Indivisibility of the Photon

Ashok. Muthukrishnan[1] and Chandrasekhar. Roychoudhuri[2]
[1]Courant Inst. of Math. Sciences, New York University, New York, N.Y. 10012-1185, USA
[2]Dept. of Physics, University of Connecticut, Storrs, CT 06269-3046, USA

Abstract
The 'graininess' in the energy content of light is reported in experiments ranging from the blackbody spectrum and photo-electric effect to revivals in the Jaynes-Cummings model. Laser shot noise and antibunching of correlations in resonance fluorescence signify a departure from continuous wave behavior for light. Such phenomena underlie the unique sense in which a photon is regarded as an indivisible particle, experimentally tied to the fact that a beam splitter does not split a single photon of a two-photon pair. We consider three arguments for indivisibility - quantization of energy, particle-like fluctuations, and which-way measurements. We argue that in each case, photon indivisibility is an inference based on energy conserving interactions where the detection mechanism involves countable electrons subject to space and bandwidth limitations. The indivisibility of the photon thus remains an open question, and one that we can use to probe the foundations of quantum electrodynamics.

Keywords: Divisible photon; Indivisible photon; Photoelectric time lag; Non-Interference of Light (NIL).

1 INTRODUCTION

In quantum electrodynamics (QED), the basic interaction between a photon and an electron is one in which a photon is completely absorbed or created, while the electron only suffers a change in energy or momentum. This relative *quantization of light energy* is based on observations such as the blackbody spectrum and the photoelectric effect. This quantization has often been the first line of defense for declaring the existence of an indivisible light quantum, and hence, departing from a wave picture for light. However, semiclassical theories which do not make this assumption have consistently challenged QED ever since the introduction of quantum mechanics. The inertia to accept the *second* quantization of light into indivisible particles as readily as that for matter is witnessed by the experimental efforts that have been pursued well into the 80s to test this notion, such as in photon correlation work, in contrast to the relative dearth of concern for the same notion for the electron. The indivisibility of the electron is usually accepted as an apriori attribute inherited from classical particle mechanics.

One way to understand this disparity between light and matter is by looking at the spin statistics of the photon and electron. The standard argument for introducing the light quantum in the Dirac theory is the instantaneous collapse of the electromagnetic field energy in a photoelectric measurement. A similar collapse happens for the electron wave function in a position measurement of the electron, however, this does not call into question the divisibility of energy between electrons, or motivate Dirac field quantization. This is because, unlike fermions which are restricted from aggregating in the same mode, the photon inherits a classical field limit which allows a continuous, macroscopic energy description. The inertia to accept photon indivisibility is really a resistance to sacrificing this energy continuum to the Planck relation. No similar issue arises for the electron.

The indivisibility of the photon [1] seems to demand a special burden of proof due to the existence of an aggregate wave theory of the photon that serves as the correspondence limit of the quantum theory of radiation. A classical wave is an infinitely divisible object, and the reconciliation of the photon as a quantum realization of this wave offers some insight into the historical development of quantum theory [2], and attests to the resistance in accepting the notion of a light quantum. In 1909, Einstein [3] showed that the fluctuations in blackbody radiation can be separated into two parts, one that looked like it arises from random waves, and one that arises from particle-like shot noise. He argued that any future theory of light has to take seriously its new found particulate nature. However, there were dissenters who did not believe in the necessity of the light quantum hypothesis, notably Pascal Jordan. In 1925, along with Born and Heisenberg, Jordan was able to derive the same fluctuations without invoking the light quantum hypothesis [4], a little known paper which noted, two years before Dirac, the formal correspondence between the electromagnetic field and uncoupled harmonic oscillators in matrix mechanics. Quoting from the book by Born and Jordan in 1930 [5]:

"Consideration of the Wien limit of the Planck radiation law suggests, according to Einstein, that the wave picture has to be replaced or supplemented by the particle picture. Quantum mechanics, however, makes it possible to restore agreement with Planck's law and all its consequences without giving up the wave picture. It suffices to work through the model [Modellvorstellung] of the classical wave theory with the exact quantum-theoretical kinematics and mechanics. The characteristic light-quantum effects then emerge automatically, without the addition of new hypotheses, as necessary consequences of the wave theory."

It was important to these authors to bring the discovery of the photon into the framework of quantum mechanics, and show that the classical wave theory of light does not need to be sacrificed to accommodate a light quantum. However, two years later, in the way Dirac formulated the problem, the wave aspects of the photon are included in the field mode functions which satisfy Maxwell equations, and the particle aspects in discrete occupations of these modes, and in this way, the theory gave equal play to both aspects of light. In some ways, it was a tactful solution that kept both camps happy. In particular, the Dirac theory was able to provide a rigorous framework for calculating the 'corpuscular' properties of light such as Compton scattering.

In Compton scattering, the momentum of the incident photon is partly shared with the scattered electron and the rest of the photon energy comes out as a scattered photon, giving the observed two peaks:

$$p_{\gamma,i} = p_{\gamma,s} + p_{\gamma,s} \tag{1}$$

$$\frac{\nu_s - \nu_i}{\nu_s \nu_i} = \frac{h}{m_e c^2}[1 - \cos\theta] \tag{2}$$

where θ is the angle the photon is scattered in the lab frame. Surprisingly, this momentum exchange between two "particles" clearly implies that a photon is *divisible*, in the sense that it only gives up part of its energy and momentum to the electron. The Planck relation apparently does not hold when the radiation is only partly absorbed. Further, this computation can be regarded as a "lucky coincidence" for the Dirac theory. As early as 1927, Schrodinger offered a semiclassical analysis [6, 7] that reproduced the Compton formula. Quoting from this paper:

"According to the wave theory of light all changes in frequency and wave normal can be predicted, as is well known, on the basis of very simple and general considerations on the phase, without going into any detail of the phenomenon.. . If the assumption is correct that with the de Broglie waves we have at hand a tool, equivalent to wave optics, for the treatment of those phenomena that were formerly understood exclusively as motions of particles, we should expect and demand that on the basis of simple phase considerations of the stated kind one should understand the changes in direction and frequency of the aether wave in the Compton effect connected with the velocity change of the electron."

With a semiclassical description of the Compton Effect at hand, we have to question the raison d'etre for the light quantum in the Dirac theory. In his photoelectric paper, Einstein tacitly assumed, without probably explicit declaration, that a bound quantum particle must completely absorb all the energy from the donating particle. As we have seen, this is contradicted in the above Compton scattering model. Besides, a kinetic electron can deliver the necessary quantum of energy, out of its total kinetic energy, to excite an atom from one lower level to another higher level, in much the same way as can a photon, attesting to a formal similarity between light and matter.

The quantization of energy notwithstanding, experiments today purport to observe independently the wave and particle aspects of the photon, for example, in the phenomena of bunching and antibunching, respectively. This prompts us to introduce a criterion of indivisibility based on the existence of *particle like fluctuations* as a real attribute determined by the light source. However, we will argue below that any time particle-like fluctuations arise for the photon (e.g. resonance fluorescence or laser shot noise), photon indivisibility cannot be discriminated from the attributes of the material particles creating or absorbing the radiation. All the evidence pointing toward a particle-like description of light, the revival of which is credited to Einstein, are necessarily inferences made from the details of the material source and/or detector. Thus, particle-like fluctuations, or even departures from Poissonian statistics, do not warrant a declaration of indivisibility for the photon.

Finally, we turn to indivisibility ascribable to *which-way measurements*. Since quantum mechanics is a statistical theory, the wave attributes of the quantum derives its meaning from an aggregate of measurements, each one registering as a localized data point attributable to a single elementary event (however, see discussion of the 'photon clump model' [39]). That a beam splitter does not split a single photon is a retrodiction based on the measurement of the photon, which applies equally to the electron. However, as readily as this leads to a determination of indivisibility for the electron, the same is not true for the photon. Given the special status of light as a mediator of electromagnetic interactions, the sense in which a single quantum measurement can prove the indivisibility of the photon has to be reconsidered. Apart from the state of the art of particle number resolving technology, the detection mechanism always involves countable electrons that are spatially and temporally delocalized (finite size and bandwidth), and hence the ideal of a space-time localized quantum measurement does not apply, and the accountability of measurement events do not necessarily imply discreteness to the radiation.

To summarize, we feel that the indivisibility of the light quantum is really an open question that underlies QED, and part of the motivation of this paper is to urge further experimental efforts in this direction, which we view as tantamount to tests of QED itself.

2. DIVISIBILTY OF LIGHT ENERGY

Historically, the argument for second-quantizing the radiation field is derived from a null experiment: the lack of an appreciable time lag between the incidence of light on a metallic surface and the photoelectric emission of an electron [8, 9, 10]. A year after Dirac's paper on the quantum theory of radiation, Lawrence and Beams [11] did a careful study of this time lag. They used electro-optic shutters to turn on and off a flash of light that was incident on a potassium hydride surface in a photoelectric cell. The resulting steepness in the wavefront of the current indicated that the time lag cannot be larger than approximately 3 ns. This time lag was brought down by an order of magnitude in 1955 [12], and to the picosecond level in the 1960s [13, 14]. Current state-of-the-art in photodetector response times [15, 16, 17] makes a direct observation of the time lag below a picosecond impractical.

Millikan was one of the first people to worry about the time lag issue [10]. In the same paper where he experimentally demonstrated Einstein's photoelectric equation, he calculates that it would take at least 4 hours for a standard candle at 3 meters to deposit $h\nu$ of energy on an atom. Faced with 16 orders of magnitude discrepancy with experiment, we might question the validity of a continuous energy distribution in Maxwell theory. We are tempted to fault the Poynting theorem for its lack of preciseness in defining the localization and flux of light energy [18]. That is, we are not able to tell where exactly the potential energy of the field is stored since photons do not interact directly, and hence the indeterminism of classical field theory is carried over into the quantum domain. Arguing this way, we may give classical electromagnetism the benefit of the doubt as Paul does in his quantum optics book [19]:

> "Can it be that the particle nature of light is only mimicked by the detector? The atom participating in the elementary process can, due to its structure dictated by quantum mechanics, only either take from the radiation field of frequency ν the energy $h\nu$ or not act at all. Is it not possible that the electromagnetic field does not have a grainy structure at all, but is instead similar to a soup which is 'quantized' only when it is eaten portion-wise with a spoon?"

Paul's statement is further supported by the keen observation presented by Roychoudhuri [43, 44] that light beams by themselves do not interfere or re-organize their energy distributions. They are Bosons and hence they can propagate through the same constrained space and emerge unperturbed with their original beam characteristics. Thus, in superposition experiments, with two or more beams, it is the detecting dipole "cup" that determines the manifest superposition effect by summing "photons" from different incident beams.

Coming back to photoelectric time lag, Paul carries out a more direct calculation of the time lag based on a Lorentzian atom absorbing energy from an oscillating electric field. The incident wave induces an oscillating charge dipole, and the interference of the re-emitted wave with the incident wave creates a "suction effect" familiar in antenna theory, whereby the atom absorbs energy not just in its immediate vicinity, but in a much larger neighborhood surrounding it. The effective increase in the atomic cross section decreases the time lag needed for energy deposition. In this way, Paul shows that the discrepancy between the observed and predicted time lags can be shrunken by about seven orders of magnitude. Yet the discrepancy still remains.

Faced with this problem, we should take a closer look at what kind of process occurs in the photoelectric effect. With the insights gained from the work of Glauber, we know that photoelectron emission is the seed that initiates a quantum measurement of the radiation field. In the mainstream view, a single photon of energy $h\nu$ is said to be destroyed, and the emitted electron cascades into many electrons ultimately registering as a classical current. A quantum measurement is a process that divides the reversible microscopic world from the irreversible macroscopic world, and hence all Hamiltonian time evolution processes become invalid at some point when sufficiently many degrees of freedom start to matter. Hence, all our calculations of the time lag above may be incapable of predicting what is really going on. From both the point of view of the light field and the atom, a quantum collapse may be said to take place, the details of which are not microscopically predictable. It is just such a collapse that is taken to be the raison d'etre of Dirac's second quantization of the light field. However, we reiterate that from the point of view of light, we are just not able to state with precision in what manner energy accumulates in space, even in classical field theory, and hence a determination of indivisibility based on the photoelectric effect alone is not defensible.

Indirect measurements of the photon wave packet offer one way around the limitation of photodetector response time. The prime example of this is the Hong-Ou-Mandel dip [21]. Here the arrival time of one photon with respect to another photon at a beam splitter is measured via an interference-induced dip in the two-photon correlation. The correlation is mapped out as a function of the beam splitter translation which, in the temporal domain, allows us to probe the width of the photon wave packet with a precision greater than that allowed by a direct photoelectric measurement. Applying the Born probability rule to the photon field mode, the wave-like aspects of the quantum can be probed directly this way, resulting in a picture for the photon much like that for the electron: a point particle obeying a probabilistic wave equation. This is even more apparent in the recent experiments of Gouliemakis et al. [20], where the temporal shape of a few-cycle visible laser pulse is mapped out by the momentum transfer given to an XUV initiated attosecond electron burst. Measuring the electron momentum spread allows these authors to infer the shape of the laser pulse via the Lorentz force law. Experiments such as these restore full confidence in the electromagnetic wave description of the photon, and indicate that energy transfer from the photon to the electron acts in a space-time continuous fashion as predicted by classical field theory, at least for a coherent state.

What the Hong-Ou-Mandel and Gouliemakis et al experiments do is to map the light attributes to a material coordinate, which then serves as the independent parameter in the measurement (beam splitter position or electron momentum). Thus, any quantum jump that happens to light is delayed until it has 'given up' its wave character to the material coordinate so to speak, and thus a determination of indivisibility is not possible in such indirect measurements.

Let us return to the question of photon indivisibility as it historically appeared in the context of light energy. Planck's quantization of energy in a blackbody applied to material oscillators [22], and in his view, was inadequate as a logical argument for the existence of a light quantum. It is often stated that the 'graininess' in light energy is directly seen in the revivals of the atomic inversion in cavity QED, i.e. the Jaynes-Cummings model [23] (see, for example, [24] for experimental verification). Here, the presence of a superposition state of multiple photon numbers (such as in a coherent state) causes the discreteness in the interaction energies (Rabi frequencies) to imprint their periodic time evolution on the atomic inversion, as collapse and revival. In the absence of discrete photon numbers, one would not see this phenomenon. However, we caution that just as in the case of the blackbody problem, the discreteness of the interaction owing to the quantization of atomic energy cannot be separated from that of light, and hence it is not logically straightforward to ascribe quantization to light. That is, it is equally possible to render this effect as due to the successive annihilations of energy $h\nu$ from the coherent state by a two-level atom. A more recent instance of this interpretative fallacy is the idea of quantum lithography [25], where the fringe spacing of a multi-photon interference pattern is smaller than the single photon wavelength by an integer factor equal to the photon number. The discreteness in this case owes to the nonlinearity in the multi-photon absorbing material [26, 27].

3. PARTICLE-LIKE FLUCTUATIONS

A second approach to indivisibility for light is through fluctuations. Einstein was the first, following his work on Brownian motion, to pursue fluctuation arguments for light. Having introduced a light quantum hypothesis, he was interested to see how it fared in second order. As we have mentioned, his 1909 paper [3] was a key contribution, where he showed how the wave and particle fluctuations 'co-exist', (viz. $(\Delta n)^2 = n^2 + n$, where energy $E = nh\nu$), again an interpretation that is subjective from the point of view that all we can be sure of is that the full fluctuation in photon number (i.e. the sum of particle and wave contributions) has to obey Bose-Einstein statistics. Einstein saw in it more than this – the presence of a shot noise-like component, $(\Delta n)^2 = n$ was to him an affirmation of his light quantum hypothesis signifying a departure from classical wave physics. We will see that this interpretation is strictly not warranted for blackbody or thermal light, however, the issue of separating the wave and particle aspects of light has seen a modern revival in a different guise in the debate on the 'nonclassicality' of light.

In 1958, Mandel showed that photon bunching (as seen, for example, in the Hanbury-Brown and Twiss experiments) can be fully accounted for by associating photons with Gaussian random waves [28]. Hence, electromagnetic wave physics is seen to be equivalent to Bose-Einstein statistics of thermal light (for sufficiently long coherence times), which includes the so-called 'particle' (shot noise) aspects of the fluctuations that Einstein falsely attributed to the light quantum. However, not all states of light obey Bose Einstein statistics. A notable exception is the coherent state modeling a laser, which displays purely shot noise. As Carmichael notes [32], in experiments where the semiclassical theory of photodetection prevails, i.e., where light does not display 'nonclassical' behavior (see below), the wave aspects of the photon number fluctuations can be assigned to a classical, stochastic light wave and the particle aspects can be assigned to the quantum, discrete photoelectron counts. Hence, the countability of photons in shot noise is inferred from the countability of electrons [33], and the presence of this component in all photoelectron measurements does not speak to the indivisibility of light.

The story of 'nonclassical' light, however, is a bit more subtle. Karp [29] considered another example based on a statistical ensemble of randomly phased wave packets which he claimed to question the validity of photons in so far as it departed from Bose-Einstein statistics. Mandel [30] countered by arguing that in all cases where a non-negative phase space probability distribution exists for light (e.g. the Glauber-Sudarshan coherent state representation or the Wigner representation), it is impossible to determine, via photoelectron statistics, any property of the radiation field that distinguishes it from classical waves. However, with his discovery of antibunching of resonance fluorescence in 1977 [31], for the first time there seemed to be experimental evidence for a departure from classical wave optics, represented equivalently by a negative phase space density, a sub-Poissonian number fluctuation, or a minimum in the temporal autocorrelation of the light intensity.

In situations where 'nonclassical' light states are expected to predominate, such as in particle antibunching or quandrature wave squeezing, the separation of 'classical light wave' from 'quantum detecting particle' is no longer permissible [32]. One needs to regard the interaction problem as mixing the wave aspects of the light with the particle aspects of the detector in a way that is reminiscent of the way Dirac solved the problem of the quantum theory of radiation: by assigning wave aspects to the field modes and particle aspects to the absorption and emission operations effected by interaction with matter.

We would argue that nonclassicality is not tied to our pronouncement of light as wave or particle, but rather to the appearance of quantum aspects, notably the use of a 'quantum jump' or measurement postulate, to describe the light wave analogous to that for a matter wave. For example, quadrature squeezing produces the same nonclassical behavior as antibunching that sets it beyond the domain of classical wave theory, however, unlike antibunching, it does not call on a particle-like interpretation of light. Rather, it signifies the need for a quantum epistemology for light: the two quadratures of the electric field cannot be assigned fluctuations that are in violation of the uncertainty principle. The same is true for electron position and momentum. However, unlike the electron for which a quantum wave is associated with a single indivisible particle, the case for light is not so clear. That is, the applicability of quantum jumps to light does not necessitate the existence of an indivisible particle of light. This is because light is never directly measured but only through its interaction with matter. For example, antibunching results from the time lapse between successive atomic emissions governed by the Rabi period, and hence this is a property imposed upon the emitted light by the atomic dynamics. Similarly, squeezing results from nonlinear interactions with matter governed by the second order susceptibility.

To summarize, in all cases where we can infer particle-like indivisibility for light based on photoelectron count statistics, the indivisibility is seen to arise from a) the countability of photoelectrons, or b) the quantum nature of light-matter interactions. The extent to which nonclassical light phenomena such as antibunching and squeezing can lend a determination of indivisibility to the photon is the extent to which we can piece apart the quantum epistemology of light from that of matter, and that is something that we are unable to do except as an inference. Thus, the hypothesis of the light quantum remains a subjective interpretation today as it was for Einstein in his paper in 1909.

4. BEAMSPLITTER INDIVISIBILITY

Direct experimental tests of the indivisibility of photons require the technology to produce single photons at will from atomic sources. Thermal light sources produces bunches of photons which are not adequate. Even in single photon sources, the probabilistic nature of atomic emission makes it impossible to know when a particular photon was emitted, and hence discriminating against dark counts becomes impractical. Hence, the first beam splitter experiments to test indivisibility were carried out with two photon entangled states obtained from cascade atomic emission. Notably, the experiments of Clauser [34] and Grangier et al. [35] are seen to be conclusive tests of the fact that a beam splitter cannot split a single photon. In the Grangier experiment, one of the photons from the cascade is used to gate the measurement of the other photon after it has passed through a beam splitter. The coincidence rate of the two detectors at the output ports of the beam splitter measure the divisibility of the second photon. If light was a wave *and* the probability of photoemission was proportional to the intensity of light incident on each detector, the coincidence rate would be at least the product of single detector rates, but not smaller. However, the experiment reported a coincidence rate 13 standard deviations below the expected semiclassical result, indicating that the photon was really an indivisible whole that made a 'decision' to either reflect or transmit through the beam splitter but not both.

We first take issue with the language used to describe beam splitter indivisibility, often repeated in many quantum optics textbooks. It is most certainly not the case that the photon made a decision at the location of the beam splitter, since propagation in quantum theory is completely causal and wave-like until the measurement event occurs. Indeed, transmission and reflection at a beam splitter are described by wave propagation matrices. Even as a retrodiction based on the measurement outcome, there is a fallacy in interpreting the above experiments. A 50-50 beam splitter can become a 100% reflector or a 100% transmitter depending upon the counter-acting phase of one or the other beam incident on the beam splitter from the opposite side. Since light beams cannot interfere by themselves, they need mediation by the material dipoles on the boundary of the beam splitter from both the sides. This boundary also provides a π phase difference between the 'external' and 'internal' reflections. This relative phase shift is a critical value that determines the exact order of interference. Without the presence of another light signal with in-phase or out-of-phase signal from the opposite side, "photons" of the desired beam cannot change their direction. Further, an un-coated, say 15% reflecting beam splitter in a Mach-Zehnder will never be able to become a 100% reflector or transmitter if the two beams from opposite sides are made to be of equal amplitudes (energy)! This basic classical physics π phase shift between the two sides is profoundly correct in all experiments. This is how we ascertain the relative and/or absolute order of interference and determine whether a surface error is depressed or protruded (concave or convex), etc.

As a consequence of wave optics, an indivisible single photon cannot be directed intact (un-broken) in one or the other direction incident on one side of a beam splitter without the simultaneous presence of another same frequency photon from the other side with exactly the required matching or π-shifted phase. Light beams containing innumerable "photons" do not interfere with each other. They are bosons.
So, reduction of "photon" number from a beam to one photon cannot change the fundamental physics abruptly! Which-way measurements of the photon at a beam splitter are thus subject to an interpretive fallacy.

There is yet another sense in which retrodictive analyses fail to be conclusive for photon indivisibility. This involves the assumption that the light energy can be imparted to the detector atoms in a continuous fashion (viz. the disagreement between Planck and Einstein). As we have seen, the quantization of atomic energies requires either the absorption of $h\nu$ from the light or no action at all. We cannot infer space-time indivisibility even at the location of the detectors since it is predicated on quantized energy-conserving exchanges with material oscillators.

If we had detectors that could respond to, say, half the frequency of the light, an interesting question would be whether a 'single' photon would deposit half its energy on one detector and the other half on another detector. One could visualize, for example, a Compton event followed by photo-absorption, both of which independently lead to observable currents. To our knowledge, such observations have not been tested, and since current theory does not predict the efficiency of this process, one would require 100% detector efficiency to rule out this possibility. Indeed, in solid state detectors where electrons are excited to the continuum, we cannot even be sure whether a single electron provides the seed for the photocurrent, or more than one electron contributes. Conversely, we cannot also be sure that a single photon of energy $h\nu$ was the exciting mechanism, as opposed to, say, two 'photons' of energy $h\nu/2$. The supposed one-to-one correspondence between a light quantum and a detecting particle is a key assumption of all experiments thus far. Whether measurement collapse of countable material quanta translates to that of a single light quantum is the central question that pertains to the indivisibility of the photon, and is as yet unanswered.

To summarize, the experiments thus far leave open many thinkable alternatives to indivisibility, and we need further experiments to increase our confidence using state-of-the-art technology, for example, photon number-resolving detectors [36, 37, 38]. What the photon correlation experiments of Clauser and Grangier et al. do show conclusively is the inadequacy of a particular model for light, namely the semiclassical model of photoelectric detection. As we have seen already, this model is incapable of accounting for the 'nonclassical' states of light that arise in antibunching or squeezing. However, current experimental literature does not show conclusive proof of the indivisibility of light as a necessary premise of a quantum theory of light.

5. DIFFRACTION-BASED TESTS

Pursuing the indivisibility question is relevant not only for our visual model for the photon but can also serve as a probe into the foundations of QED in experimental regimes in which it has not been tested before. Panarella has noted possible deviations from QED in both low-intensity [39] and high-intensity [40] limits of laser-matter interactions. In both cases, deviations from linearity were observed, i.e. the photo-ionization rate (assuming single photon absorption) was not linear in the light intensity. In the high-intensity case, seen in laser-induced gas ionizations, Panarella suggested photon-photon interactions that modifies the Planck relation $E = h\nu$ to allow for an intensity-dependent frequency, which he claimed worked better than multiphoton theories. For example, photons in focused light beams display photoionization counts even though they lack sufficient energy, per photon.

In the low-intensity regime, which concerns us here, Panarella's analysis is based on diffraction-based tests of wave-particle duality [41]. One of these tests found that at low light levels (□ 104 photons per second), the diffraction side lobes are suppressed even for long exposure times. That is, the wave aspects of light, which usually show up as aggregate build up of statistically independent photo-ionization events, seemed to care about the photon flux, not just the absolute photon number. This led Panarella to suggest a 'photon clump model' to explain the threshold behavior, whereby a single photographic spot is created by the presence of a threshold number of photons, acting cooperatively, typically 3-4.

Roychoudhuri and Tirfessa [42] have suggested an alternate interpretation of this diffraction threshold. Returning to the issue of the time lag in the photo-electric effect, they propose that if the time lag is really existent but below detector response times, the Panerella finding offers one way to detect it. By designing an experiment with pulse diffraction, they argued that the differential stretching of each pulse in different diffraction orders can be used as a marker to study the drop-off in photo-ionization. This would indicate whether each photon's energy can be absorbed in the time scale during which it is in contact with the atom, or when the energy is in the appropriate vicinity of the atom. If there is indeed a temporal effect, the energy deposition rate can be quantified in accordance with Maxwell theory, and we have a powerful tool to qualify the 'instantaneous wave-packet collapse' of the quantum.

We conclude this section by underscoring that the principle of Non-Interference of Light (NIL) underscored by Roychoudhuri [43,44] helps remove many of the non-causal hypothesis like "photon can interfere only with itself", by realizing that the superposition effects become manifest only when a detector undergoes some measurable transformation (photoelectric transition) under the joint stimulation of all the superposed fields. The NIL-principle has recently been extended to optical diffraction phenomenon [45], which indicates that the Huygens-Fresnel secondary wavelets may not be just a fortuitous working hypothesis.

6. CONCLUSION

We have looked at three different approaches to photon indivisibility based on current experiments – quantization of energy, particle-like fluctuations, and which-way measurements – and found that none of these leads to a definitive conclusion. As this issue pertains to our visual model for the photon, and guides our theory of photon-matter interactions, we need to pursue the state-of-the-art in technology to conduct further experiments, and photon-number resolving detectors and diffraction-based probes of photo-ionization thresholds are two such examples on the horizon. Any inferences made from the data have to rule out all possible routes to photon indivisibility based on the discreteness of matter. We do not "see" light directly. We see light only through the response of matter particles. Since the photon is a boson with a well-defined macroscopic field limit, and given the undue successes of semiclassical theories against QED for which photon indivisibility is but an ad hoc premise, the question of the existence of an irreducible light quantum has to be re-examined.

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