ON THE FUNDAMENTAL NATURE OF THE ELECTROMAGNETIC INTERACTION

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We propose an experiment based on statistical analysis to test the currently accepted statement that, "a photon cannot be split.". The essential statistical phenomenon pertains not only to beam splitters, but also the generation of correlated photon pairs used extensively in quantum optics experiments. A consequence of this analysis is that, arguably the tactic of reducing the window defining a coincidence has the unexpected effect of preferentially selecting uncorrelated photon pairs, thereby undermining an essential prerequisite for the conclusions drawn from such experiments.

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1. Introduction: the issue

The mathematical rendition of a physics theory comprises equations involving various symbols, of which only a few actually pertain to ontological (physical) entities. Many others pertain to concepts or abstractions for which the use and purpose is convenience in formulating the theory, especially its mathematical exposition. Ideally, it might be preferred that, symbols for ontological entities represent only invariants in the mathematical formulation --- after all, real, existing objects, logically cannot depend on arbitrary mathematical choices, such as coordinate systems, units, etc. An example of the second type of symbol-concept, namely a contrivance for convenience, is *energy*. The amount of kinetic energy of an entity depends on its velocity so that obviously it is a concept relative to whatever frame in which the velocity is expressed. Basically, kinetic energy, for example, is a bookkeeping concept; it specifies how much work would have to be done on the entity of interest to bring it to a halt in the frame in which its velocity is expressed (and presumably, measured).

Often times a symbol-concept becomes so familiar, that in the minds of some it is taken (mistakenly) as an ontological entity. This can have the deleterious consequence, that an implicit (secondary) goal of theorizing unconsciously becomes clarifying its physical nature, even while in reality it can have no such nature. Herein our central interest is electrodynamics as formulated nowadays in terms Maxwell's Equations for electric and magnetic *fields*. It should be recognized immediately that, fields cannot be ontological entities. First, they are not invariant with respect to an observer's choice of coordinates, indeed, with a suitable choice either one or the other can be reduced to zero. In addition, they are essentially *unobservable*. That is to say, in order to observe a field strength at some point, x , it is necessary to insert a "test charge" at that point so as to observe its reaction to the impugned "field." It is the test charge which is observable, not any field in which it is ostensibly bathed. Further, fields for static situations are conceptually clumsy; are or are they not in motion? Nevertheless, much analysis on the behavior of systems of charged particles is discussed as if fields in fact are ontological entities filling space with some kind of substance that has been "emitted" by source charges and in turn will be "absorbed" by sink ("test") charges, usually in the form of a receiving antenna, eye or other photo sensitive measuring instrument.

This circumstance carries over to the concept of "photon" in which it is imagined that, whatever the substance ultimately constituting waves is, it is, in addition, confined to a specific, finite volume propagating similarly to a particle. Thus, nowadays photons are categorized often as particles (albeit bosonic) and customarily discussed as if they are virtually micro bullets, i.e., an ontological entity of fundamental significance, and not just an abstraction useful in describing interaction among charged ontological entities, (particles --- fermions). One of the central and most popular arguments in favor of the concept of a particle-like photon is the empirical fact that if beam of electromagnetic radiation (ostensibly a photon stream) is sent through a beam splitter, then at the one-photon intensity level, no (within tolerances) coincidences are observed between its output channels. This, it is said, reflects the fact that photons "cannot be split," which in turn implies that they have some kind of real, ontological particle-like character or existence. This argument, however, overlooks certain subtleties. To begin, at the lowest, i.e., one-photon intensity level, it is imagined that, a photon in transit has something of the character of a finite duration electromagnetic pulse comprising one (at least) signal (in the sense of being a Fourier component) with that frequency being attributed to the photon. Of course, none of this is known for certain; all that is known in fact is that, repeated observations of reputed single photon pulses do not conflict with the following description: The pulses travel through space essentially as customarily imagined wave pulses until they impinge on a "photo-detector" within which they elevate an electron from the valence to conduction band of the detector material. This elevated electron is then drawn off and amplified to give a practically detectable signal, which is counted and attributed with a specific "arrival time" considered to be that corresponding to the arrival time of the photo-electron in the counting circuitry. Again, although it cannot be known for certain, laboratory observations are consistent with the idea that arrival times of photo-electrons are distributed in time stochastically within the duration of their eliciting pulse. It is said that, some electrons "arrive" virtually instantaneously with the arrival of the leading edge of the pulse itself, before even the pulse could have deposited energy sufficient to lift the electron from its valence band environment. So much is conventional nowadays.

This paradigm for detection, however, inadvertently renders any argument against photon splitting mute. Whether or not a photon is split, given that all detections are statistically distributed over a time interval equaling some pulse length, the probability for a coincidence detection, as a continuous density, will be essentially vanishing small to the extent that the detection window within which detections are considered "simultaneous," is narrowed. It is the purpose herein, therefore, to closely analyze this situation for the purpose of discerning whether there exists alternate evidence of correlation between the detections in the output channels of a beam splitter in stead of just noting that the probability of a coincidence vanishes as the detection window is narrowed, which it always does (given a sufficiently narrow window).If there is evidence of correlation, then there is *ipso facto* evidence that the pulse (or a so-regarded photon in flight) has been split. If evidence of correlation is not found, then a "no-splitting" claim survives intact.

2. The essential difference

The essential difference between coincident detections of photo-electrons evoked by split "photons" on the one hand, and two accidentally somewhat overlapping pulses on the other hand, is that, split pulses (if they exist), would have had a common progenitor pulse, and therefore should have identical arrival times of the leading edges at the output detectors. There can be no systematic relationship, on the other hand, for independent but accidentally overlapping pulses. It shall be shown below that this leads to consequences, observable at least in principle.

The essential nature of the difference in the structure of coincidences generated by split and overlapping pulses is that, in the former case all the stochastic character of the photo-electron arrival times is due to processes in the detectors on the output channels of the beams splitter. In the case of simply overlapping pulses there is an additional random input unique to each pulse which is due to the random time off-sets of the overlapping pulses incidental to processes in the source crystal.

Let us first consider the case in which the two pulses are absolutely independent but overlapping sufficiently so that the photo-electrons they evoke are detected within the window (by definition chosen by the experimenter, not Nature) defining a "coincidence." The detection instant in each output channel is a random variable, t_1 and t_2, are in fact the sum of two random processes, „

$$t_{1,2}=T_{1,2}+\tau_{1,2},$$

where the $T_{1,2}$ are the random instants of the leading edge of generating pulse (which depends on processes in the source crystal) and the τ_j are the random instants of photo-electron appearance within the pulse length in the photo detector. What we propose studying is the distribution function of the difference in arrival times, $\delta t=t_1-t_2$ of the photo electrons in the output channels. δt is again a random variable and its distribution function, $F(\delta t)$, is the integral of the probability density function of the random variable, δt, namely:

$$F_{\delta t}(w) \equiv \int_{-\infty}^{w} \rho(\delta t)\, d\delta t,$$

where w denotes the "window width" chosen as the definition of a "coincidence." $F_{\delta t}(w)$, therefore, gives the number of coincidences seen between the output channels of a beam splitter as a function of the selected window width w; for brevity below it is denoted $F_C(w)$.

To obtain this density function, in turn, we need to compute $\rho(\delta t)$,which, being a probability density, would be given by the convolution of the density functions of t_1 and $-t_2$:

$$\rho(w) = \int_{-\infty}^{+\infty} \rho_2(w)\rho_1(w+\delta t)\, d(\delta t).$$

Now, each of the densities under this integral pertains to a random variable which itself is the sum of two other random variables, that is of T_j (determined by emission processes in the source) and τ_j (determined by absorption processes in the detectors), i.e.,

$$\rho_j(t_j) = \int_{-\infty}^{+\infty} \rho_S(t_j - \tau_j)\rho_D(\tau_j)\, d\tau_j,$$

where $\rho_S(t_j - \tau_j)$ is the probability distribution for $T_j = t_j - \tau_j$, i.e., the instant of arrival of the leading edge of the "pulse" emitted by the source. Most often it is taken that, the distribution of these instants is uniformly distributed over a pulse length, which itself can be determine or estimated from the average of the frequency, f^{-1}, of photons per unit time of the source:

$$\rho_S(T) = 1;\ \ 0 \le T \le f^{-1},\ \ 0,\ otherwise$$

Correspondingly, $\rho_D(\tau_j)$ is the probability density for the detection process, i.e., the arrival instant of a photo-electron, as found from a straight forward quantum calculation to be given by an exponential decay:

$$\rho_D(\tau_j) = \lambda e^{-\lambda\tau},\ \ \tau \ge 0,\ 0,\ otherwise$$

Now, our central point herein is to compare $F_{\delta t}(w)$ for the two distinct cases: 1) in which the stimulus pulses are just accidentally overlapping ($T_1 \ne T_2$) and 2) when a single pulse is split in two by the beam splitter ($T_1 = T_2$).

So for case 1) the following sequence in "Mathematica" coding can be used to get a distribution function for at east a first approximation for the case in which the "photons" are imagined to be just accidentally overlapping.

```
In[1]:= ρs[L_, T_] := If[0 < T < L, 1, 0]

In[2]:= ρD[λ_, τ_] := λ * Exp[-λ * τ] * UnitStep[τ]

In[3]:= ρj[λ_, L_, t_] := Integrate[ρD[λ, t - y] * ρs[L, y], {y, 0, 5}]

In[4]:= ρc[λ_, L_, τ_] := Integrate[ρj[λ, L, τ + t] * ρj[λ, L, t], {t, 0, 3}]

In[5]:= Fρc[λ_, L_, w_] := Integrate[ρc[λ, L, z], {z, 0, w}]
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Block 1: Mathematica code to compute the probability density function for accidentally overlapping pulses. Lambda, the decay constant, and the pulse length, T, are model dependant parameters.

For the case in which they are "split" (if possible), the following code gives the distribution function.

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In[7]:= ρd[λ_, y_] := Integrate[ρD[λ, t + y] * ρD[λ, t], {t, 0, 10}]

In[8]:= Fρd[λ_, w_] := Integrate[ρd[λ, y], {y, 0, w}]
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Block 2: Code to compute (hypothetical) "split photon" coincidence probability distributions. Lambda is a physical model dependant parameter. Alternate model may involve different and additional paramters.

Figure 1 presents the results:

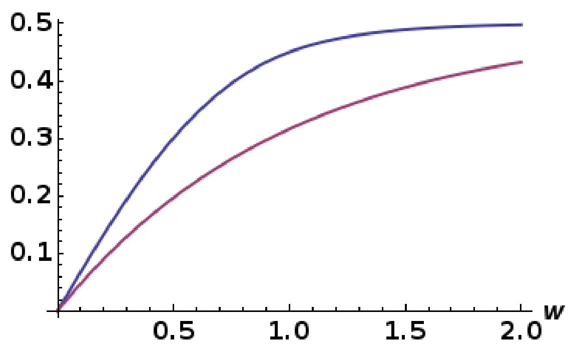

Figure 1: Probability distributions as functions of the window width. The upper curve is for accidentally overlapping pulses, the lower for "split photons."

From this graph it can be deduced that there should be a distinct difference in the curves between these two cases. Conceivably, this difference can be interpreted for specific experiments to evaluate the validity the claim that photons cannot be split.

3. An experiment

Given the structure described above, one might imagine the following experiment, requiring no more than a reexamination of the data available from conventional beam splitter experiments. Suppose the output from both channels of a beam splitter is available in the form of two streams of time instances corresponding to the arrival times of the photo-electrons in each channel, i.e.: $\{t_i\}_{trans}$ in the transmitted channel, and $\{t_j\}_{refl}$ in the reflected channel. Then, the frequency of the occurrence of a given value of

$$\{t_i\}_{trans} - \{t_j\}_{refl} = \delta_{ij} ,$$

can be found by scanning in parallel the two streams progressively in increasing magnitude until a recorded data point is encountered, which is then taken as the opening instant of a window for the which the closing instant is the next encountered value in the other channel. By continuing in this manner, a population distribution of values of δ_{ij} or δ_{ji} conveniently relabeled as a value of w . Continuing this count procedure will reveal a distribution of undetermined character; that is, it can be anything from a pure case 1 distribution or some mixture with non split photons.

On the other hand, to obtain the same distribution corresponding to the case of pure coincidences any given value of w arising from simply overlapping pulses, the same analysis can be done on two streams where one of them is any portion of either stream offset by a fixed amount large enough to be reasonably assured that coincidences cannot result of the split photons. That is, the pulses are so displaced in time that they cannot represent a single photon no matter how defined.

Now, the results of the first analysis can result in a stream containing some percentage of split photons, whereas the second cannot. Thus, the validity of the proposition that “photons cannot be split” is challenged if the results are sufficiently distinct.

The analysis presented herein is strictly abstract with little insight regarding practical impediments. It may well be that although the effect considered here does exist, that the practically available regimes, essentially suitable ratios of λ / f^{-1} , render the consequences to small to be observable, for example. Additionally, the probability densities attributed to the processes in the source and detector, conceivably could involve features that conceal a real effect. These are issues hopefully to be resolved by experimentalists. In the end, we see no reason that some variation of the structure suggested by the above analysis could well exist in nature and be discernible experimentally.

4. An application

Beyond the purely conceptual interest in the fundamental nature of the electromagnetic interaction, the consequences of the effect considered here have important significance for many experiments done nowadays to fathom the quantum nature of the electromagnetic interaction.

Many essential experiments in this area employ the coincident emission of two correlated photons, similar in constitution to the outputs of a beam splitter. The sources employed for such experiments are usually such that the individual pairs are generated by individual molecules, or other microscopic structures, constituting the source. The multitude of micro-sources in the macro source (crystal, gas, etc.) can be expected to generate many undesired accidental overlapping micro-signals. However, for the purposes of these experiments, it is essential that the photon pairs actually be correlated (actually in a circustance in which they are said to be “entangled,” which is thought to be stronger than statistically correlated) and not just accidentally coincident. To obtain such ideal pairs, the customary technique used to procure actually correlated pairs is to employ as small a coincidence window as possible. Obviously, the assumption is that, real coincidences will outnumber accidentals to an increasing extent as the definition of a coincidence window, w , is reduced.

However, if the ratio of the density of uncorrelated, or accidental coincidences to that of the truly correlated is graphed; for the ratio arbitrarily employed above, one obtains results like shown in Figure 2, which illustrates that the relative reduction of truly correlated pairs is, contrary to the conventional and intuitive expectation, *reduced* upon reduction of the window width. This phenomena is not only counterintuitive, but counterproductive for the purposes these experiments. It in fact achieves just the opposite of the intended purpose for reducing the window width in the first place.

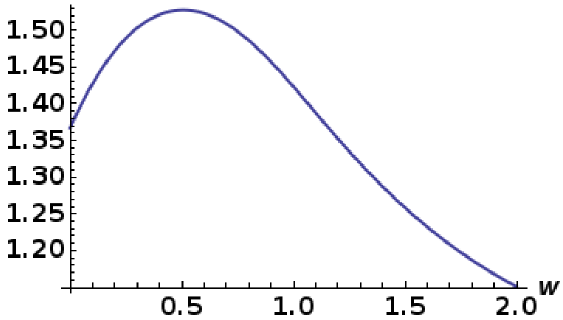

Figure 2: An illustration of the relative abundance of uncorrelated to correlated conincidences for an arbitrary choice of model dependant paramenters. Other models lead to a virtual vanishing of correlated pairs as the window width is reduced, contrary to expectations.

For many crucial quantum optical experiments this effect can lead, arguably, to the perverse situation of spoofing some features peculiar to quantum theory by providing perfectly classical structure where it has been precluded in principle --- based on the inappropriate assumption that spurious, uncorrelated pairs have been excluded when actually this effect lowers the relative abundance of correlated pairs. This consequences of this effect for the conclusions drawn from certain quantum optics experiments has been analyzed in greater detail elsewhere [1].

References

1.A. F. Kracklauer, *Proc.* **SPIE 8121**, 1812102-5 (2011).