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Do we count indivisible photons or discrete quantum events experienced by detectors?

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ABSTRACT

As low light detection technologies are advancing, novel experiments like single molecule spectroscopy, quantum computation, quantum encryption are proliferating. Quantum mechanical detectors can produce only discrete "clicks" at different rates based on the propagating field energy through them, irrespective of whether the photons are divisible or indivisible packets of energy. This is because electrons are quantized elementary particles and they are always bound in quantized energy levels in different quantum systems. Highly successful quantum formalism is not capable of providing the microscopic picture of the processes undergoing during QM interactions; that is left to human imaginations allowing for sustained controversies and mis-interpretations. This paper underscores the paradoxes that arise with the assumption that photons are indivisible elementary particles based on the obvious but generally ignored fact that EM fields do not operate on (interfere with) each other. Then we propose that atomic or molecular emissions emerge and propagate out as space and time finite classical wave packets. We also suggest experiments to validate that the amplitude of a photon wave packet can be split and combined by classical optical components using the specific example of an N-slit grating.

Key words: single photon counting, photo detection, non-interference of light, non-interaction of EM fields, divisible photon wave packet.

1. INTRODUCTION

The current scientific culture accepts that light energy constitutes discrete indivisible packets of energy, we call photons. The concept is supported by underscoring that in all photoelectric emission experiments only an integral number of electrons are emitted. But electrons being quantized themselves and always bound to quantized energy levels, discrete photoelectron emission does not establish beyond doubt that the EM field energy constitutes only indivisible packets of energy. Let us briefly review the origin of the quantized photon concept. A little over a century years ago in 1903 Planck introduced the concept that light energy is emitted and absorbed by atoms and molecules with discrete quantized amount of energy $h\nu$ and a unique carrier frequency ν. His idea was to correctly map the measured energy distribution of frequency-continuous blackbody radiation. His proposal also easily accommodated the measured discrete frequency spectrum of many gas-discharge emissions, both terrestrial and cosmic, given by already known Rydberg formula. But Planck never accepted that the photons themselves, containing quantized energy at emission,

were indivisible packets as they propagate out. Einstein proposed in 1905 that the photons might behave like indivisible packets of energy to explain the contemporary photoelectric emission experiments. However, he was strongly doubtful in the later part of his life whether he understood what a photon is [see, for example, the beginning of page S-2 of ref.1]. Because of such prevailing doubts, we took the effort to publish the reference-1 that brings together the views of five global experts in quantum optics. Recently Goulielmakis et. al. [2] has published a paper describing the successful direct measurement of the sinusoidal undulation of the electric field strength of a carefully generated laser pulse with Gaussian-like envelope containing barely five cycles of light. If this pulse consisted of indivisible photons, then the electric vectors of the photons in the pulse were marching in remarkable unison to each other mimicking Maxwell's classical description of an EM pulse. Since laser pulses are manipulatable by various established techniques, one can conclude that the photons can have flexible temporal amplitude envelopes. Then we face the contradiction that a photon with a uniquely defined frequency ν at the moment of emission can have different temporal envelopes as it propagates through different optical systems that manipulates the pulse shapes. This would conflict with the time-frequency Fourier theorem that customarily dictates what the spectrum of a time-finite signal should be. Lamb, whose work gave credence to the quantum electrodynamics, also has shown consistent critical views against associating a discrete photon with the emission of a discrete photo electron [3, 4]. Further, Panarella [5] has experimentally demonstrated that a minimum of four photon equivalent energy is required to detect discernable diffraction pattern at very low light levels. This clearly raises doubt regarding one-to-one correspondence for photoelectron emission. Comprehensive classical and quantum treatments of photo detection processes are given by Mandel and Wolf [6].

This paper underscores the reasons for holding healthy doubts against the concept of photon as an indivisible elementary particle. *We propose that photons are space and time finite classical wave packets that propagate out from light emitting atoms and molecules following Huygens-Fresnel principle.* Our key logical platform derives form the commonsense fact, neglected in the books and literature that electromagnetic fields do not interfere with or operate on each other. Well formed light beams cross through each other without redistributing their spatial or temporal energy distributions. *The effects of superposition of EM fields become manifest when the right detector molecule, allowed by QM rules, is able to respond to all the fields superposed on it, there by summing all the filed induced effects and absorbing proportionate amount of energy*. QM formalism does not restrict simultaneous energy absorption from multiple sources. In fact, that is what the prescription given by the Superposition Principle. We have spent considerable amount of time looking at the various aspects of optical phenomena where two or more optical beams are simultaneously superposed, but the superposed EM fields do not interfere [7-17]

In section 2 we discuss Einstein's photoelectric equation to emphasize the role played by detectors (atoms and molecules). In section 3, we present the semi classical description of the photo detection process. In section 4, some examples of the physical world that create paradoxes if we use the notion that light beams interfere with each other by themselves. Section 5 presents results and implications of an important experimental observation made by Panarella [5] using low level light. In section 6 we discuss our photon wave packet model (rapidly rising exponential pulse envelope amplitude) and compare with a pure exponential model. The finite time and finite energy associated with photo induced transitions is discussed in section 7. In section 8 we discuss the implications of our divisible photon model.

2. EINSTEIN'S PHOTOELECTRIC EQUATION

Our position is that Einstein's photoelectric equation does not establish photons as indivisible packets of energy beyond any doubt. Since electrons are quantized elementary particles, they can be detected only as indivisible particles. Also electron transition (binding) energy is always quantized to a characteristic value $\Delta E = h\nu$ in all quantum systems. A particular quantum system must first undulate like a dipole at a frequency ν while holding the electron before it can absorb energy ΔE and release the electron. Einstein's 1905 paper on photoelectric effect reflects the experimental observations of Hertz (1887) and others after

him. In all these early experiments electrons were released free from metal plates and measured as a current through a collection plate whose voltage was manipulated to measure the kinetic energy of the free electrons. Einstein correctly formulated the observed results as if a photon carries a packet of energy $h\nu$ which is expended to provide the binding energy of the electron in the metal (work function) and the rest is used by the electron as its kinetic energy (KE) as a free particle. This is a bound-free transition:

$$h\nu = \text{Work function} + \text{Electron KE} \quad (1)$$

In contrast, electrons in modern photo detectors undergo bound-bound transition. These detectors, including "single photon" counters, are essentially semiconductor p-n junction devices where electrons experience quantum mechanical (QM) level transition from valance to the conduction band after absorbing energy from an incident EM field. The conduction band electrons are then measured as a photoelectric current by applying external voltage across the p-n junction. In this bound-bound QM transition kinetic energy does not play any explicit role. The transition can take place as long as the incident EM field frequency is such that the equivalent photon energy $h\nu$ is bounded by:

$$\left(\Delta E_{\min} =\right) h\nu_{\min} \le h\nu \le h\nu_{\max} \left(= \Delta E_{\max}\right) \quad (2)$$

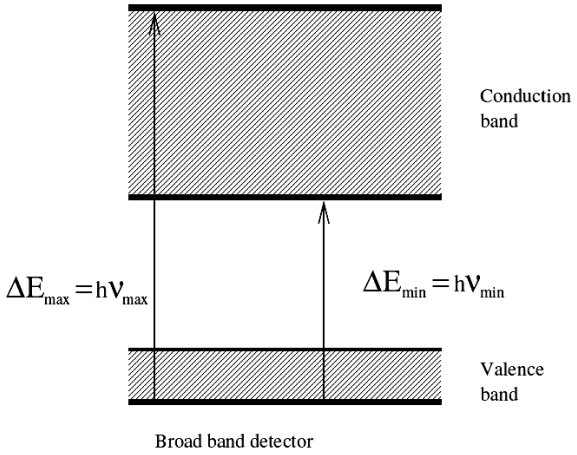

Figure 1. A photon with a higher energy than $h\nu_{\max}$ will not transfer an electron to the conduction band. Unlike Einstein's photoelectric equation, higher frequency (energy) "photon" does not get counted.

A photon with higher frequency than $h\nu_{\max}$ will not help transfer an electron to the conduction band. Such EM radiation will not be detected by the photo detector. A silicon detector can be damaged by intense x-rays, but as a device it will keep on reporting that it is in "dark".

The physical process behind Einstein's photoelectric emission in free space is very different from photo induced photoconduction inside semiconductors (p-n, p-i-n, APD, etc.). In the first case, electrons are stimulated to acquire kinetic energy from the field and then use a portion of that energy to overcome the binding energy of the metal; the rest of the kinetic energy remains measurable externally. In the second case, electrons undergo pure band-to-band QM transition without acquiring any freely available kinetic energy. In fact, avalanche photo diodes (APD) have been constructed where one applies voltage gradient across the detector to provide extra kinetic energy to the conduction electron such that it can generate more charges via collision to provide photoconductive gain within the same structure [18]. Let us carefully recapitulate: (i) Electrons are quantized, (ii) their binding energies within the material are quantized and (iii) their release or QM level change is always stimulated by dipole-like stimulations requiring unique frequency ν of the EM fields (relations 1 and 2). Thus, photoelectric emission or photoconduction current will always consist of discrete number of electrons requiring trigger by unique frequency of the EM field. Accordingly, we cannot unambiguously claim that propagating EM field energy definitely consists of discrete, indivisible packets. Quantized energy exchange behavior $h\nu$ and their dipolar behavior with

characteristic frequency ν may be sufficient to explain relations 1 and 2 without quantizing the EM field itself [3, 4, 19].

3. SEMICLASSICAL MODEL ADEQUATELY EXPLAINS PHOTO INDUCED TRANSITIONS

It is well recognized that for most of the normal photoelectric detection, the semiclassical model (without quantization of the EM field) is adequate (3, 4, 19). Here we will underscore the key process undergoing behind photo induced transition that are obvious in the semiclassical model. Any EM field incident on a material body will attempt to induce dipolar undulation in the constituent atoms and molecules. The total polarization $\vec{P}(t)$ is the sum of linear polarizability χ_1 and all the non-linear polarizability χ_n (n>1), which are intrinsic properties of the medium dictated by the quantum properties of the constituents.

$$\vec{P}(t) = \chi_1 \vec{E}(t) + \chi_2 \vec{E}^2(t) + \chi_3 \vec{E}^3(t) + \ldots \tag{3}$$

where $\vec{E}(t) = \vec{a}(t)\exp[2\pi\nu t]$

Normally $\chi_n \ll 1$ for quantum mechanically un-allowed frequencies. When the field frequency ν matches with the required energy exchange relation,

$$\Delta E = h\nu \tag{4}$$

the polarizability χ_1 is strong and the atom undergoes through the quantum transitions by absorbing the required amount of energy $h\nu$ if it is available from the field within its vicinity. The detector current is then given by the standard square modulus of the field:

$$D(t) = \left|\chi_1 a(t)\exp[2\pi\nu t]\right|^2 = \chi_1{}^2 a^2(t) \tag{5}$$

4. PARADOX OF NON-INTERFERENCE OF LIGHT

It is quite common to explain that no photons arrive at the location of dark fringes in a two beam interferometer (Mach-Zehnder, Michelson, Young's double slit, etc.). The implication is that it does not matter whether the light beam contains one or multitude of indivisible photons, the outcome will always be the same. If photons are really indivisible packets of energy and "photon interferes only with itself", then why do we need phase and frequency coherence properties between different parts of a light beam? Our viewpoint is that the belief in "single photon interference" is a highly flawed simply because light beams do not interfere with each other, whether they contain one photon or trillions of photons. Both classical and QM mathematical formulations tacitly assume that EM fields do not interact with (operate on) each other. Then how can crossing light beams redistribute the field energy by themselves? Our model of expanding universe is based upon the measurement of Doppler frequency shifts of light from distant stars. Light from specific stars and galaxies from many light years distance away are always crossed by trillions of the light beam from other stars. Yet the Doppler shift remains unchanged characteristic signature of each individual star. In our daily life, we have no problem recognizing a face from a distance even though the image carrying beam had to cross multitudes of other the light beams going in different directions. Well formed light beams do not interfere with each other. They pass through each other unperturbed in the absence of interacting molecules (detectors). Light does not interfere with light. This is why the WDM communication system works. We combine a large number of communication channels by wavelength domain multiplexing (WDM) using light beam with a distinct set of frequencies and send them through a common path of hair-thin fiber of tens of kilometer and we separate each channel by demultiplexing without loosing any data. If light beams of different frequencies interacted on each other by themselves, the output signal would have become chaotic pulses.

But we do record and measure the absence of any EM field energy at the dark fringes due to superposition of coherent beams on a detector array or a photographic plate. For two superposed coherent beams of equal amplitude with a delay τ, the detector response produces sinusoidal fringes:

$$D = \left| \chi_1 a e^{i2\pi\nu t} + \chi_1 a e^{i2\pi\nu(t+\tau)} \right|^2 = 2\chi_1{}^2 a^2 \left[1 + \cos 2\pi\nu\tau\right] \quad (6)$$

At a location where the two equal amplitudes fields are undulating with opposite phases, the detector dipoles cannot execute opposing dipolar undulations at the same time. So they are not stimulated and hence they cannot absorb energy from superposed fields. EM field energy passes through them since they cannot redistribute their field energy by themselves [11].

5. PANARELLA'S LOW LIGHT LEVEL EXPERIMENT

In view of the persisting claims of "single photon interference" for almost a century, we want to draw attention of the readers to a publication by Panarella [5]. He carried out the measurements of the diffraction patterns due to a pin hole illuminated by a CW He-Ne laser beam whose intensity was systematically reduced by carefully calibrated steps. He found out that when the beam power drops below four-photon equivalent energy, the side lobes of diffraction rings cannot be recorded even with prolonged integration time. This result conforms to our semiclassical view. The detectors first stimulated as dipoles by the superposed fields can undergo QM transition provided there was enough field energy with in their vicinity to absorb $h\nu$ amount of energy. However, Panarella's experiment brings up another important question. Why does his experiment require the simultaneous presence of more than 4-photons to register a "click"? We believe that it is because photons, after being emitted by atoms and molecules, propagate as expanding (diffractive) wave packets with reduced energy densities.

6. PHOTONS ARE DIVISIBLE CLASSICAL WAVE PACKETS

The field of optics has been successfully modeling the propagation of light beams using the mathematically advanced version of the Huygens-Fresnel (HF) principle [20]. The HF integral correctly predicts (i) the emergence of spatial coherence out completely incoherent thermal light (Van Cittert-Zernicke theorem), (ii) near field and far field diffraction patterns due to any simple and complex diffracting aperture, (iii) generation inside a laser and propagation outside a laser of Gaussian transverse mode pattern, (iv) evolution of spatial modes and the propagation characteristics in exquisite details inside simple single mode waveguides and the most complex nano-photonic waveguides. Quantum Mechanics has not produced any better substitute for HF integral. HF integral does not require quantization of EM fields. It is worth noting that the quantization of atoms has revolutionized our understanding of the material world by providing us with a staggering amount of new knowledge about the material world. In contrast, the quantization of the EM field has actually suppressed the exploration of the real physical process taking place during the detection process of superposed light beams and gave birth to non-casual and non-local interpretation of superposition phenomenon. Embedded in HF integral are two profoundly important but dialectical characteristics of all wave phenomena. A wave is a collective phenomenon that will always have a finite space and time extension. The waves propagate as a group even though they constantly expand as if they have a built in propensity to diverge but evolve into a sustainable far-field pattern whose divergence angle remains constant [20]. Yet, if such a self-sustainable wave front is disrupted, the broken wave fronts always regroup themselves into a new pattern whose near field pattern and angular divergence evolve again into a new sustainable far field pattern. Thus, the field pattern or amplitudes distribution of a wave front is constantly evolving, which is equivalent to an evolution of available energy re-distribution of the field. Describing a light beam as consisting of multitudes indivisible photons and make them conform to these changing angular redistribution from near field into far field, are beyond casual description. Accordingly, we are forced to impose non-casual, non-local behavior on the indivisible photons.

We define photons as classical wave packets that evolve after atoms and molecules release their quantum of energy $\Delta E = h\nu$ into the cosmic medium as a time finite pulse with a carrier frequency exactly equal to ν:

$$\vec{E}(t) = \vec{a}(t)\cos 2\pi\nu t = \mathrm{Re}\left[\vec{a}(t)e^{i2\pi\nu t}\right] \quad (7)$$

In the far field from the atoms and molecules, the wave packet would have the physical shape of a Gaussian spatial wave front and a semi-exponential temporal envelope (Fig.2 top curve). We are choosing Gaussian spatial cross-section in analogy with the spatially stable mode that always evolves in laser cavities and in long single mode wave guides [18, see Chapters. 7, 8, 9]. The choice of semi-exponential temporal wave

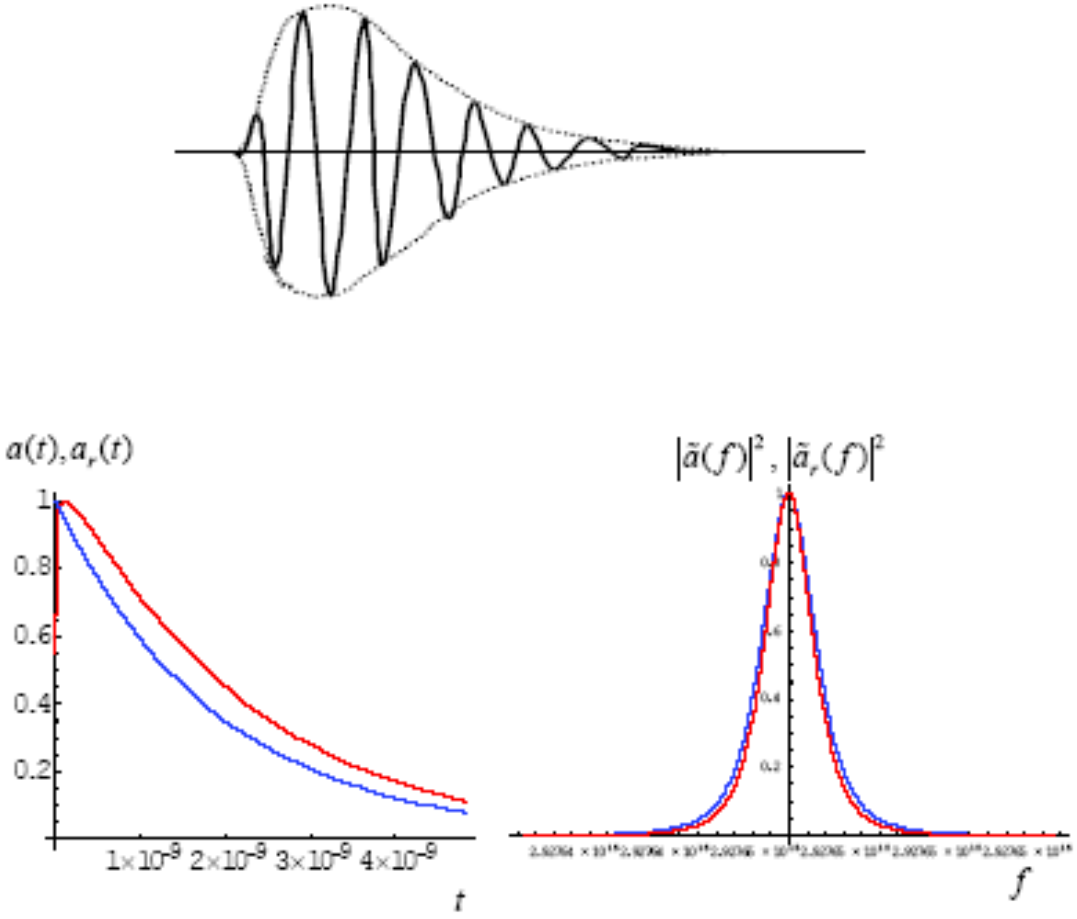

Figure 2. Top: A model for a rapidly rising and exponentially dying photon wave packet envelope with carrier frequency ν. Bottom Left: Pure exponential (lower curve) and rapidly rising but exponentially dying (upper curve) photon wave packet amplitudes. The pure exponential $a(t)$ used here is given by $a(t) = e^{-t/2\tau}$, where $\tau \simeq 1ns$. The rapidly rising and exponential dying amplitude $a_r(t)$ model is given by $a_r(t) = t^r e^{-t/2\tau}$, where r =0.05. Bottom Right: Fourier transform of the pure exponential has a slightly larger FWHM (upper curve) than the rapidly rising but exponentially dying amplitude model (lower curve). We have used the frequency of red cadmium light as the resonance frequency.

envelope derives from the well established and measured spectral envelope of the so-called natural line width of spontaneous emission. Exponential and Lorentzian curves form a Fourier transform pair (Fig.2 lower set of curves). It is important to recognize that the experimental time integrated spectral fringe shape due to a pulse can also be mathematically shown to be the Fourier transform of the pulse envelope while the carrier frequency of the pulse determines the central location of the spectral fringe [8, 14, 17]. But why choose a semi-exponential pulse envelope? We believe that nothing in the universe can happen instantaneously or continue over an infinite duration. So it is physically impossible to start the rise of a pulse envelope at the peak exponential value instantaneously. It must start from zero value and very rapidly rise to the required exponential peak value and die down exponentially. We are also assuming that this rise time to exponential peak value is extremely short so that the Fourier transform of this semi-exponential envelope is still a small deviation from the true Lorentzian, the shape of the natural linewidth that a

traditional spectrometer measures. Our final assumption in constructing this semi-exponential pulse is that the electromagnetic energy carried under this envelope is exactly $\Delta E = h\nu$.

7. FINITE TIME AND ENERGY FOR A SINGLE PHOTO INDUCED TRANSITION

Both the proponents and opponents of photons (spontaneous emission from individual atoms or molecules) as indivisible packets of energy concur with the experimental observations that the transition time required for a photo induced transition is extremely short. For visible range ($\nu \sim 10^{15}$ Hz) it is in the domain of 10^{-15} seconds or around one femto second. They also concur that even at very low intensity, if there is any photo induced transition, it always happens within the fs time constant; only the rates of clicks are very low. In this context we find the observation of Panarella [5] very interesting. At extremely low intensity he was unable to detect the secondary diffraction rings even after very long time integration when the low count rate for the central disc was still measurable. While Panarella has proposed a "photon clump" theory to explain his observation, we are proposing that it is due to photons being *divisible, diffractively spreading classical wave packets*, they present much weaker field energy densities at larger diffraction angles.

For photo induced transition to take place, the quantum device must be bathed in sea of EM field energy with $\Delta E = h\nu$ amount of energy within its immediate vicinity whose E-vector undulation frequency ν matches with that for the quantum transition. This will allow the field to induce dipole undulation on the detecting device and trigger the required amount of energy absorption provided it is available in its immediate vicinity. It will take the EM filed at least one cycle, if not more, of time to find its compatibility with the QM required dipole frequency ν to trigger the quantum transition and energy absorption. While this time is finite, it is very short, a few fs, in the domain of visible light. So, Panarella's experiment implies that when the field energy density (due to diffraction or wave front spreading) falls below some density, the detecting dipoles fails to absorb any energy. So one of the conclusions is that dipoles cannot keep on integrating energy from the flowing weak field over a very long period to accumulate ΔE amount of energy. This is in congruence with the photo detecting community. Since we can never produce any abruptly rising sharp pulse, we may be ignoring the possibility that low energy tails of weak pulses prepare the detectors to undergo rapid transition when sufficient amount energy become available around its vicinity.

To test this possibility, we suggest the following experiment using a planar grating that produces multiple higher order diffraction spots with diminishing intensity. Each measurement should be carried out by illuminating the grating with a single short pulse whose input intensity is gradually diminished in a series of experiments to see which diffraction orders stop producing photoelectrons. There is an advantage in using a single pulse and many diffraction orders with an array of identical detectors. Once a laser-optical system has been well calibrated to produce a desired single pulse, it is easy to reproduce it. Second, the differential stretching of the single input pulse at different diffraction orders can be calculated analytically [17]. In fact, the peak to peak stretching of a pulse at the m-th order for an N-slit planar grating will be $T_m = N\tau_m = Nm\lambda / c$. The experiment should first be calibrated with CW light to identify at what low intensity levels the different orders stop producing photoelectrons. This should then be compared with the results for pulsed light. We believe it might reveal whether photoelectrons require $h\nu$ quantity of field energy within its immediate vicinity for instantaneous ("wave function collapse") transition or it can accumulate energy from the traveling EM field over a finite period including the influence, if any, of the weak tails of pulses.

So far this N-slit grating experiment has been designed to validate that photon wave packets are classical and divisible. Then by the same classical model we should be able to synthesize a stronger field out of the many undetectable weak fields. Let us now propose another experiment using the same N-slit grating to establish our proposition. This experiment can be done with a CW light source assuming that each of the N-slits of the grating has identical opening and all the slits are illuminated with a uniform amplitude wave front. An array of identical detectors placed at the various orders with ample intensity in the beam would produce photoelectrons in all the detectors. Let us then place a broad opaque aperture with only one single

slit matching that of the grating immediately after the grating on a translatable stage. This translatable single slit can now allow one to measure the photo count at selected places due to any one of the single slit out of the N-slits. Then one can reduce the input intensity to the minimum level that just stops the photoelectron production even after long integration time (except inevitable steady dark current). Then we remove the broad screen to allow all the N-diffracted wave fronts to arrive on the detection plane. The new intensity will now be $(N\sqrt{i_{\min}})^2$ or $N^2 i_{\min}$, where $i_{\min}$ is the intensity passing through one slit. With a typical 5 cm grating with $N = 3\times10^4$ slits one can enhance intensity by a factor of 9×10^8. We believe that under this new condition, photoelectrons can be counted again. The above two proposed experiments will establish that photons are classical wave packets that can both be split by optical components and recombined by detectors with proper experimental set up.

8. WHAT ARE THE POSSIBLE IMPACTS IF PHOTONS ARE DIVISIBLE WAVE PACKETS?

First, the unnecessary claims that interference phenomenon is non-local can be replaced by a casual and local model without compromising any prediction of quantum mechanics [7]. Of course, we will have to give up the interpretation that each photoelectron implies the registration of a specific indivisible photon. We will have to give up the notion that no photons arrive at the location of the dark interference fringes. We also have to give up Dirac's statement, "Each photon then interferes only with itself. Interference between two different photons never occurs" [21]. And, of course, those conceived experiments that literally require the production, propagation, manipulation and detection of the same original indivisible photon, will have to be re-designed. EM field wave packets changes constantly through incessant diffractive propagation. Also as a photon propagates through a material medium, it interacts with the dipoles of the medium and emerges as a different photon undergoing various changes in amplitude, phase, polarization and frequencies, depending upon the incident beam intensity and the polarizability χ_n of the medium. One should recognize that if photons were really indivisible and independent packets of energy and they can use their non-local properties to determine which place in an interferometer to appear or disappear from, then we should not have required any phase coherence property for superposition measurements (interferometry). The phase coherence is required by the detecting dipoles when they try to sum the induced dipole undulation amplitudes due to all the superposed fields at the same time. This is why the superposition effects necessarily have to be local (volume of the participating detecting molecules).

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