluctuation in the detected PCP number, both higher and lower, for the same time-window. The plot of the normalized curves for the case of the mean PCP number $\bar{n} = 1$ would look very similar to those in the Fig. 5. Implication is that when one records the mean PCP number to be one for a given fixed time interval. During many intervals, the real count would be none (less than one is not possible!). And during many other time intervals, the count would be many more than one. Thus, our statistical model cannot claim that at low light intensity, one always had ***a single bullet photon at a time*** to build up the superposition pattern [17].

3.2 Building the Model

We assume that we have created a narrow collimated light beam out of a pinhole, illuminated by different kinds of light sources under study, which we would like to model. We would propagate many quasi-exponential pulses, purely randomly distributed in time, shown vertically staggered for convenience of pictorial presentation in Fig.6. Our objective is to show the emergence of Poissonian, super-Poissonian and sub-Poissonian distribution in the number of $h\nu$ -quantity of deliverable energy to the photo-electron counter during a specified repeated time-window. The characteristics of the distribution should be solely determined by the phase coherence and amplitude strengths of the stack of pulses considered within a rationally chosen time interval.

Each pulse can be described as $a_1 e^{-t/\tau} e^{i(2\pi\nu t+\phi)}$. Other key parameters are, $h\nu = 2.55\times10^{-19} J$, where $\nu = 3.84615\times10^{14} Hz$ for $\lambda = 780nm$, Rb-red resonance line. We equate the total area under the entire temporal duration of the intensity curve $a_1^2 e^{-2t/\tau}$, as the energy of the original quantum packet $h\nu$:

$$\int_0^{+\infty} a_1^2 e^{-2t/\tau}\, dt \equiv h\nu \tag{6}$$

The generic expression for the intensity due to the sum of all the pulses, somewhat as in Fig.5, can be expressed as:

$$I(t) = \left|\sum_n q\chi_1 a_1 e^{-(t_0-t_n)/\tau} e^{i(2\pi\nu t+\phi)}\right|^2 \tag{7}$$

Eq.7 gives us important physical process information. The PCP statistics arises due to simultaneous stimulation of the detecting dipoles by multitudes of light pulses bringing different phases and amplitudes. This cannot happen if the light pulses or the photons were to arrive one at a time. Light waves or photons do not interact with each other to create new energy distribution. Self-interference is not allowed in nature in the absence of interaction-facilitating medium. Thus, single photon hitting the detector, one at a time, cannot generate the specific PCP statistics we observe for different kinds of sources of light.

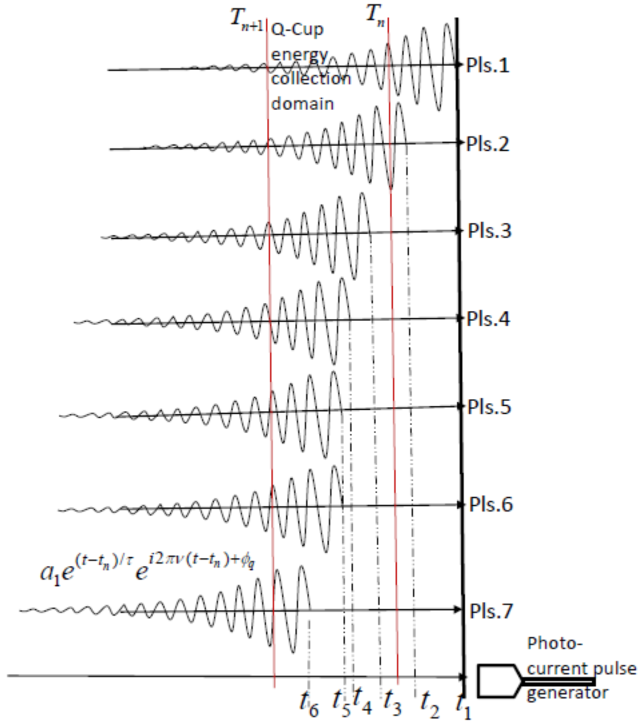


Figure 6. A low intensity narrow collimated beam of light is incident on a photo-current-pulse (PCP) counter (lower bottom). The temporally distributed random collinear pulses are staggered vertically for pictorial clarity.

Here the fractional factor q denotes the limited amount of energy accessible to an active detection site due to diffractive spreading of the original wave packet containing the full amount of energy $h\nu$. The sum total area under the intensity curve of Eq.7 within the judicially chosen time interval, as shown by the solid pair of vertical lines in Fig.5, will be divided by the area of the integral in Eq.6. This will determine the number of available *photon-equivalent energy units*, which in turn, should release that many bound electrons. For different kinds of light, the statistical fluctuations in the phase parameter ϕ and the variations in the amplitude a_1 would determine the statistical distribution in the number of available $h\nu$-units of energy. Thus, the relative phase and amplitude variations between the various wave packets that are simultaneously stimulating the detector, dictate the emergence of temporal statistical properties of the released photoelectrons generated locally on the detector. Of course, the statistical time fluctuations in the moments of release of individual photoelectrons out of the different stimulated detecting elements also play an integral part in the determining the final statistical properties in the final photoelectric-current-pulses (PCP's).

$$\mathrm{N}_{h\nu} = \frac{\int_{t_1}^{t_2} \left\{ \left| \sum_n q a_1 e^{-(t_0 - t_n)/\tau} e^{i(2\pi\nu t + \phi)} \right|^2 \right\} dt}{a_1^2 \int_{-\infty}^{+\infty} e^{-2t/\tau} \, dt} \tag{8}$$

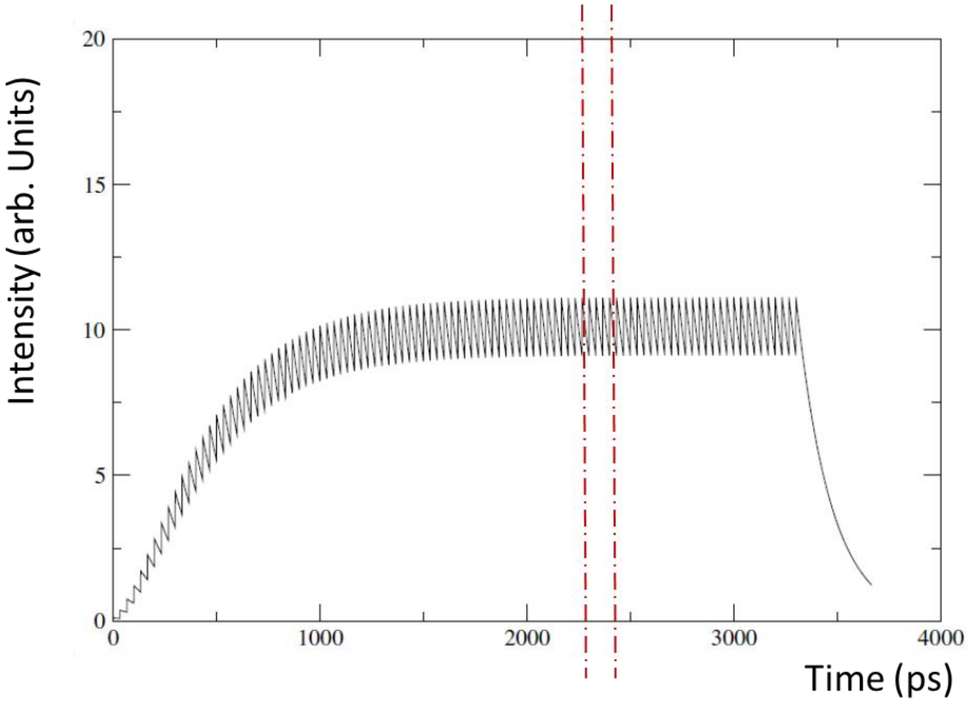


Figure 7. A plot of the temporal intensity fluctuations due to 100 in-phase (laser) exponential photon wave packets of 1ns duration, with a periodic spacing of 100ps. Even under steady state condition, after 1ns, the intensity is fluctuating in the fs domain. Thus the absorbable energy by a detector during very short periods of time (indicated by a pair of vertical dashed lines) would be fluctuating.

As a preliminary case example, consider the case of the intensity due to 100 of 1ns-duration in-phase and temporally equally spaced (100ps) train of wave packets (stimulated emissions from a CW laser) exciting a detector (Fig.7). The available absorbable energy by the detector is fluctuating in the fs domain. Does the area under the dashed vertical line contain more than one $h\nu$ equivalent energy to dislodge a single bound electron? We are trying to underscore that it is the classical flux density available over a specific spatial volume that determines the release of a single photo-electron, provided the available energy is more than enough to fill up the quantum cup of the molecule. Is there an energy threshold limit for electron release even higher than the single photon-equivalent energy? Is there some nonlinearity at very low energy density, as has been found for Ag-Halide crystallites [31]. We do not know. However, such questions are relevant in fundamental physics. Such questions arise naturally through our semi-classical model.

Let us back calculate the density of the number of wave packets within a collimated laser beam of 1mW (1mJ/sec) power and 1mm diameter. If we assume the laser has $\lambda = 780nm$ and $h\nu = 1.588eV$, then the number of photon that would flow into a detector per second would be $4.34\text{x}10^{15}$; or $4.34\text{x}10^{6}$ photon wave packets will flow in during every nanosecond window. Since we have assumed that the photon wave packets are ~1ns long, we have a flow of $4.34\text{x}10^{6}$ wave packets within every 1ns interval, or $4.34\text{x}10^{3}$ wave packets during every ps interval.

Thus, the semi-classical model implies that our photodetectors are always being stimulated by multitudes of photon wave packets, propagating classically. When the available energy in number of $h\nu$ (Eq.8) is definitely greater than one, then only our detector can release a photo electron, which can be converted into a photo-current-pulse (PCP) through the amplification process. Absence of PCP does not necessarily imply complete absence EM energy flowing through the detector.

Further details for the emergence of the different statistical distribution for different light sources will be presented elsewhere.

4. DISCUSSIONS

Einstein's energy-balancing equation does not explain the physical processes that precedes the release of a photo electron. The semi-classical model we have presented here automatically brings out the role and the significance of the Superposition Principle (SP) in photoelectric effect by explicitly incorporating the following concepts:

(i) light-matter interaction processes as in Eq.1;

(ii) semi-classical representation of the energy pulses emitted through spontaneous and stimulated emissions that evolves into space and time finite EM wave packets as shown in Fig.1.

(iii) frequency-resonant detecting entities function like quantum cups and fill up the cup with the required quantum of energy $h\nu$ out of many semi-classical pulses propagating as diffractive pulses through the detector, as in Eq.2 representing SP and Eq.3 representing energy transfer.

It is important to appreciate that in an interferometer, or in a diffractometer, the registration of a dark fringe does not imply that "photons" do not arrive in such physical locations (spatial fringe detection arrangement), or during such temporal intervals (scanning fringe detection conditions, or heterodyne detection conditions). The causal explanation of the absence of "photon" energy detection is explained by the SP, as in Eq.1. When the resultant amplitude due to multiple wave elements is zero, the detecting dipole is not stimulated at all and hence it cannot open up its "quantum cup" to absorb the $h\nu$ quantity of energy. The concept that an elementary particle, the "photon", can interfere with itself and can make itself appear or disappear from specific spatial location, or temporal interval, is a non-causal hypothesis. Besides, our working wave equation (due to Maxwell) and the diffraction integral representing wave propagation (due to Huygens-Fresnel) automatically imply that multiple wave packets can simultaneously co-propagate or cross-propagate through the same spatial volume without altering each other's wave properties (amplitudes and phases), as long as the medium is linear. This Non-Interaction of Waves (NIW) is a generic property of all waves, built into the wave equation. The book cited in ref.8 elaborates most of the optical phenomena by incorporating this NIW property. The diverse consequences of the benign neglect of this NIW-property in applied and fundamental physics have been summarized in ref.32.

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