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Understanding the physical processes behind the photoelectric current pulse (PCP) statistics and designing better sources

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ABSTRACT

A deeper understanding of the physical processes behind the emergence of photoelectron current pulse (PCP) statistics could help relaxing the source requirements for quantum computers, in choosing nonlinear vs. linear processing of light. Einstein's photoelectric equation is an energy-balancing "bullet model". The "bullet-model" over-rides both the classical and the quantum Superposition Principle (SP). SP requires first summing the joint amplitude stimulation experienced by the detecting dipoles by all the incident complex amplitudes, followed by the square modulus operation executed by the detecting dipoles to absorb the quantum-cupful of energy. We have been accommodating this "bullet model" via the prevailing belief that wave-particle duality is our new "confirmed knowledge", instead of acknowledging our ignorance about the true nature of light. We will use the semiclassical model of photons as time-finite random light pulses stimulating a detecting molecule to its excited state of Ψ . The molecule then absorbs the quantum of energy through the execution of the square modulus operation, $\Psi^*\Psi$, and release the quantum mechanically bound electron. The lifetime of releasing the bound electron is very short as they are in quantum bands, rather than in sharp quantum levels. Each one of the released electron is then amplified, through complex electronic processes, by a factor of as much as 10^9 , to generate one easily measurable photoelectric current pulse, or a PCP. Therefore, the emergence of the PCP statistics is a combined function of (i) fluctuations in the incident light, (ii) fluctuations in the electron emission moments and (iii) noise introduced during the amplification process. In this paper, we will consider a classical linear approach in smoothing the average energy delivery on to a photodetector using the natural pulse replication property of a Fabry-Perot interferometer (FPI) and hence narrow the PCP statistical spread. If our model is correct, we should be able to derive the PCP-statistics for different sources using the fundamental amplitude and phase characteristics of various real sources. We have also proposed specific experiments to validate our model.

Keywords: Photon counting theory; Photoelectron Current Pulses (PCP), generation of; Semiclassical theory of PCP generation; Coherence manipulation to control PCP statistics; Fabry-Perot as a pulse replicator, Photodetectors; Coherence & Quantum optics.

1. INTRODUCTION

Using a suitable source to generate photoelectrons and counting them are at the foundation of constructing photon-counting quantum computing system. The inherent noisy statistical fluctuations generated during the counting process of photoelectric current pulses (PCP) are complex and the related important physics and engineering issues are being analyzed for many decades [1-6].

In spite of the staggering and the continued successes of Maxwell's and Schrodinger's equations guiding our understanding of light-matter interactions, we have not resolved our ignorance behind the persisting concept of wave-particle duality (WPD). This paper assumes quantized energy emission from atoms and molecules, which propagates out as an exponential Maxwellian wave pulse. We use this model for the possible practical application of reducing the statistical fluctuations in the photoelectric current pulse (PCP) count. Our overall approach is to understand the physical interaction processes that nature utilizes to keep making observable and measurable changes everywhere. We believe the purpose of physics is to help visualize these invisible interaction processes while leveraging the tools of mathematics and experiments.

We define our visualizable model of light in Section 1.1. Then we summarize the ongoing historical debate in the interpretation of light from our viewpoint in Section 1.2. Then we propose a basic semi-classical model behind the origin of PCP in Section 1.3, which we cannot explain easily by using Einstein's energy-balancing photoelectric equation (Section 1.4). Then, to empower the semiclassical model, we introduce the concept of "Push-Pull" *interaction process* between classical EM wave and quantum dipole atoms in Section 1.5. In Section 1.6, we explain the emergence of the spatial and temporal granularity in detectors as due to the combination of quantum-ness in the detecting molecules and their physically granular fabrication process. Implication is that the quantization of the Maxwellian wave is not a necessity. Then we present the model for smoothing the temporal flow of pulsed energy flux, using a passive Fabry-Perot Interferometer (FPI) in Section 1.7. In Section 1.8, we suggest experiments to validate the proposed amplitude smoothing technique, which could provide a low-cost and low-noise optical source for various practical applications. This would also validate our proposal for the resolution of the wave-particle duality, which has been dragging on since the times of Newton and Huygens. In the "Conclusion and Discussion" section, we have underscored the deeper significance of the paper in bridging the strengths of Maxwell's classical wave equation and the Schrodinger's quantum equation.

1.1 The model of light we are using.

The purpose of this paper is to explore the possibility of developing low cost manipulation of existing laser light sources that could generate lower PCP noise for various low-light applications. The motivation derives from wide ranges of successes of the semi classical model of light, in spite of our strong affinity to the culturally catchy word, "photon" [7-12]. EM waves are classical waves and atoms and molecules can emit and absorb EM energy only in discrete packets of $h\nu$, as required by Planck's blackbody radiation formalism, which was later formalized by Quantum Mechanics. The basic propagation physics of EM waves obey Maxwell's equations and the physics of diffractive spreading of waves follow the Huygens-Fresnel Diffraction Integral (HFDI), or its variations [13]. Optical science and engineering have been continuously advancing un-interrupted for more than a couple of centuries based on these two classical formalisms. Similarly, Quantum Mechanics (QM) is the best prevailing theory to model the properties of atoms and molecules and their interaction with Maxwellian EM waves. EM waves travel as oscillating wave *amplitudes of an energetic tension field* with electric and magnetic tension properties identified by Maxwell's wave equation, $c_{med.} = (\epsilon_{med} \mu_{med})^{-1/2}$ (here we imply that the cosmic space is also a medium, which is normally expressed as ϵ_0 & μ_0). The waves can assist the transfer of electromagnetic energy out of the tension field, but only to frequency resonant atomic/molecular dipoles; and only after, these dipoles *execute the square modulus operation*. Further, EM waves do not propagate as "energy", but as Maxwellian wave amplitude. Otherwise, Schrodinger's wave equation, representing "stimulated amplitudes" of quantum entities could not have been applicable to model light-atom interactions.

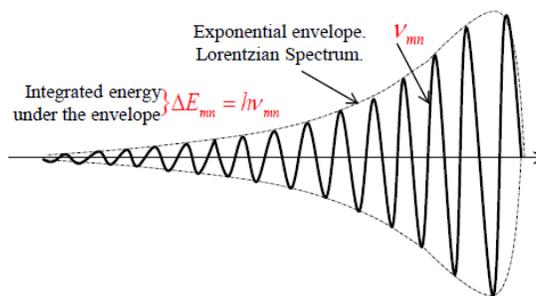


Figure 1. The model of a Newtonian "corpuscular" photon, after emission by an atom. It propagates out as a Huygens' wave packet obeying Maxwell's wave equation. It has a carrier frequency that matches the prediction of quantum mechanics, carrying the quantum of energy with a quasi-exponential amplitude envelope, which generates a spectral line-width function closely matching the Lorentzian function (spontaneous emission line width) [16].

We also know that quantum entities can be stimulated to higher energy quantum level through classical collisions, while absorbing only the necessary quantum of energy out of the available kinetic energy out of the colliding particle. That is why Boltzmann's thermal population density relation is consistently used in quantum formalism.

The implications of these semi-classical views is that the discrete energy packets, emitted by atoms and molecules, must immediately evolve into classical exponential pulses as per classical dipole model [14, 15] and supported by general observations, confirming that the spectral line width of spontaneous emission is Lorentzian, which is the Fourier transform of an exponential pulse [Ch.5 in 16].

Since the times of Newton and Huygens, the need for a tension field as ether used to be the norm (until the end of 1800) to sustain the perpetual propagation of light. However, Huygens had also introduced two important postulates behind the perpetual propagation of waves. The first one is that every point of a wave front keep generating secondary spherical wavelets [17]. The second concepts is that these secondary wavelets keep expanding through each other without perturbing each other's functional properties as secondary waves, which we would call as Non-Interaction of Waves, or NIW [16]. The HFDI literally sums superposition of spherical wavelets emerging out of every point on the wavefront illuminating an aperture, S, with a caveat introduced by Fresnel that the spreading of the wavelet amplitude is constrained by a $\cos \theta$ factor [13], as in Eq.1, assuming a continuous wave. For a time finite pulse, the diffraction integral should be written as Eq.2. Note that the summation or the integral *operation* has to be executed by a material detector or a human calculator to obtain the energy. The NIW property deprives waves from self-summing. Otherwise, our eyes could not have registered unperturbed scenarios while we look around ourselves.

$$U(P_{out}) = \frac{-i}{\lambda} \iint_S U(P_{app.}) \frac{\exp(ikr_{01})}{r_{01}} \cos \theta ds \quad (1)$$

$$U(P_{out}, t) = \frac{-iv}{c} \iint_S U(P_{app.}, t) \frac{\exp(i2\pi vt)}{r_{01}} \cos \theta ds; \quad t = (r_{01} / c) \quad (2)$$

The acceptance of the propagation of the discrete atomic and molecular emissions as exponential pulses and combining that with Huygens' NIW implies that all light coming out of atoms/molecules, whether the emission process is spontaneous or stimulated, must consist of innumerable non-interacting pulses. Therefore, all light sensors, or detectors must be receiving innumerable pulses with random phases and with random times of arrivals from thermal sources. This was understood early on and the classical optics developed the coherence theory to characterize the fluctuations in the detected energy out of any light beam. However, the concept has not been fully integrated into the basic theories of classical physics, which still formulates most basic optical phenomena using continuous wave (CW). For example, the basic diffraction integral, HF-DI, should be written as in Eq.2, where $U(P_{app.}, t)$ is a time finite input pulse, and $U(P_{out}, t)$ is a time-stressed diffracted output [see section 4.5 in 16].

1.2 Ongoing historical debate on what light is, or what a photon is.

We consider the above approach of considering light emitted by atoms/molecules as individual pulses, is an excellent solution to the historically persisting debate on wave-particle duality (WPD), which had started during the latter part of 1600 between Newton ("corpuscular") and Huygens ("secondary wavelets"). Looking back, it is obvious that Newton was focused on the light *emission process*. Minuscule atoms and molecules clearly cannot keep on emitting light energy continuously. Whereas, Huygens was focused on the light *propagation process*. Naturally, with the focuses being on two different *physical processes* about light, they could not resolve the debate. However, Young's demonstration of the double-slit experiment (1802) on the superposition effect of light established the wave properties of light, which was then formalized by Fresnel (1817) as the propagation of innumerable secondary spherical wavelets (Eq.1 & 2). These two milestones had appeared to resolve the WPD, at least, through 1901. Optical science and engineering were thriving through multiple sub-disciplines, while empowering physics to reach some maturity through the measurements of Blackbody radiations and Ritz-Rydberg formula for discrete atomic spectra, both of which guided the then physicists to explore the origin of the discreteness in the emission and absorption of atomic and molecular radiations, creating the platform to invent the Quantum Mechanics.

However, in1905, Einstein triggered the revival of the WPD while theorizing the experimental data for photoelectric effect. Based on the observation of the data that there was a threshold frequency, below which no bound electron could be released, Einstein *correctly postulated* that the photoelectric emission phenomenon represented a quantum-like behavior. Unfortunately, Einstein assigned the quantumness to the Maxwellian waves, rather than to the actual quantum mechanically bound electrons in materials. Einstein has used the phrase, "indivisible light quanta". This had later resonated with de Broglie's 1924 experimental observations of electron diffraction patterns and the WPD has been re-affirmed with

his experimentally correct postulate of $\lambda = h / mv$ for freely moving electrons. However, de Broglie's "Pilot Wave" model remains controversial. Note that a particle's wavelength diverges as its velocity goes towards zero. Soon, Schrodinger's quantum mechanical wave equation of 1926 codified the duality and the WPD became a "fundamental requirement" to understand quantum mechanics. Both the linear differential wave equations of Maxwell (Eq.3) and Schrodinger (Eq.4) has the built-in Superposition Principle (SP) and hence the applicability of the coherence theory, which explicitly accounts for the joint effects of amplitude and phase variations between multiple EM waves packets when they stimulate atoms or molecules simultaneously. Mathematically, any linear combination of the allowed solutions is also a solution to their respective equation. In other words, $\sum_n E_n$ and $\sum_n \psi_n$ are correct solutions of Eq.3 and Eq.4, respectively.

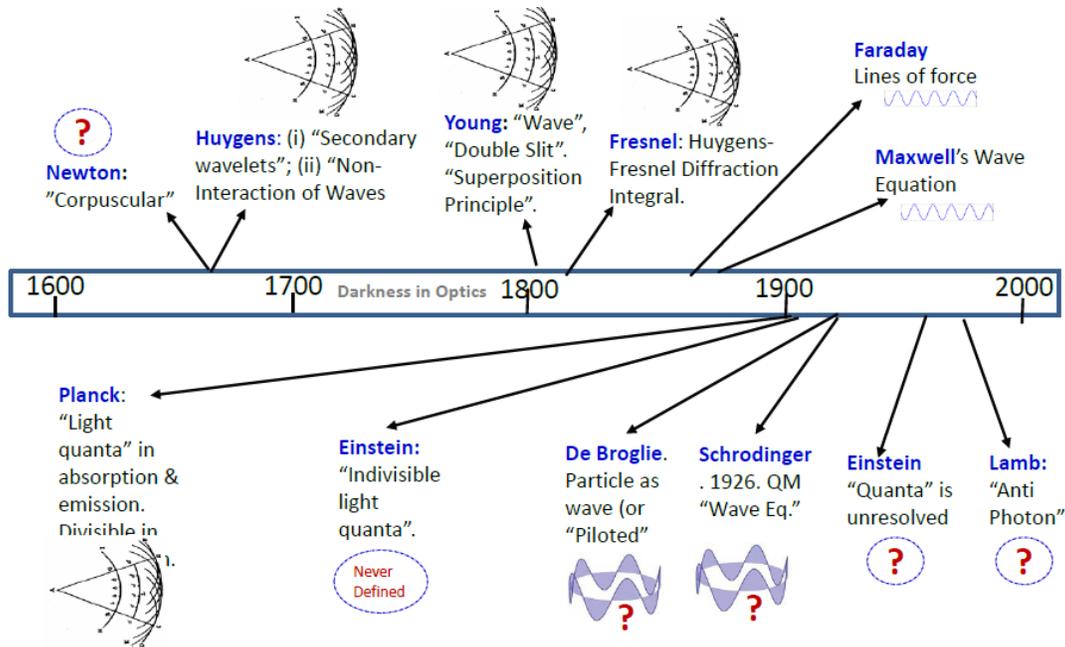


Figure 2. The unresolved wave-particle duality implies that the foundational postulates of our current working theories are still not self-congruent, which is still holding back the progress in Physics. A brief history of the origin of the debate over the wave-particle duality starting between Newton and Huygens and its modern evolution towards accepting it as a reality, rather than as our continuing ignorance about the deeper physical nature of light, which was the conclusion of Newton. For details, see the text. [The secondary wavelets are a copy from Huygens book [17] and the wiggly self-looped waves are a copy from the google-web.]

$$\frac{\partial^2 E(x,t)}{\partial t^2} = \frac{1}{\epsilon\mu} \frac{\partial^2 E(x,t)}{\partial x^2} \equiv c^2 \frac{\partial^2 E(x,t)}{\partial x^2}; c^2 \equiv \frac{1}{\epsilon\mu} \quad (3)$$

$$\frac{\partial \psi(x,t)}{\partial t} = \frac{i\hbar}{2m} \frac{\partial^2 \psi(x,t)}{\partial x^2} + \frac{1}{i\hbar} V(x,t)\psi(x,t) \quad (4)$$

Both the above equations accept harmonically oscillating functions like $\exp[i\omega t]$ as solutions and Schrodinger assigned the characteristics of "plane wave" to the quantum particles, and de Broglie assigned the concept of "Pilot Waves" guiding the "localized" quantum particles.

We need to recognize that even though mathematically both the Eq.3 and Eq.4 accommodate the linear Superposition Principle, only Maxwell's equation supports the generation, as well as, the *perpetual propagation* of a wave (here electromagnetic), once generated. The perpetual velocity is supported by the very electromagnetic tension field with their built-in tension properties, ϵ & μ [18]. In contrast, a quantum entity in Schrodinger's equation requires a separately acting potential gradient $V(x,t)$ for it to be able to move in the spatial dimension. Therefore, strictly speaking, Eq.2 is not a wave equation. It is an equation to model the behavior of complex localized particle-like oscillators. It does not have the

complementary term of “temporal acceleration”, $(\partial^2 / \partial t^2)$, as Maxwell’s equation does. Further, we need to recognize that the localized quantum *particles cannot be plane waves*; then, mathematically, they would exist in all space and all time, which is energetically not allowed by the principle of conservation of energy. In optics, this is built into the Huygens-Fresnel diffraction integral via the factor $\cos \theta$, effectively, spatially confining the diffractively spreading EM waves within approximately $\pm 5^\circ$. Further, we should note that we routinely use the expression $\exp[i\omega t]$ to analyze harmonically oscillating entities like classical pendulum, electrical LCR-circuits, etc., etc. Therefore, this expression $\exp[i\omega t]$ does not exclusively represent a propagating wave. Particles are just complex localized harmonic oscillators subject to quantum mechanical and classical force gradients [18].

Let us underscore another important issue related to use of mathematical logics to emulate functional principles of nature. We normally write the mathematical Superposition Principle (SP) as $\sum_n E_n$ or $\sum_n \psi_n$. However, in the real world of nature, neither of these mathematical SP’s (*resultant* amplitudes), is directly observable, or measurable. Besides, observables physical transformations happens only through the *energy exchange process* between interactants, which is a quadratic (square modulus) operation. For EM waves, it is the Non-Interaction of Waves (NIW) [16], which was recognized as early as 1080 by Alazehn, and formally articulated by Huygens [17] as his non-interacting secondary wavelets. Observables or data are real physical transformations in some sensors (detectors) through energy transfer between the sensor and the entity under observation. The energy transfer process is always guided by an interaction parameter, defined by the mutually allowed force of interaction. Therefore, one would represent an atom or molecule getting stimulated by multiple EM wave packets as $\Psi = \sum_n \psi_n = \sum_n \chi(\nu) E_n(\nu)$, where χ is the linear dipolar polarizability parameter for the light sensing atom or molecule. Again, only $\Psi^* \Psi$ is observable, and not the resultant amplitude Ψ . (For high intensity-induced non-linear interactions, higher order polarizability, $\chi_n(\nu)$ need to be used). In the linear domain, for quantum atoms and molecules to be responsive to the incident light, they have to be frequency resonant. The quantumness in photoelectric effect is coded in $\chi(\nu)$ of matter. In reality, the consistent success of QM in modeling light-atom interactions is because the two equations, Eq.3 and Eq.4, allow (guide) mutual amplitude-amplitude stimulation when they are in frequency resonance in the linear domain. Then the atomic dipole is excited, which then leads to the execution of the nonlinear *quadratic* action to absorb the necessary quantum cupful of energy out of the oscillating EM wave field [19]. EM waves do not travel as “bullets”; they are propagating as Maxwellian harmonic waves, energized by the electromagnetic tension values ϵ & μ . Thus, the mutual compatibility between Maxwell’s and of Schrodinger’s equations and their continued joint successes lend no credence to the concept that EM waves travel as “bullet photons”. If individual bullet photons do really generate superposition effects, then what are the physical roles of the superposition principle, coherence theory and the detectors?

We would like to underscore at this point other supporting logics behind the semiclassical model. Since the publication of Huygens-Fresnel Diffraction Integral (HF-DI) in 1817, the field of classical optical science and engineering started evolving uninterrupted. With the publication of Maxwell’s wave equation, HF-DI was recognized as an obvious spatial superposition equation, obeying Maxwell’s equation. Of course, QM opened up the wider vista of the atomic and molecular universe – lasers were invented; then emerged the fields of Nanophotonics, Plasmonic Photonics, Metamaterials, etc. These fields are now harmoniously bridging the efficient use of the tools of QM and Maxwell’s equations. Besides, QM has not succeeded in explaining the origin of the perpetual high velocity of EM waves, $c_{med.} = (\epsilon_{med} \mu_{med})^{-1/2}$.

We believe that the unresolved wave-particle duality implies that the different sets of foundational postulates of our different working theories are still not self-congruent, which is still holding back the progress in Physics. Hence, the importance of validating, through practical applications, that all light emitted by atoms/molecules propagate as quasi-exponential pulses, as postulated in Fig.1.

1.3 Basic semi-classical model for photoelectron emission.

As we have underscored, all atomic/molecular sources emit Newtonian “corpuscles”, which we have re-defined, based on the successes of classical optics and QM, as quasi-exponential time finite pulses [14, 20], as classical dipoles do. We are assuming that the light beam is collimated to avoid changing energy flux during propagation on to the photodetector.

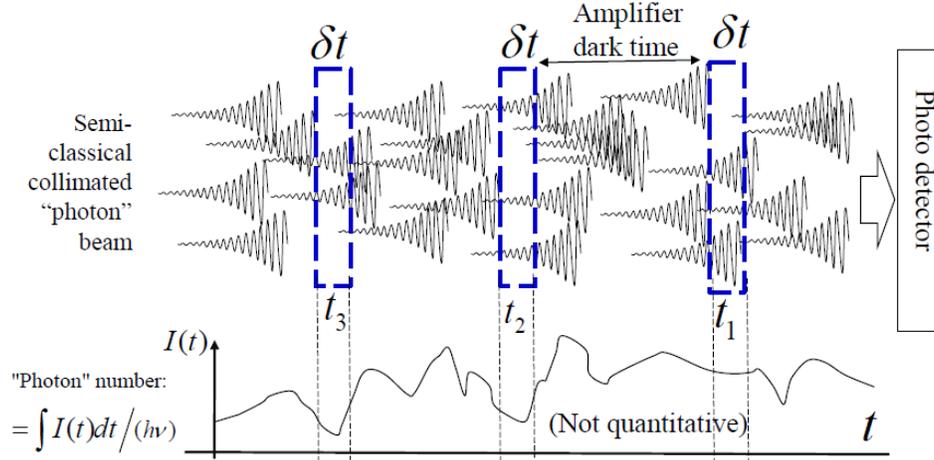


Figure 3. The above cartoon shows a set of quasi-exponential pulses, randomly distributed in the time-domain, on their way propagating to a photodetector. The photodetector keeps receiving time-varying joint stimulations by multiple superposed semi-classical photon pulses. All quantum mechanical processes take finite time. Let us assume that the required time-period for quantum-cup filling and the release of a photoelectron is δt , required by the dipoles, shown as by blue rectangles above, whether it is $\sim 100\text{fs}$, or 1ps . Our key point is that during the same intervals at moments of t_1 , t_2 and t_3 , the superposed EM wave flux will be delivering different quantities of energy, and hence would release different number of photoelectrons. As per coherence theory, the relative phases between the many pulses and the temporal amplitudes at any moment would determine the joint dipolar stimulation. The square modulus operation during a couple of cycles of wave oscillation, the detecting dipole will fill up its quantum-cup with the required $h\nu$ quantity of energy while releasing a photoelectron.

The Fig.3 is a qualitative representation of our core model behind the time-varying resultant stimulations received by the light detecting molecules due to random arrival of multiple pulses with time-varying density, along with both amplitude and phase variations for thermal lights, and mostly amplitude variations for laser lights. The resultant amplitude stimulation experienced by a photodetector will vary with time as the random pulses arrive on it:

$$i(t) = \sum_n \chi_1(\nu) a e^{-t_n/\tau} e^{i(2\pi\nu t_n + \phi_n)} \quad (5)$$

Eq.5 represents the generic amplitude superposition principle for n-pulses. Here, $a \exp(-t_n/\tau)$ is the common exponential light pulse envelope. The detector's linear dipolar stimulation strength parameter is $\chi_1(\nu)$ and $\exp[i(2\pi\nu t_n + \phi_n)]$ is the total time varying phase and ϕ_n is the absolute phase for the n-th pulse. The time-varying classical intensity flux is given by the square modulus of Eq.5:

$$I(t) = \left| \sum_n \chi_1(\nu) a e^{-t_n/\tau} e^{i(2\pi\nu t_n + \phi_n)} \right|^2 \quad (6)$$

The number of photoelectrons $N(t_n)$ released during different time slots around t_1 , t_2 , t_3 , etc., can be given by:

$$N(t_n) = \left[\int I(t_n) dt \right] / (h\nu) \quad (7)$$

Modern photon counting electronics is quite complex requiring enormous gain ($\sim 10^8$ or more) of the original single photoelectron into a clearly measurable photoelectron current pulse (PCP). The electronic system also has "dead times" in between generating PCP's, besides many other electronic complexities [21]. This is why the measured PCP's do not directly validate that the incident EM waves should be treated as "indivisible light quanta". Especially, when we know that the electrons are quantized particles and they are always bound quantum mechanically inside atoms and materials. The key point is that during the same δt intervals at times at t_1 , t_2 and t_3 (Fig.3), the superposed EM wave flux will be

delivering different quantities of energy, and hence would release different number of photoelectrons (Eq.7). As per coherence theory, the relative phases between many pulses and the temporal amplitudes at any moment would determine joint dipolar stimulation, as given by Eq.5 and Eq.6. The execution of the square modulus operation to fill up the quantum-cup with $h\nu$ quantity of energy would need at least a couple of cycles of the incident wave [16] by the oscillating dipole to determine its quantum compatibility with the incident frequency. This quantum compatibility dance is frequency resonant. All quantum mechanical processes (stimulation and decay) take a finite time. Attempts to measure the emission time of photoelectron is still not definitive, but recent finding implies it to be in the domain of ~ 100 fs [22].

Lamb and Scully [8] gave a semi-classical formulation for photoelectron emission. Greenstein and Zajonc [2] elaborated on it, as shown in Eq.8, where $P_k(t)$ is the probability of one photoelectron emission; X_{kg} is the Matrix elements for the states “k” and “g”; E_0 is the E-vector amplitude; ω is the frequency of the incident wave and ω_{res} is the resonance frequency of the bound electron.

$$P_k(t) = \frac{4 \left| X_{kg} \frac{eE_0}{2\hbar} \right|^2 \sin^2 \left[(\omega_{res} - \omega) \left(\frac{t}{2} \right) \right]}{(\omega_{res} - \omega)^2} \quad (8)$$

1.4. Why do we need to go beyond Einstein’s photometric equation?

Einstein’s photoelectric equation was constructed as an energy balancing equation to fit the measured variation in the *classical* kinetic energy of the released *free electrons*, which were decelerated by using *classical repulsive force* (Fig.4a). It is important to appreciate that this *classical physical process* of measurements that had generated the velocity-reduction data of free photoelectrons inside a vacuum tube, *does not model the physical process that had taken place inside the material to release the photoelectron*. Nonetheless, Einstein correctly understood that the phenomenon is a quantum mechanical one from the frequency-threshold in the measured data (Fig.4a) since the total absorbed energy is shared

$$h\nu = \phi_{work\ fn.} + (1/2)mv^2 \quad (9)$$

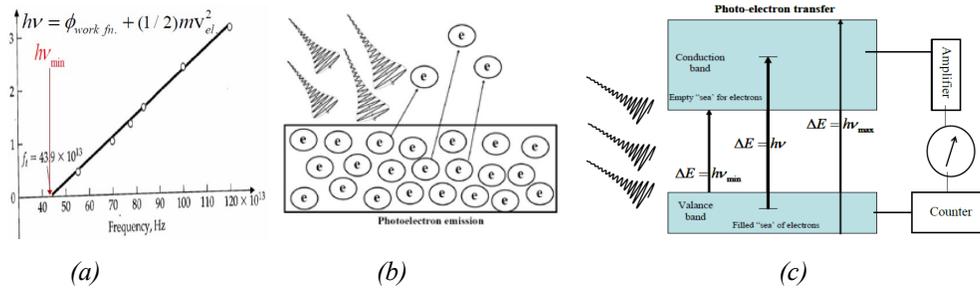


Figure 4. Einstein’s photoelectric equation, on the top of (a), is an energy balancing equation to fit the measured variation in the classical kinetic energy of the released free electrons. Einstein correctly assumed that the phenomenon is a quantum mechanical one from the observed “frequency threshold”. (b) Shows a cartoon of emission of photoelectron in free space. (c) Shows the internal band-to-band transfer of photoelectrons and external amplifying electronics to measure it as a current pulse.

between the “work function” and the “kinetic energy” of the electron. Similar conclusion could not be drawn for the photoelectron transfer, which takes place internally between energy bands of modern semiconductor photodetectors [see Fig.4c]. However, Einstein assigned the quantumness to Maxwellian light waves, instead of to the electrons, which are always bound quantum mechanically to all material atoms and molecules. Unfortunately, this was 1905. Quantum Mechanics was formulated during 1925-26. Even Bohr’s quantized Hydrogen model was published in 1913.

Of course, it was difficult for Einstein to visualize the physical light-matter interaction process inside the material and model the release of quantum mechanically bound electrons out in the free space of vacuum tubes (photomultipliers, Fig.4b), or released internally in modern semiconductor photodetectors (Fig.4c). Modern quantum mechanics models these *physical processes* quite efficiently using classical EM waves and quantum mechanically bound electrons. The oscillating E-vector-amplitude of perpetually propagating EM waves (Eq.3) stimulates the “oscillation amplitudes” of the complex material dipoles, strongly, if they are frequency resonant. If the local energy flux density of the EM wave is sufficiently strong to quickly fillup the quantum-cup of the stimulated dipole-complex, it absorbs the necessary cupful of energy $h\nu$ and releases the bound electron. It is a two step process, first the linear amplitude stimulation of the electron holding dipole ψ ; then the dipole-complex executes the QM operation, Eq.5 and 6, according to the QM recipe $\psi^* \psi$. Note that this is possible because both the classical Maxwell’s wave, Eq.3, and Schrodinger’s quantum equation, Eq.4, allow harmonic amplitude-amplitude light-matter stimulations before the quadratic step of energy exchange can be executed by material dipoles. This has been the built-in strength of these two powerful working theories. That is why Einstein’s model of bullet-photon, “indivisible light quanta”, cannot guide us to develop deeper understanding of the physical processes behind the phenomenon of photoelectric effect and the emergence of the statistics behind the photoelectron current pulses (PCP). We have been accepting the observed PCP statistics, without deriving it from the fundamental principle, as we attempted to do (Fig.3) in this paper.

1.5. Defining the “Push-Pull” concept and the rationale behind it.

In the world of various advanced quantum theories, the velocity of light is accepted as a fundamental constant, rather than deriving it from the fundamental principle, as does Maxwell’s wave equation, which is a consequence of the physical existence of the electric and magnetic tension properties in all media, $c_{med.} = (\epsilon_{med} \mu_{med})^{-1/2}$. However, QM has never succeeded in deriving or defining the actual physical size of the “bullet photons”, or the “indivisible light quanta”. Because of the NIW-property of light in free space, Fourier summation cannot be invoked to create a space-finite pulse out of many continuous waves; besides continuous waves cannot exist. Further, the mathematics of diffractively spreading and perpetually propagating classical waves cannot directly deliver the energy. Material bodies and particles must first respond to the waving electric vector and then execute the square modulus operation on the waves to absorb the energy proportional to the square modulus of the induced amplitude. This two-step mathematical recipe has been developed by both classical electromagnetism and quantum mechanics. This two-step physical processes behind photoelectric effect cannot be explained by Einstein’s photoelectric Eq.9.

The concept of the “bullet photon” has further problems. Propagating light beams are waving amplitudes and provides a well defined energy flux available to appropriately undulating material dipoles. However, the physical size of atoms are fairly well defined and validated to be around $\sim 1\text{A}$ (10^{-8}cm). Let us consider a typical collimated beam of Rb-resonant red light of frequency $\nu = 3.8 \times 10^{14} \text{ Hz}$, of intensity 1mW or 1mJ/sec is passing through Rb-vapor tube. The corresponding “photon” energy is $h\nu_{Rb} = 2.52 \times 10^{-19} \text{ J}$. A flow of 1mJ/sec of EM wave energy is equivalent to a flow of 3.97×10^{15} photons/sec. If the photoelectric electron emission takes 10^{-13}s or 100fs [22], then the number of photons passing-by through 1mm cross section is about ~ 400 photons/sec through a cross section of $\pi \times (0.1)^2 \text{ cm}^2$. We have assumed that the velocity of the light flux is still the same $c = 3 \times 10^{10} \text{ cm/sec}$. However, a physical atom offers only a $\pi(0.5 \times 10^{-8})^2 \text{ cm}^2$. Then, the number of “bullet photons” that can be intercepted by an atom is $\sim 10^{-16}$ photons during 100fs. However, in a real experiment of low pressure Rb-tube, one can find a glowing resonance fluorescence that can be easily seen by the naked eye and can be photographed in a regular laboratory table using a regular camera (see Fig.4b). Given the correctness of quantum mechanics, the delivery of the $h\nu$ quantity of energy is not in question. However, we definitely are missing the detailed physical processes involved behind this large fluorescence energy transfer to so many Rb atoms. Neither the Einstein’s “bullet photon” model nor the preferable semiclassical model are providing adequate physical explanation for the much higher rate of energy transfer process. The possibilities are that (i) the effective area of cross-section of energy collection by a resonant atom (quantum-cup) is many orders of magnitude larger than 1A atomic diameter, as shown in Fig.4a; along with (ii) a much higher local velocity of EM wave energy within this *quantum-cup*

region in the immediate vicinity of a frequency-resonant dipole. This second effect, just alluded to, may explain the interpretation of “collapse of the wave function”. However, we believe that an energy absorbing dipole has to execute at least one complete cycle of dipolar-oscillation with the incident field to assess whether the incident wave frequency is compatible with its internal quantum structure. Implication of this quantum-compatibility dancing is that the photoelectron emission cannot be faster than ν^{-1} sec, or 2.5 to 1.25×10^{-15} sec (the frequency range for

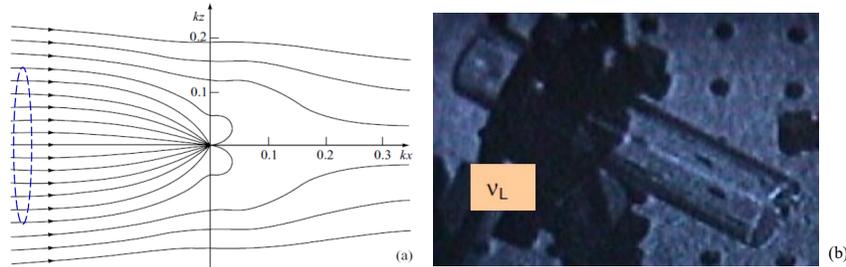


Figure 5. Left, (a): “Push-Pull”, or “suction effect” of convergence of the EM wave field lines, on to a frequency-resonant dipole, which allows a miniscule dipole to absorb energy out of a very large volume of space. Classical antenna theory can be used to draw the energy converging lines of Poynting vectors [3, 23], as in (a). However, for complex quantum atoms, the diameter of the dashed-blue circle could be 10, 100 wavelength, or larger, for quantum atoms, yet to be theorized properly. Therefore an one Angstrom size atom can pull in energy out of a much larger cross section. Right, (b): The photo shows a low-pressure Rb vapour lamp illuminated by less than 1mW 780nm resonance laser light beam [24]. Although faint, the visible glow implies that the number of “bullet photons” intercepted and emitted by the 1A-size Rb-atoms in the photo must be the result of absorption/emission out of a very large number of “photons”, and not $\sim 10^{-16}$ photons as calculated in the above text.

visible light is ~ 4 to 8×10^{14} / sec). Further, transition from an excited quantum state to its ground level (the release of an excited electron) always have a finite lifetime.

Another way to look at the quantum cup of Fig.5a is the existence of a push-pull energy transfer process. The “push” concept is already built into the wave equation [16, 18]. Maxwell’s wave equation clearly implies a perpetual velocity of light, which is validated by the fact that EM waves can travel across the entire galaxy with the same velocity $c_{vac}^2 = \epsilon_0^{-1} / \mu_0$ leveraging the electric tension, ϵ_0^{-1} , and the magnetic resistance, μ_0 [18]. The velocity of the light emitting source has no contribution to the velocity of light. Source velocity results in the Doppler Effect. If we re-derive the Maxwell’s wave equation using Newton’s second law [18], one can appreciate that the electromagnetic tension field is perpetually trying to restore its energetic quiescent state at every location of the propagating wave by pushing it farther away. The wave equation for a mechanically stretched string works exactly the same way. The implication is that the electromagnetic tension field of the free space is constantly *pushing away* the EM waves, once created, or imposed on the tension field by the energy releasing dipole. This perpetual “pushing away” of the perturbation (waving) energy could be interpreted as if the parent tension field is always searching for a sink to get rid of this energy. We can now appreciate the classical theory, developed for radio and cellphone communications. The frequency-resonant dipole antenna *pulls* in the waving energy out of a much larger volume than its physical cross section. We know that classical resonant LCR oscillators can keep on absorbing radio or cell phone waves as long as they circuits are “on”. For quantum atoms, they only have a finite “quantum cup” that can be filled up only once at a time. Then they need to be recycled. The “pull” concept is indirectly modeled for a classical dipole as “suction effect” where the energy absorbing field lines of force (Poynting vectors) converge into the small-stimulated dipole antenna out of a wide forward field [p.53 in 3, 23], as shown in Fig.5a. Since the atoms are truly quantum mechanical and much more complex than classical LCR-dipoles, this conceptual theory needs a much more careful and detailed mathematical development.

1.6. Does granularity in photographic and photoelectric record validate existence of light with granular structure?

One of the key issues we need to appreciate in measuring and quantifying the energy of visible light is that the electromagnetic waves propagate as Maxwellian oscillating wave *amplitudes with a finite velocity, c*, not directly as

continuous energy, or as energy bullets. Detectors resonate to these EM oscillating wave amplitudes and then absorb energy through their square modulus action on the waves, which is the synergy between the Eq.3 and Eq.4, as mentioned earlier. Light does not flow as ‘so many indivisible light quanta’ per unit time per unit area. For the visible domain, unlike in the radio domain, we cannot directly quantify this amplitude. We have to back-calculate. We quantify the detected light energy E_d over a finite period of Δt , then define the intensity as energy flow per unit time, $I(t) = E_d / \Delta t$. Then we back-calculate the amplitude of the wave as the square root of $I(t)$ and represent the Maxwellian wave as $\sqrt{I(t)} \exp[i2\pi\nu t]$. However, when the detector is quantum mechanical, Einstein’s photoelectric equation correctly gives the energy absorbed for the release of each quantum mechanically bound electron as $h\nu = \phi_{\text{work fn.}} + (1/2)mv^2$. *This quantization of the absorbed energy is due to the electron being bound quantum mechanically*, and not because the Maxwellian field itself is quantized. Planck also believed that light propagates diffractively [25]. Of course, we can also claim that we have detected $n = E_d/h\nu$ photons, since Einstein’s equation is mathematically correct as an energy balancing equation. Here, we need to appreciate that for centuries, the consistently thriving fields of optical science and engineering have been advancing uninterrupted using the mathematics of Maxwell’s set of equations and the Huygens-Fresnel diffraction integral. Quantum Mechanics has not succeeded in developing any improved versions that can replace Eq.1, Eq.2 and Eq.3. Unlike Maxwell’s wave equation, QM has not even derived the velocity of light. It just uses “c” as a fundamental constant; even though, in reality, it is a derived secondary parameter out of ϵ_0 and μ_0 for free space, which are more fundamental and functional physical parameters representing the physical properties of the free space. With this background, let us explore whether the granularity of light detection can really validate the “granularity”, or the “quantumness” of light.

Both the photographic emulsion (with embedded Ag-Halide crystallites) plate and the modern CCD array have physically granular structure, random crystallites and pixels, respectively, of different sizes to create high-resolution pictures (Fig.6(i)). They are frequency sensitive quantum detectors. Therefore, all such records, when enlarged sufficiently, will show the granularity in the recorded images due to the finite “pixel” sizes, irrespective of the total exposure level (intensity x time). The physical exposure process for both these recording materials are quantum mechanical. Optical frequency sensitivity bands for both of these types of recording materials are broadband and must match the frequency-band of the light used for recording. E-vector of the light must resonetically stimulate the light detecting material dipoles.

When we reduce the intensity of the light beam, or the rate of flow of amplitude-waves, falling on an array of quantum detectors, we reduce the probability of energy availability per pixel. Because of the joint push-pull response of the field and the resonant dipoles, and the convergence of the beam flow lines of the inflowing waves (Fig.5a), some neighboring pixels are statistically deprived from the incoming energy to fill up their quantum cups due to statistical competitions. With longer and longer exposures, more and more quantum cups are filled up and, effectively, are removed from the mutual competition, and the unfilled cups acquire the opportunity to fill up their cups (Fig.6(ii)). Consequently, at very low intensity flux, a longer period of exposure is essential to obtain higher density of exposed pixels. This is congruent with the suggested “push-pull” concept of interactions between quantum dipole and classical Maxwellian EM waves for the transfer of a quantum cupful of energy $h\nu$ to each quantum event.

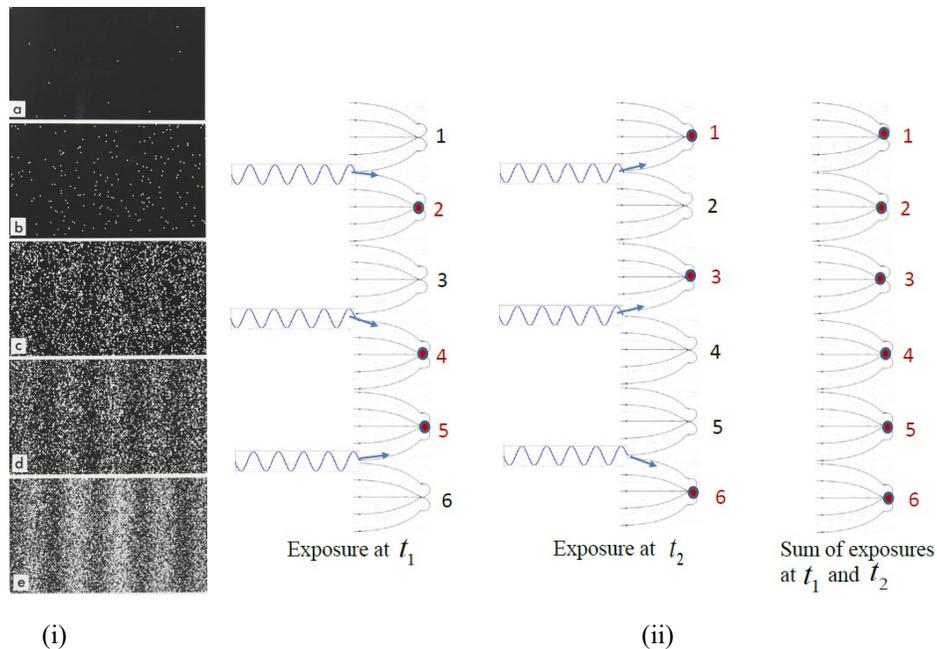


Figure 6. Origin of granularity at low light level is due to the “quantum cup” filling property of the frequency-resonant and energy-sucking quantum dipoles, the field-dipole interaction process and mutual competition for energy. Left vertical line of photographs, copied from a well-known double-slit pattern, shows the build-up of granularity towards well-defined double-slit fringes with increasing exposure from (a) to (e). On the right are three layers of cartoons dipoles with their “Push-Pull” dipolar energy absorption lines, as in Fig.5a, with “low intensity” wavy incident light. At the exposure moment t_1 , the dipole-pairs (1, 2), (3, 4) and (5, 6) compete for the same low flux. The cartoon shows that the dipoles 2, 4 and 6 “wins”. They absorb the necessary energy to fill up their quantum cups. When a new batch of energy comes in, the dipoles 1, 3 and 6 have the opportunity to absorb the necessary energy and receives the exposure without any competition. Thus, the origin of the temporal evolution of granular exposure can be understood better without the arrival of discrete “bullet photons”.

1.7. Smoothing the temporal flow of pulsed energy flux.

Most classical theory of optical phenomena have been derived by using continuous waves (CW) since that used to be the standard experimental observations, using very slow response of human eyes and the photographic plates., until the invention of fast photo diode and fast photomultipliers. However, by this time and until today, Einstein’s “bullet photon” or the wave-particle duality has remained the dominantly accepted model for light and the noisy statistics of the detected photoelectric current pulse (PCP) is assumed as temporal distribution of arrival of “bullet photons” on the detector. This temporal distribution is assumed to be the characteristics of the light sources (thermal, laser, nonlinear conversion, etc.).

However, as explained earlier, we are integrating the concepts of Newtonian “corpuscles” (at the moment of atomic emission) with Huygens’s secondary wavelet as diffractively propagating of time finite exponential pulses. The emission moments of such light pulses will be completely random out of thermal sources, and somewhat less random out of lasers due to the physics behind stimulated emissions.

We are now introducing a well-known multiple beam, plane-parallel-mirror Fabry-Perot interferometer (FPI), also used as a high-resolution spectrometer. The key classical property of a plane parallel Fabry-Perot spectrometer is to replicate the incident pulse into a discrete train of pulses with diminishing amplitudes and a periodic round-trip step-delay, as depicted in the Fig.7. Superposition of these delayed train of pulses on a time-integrating detector, generates the classical spectral distribution of the output energy [Ch.5 in 16]. We are using the pulse replicating property as a tool to smooth the amplitude variation, and hence the intensity variation. When there are many random pulses, whether out of thermal or

laser sources, they should generate smoother intensity variation on a photodetector and hence, reduce the range of statistical fluctuation in the count of the photoelectron current pulses (PCP).

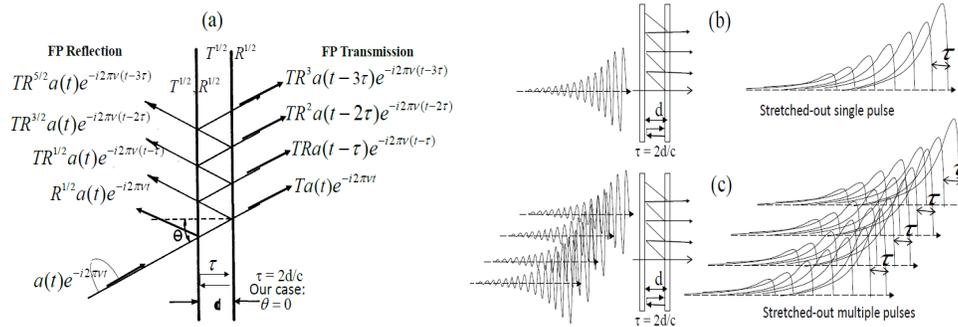


Figure 7. The key classical property of a plane parallel Fabry-Perot interferometer (FPI) is to replicate the incident pulse into discrete train of pulses with diminishing amplitudes and a periodic round-trip step-delay, as depicted in the diagram. The fixed periodic delay keeps them in phase. (a) Quantifying the series of reflected and transmitted rays by an FPI. (b) The replication of a single pulse and the resultant time-stretched output. (c) Replication of multiple delayed pulses into a longer time-stretched pulse. (b) and (c) effectively generates smoother intensity fluctuations over a longer period. This would result into smoother fluctuations in the photoelectric current pulse statistics [26].

For a given input pulse $a(t)$ on to an FPI, the expression for the output amplitude-pulse-train would be given by:

$$i(t, \nu) = \sum_{n=0}^{M-1} TR^n a(t - n\tau) e^{i2\pi\nu(t - n\tau)}; M \approx \text{"Finesse"} \equiv \pi\sqrt{R}/(1 - R) \quad (10)$$

The corresponding temporal output intensity variation for a given FPI round-trip delay τ is the square modulus of Eq.10:

$$|i_{pls}^{norm}(t)|^2 = \sum_{n=m=0}^{M-1} T^2 R^{2n} a^2(t - n\tau) + 2 \sum_{n \neq m} T^2 R^{n+m} a(t - n\tau) a(t - m\tau) \cdot \cos[2\pi(n - m)\nu\tau] \quad (11)$$

Theoretically, the summation should be infinite. However, since the amplitudes of the consecutive transmitted pulses keeps decrease by the factor TR^n , the sum can be terminated by the finite number M, which can be the classical finesse number for the FPI [Ch.5 in 16]. This can be judiciously chosen depending upon when the effective energy carried by the M-th pulse becomes negligible. With this pragmatically chosen value of M, we have defined the effective stretched-out output duration of the transmitted pulse as $\tau_0 = M\tau$, where τ is the one round-trip delay of the FPI. Since we do not accept the "bullet photos" model, we do not recommend the concept of the "photon life time" inside a passive Fabry-Perot cavity. Besides, the light-matter interaction properties of a pair of parallel mirrors are completely characterized by the classical boundary conditions of amplitude reflectivity $R^{1/2}$ and the amplitude transmissivity $T^{1/2}$. There is nothing quantum mechanical about this multi-century old classical light-matter interactions process with the boundary reflection coating of the mirrors.

We are considering a collimated input beam of very narrow frequency band, and incident exactly orthogonal to the parallel pair of mirrors. This implies that the all the Poynting vectors, orthogonal to each one of the wave fronts, are parallel and coincident to each other. This has the consequence that the boundary layers of each of the FPI mirrors execute the *amplitude superposition operation* implied by the Eq.10 and transmits the resultant time-varying amplitude determined by all the time varying amplitudes and the phase factors in Eq.10. For our proposed amplitude smoothing, the round-trip delay in the FPI would be set to resonance transmission, $2d = m\lambda$, or $\nu\tau = m$ (integer). Under this resonant transmission condition, the Eq.10 simplifies to Eq.12, since the factor $\exp[i2\pi n(\nu\tau)]$ reduces to unity for all n:

$$i_{FPI}(t) = T \left(\sum_{n=0}^{M-1} R^n e^{-(t-n\tau)/t_0} \right) e^{-i2\pi\nu t} \quad (12)$$

When this output amplitude is incident on a photodetector of linear dipolar polarizability $\chi(\nu)$, its dipolar amplitude stimulation would be given as:

$$i_{phot.det.}(t) = T \chi(\nu) \left(\sum_{n=0}^{M-1} R^n e^{-(t-n\tau)/t_0} \right) e^{-i2\pi\nu t} \quad (13)$$

The corresponding time varying intensity flowing through the photodetector would be:

$$I_{phot.det.}(t) = |i_{phot.det.}(t)|^2 = T^2 \chi^2(\nu) \left(\sum_{n=0}^{M-1} R^n e^{-(t-n\tau)/t_0} \right)^2 \quad (14)$$

The electrons are bound quantum mechanically inside the photodetector material. Hence the release of each electron will require filling up the corresponding quantum cup with the required amount of energy out of the propagating EM wave amplitude over a finite time duration, however, small that could be. See the proposed models in Fig.3, Fig.5 and Fig.7. We are simply accepting the correctness of Maxwell's wave equation that EM waves keep propagating as *waving amplitudes* with a velocity $c = (\epsilon\mu)^{-1/2}$.

The corresponding time-stretched intensity is represented by Eq.14. Fig.7 (b) and (c) represent the cartoon versions of time-stretched amplitude output (without summing them). The bottom curve of Fig.3 gives a sense of the intensity that would be flowing through a photodetector. This model of intensity-smoothed output will create photoelectron current pulses (PCP) with less statistical fluctuations compared to using the unfiltered light directly on a photodetector.

We want to underscore that this is not due to the spectral filtering (narrowing) effect by a Fabry-Perot, even though it can do that as a spectrometer. Besides, most photodetectors usually have very wide band frequency sensitivity. The resonant transmission of a Fabry-Perot is dictated by the real physical phase matching condition of, $2d = m\lambda$, or $\nu\tau = m$ (integer), as has already been mentioned. We have proposed 1ns pulses with a *single carrier frequency*. While, by Fourier theorem, a one nano second pulse would have 1 GHz spectra bandwidth, a liner pair of partially reflecting mirror cannot execute the Fourier algorithm because it does not have the capability of, first, reading the temporal pulse shape, then storing the pulse-shape information in some memory bank, and after that, execute the Fourier integral transform! A Fabry-Perot interferometer is merely a passive pulse replicator. For spectrometric interpretation of the Fabry-Perot output, the Eq.11 has to be integrated by a detector with an exposure period long enough to accommodate the entire replicated pulse train [Ch.5 in 16].

1.8. Suggested experiments to validate the proposed amplitude smoothing technique.

One can find in the literature that the measured PCP statistical spread from different light sources show different widths. We show this in the upper-left inset of Fig.7 [5]. Super-Poissonian spread is generally shown by thermal light sources. The narrower Poissonian spread is due to laser light sources and even narrower spread is from sources like those generated by non-linear down conversions.

A He-Ne laser could be a low-cost source to use for validating the amplitude smoothing capability of a high-finesse FPI (see Fig.7). The axial beam is the standard He-Ne laser beam. This laser beam, when evaluated directly, should generate PCP's with the Poissonian statistical fluctuations. This is because even the stimulated in-phase emissions within a gas laser medium will not generate a perfect CW wave, even though the average energy flow will be CW. There will be a resultant random amplitude variation as depicted in the cartoons of Fig.2. Now, if we send the laser beam first through a

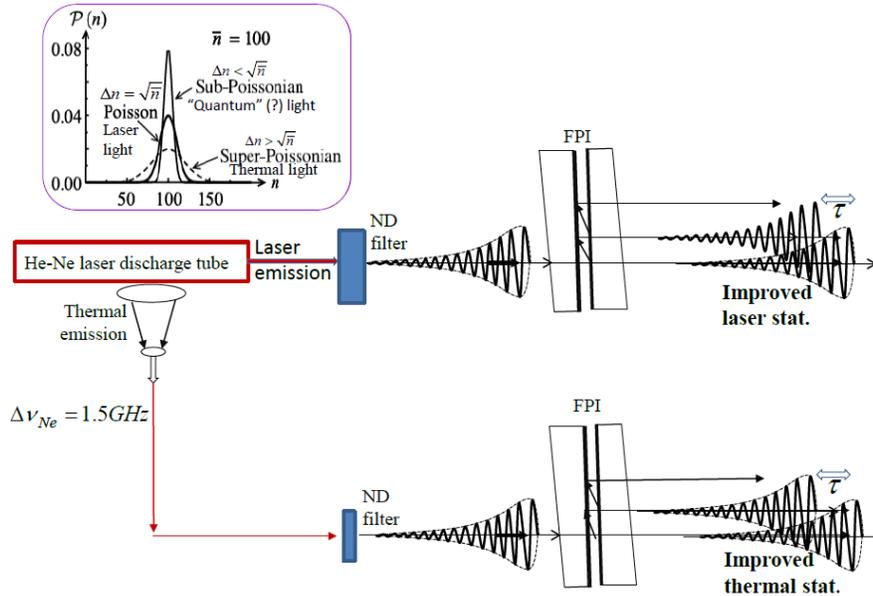


Figure 8. Fabry-Perot Interferometer, being a pulse replicator [26], can be used as a tool to smooth out the amplitude fluctuation of intrinsically pulsed light. The sketch indicates the possibility of demonstrating amplitude smoothing and narrowing the spread of photoelectric current pulse (PCP) statistics of both laser light and thermal light using a He-Ne gas laser tube. Upper-left inset [5] shows the characteristics curves of PCP statistics for different light sources.

resonant FPI (see Fig.8, upper FPI), then, as shown in Fig.6c, the resultant amplitude stimulation and the corresponding energy transfer to a photodetector will become smoother and the PCP statistics should change from Poissonian towards the sub-Poissonian narrower curve. The degree of narrowing can be enhanced by using a resonant FPI with higher and higher reflectivity and thinner spacing between the mirrors. Normal He-Ne laser will have several very narrow longitudinal modes spread over 1.5 GHz due to the in-homogeneously Doppler-broadened spontaneous emission line width of Ne-atoms. The free spectral range, or FSR, is given by $\Delta\nu_{fsr} \equiv c / 2nd$. Therefore, a regular FPI with a spacing thinner than 10cm will give the necessary 1.5 GHz FSR. However, a much narrower spacing would be needed to smooth the amplitude variation, which will automatically provide a much wider frequency transmission band than the needed 1.5GHz [27]. We also need high reflectivity mirrors to generate long train of closely spaced resonance replication of each of the incident pulsed light in the incident beam. This high finesse is given by $M_{fns} = \pi\sqrt{R} / (1 - R)$. Then the frequency transmission bandwidth at resonance is $\delta\nu = \Delta\nu_{fsr} / M_{fns}$. For mirror reflectance of 0.99 and a 30cm He-Ne laser cavity, one should easily be able to select the resonance transmission of a single longitudinal mode of the laser by tuning the FPI mirror spacing. We are working on the numerical modeling of the proposed model for future publication. If our conceptual model is correct, then a gas laser beam, amplitude smoothed through a resonant FPI, could serve as a lower cost source with narrower than Poissonian statistical spread. Then, one could also use a multi-pass FPI to obtain even narrower than Poissonian curve.

To validate the proposed concept for achieving narrower statistical fluctuations out of thermal light, we suggest that one collect the Ne-spontaneous emission from the side of the He-Ne laser tube and send it through the same FPI tuned for maximum intensity transmission (the peak of the Gaussian broadened spontaneous emission). In this case, only the individual spontaneously emitted pulse would generate in-phase long train of pulses. The original phase randomness between different pulses will remain as such.

Both of these above experiments would be very valuable to validate that light generated out of individual atoms and molecules are pulses (Newton's "corpuscular") and they remain so while propagating through homogeneous media as per

Huygens' Non-Interaction of Waves. However, when they jointly encounter boundary layer materials, the phase-dependent *collinear Poynting vectors* facilitate re-structuring of the amplitudes in transmission and reflection. The FPI and Mach-Zehnder Interferometers tuned to modulo- 2π relative phase delay and illuminated with light beams with perfectly collinear Poynting vectors, one can easily observe the *classical* re-direction of wave energy or the superposition effect; no quantum interpretation is necessary. These are well-established examples of pure classical superposition effect and re-direction of energy of Maxwellian waves. We also know this through the generation of single mode light beam output through a long single-mode fiber while focusing a thermal multimode beam into it. The "bullet photon" model cannot generate such temporal and/or spatial evolution of mode behavior out of different light beams.

2. CONCLUSION AND DISCUSSIONS

We have attempted to extend and strengthen the semiclassical model of light-matter interaction, paying special attention to the detailed *physical processes* that do not appear obvious just from our current emphasis only on the theories that are successfully validated by the data. We have chosen to elaborate on the photoelectric effect because of its unusual importance (i) in fundamental physics, (ii) in the continuing and persistent debates on the wave-particle duality (WPD) since the times of Newton and Huygens, and (iii) the global engineering/technological interests to construct quantum computers using "single photons" and "entangled photons" sources. We believe we should strive for a much deeper understanding of the physical nature of light.

The physics community understood for quite some time that Einstein's photoelectric equation does not model the detailed physical processes behind the stimulation and release of quantum mechanically bound electrons within materials [7-10]. Even Einstein, towards the end of his life, lamented that his model of 1905 of "indivisible light quanta", which earned him his Nobel Prize, was not correct. Therefore, emphasis on utilizing physics models that are very weak in interaction process visualization, could slow down the progress in physics. At the same time, we should pay closer attentions to successful mathematical theories and leverage them to explore deeper into the invisible interaction processes, which they could reveal. We see that the mathematical theories from two different domains like the set of Maxwell's classical equation and the Schrodinger's quantum equation have been working successfully in tandem. Therefore, we should not ignore the guidance they can provide. Studying light-matter interactions has given us the broadest platform to understand the macro and the micro universe. Maxwell's equation models how to propagate EM waves through complex materials or free space. Unlike Schrodinger's equation, Maxwell's wave equation does not have any interaction term. Light beams, by themselves, do not interact in the absence of material dipoles. This is Non-Interaction of Waves (NIW) [16]. These two equations represent, first, the amplitude-amplitude stimulation at the initiation of the light-matter interaction process, and then the energy exchange as the *square modulus of the amplitude stimulation*, executed by the interacting material dipole. Therefore, even for the Schrodinger's equation, light must provide the frequency-resonant amplitude-amplitude stimulation first. Hence, light cannot be traveling as bullets of *energy*. In other words, our proposed model of photons as a classical wave of frequency ν under an exponential time-envelope bridges the successes of these two equations.

Successful engineering tool making requires emulating *nature allowed processes* in any particular phenomenon we try to exploit, irrespective of whether we have developed a perfect theory to explain the phenomenon. For example, by simply learning to generate, modulate, propagate and detect EM waves, we have succeeded in ushering in the Knowledge Age, through the global fiber-optic communication network, without resolving the wave-particle duality. Deeper understanding of nature allows us to invent more tools. Einstein's mathematical conjecture and formulation of "Stimulated Emission" eventually gave rise to the invention lasers. Now we cannot even imagine a world without lasers. Therefore, a further and deeper understanding of the physical *interaction-process-model* of light in every step of generation, propagation, modulation and detection would help us invent many more tools of great utility [16]. Modern optical scientists and engineers need to take active roles in advancing new physics as they were doing during the entire century of 1800.

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