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Reinterpretation of the Grangier experiment using a multiple-triggering single-photon model

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The classic Grangier *et al.* (1996) experiment is revisited to suggest an alternative model of a single photon. Photon-counting experiments using spontaneous parametric down conversion (SPDC) show that not every single-photon incident on a detector triggers it, and that coincident triggering of detectors can occur during a single gate. The latter is usually interpreted as being caused by spurious photons entering the gate from different SPDC events. However, a pseudo-classical-type model is suggested which dispenses with these intruder photons. Here, a single-photon manifests as a transversely-iterated front of non-rotating screw threads. Each advancing thread has the potential to trigger a detector, and each allows the transfer of spin angular momentum (SAM). On exiting a beam splitter, a single-photon front can produce multiple triggering of detectors on different parts of the front with a probability of at most $5.02 \times 10^{-5} - 3.54 \times 10^{-4}$ for the experiments presented.

Keywords: Photonics; optics; second-order correlation function; spontaneous parametric down conversion; photon counting; optical spin angular momentum.

1. Introduction

The structure of a single photon remains an unsolved problem. Einstein saw photon energy as being "discontinuously distributed in space"[a] and "localized in space points".[1,b] Nevertheless, in 1930, Dirac asserted that "Interference between two photons never occurs," and that a photon always interferes with itself.[2] Early experiments were designed to isolate a single photon by employing various obstacles to reduce the intensity of an aggregate beam. Even before Dirac's pronouncement,

[a] "[...] das die Energie des Lichtesdiskontinuierlich in Raume."
[b] "[...] in Raumpunkten lokalisierten Energiequanten."

Taylor had set out to show that a photon was capable of self-interference.[3] After reducing the intensity of light from a gas source by passing it through a narrow slit followed by smoked glass screens, he diffracted it around a sewing needle onto a photographic plate to demonstrate interference effects. He estimated the power of the beam falling on 1 cm^2 to be 5×10^{-6} erg s^{-1}, but since a single photon of red light has energy 2.7×10^{-12} ergs, approximately 10^6 photons were striking 1 cm^2 of his photographic plate per second.

The attempt to produce single photons was continued by Dempster and Batho who used a blackbody as reference to estimate that the energy radiated in the helium line 4471 Å from their low-pressure glow discharge averaged 95 photons s^{-1}.[4] From the product of the transition time 5×10^{-8} s and the speed of light in vacuum they calculated the minimum spatial separation between successive emissions from a single source to be 15 m yielding an average density of about 6 photons m^{-1}. They concluded that to produce the interference effects that they observed, a single photon must cover a wave-front area of at least 32 mm^2. In a second experiment, they claimed to have separated an individual photon into components using a half-silvered mirror and then to have recombined it with a relative phase difference.

Reynolds *et al.* managed to improve on the experiment by investigating whether or not the quality of the interference pattern diminished as the light intensity approached that of a single photon.[5] In two experiments, one with a mercury discharge tube and the second with an RF excited low-pressure Hg lamp, they estimated that their Fabry–Perot interference patterns were formed from a beam of 15 photons s^{-1} and 30 photons s^{-1}, respectively. Confident that no more than one photon was ever engaged in an interference interaction, they reported no evidence that the contrast of their interference pattern was diminished by the use of single photons. Reproducing the experiment, Dontsov and Baz found a deterioration in contrast but attempts to reproduce their findings have met with failure.[6] The occurrence of single photons that produce interference is now well established.[7–9]

For single-electron interference, Feynman's[10] double-slit thought experiment from 1965 inspired Tonomura *et al.* to fit an electron microscope with an electron biprism to record the accumulation of an interference pattern when "there is very little chance for two electrons to be present simultaneously between the source and the detector, and much less chance for two wave packets to overlap."[11] Frabboni has also demonstrated diffraction interference for single electrons passing through a slit just 83 nm wide using an electron microscope operating at 200 keV.[12] Finally, Feynman's proposed single-electron double-slit interference has been realized by Bach *et al.* who have guaranteed the presence of only one electron with a probability greater than 99.9999%.[13]

If the concern is with preserving realism, the particle model of a photon — when a substance of unknown quality is confined to an arbitrarily small bounded volume — does not sit well with the notion of phase and polarization. The difficulty becomes most acute when one considers that it is necessary for a single photon to have its laterally-separated *parts* diverted into coincidence for interference to occur. In a realistic model, these diverse parts must have substance. Indeed, each part taken in isolation — for example, of a front passing through a double-slit apparatus — must have the potential to excite a detector all by itself. The real mystery is why most of the front fails to register at a detector. This was precisely the problem faced by the classical-wave model. Now, there seems to be an unconscious assumption that with a substance-based front, any part that impinges on a detector must *necessarily* trigger it, so that if the detector is not triggered then no substance is incident on it. This has led to the view that if a detector registration occurs on one part of the front, then this excludes a registration occurring from another part. In other words, following Einstein, the single photon manifests itself as a locally-bounded volume. The notion that a single photon is a laterally extended substance has now been abandoned and it was Born who introduced the idea that it is not *substantial* parts of a front that interfere but *idealized* mathematical parts in the form of a guiding field.[14,c]

The aim here is to contest the view that if a part of the front is substance — rather than ideal — then it must *necessarily* trigger a detector. Instead, it will be argued that in a photon-counting experiment, *more than one* part of a front might excite a detector, but the probability of coincidence is so low (as we shall see) that it creates the illusion that *only one* part at a time can produce an excitation. The suggestion made here is that a single photon is not locally bounded but is an advancing front of non-rotating screw threads iterated laterally that can produce circular polarization. Each thread has substance and allows spin angular momentum (SAM) to be conveyed to matter in a stationary plane perpendicular to the optic axis.[15–18] This raises the intriguing possibility that if a target surface could be favorably prepared, a large number of excitations might potentially be extracted from a single-photon front. In other words, a signal might be amplified.

2. Coincidence Counting

Grangier *et al.* expressed dissatisfaction with methods that rely on strongly attenuated beams, suggesting that "none has been performed with single-photon states of light. As a matter of fact, all have been carried out with chaotic light."[19] An earlier collaboration had measured "the linear polarization correlation of the photons emitted in a radiative atomic cascade of calcium" which were selectively pumped to the upper level of the cascade.[20] In the process, two photons were produced from the transitions $4p^{21}S_0 - 4s4p^1P_1 - 4s^{21}S_0$, correlated in polarization, with wavelengths $\lambda_1 = 551.3$ nm and $\lambda_2 = 442.7$ nm, see Fig. 1. The photons were sent in opposite directions through aspheric lenses ($f = 40$ mm, diameter $= 50$ mm) followed by a set of 10 optically flat polarization plates inclined near Brewster's angle, and then through filters to remove unwanted wavelengths. They eventually

[c]Born introduced the idea of a "Führungsfeld" or "guiding field".

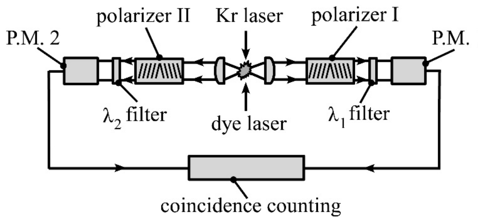

Fig. 1. Schematic of apparatus for counting coincidence detections between two simultaneously generated photons, see Aspect *et al.*[20] The laser beams are focused onto the atomic beam which runs perpendicular to the figure. Filters ensure that the photomultipliers (P.M.) only receive photons of wavelength λ_1 at P.M. 1 and wavelength λ_2 at P.M. 2.

arrived at the photomultiplier detectors P.M. 1 and P.M. 2 where the excitation-event signalling was routed into coincidence-counting electronics. The time delay between coincident detections was measured and results were recorded around the null delay in a 19 ns coincidence window. The authors reported singles counting rates of "40,000 and 120,000 counts per second" for λ_1 and λ_2, respectively, and "coincidence rates without polarizers [of] 240 coincidences per second".[20,d]

The probability P_C of detecting a coincidence given that the idler detector has been excited can be approximated from

$$P_C = \frac{B}{A+B}, \tag{1}$$

where A is the total singles count taken over both detectors and B is the coincidence count. From this we find that $P_C = 1.5 \times 10^{-3}$. The fact that a photon pair is generated means that P_C can also be interpreted as the probability that a particular detector registers an absorption given that a photon is incident on it.

Similar experiments have also been performed using spontaneous parametric down conversion (SPDC) to generate equal frequency photon pairs — the signal and idler — which are each sent to their own detector to obtain singles and coincidence counts, see Table 1.[21–24,e] Noh *et al.* have remarked that the singles count rates can vary with the focal length of the aspheric lens in the fibre optic collimators and the "accidental" coincidence counts can vary with the laser output power, and although "accidental" counts are understood to be fewer than "true" ones, the authors have omitted details as to how they are to be distinguished.[22] Kwiat *et al.* have stated that "typical "accidental" coincidence rates are negligible ($< 1\ \mathrm{s}^{-1}$)".[21]

[d]The bandwidth was 15 nm. The authors estimate "accidental coincidences" by counting coincidences 100 ns after the null delay and have found 90 s^{-1}. So a subtraction yields 150 "true coincidences per second". Here, we consider all coincidences.

[e]SPDC is a quantum optical process where a nonlinear $\chi^{(2)}$ crystal is used to down-convert a pump photon of higher energy into a pair of photons of lower energy. A continuous or pulsed laser source is used to supply the nonlinear crystal in which energy and momentum are conserved. Type I phase matching is where the photons emerge with the same linear polarization, while Type II results in mutually perpendicular (polarization-entangled) polarizations. The latter process tends to produce fewer photons than the first.

Table 1. Estimate of the probability of a detector registration P_C given that a photon is incident on it, which is known from the detection of its correlated conjugate.

P_C	A (s^{-1})	B (s^{-1})	Source
1.5×10^{-3}	160,000	240	Aspect *et al.*[20]
1.17×10^{-3}	8500	9.96	Grangier *et al.*[19,f]
1.38×10^{-2}	1,500,000	21,000	Kwiat *et al.*[21,g]
1.03×10^{-2}	2800	29	Noh *et al.*[22,h]
5.3×10^{-2}	3800	200	Galinis *et al.*[23,i]
7.494×10^{-4}	200,000	150	Ahmed *et al.*[24,j]

Their experimental arrangement used half-wave plates in both the idler and signal branches in order to rotate the plane of polarization.

Counts for six experimental studies are summarized in Table 1 from which it should be clear that when a photon is incident on a detector, known from the detection of its conjugate, then its presence is not always registered.

3. Beam-Splitting the Signal Photon

So a photon front can impinge on a detector without necessarily affecting a registration. We now ask: Is it possible for a single-photon front to be divided at a beam splitter into two components, each of which can produce a registration at their respective detectors as a coincidence?

The crucial experiment was performed by Grangier *et al.* who set up a double-photon source (atomic cascade) in which the photons emerge with different frequencies.[19] One precedes the other by a known time interval, and the first is used to trigger the detection apparatus for the second. Two experiments are then carried out, both with the same source and rate counters. The first runs the source photons into a beam splitter, without recombination of the fronts, with a photomultiplier and counter on each output path to bring out the quantum mechanical or individual nature of the photons in an anti-correlation, see Fig. 2. The second replaces the beamsplitter with a Mach–Zender interferometer, with adjustable path differences, a device that is intended to bring out the classical or relative phase relationship

[f] The signal beam was divided at the beam splitter. On subtracting dark rates, each beam splitter detector registered half the rate given under B in Table 1. The coincidence count with A arises from the sum of the two beam-splitter divisions which is 2×4.98 s^{-1}.

[g] Two relatively thin BBO nonlinear crystals cut for Type I were set adjacent to each other to create a pair of degenerate photons at 702 nm.

[h] A lithium triborate (LBO) nonlinear crystal cut for Type I was used to yield two photons at 1550 nm each.

[i] A lithium iodate crystal 20 mm long cut at 35° for Type I SPDC was used. These singles and coincidence counts are based on Fig. 2(b) of their paper with the crystal orientated at 43.4° with respect to the pump.

[j] A BiB_3O_6 (BiBO) nonlinear crystal cut for Type I was used to create two photons at 804 nm each.

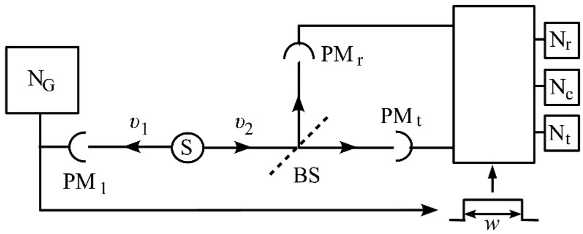

Fig. 2. Triggered anti-correlation experiment. The detection of the first photon of the cascade at PM_1 initiates a gate w, during which time the photomultipliers PM_t and PM_r are active. The probabilities of detection during the gate are $p_t = N_t/N_G$, $p_r = N_r/N_G$ for singles and $p_c = N_c/N_G$, for coincidences (see Ref. 19, Fig. 1, 174).

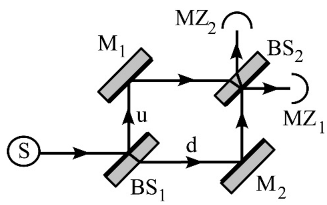

Fig. 3. A Mach–Zender interferometer. The detection probabilities in outputs MZ_1 and MZ_2 are oppositely modulated as a function of the path difference between the arms of the interferometer, varied at u. The thick lines on the beam splitters BS_1 and BS_2 indicate reflection surfaces, and M_1 and M_2 are mirrors (see Ref. 19, Fig. 3, 177).

between the two paths in a correlation, see Fig. 3. In contrast to the second case, the first is expected to raise no coincidences. In Fig. 2, detection rates are made for path r, path t, and both path r and t. The authors assert that "a single-photon can be detected once [only]" and cite their result that they measure coincidences that are "five times smaller than the classical [wave theory] lower limit" with a "maximum violation of more than 13 standard deviations" for the classical coincidence inequality.[19] The expected number of coincidences from the classical theory should be ≥ 50 whereas they measure only 9. However, the fact is, they actually measure some coincidences. Their low count does not mean that coincidences *do not* occur. It means that they *rarely* occur.

For the first Grangier experiment (Fig. 2), two photons with frequencies υ_1 and υ_2 are generated by a cascading process at the source S, with the decay of the intermediate state of the cascade having a lifetime of $\tau_s = 4.7$ ns. The detection of υ_1 at the photomultiplier PM_1 triggers a gate that allows the photomultipliers PM_r and PM_t to be exposed to the photon with frequency υ_2 for a time interval $w \approx 2\tau_s$.[k] Singles and coincidence counters are fed by the photomultipliers, and given that ΔT is the counting interval, then $N_G/\Delta T$ is the rate at which the gate is triggered, $N_r/\Delta T$ is the reflected singles rate for PM_r, $N_t/\Delta T$ is the transmitted singles rate

[k]The excitation of PM_1 triggers the start of the gate, and excitation of either PM_r or PM_t effects its termination.

for PM_t, and $N_c/\Delta T$ is the coincidence rate for a registration by both PM_r and PM_t during a single gate. It was found that during 1.53×10^8 gate events, $N_t = N_r = 89,640$ singles were counted at PM_t and PM_r with only $N_c = 9$ coincidences recorded.[l] Applying calculation (1), we find $P_C = 5.02 \times 10^{-5}$. In consequence, their report declares that "the light emitted after each triggering pulse has been shown to exhibit a specifically quantum anti-correlation behavior."[19,m] Since this part of the experiment involves only a splitting of the beam with no reconstitution, no opportunity is afforded for components of the beam to engage in interference. Although a photon is presently understood to take one path only out of the beam splitter, the occurrence of $N_c = 9$ coincidences allows the interpretation that this is not always the case. No statistical analysis of the group behavior of the photons can negate the fact that these coincidences have actually been observed.

The Grangier experiment was repeated by Thorn *et al.* using SPDC with a 2.5 ns gate over a 5 min time period.[25,n] A "gate opening" occurred by the excitation of the idler detector, and the rate of idler detection was $R_G{\sim}110,000\ \text{s}^{-1}$. So the threefold coincidence rate R_c obtained, which is not stated, can be found from their best calculated value of $\alpha = R_c R_G/(R_r R_t) = 0.0177 \pm 0.0026$, where $R_r = R_t = 4400\ \text{s}^{-1}$ at PM_r and PM_t, from which it appears that they actually measured $R_c = 3.12$ counts per second.[o] Given that a single signal emission has registered at a detector PM_r or PM_t or both, the probability of coincidence is then $P_c = 3.12/(2 \times 4400 + 3.12) = 3.54 \times 10^{-4}$. In Table 2, we see the coincidence rates from the two studies mentioned. The authors assert that the "real" coincidence rate for spatially localized photons should be $P_c = 0$ and speculate that these "accidental coincidences" are "uncorrelated photons from different down-conversion events [that] may hit the T and R detectors within our finite coincidence window" (see Ref. 25, Appendix A).[25] They suggest that whenever a coincidence occurs during

Table 2. The probability of a second post-beam-splitter detector registering, given that one of them has already registered during a gate.

Coincidence probability given photon incidence	Source
5.02×10^{-5}	Grangier *et al.*[19]
3.54×10^{-4}	Thorn *et al.*[25]

[l] The total counting time was $T = 5$ h, and the PM_1 rate N_G was $8800\ \text{s}^{-1}$ which includes a dark rate (no cascade source) of $300\ \text{s}^{-1}$. The rate N_r was $5\ \text{s}^{-1}$ which includes a dark rate of $0.02\ \text{s}^{-1}$. In Table 2, dark rates are subtracted.

[m] "Anti-correlation" means that the sum of the two photon energies is constant. Dark rates are subtracted, that is, the count with no source except the laboratory environment.

[n] Since the dark count rate was $250\ \text{s}^{-1}$ this produces a negligible 6.25×10^{-7} dark effects per gate.

[o] This was obtained from a 40 min count. A threefold coincidence is an idler detection that starts the gate with a signal detection registered at both R and T during the gate. Thorn *et al.* use the notation R_G whereas Grangier *et al.* use R_1.

a gate, an intruder-photon is passing through the beam splitter from a different SPDC event. It should be emphasized that they have no way of knowing this, that their "explanation" is actually a conjecture, and that there is space for an alternative explanation. It is suggested here that a photon front incident on a detector can produce two or more registrations, and from Table 2, its probability of doing so appears to be no more than $5.02 \times 10^{-5} - 3.54 \times 10^{-4}$.[p]

4. Recombination of the Beam-Splitter Outputs

The second part of the Grangier experiment makes use of the same triggering mechanism. Here, a Mach–Zender interferometer replaces the beam splitter BS and the photomultipliers PM_r and PM_t, so that the opportunity for a superposition of parts of the single-photon front is now available, see Fig. 3.

The interferometer operates as follows.

Principles of reflection and transmission

(1) A half-silvered mirror reflects half of the incident light and refracts the other half.
(2) A π phase shift results when a ray is reflected from a surface with a denser medium on the other side (e.g. air to glass).
(3) No phase shift results when a ray is reflected from a surface with a less dense medium on the other side (e.g. glass to air).
(4) A mirror causes a π phase shift.
(5) When a ray passes through a medium there is a phase change, the magnitude of which depends on the refractive index of the medium and the path length.

There are two possible paths for a photon to follow on exiting the first beam splitter BS_1: u (up), or d (down), where path u has variable length. Table 3 shows the relative phase shifts between these two paths for detectors MZ_1 and MZ_2.

Table 3. Relative phase shift between the u and d paths in a Mach–Zender interferometer at each detector MZ_1 and MZ_2 for a path difference δ rads. The photon wavelength is λ and the mirror location in u is adjustable using a piezo-driven mechanical system to vary the path difference δ. Here, BS is a beam splitter, M is a mirror, and the numbers that follow these symbols refer to the principles listed above.[q]

Destination	Path u	Path d	Relative phase shift
Detector MZ_1	BS_2, δ, M_4, BS_5	BS_5, M_4, BS_2	δ
Detector MZ_2	BS_2, δ, M_4, BS_5, BS_3, BS_5	BS_5, M_4, BS_5	$\pi + \delta$

[p]From Table 1 the range is $7.5 \times 10^{-4} - 5.3 \times 10^{-2}$ (1 d.p.).
[q]The beam splitter BS_2 is coated on the right-hand side in Fig. 3 which is why the u path takes two internal paths before reflection to MZ_2 (with no phase shift), while the d path reflects to MZ_1 without passing into the beam splitter (with π phase shift).

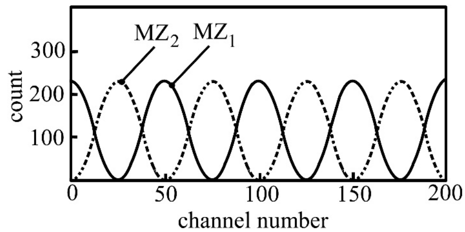

Fig. 4. Superimposed curves showing the number of counts in outputs MZ_1 and MZ_2 as a function of the path difference δ. Starting at $\delta = 0$, one channel corresponds to a $\lambda/50$ variation of δ. Total counting time 15 s (adapted from Ref. 20; Fig. 4, 178).

We can see from Table 3 that when $\delta = 0$ there is constructive interference at MZ_1 but a destructive one at MZ_2, and vice versa when $\delta = \pi$. Grangier *et al.* report varying the path difference δ in 256 steps of increment $\lambda/50$, with a counting time of 1 second per step. The accumulated count for 15 sweeps is shown in Fig. 4. The authors remark that "we are compelled to use a wave picture (the electromagnetic field is coherently split on a beam splitter) to interpret the second (interference) experiment" (see Ref. 19, 178–179).

In the first Grangier experiment, no opportunity is afforded for superposition of diverse parts of the single-photon front. However, for the second experiment, in order to accommodate superposition, we now introduce the model of an array of advancing helical space dislocations (HSDs) or non-rotating screw threads, see Fig. 5.[r] The front is divided at BS_2 with each individual HSD thread on the front carrying the possibility of exciting the detector it impinges on at MZ_1 and MZ_2. The process of absorption at a detector must then involve the participation of a single HSD interfering with another HSD,[s] during which a single quantum of linear

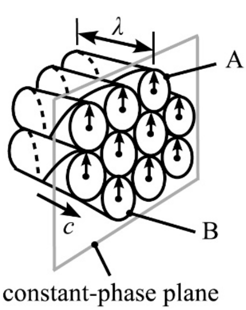

Fig. 5. Alternative single-photon model of a transverse array of HSDs. A constant-phase front of a right-circular polarization single-photon, consisting of a transversely-iterated array of left-wound HSD advancing with speed c through a stationary plane. Each single HSD has longitudinal extent λ, linear action h, and a cross-sectional area $\lambda^2/4\pi$. The HSD at A and B can take different paths and are capable of interference on being diverted into coincidence.

[r] This is the same as a transversely iterated circular polarization model.
[s] The circular area for a HSD has diameter λ/π.

action h and a SAM of magnitude $\hbar$ is transferred.[t] Let us analyze this in more detail.

Consider the Mach–Zender interferometer in Fig. 3 in relation to Fig. 5. A single circular polarization HSD at A on the front, seen prior to meeting BS_1, is to be absorbed at MZ_1 as a photon registration. If there is interference, there must be a similar HSD at B for example, separated laterally from A, that takes the alternative path and also arrives at the detector MZ_1 to coincide and interfere with A. By considering their phase relation, the HSD at B will either enhance the registration of A or diminish it depending on the path difference. Let us consider that A takes path d, and B takes path u. With a channel increment of $\lambda/50$, where λ is the wavelength of A, if a complete annihilation occurs for channel n, then we see from Fig. 4 that it also occurs for channel $n + 50$. So B maintains the same wavelength as A, reflects and transmits according to the same rules as A, and is also capable of producing a registration like A. However, there is a further consideration. If interference still occurs for changes in path difference greater than one wavelength, a thread on the front must also be iterated longitudinally with phase-matched ends. Each wavelength of transversely iterated screw threads would then represent a separate single photon.

In summary, we now have two different interpretations of how a coincidence registration might occur.

(i) *Traditional quantum mechanics hypothesis.* Different SPDC events allow more than one localized single-photon to pass through the beam splitter during the gate with each capable of registering only once. Fortuitously, the detectors are triggered by two separate localized photons. This preserves the idea that if a coincidence registration occurs, it cannot be due to a single photon.

(ii) *Proposed HSD-array model.* There is a single-photon front passing through the beam splitter during a gate that takes the form of an advancing transverse array of HSD, with each non-rotating screw thread on the front allowing a registration. Given that an SPDC event occurs — which is known from the idler photon detection — when one of the corresponding signal HSD in the array excites a detector, MZ_1 say, the rest of the divided front might produce a further registration at the other detector MZ_2 with a probability similar to that given in Table 2. Here, a coincidence registration arises from the division of a single photon represented as a transverse array of HSD.

The term "single photon" seems not to do justice to this model for there is an array of HSD arranged laterally. Also, it appears from the Grangier experiment, that the

[t] A linear polarization HSD can only transfer linear momentum and is to consist of two oppositely wound threads of the same wavelength. However, an absorbed circular polarization photon is a single-turn helix which, when moving at speed c, generates both linear and spin angular momentum in a plane perpendicular to the direction of the photon. Since the action is quantized, the linear momentum is $p = h/\lambda$ while the spin angular momentum has magnitude $h/2\pi = pa$, where $\lambda = 2\pi a$, and a is the helix cross-section radius (see Ref. 26).

limits that determine the conditions for absorption of just one of the HSD on this front are met only rarely. It is suggested here that the conditions for excitation of a detector are to be related to the orientation and state of the electron orbit in the atomic target.

5. Temporal and Second-Order Correlation Function

The first practical use of a spatial second-order correlation function, involving quantities quadratic in the field strengths, was made by Hanbury Brown and Twiss (1956).[27,28] They pointed two telescopes set a known distance D apart at the brightest star Sirius and found that the collected intensities, filtered to be monochromatic, were so correlated as to allow the angular diameter of the star to be obtained. The light from the left extremity of the star into both telescopes produces one intensity profile while that from the right extremity produces a similar intensity profile whose center is displaced from the first. The distance D between the telescopes is increased until the first-order fringes disappear at which point $\varphi \approx d/L$, where d is the star diameter and L is the stellar distance.[u] Here, angle φ is that between the rays into one of the detectors from the star extremities.

We now return to the coincidence-counting experiments of Sec. 2 in which SPDC was used to produce an idler and a signal photon. The signal photon encountered a 50–50 beam-splitter and the detection of the idler photon meant that the signal photon was also known to exist and was advancing on the beam splitter. However, the values of P_C recorded in Table 1 suggest that there is only a small probability that the signal photon can excite a detector given that a photon is incident on it. Let us reconsider the case of a beam splitter placed in the path of a signal photon υ_2, see Fig. 2. Suppose that a signal-photon registration at either one of the detectors PM_r and PM_t positioned at the beam splitter ports initiates a countable time increment or gate. Let us label these detectors 1 and 2. The sum of these increments is to constitute the measurement time interval. Table 4 shows 12 time increments. The registration of a photon at detector 1 is indicated by $I_1 = 1$ and its non-detection by $I_1 = 0$. Similarly, for detector 2 we have by $I_2 = 1$ and $I_2 = 0$. First, we examine a quantum model where *only one* of the two detectors is triggered. An example is shown in Table 4 for $n = 12$ time increments.

Table 4. A quantum second-order correlation in which only one of the detectors registers a count. Registrations recorded at detectors 1 and 2 are taken over a time interval divided into 12 equal increments. A registration is indicated by 1 and a non-registration by 0.

i	1	2	3	4	5	6	7	8	9	10	11	12
$I_1(t_i)$	1	0	0	1	1	1	0	1	0	0	0	0
$I_2(t_i)$	0	1	1	0	0	0	1	0	1	1	1	1

[u]The small angle approximation $\varphi \approx \tan\varphi$ is used.

The second-order temporal correlation function is defined as follows:[v]

$$g^{(2)}(\tau) = \frac{\langle I_1(t) I_2(t+\tau)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle}. \tag{2}$$

Here, the angled brackets indicate a mean value summed over a time interval. If the measurements are taken simultaneously as $\tau = 0$, then we have

$$g^{(2)}(0) = \frac{\langle I_1(t) I_2(t)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle}. \tag{3}$$

For the quantum model, we now calculate the second-order correlation function in Eq. (3) for Table 4 and arrive at

$$g_q^{(2)}(0) = \frac{\langle I_1(t) I_2(t)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle} = \frac{\frac{0}{12}}{(\frac{5}{12})(\frac{7}{12})} = 0. \tag{4}$$

For the classical wave model, a photon front incident on a detector necessarily produces a registration and Table 4 contains only ones and no zeroes. The calculation for Eq. (3) then becomes

$$g_c^{(2)}(0) = \frac{\langle I_1(t) I_2(t)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle} = \frac{\frac{12}{12}}{(\frac{12}{12})(\frac{12}{12})} = 1. \tag{5}$$

However, it is suggested here that neither the quantum nor the classical model reflects the "real" state of affairs. Instead, Table 1 records experiments that suggest the following. Given that a single-photon is incident on the signal detector (known from detection of the idler), there is a probability of excitation for the signal detector that is much less than one, that is

$$7.494 \times 10^{-4} \leq P_C \leq 5.3 \times 10^{-2}. \tag{6}$$

In other words, this is the probability of a coincidence detection for the idler and signal. We now construct Table 5 where in addition to only one detector being excited, occasional coincidences occur. When this occurs, a "1" appears twice in the column of a time increment. Ignoring Eq. (6), let us by way of example arbitrarily set the probability of coincidence to be $P_C = 1/3$ so that with $n = 12$ time increments there are $n/3 = 4$ coincidences.

The calculation for Eq. (3) is now

$$g_c^{(2)}(0) = \frac{\langle I_1(t) I_2(t)\rangle}{\langle I_1(t)\rangle\langle I_2(t)\rangle} = \frac{\frac{4}{12}}{(\frac{7}{12})(\frac{9}{12})} = \frac{16}{21} < 1. \tag{7}$$

This brings out the essence of "real" quantum mechanical behavior. For their experiment, Thorn *et al.*, give $g^{(2)}(0) = 0.0177 \pm 0.0026$.[25]

It is suggested here that the reason there is interference when the beam splitter outputs are recombined for a single photon (see Sec. 4) is because the photon has *real* transverse extent. So we are entitled to ask, in that case, why is it that the

[v]A mathematical treatment of coherence functions has been given by Glauber.[29]

Table 5. A classical-quantum second-order correlation in which only one or both detectors produce a registration. Registrations recorded at detectors 1 and 2 are taken over a time interval divided into 12 equal increments. A registration is indicated by a 1 and a non-registration by a 0. The probability of coincidence registrations is arbitrarily taken to be 1/3.

i	1	2	3	4	5	6	7	8	9	10	11	12
$I_1(t_i)$	1	0	0	1	1	1	0	1	1	0	1	0
$I_2(t_i)$	0	1	1	1	0	0	1	1	1	1	1	1

detections after recombination are not all coincidences? For a two-slit interference experiment with electrons, there is good reason why Feynman (III, 1–5) formed the view that "each electron either goes through hole 1 or it goes through hole 2 [but not both]".[10,w] When he recorded this assertion in a series of lectures given at Caltech during 1961–1963, the sensitivity of the experimental apparatus was such that the probability of both electrons being detected as a coincidence was too low to be noticeable.

In our analysis of single-photon counting, this is also what Eq. (6) testifies. Of course, one could claim that the coincidences are due to spurious photons from other SPDC events entering the system but it is a choice that forces us to reject local realism.[x] The advantage of the interpretation introduced here is that the suggestion that each HSD on the photon front has substance (real) and is capable of exciting a detector provides a way out of the dilemma. In a two-slit experiment, a single photon *does* go through both slits. It is extended laterally, and if the part traveling through slit 1 registers at the screen with a detector, the probability that the part going through slit 2 registers with another detector is *non-zero* can be as low as that given in Eq. (6). While the slit 2 component might not register at a detector, if it is appropriately directed (for example, by diffraction) to meet with the first component, it is still capable of cooperating with it to produce an interference effect.

6. Discussion

The Grangier experiment has brought out two seemingly irreconcilable aspects of single photon behavior. Feynman gives the mathematical relations as follows.[y]

[w]With a light source behind the slit holes to scatter the electron, he also says "we *also see* a flash of light *either* near hole 1 *or* near hole 2 but *never* both at once!".[10]

[x]Colloidal quantum dot technology based on electroluminescence has been used to produce a "highly suppressed multi-photon-emission probability", that is, photons that arrive one by one (i.e. "anti-bunched"). Coincidence counts obtained from the exit ports of a beam splitter still occur in this quasi-pure single-photon environment with 21 out of 30 electro-excited dots having second order temporal correlation function $g^{(2)}(0) > 0.07$ at null delay.[30]

[y]See Eqs. (1.6)–(1.8) in Ref. 10 (III, 1–10).

(a) The probability of an event in an ideal experiment is given by the square of the absolute value of a complex number ϕ which is called the probability amplitude:[z]

$$\begin{aligned} P &= \text{probability}, \\ \phi &= \text{probability amplitude}, \\ P &= \phi^2. \end{aligned} \tag{8}$$

(b) If an experiment is performed which is capable of determining whether one or another alternative is actually taken, the probability of the event is the sum of the probabilities for each alternative. The interference is lost:

$$P = P_1 + P_2. \tag{9}$$

(c) When an event can occur in several alternative ways, the probability amplitude for the event is the sum of the probability amplitudes for each way considered separately. There is interference:

$$\begin{aligned} \phi &= \phi_1 + \phi_2, \\ P &= |\phi|^2. \end{aligned} \tag{10}$$

Equation (9) applies to the first part of the Grangier experiment in which the front is divided with a beam splitter. Feynman implies that there is *only one* single localized area on the front capable of triggering a detector and so it must take either one path or the other at a beam splitter but not both. Equation (10) applies to the second part of the Grangier experiment in which an interferometer is installed in place of the beam splitter. This now provides an opportunity for the two paths to interact and interfere.

If we examine a single photon passing through a Mach–Zender interferometer in Sec. 4, the conclusion seems unavoidable that in order for superimposed parts of the front to be capable of constructive and destructive interference, there must be separate regions of identical phase and structure on the beam front that simultaneously have substance. An idealized front, as represented by a mathematical probability amplitude, is not an interaction of substances.

The question then arises: If each part of the front has substance why do we observe only one part of the front triggering a detector while the other parts do not? The results given in Table 2 contest the premise of this question. The work of Thorn *et al.* suggests that the coincidence probability might actually be *non-zero* and as low $P_c = 3.54 \times 10^{-4}$.[25] Table 1 suggests that the probability that a photon front triggers a detector, given that it is incident on it, is $7.5 \times 10^{-4} - 5.3 \times 10^{-2}$. So the question needs to be: Given that a substance is incident on a detector, why are the conditions for excitation met with such low regularity? It is conceivable that characteristics such as target-electron orientation might enter into the analysis.

[z]It was Born who introduced the concept of a "ghost wave" in the Introduction to his paper.[14]

The final point relates to the structure of the single-photon front. As first discovered by Beth,[15] a single photon is known to possess SAM.[15–18] This is conveyed to a target atom as circular polarization. The problem with the Maxwellian representation of light is that the Poynting vector of an infinite plane wave is directed along the propagation direction and so carries no SAM (see Ref. 31 (222–230)). Once it is given an azimuthal component, then magnetic and electric vector components arise in the propagation direction and it is not then a pure transverse wave. Mansuripur has suggested a solution by approximating a plane wave with a sum of mathematical components that are at a non-zero angle to the propagation direction.[32] Allen and Padgett have also attempted to salvage Maxwell's theory by suggesting that a target that absorbs angular momentum creates a gradient in the beam intensity $|u|^2$ at its boundary, which is where the torque materializes.[33] This then permits a spin density j_z to exist as follows:

$$j_z = -\frac{r}{2}\frac{1}{|u|^2}\frac{\partial |u|^2}{\partial r}\hbar\sigma. \tag{11}$$

where $\sigma = 0$ for linear polarized light, $\sigma = \pm 1$ for right- and left-circular polarized light, respectively, and r is the radial distance from the axis. However, there are observed cases in which SAM is conveyed but a torque does *not* manifest at the target boundary. For example, Friese *et al.* took calcite fragments measuring $1 - 15\ \mu$m across and 3 μm thick, then exposed them to a 1064 nm laser source.[34] Here, it is known that a torque has been transferred to a fragment from the detection of a change in angular momentum of an incident photon. However, in their investigation, this occurred when the diameter of the radiation tube $\lambda/\pi = 3.6 \times 10^{-7}$ m was less than the minimum fragment diameter 1.0×10^{-6} m. For Maxwell's theory to work, the variation in beam intensity and the applied torque need to occur at the boundary of the absorbing target. Here, they occur well inside.

It is suggested here that a better structure for a single-photon front is an array of non-rotating traveling screw threads (or HSDs) distributed uniformly over the front. These can induce circular polarization effects in a stationary plane set perpendicular to the propagation axis, see Fig. 5. In experiments where path differences greater than one wavelength are significant (e.g. the two-slit experiment), there would also need to be a longitudinal iteration of the transverse array with phase-matched ends. There are bounded areas on the photon front which are tube cross-sections, each guiding the passage of an identical screw thread at light speed c. With an array of threads each capable of triggering a detector, this undoubtedly leads to an unlimited energy content taken across a laterally unbounded single-photon front. However, it is suggested that access to the energy of any HSD on the front is only possible on the infrequent occasion when the relative orientation and phase of the target electron in the detection surface is favorable.

Feynman (III, 1–10) has remarked that "No one has found any machinery behind the law [of quantum mechanical probability amplitudes . . .] We have no ideas about a more basic mechanism from which these results can be deduced."[10] However, it is suggested here that the difficulties persist only so long as the assumption is upheld that only a *single* localized area of the photon front can affect a detector in a gate. Once we remove this prohibition, and admit a coexisting array of real localized areas on the front, each with substance, and each capable of affecting a detector, then the phenomenon of interference becomes an interaction between *real* coexistences instead of between *possible* ones.

7. Concluding Remarks

The evidence that multiple parts of a single-photon front can have substance yet *not* trigger a detector is presented in Table 1. In the experiments tabulated, this triggering occurs with probability $7.494 \times 10^{-4} - 5.3 \times 10^{-2}$. The photon-counting results of Grangier *et al.* and Thorn *et al.* in Table 2 are then reinterpreted to suggest that the coincidences observed during a single gate are not from spurious SPDC events, but are instances of a single-photon front triggering more than one detector simultaneously. These coincidences are recorded to have probability $5.02 \times 10^{-5} - 3.54 \times 10^{-4}$. The results in both of these tables suggest that the idea of a *non-substantial* wave-front cannot be sustained. Instead, we should adopt a pseudo-classical-wave model in which *all parts* of a single-photon front have substance rather than being an idealized mathematical representation. However, in order to convey SAM, this front is to consist of an array of HSDs in the form of non-rotating screw threads advancing at speed c. We should then consider the target surface to ascertain when the conditions for excitation are met.

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