Two−slit experiment

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Timo A. Nieminen wrote:
http://groups.google.com/group/sci.physics.research/browse_frm/thread/29a7934b4fb64637

> If photons are waves, and massive particles are waves,
> then why is the exchange of energy between matter and EM
> fields quantised?

The exchange is quantized only for bound electrons, not for free electrons. In the case of bound or spatially constrained electrons, the available frequencies for the electron matter field are discrete for the same reason that the frequencies of constrained guitar wires are discrete. The discrete spectrum is a property of the solutions of those types of PDEs with those boundary conditions.

Of course, you may object that since Schrodinger equation is linear, if Psi(x) is a solution, then a function C*Psi(x), for any constant C is also a solution (with the same bound state boundary conditions, zero Psi at infinity). Hence the dynamical equations with their boundary conditions are not sufficient mechanism capable of producing discrete energy spectrum.

This objection to Schrodinger' s original interpretation of his 'wave mechanics' was raised by Tomonaga (cf. [7] pp. 25−31, where Dorling discusses and answers Tomonaga's objection). In other words, there is an _additional_ condition, the normalization to 1 of the integral of |Psi(x)|^2, which is used in order for Schrodinger equation to yield discrete spectrum for bound states. Hence, this is a question as to why is the electron matter field in the atom normalized to have charge n*e, where n is an integer (since without this discrete normalization the solutions would have continuum for the energy spectrum, with different energies corresponding to different total charge integrals). There is presently no dynamical theory (other than isolated speculations, including those by Dirac and Barut) of charge quantization which could deduce this quantization and the particular observed charge values, so we have to leave this question alone, even though it is certainly relevant for the origin of the discrete energy spectra of bound states.

The answer by Schrodinger to this objection is that the correct equations are not linear, but rather a nonlinear PDE system of coupled Maxwell−Schrodinger/Dirac equations. It is then easy to see that, for example, if this PDE system has a solution Psi(x), then no other value C*Psi(x) is a solution, unless |C|=1, hence the correct equations for the full system (EM+matter fields) do have a preferred value for the charge within the family of functions C*Psi. While invalidating the objection at the fundamental level, this answer still falls short of providing the possible values (the n*e values) of the total charge. Some progress toward a more complete answer has been made in 1990s, when the existence of solition solutions of coupled Maxwell−Dirac system with some electron properties was demonstrated (cf. [8] and references there).

The photons emitted by the excited atom are simply the beats between the (quasi−)stationary electron matter field frequencies. There is nothing in the derivation of the spontaneous emissions, in QED or semi−classically, that describes a localized or pointlike object, or any kind of 'individual' hv kind of object, departing the atom. All that is departing is an EM field disturbance with the spectrum concentrated around the beat frequencies of the electron field. Since the combined EM and matter fields satisfy the energy−momentum conservation (which follows from the invariance properties of the combined EM + matter fields Lagrangian), if the atom state changed between the two stationary levels, the total energy carried by the EM field beats must be the difference of the energies of these two stationary levels.

In the inverse process, which is simply a time reverse of the emission, the electron matter field resonantly absorbs the beat frequencies between its quasi−stationary levels from the EM field, and the same energy−momentum conservation holds here as well.

Further, the EM field of spontaneous emission described in QED is superposed of infinitely many free field modes (which are the QED photons, described by plane waves with sharp energy−momentum eigenvalues). The individual modes, or individual QED photons, appear in those derivation only as mathematical artifacts of particular basis arbitrarily chosen for perturbative expansion, in the same manner that the plane waves appear in Fourier expansion used in the semi−classical treatment.

The above physical picture was the original Schrodinger's view of his wave mechanics (as described in his 1926 series of papers introducing the wave mechanics). The (first) quantization was in his view merely a transition from the classical particles to classical matter fields, a natural completion of the process initiated by Faraday and Maxwell. The matter fields are in that picture real objects on par with EM field and the two coupled fields are nonlinear classical system.

Although Schrodinger tried modeling the spontaneous emission and radiative corrections based on the coupled Maxwell−KG fields (he discovered KG eqations independently from Klein & Gordon, along with several others), the numbers he obtained were wrong even for basic spectrum of Hydrogen, so he gave up on that approach and turned to the multiparticle QM formalism (previously discovered by Heisenberg). It was only in 1985−1992 that Schrodinger original program was carried out to near completion by A. Barut and collaborators, under the name "Self−Field Electrodynamics" (SFED). A brief intro with key references (most available online) to SFED was posted in an earlier s.p.r thread (and a followup):

http://groups.google.com/group/sci.physics.research/msg/386f48731520d145
http://groups.google.com/group/sci.physics.research/msg/bb1225c256c34c02

The review of Schrodinger's original attempt (and reasons it failed) is given in ref [3a] there, discussion of charge quantization and how one might solve it within SFED is in [3h], and meaning of the energy quantum hv from the wave mechanics / SFED perspective in [3j].

> The proposal is just to address the claim that the photon has a size equal to the spread of its wavefunction,...

The size or location of photon can only be defined as a matter of arbitrary convention. QED photon is quantized mode of the _free_ EM field with sharp energy−momentum, appearing in perturbative treatment, just like the equivalent Fourier transforms appear in the semiclassical or SFED treatments. The QED photons have infinite spatio−temporal extent, thus they are not elements of the formalism which map operationally to the coincidence measurements in Quantum Optics. The Quantum Opticians have their own QO photon, which is a different entity than QED photon. The QO photon is a superposition (and sometimes even a mixture) of infinitely many QED photons with different energy−momenta, but with sharp photon number eigenvalue (as discussed some more later). They are more meaningful theoretical objects (EM field states) for QO since they can be approximately localized and thus brought into the operational correspondence with QO coincidence setups. But the interactions between EM field and the matter fields, such as photodections, are still described via QED photons. The "single" QO photon can trigger multiple remote detectors (each trigger caused by absorption of one QED photon), while a single QED photon can be absorbed only once, thus trigger only one detector.

The confusion on this key distinction (and its operational interpretation) is the root of the miscommunications and confusions between Quantum Opticians and the rest of physicists as to what the experimental facts are. For example, while one can say that a PDC source emits a single pair of QO photons in a given time window, it is also true that the very same EM field state contains infinitely many QED photons, hence the number of possible photo−ionisations (which are the result of the QED photon absorptions by electron's matter field) per sampling window is not limited to one per member of the PDC QO photon pair, as the QO photon terminology would suggest (and which sometimes gets stated explicitly).

> ... and that detection probability is simply proportional to E.

Informally speaking, the detection probability _is_ proportional to the EM energy (the integral of intensity) incident on the cathode in a given sampling time window. More formally, it is proportional to the time integral of the expectation value of the normally ordered product [E−][E+] of electric field operators (negative and positive frequency components) on the cathode. The normal ordering requirement is due to the removal of the vacuum photon terms (1/2 photon per mode in the free EM field Hamiltonian). This removal of vacuum photons is operationally mapped by the QO counting rules to the subtraction of the vacuum fluctuations effects (the 'dark currents', which are partially suppressed by the design which minimizes the dark rates, and partially by the explicit subtractions of the background rates from all actual counts & correlations).

Note though, that the electric field operator in Heisenberg picture [E(x,t)]=[E+] + [E−] evolves via Maxwell equations and it does not "collapse" or vanish from detector A cathode when a remote detector B triggers, even though the combined EM field state corresponds to a single QO photon. Its evolution on the A cathode, thus the trigger probability of detector A, is entirely independent of the events on a remote detector B, or of anything outside of the backward light cone of the A cathode in that time window.

The point of the experiments such as [1] is precisely to try demonstrating that the probability is not proportional simply to E, but that it drops to zero on detector A, as soon as detector B triggers. As explained in [2], neither experiment [1] nor any other has demonstrated such phenomenon. Nor has it been shown to exist as a theoretical prediction of QED model for PDC source. As demonstrated in the series of papers [5], PDC source is completely classical source regarding the photon statistics in any coincidence setup, hence no such anticorrelation phenomenon can be observed with PDC pairs even in principle (e.g. by trying to deduce it via the full QED treatment).

You are welcome to bring up an experiment or a QED prediction (the formalism plus the proper operational mapping of the elements of the formalism to events in a QO coincidence setup, counts, etc) that shows how is the actual (non−adjusted) photo−count statistics different in a beam−splitter experiment, such as [1], from what a classical field model (such as Stochastic Electrodynamics, cf. [5]) would predict based on simple thresholding of the field energy measurements.

For experiment, you need to bring in the non−adjusted data and how were the coincidence units configured, so one can check whether any classical inequality was violated by the actual counts properly collected.

For the theory part, show how the full QED dynamical treatment of detection reduces the probability of trigger on A, when a remote detector B triggers. Glauber did that kind of calculation for a general EM field state and any number of detectors in his 1964 Les Houches lectures, and no such reduction in probability of A trigger comes out at the end (see [2] for references and the discussion of the Glauber's theory). Or try at least showing how such QED treatment could do it in principle, even though we may not be able to actually carry out such detailed calculations. What is the device or mechanism in the formalism which could do it?

In short, the original poster was essentially correct, however informal his statement may have been.

> Have a weak enough source so that in some time interval longer
> than the time required for the detector to click and recover,
> you only expect one photon to be emitted, or else there's
> no point to the experiment. It's not intended as a "collapse

of the wavefunction" experiment.

Without "collapse" all you have is equivalent to measuring EM field energy in some sampling windows and thresholding the result to a binary value 0=no trigger 1=trigger.
To show that there is anything going on that would surprise a 19th century physicist you need to show:

a) The EM field sampling windows are selecting coherent wave packet fragments (called here fragments A and B).

b) The remote fragments A and B are equal (other than spatial translation & rotation), hence they can interfere with nearly perfect visibility (the "dark" regions have negligible counts, while the maxima have nearly full sum of the A and B counts).

c) The probability P(AB) of two coincident triggers in a sampling window is smaller than the product of individual detectors trigger probabilities in the same sampling window
P(AB) < P(A) P(B). The probabilities are estimated from the counts:

N=# of sampling windows,
N(AB)=# of coincident triggers of DA and DB
N(A)=# of triggers of DA,
N(B)=# of triggers of DB,

via P(x)=N(x)/N, for x=A,B,AB. Hence the classical counts must satisfy inequality (cf. eqs. (7),(14) in [1]):

g2 = N*N(AB) / N(A)*N(B) >= 1 .... (1)

The violation of (1) is the "collapse" criterium i.e. a mere trigger of a detector DA makes the trigger of DB in the same sampling window less likely (smaller value N(AB)), as if the trigger DA has collapsed the remote wave packet B. This is the conjectured phenomenon that [1] was trying to demonstrate.
Experiment [1] added a third coincidence unit to count N(AB) (even though the results collected from DA and DB already provide the results for AB coincidence), then, as shown in [2], the signal delays feeding this unit were configured so that the signals fell well outside of the 'ready' state of the unit, resulting in virtually zero counts reported for N(AB).

{ Further, for whatever reason, this particular incorrect delay value of 6 ns for the third unit, which is the critical parameter responsible for the N(AB) count coming out as essentially zero, was explictly brought up 11 times in the article [1], making it by far the most repeated and emphasized single figure describing the entire experiment and all of its settings. It seems the authors wanted very badly to make sure it "worked" the way they imagined those finicky "single photons" ought to work, and not the way they actually work.}

The properties (a) and (b) are verified by bringing the two fragments into a common region to interfere. The property (c) is verified by counting triggers & non−triggers of detectors DA and DB within the sampling windows. Only the combination of all three (a)−(c) would surprise a 19th century physicist. Important details to watch:

1. The sampling windows used to verify (a) & (b) via interference must be the "same" sampling windows as those used in (c) i.e. they are the "same" with at most the spatio−temporal translation (for given optical paths) which is required to bring the non−overlapping fragments A and B from the experiment (c) into the same region needed for interference experiment (a)−(b).

Further, in case of three coincidence units (such as the setup of experiment [1]) the sampling windows used to count N(A) and N(B) must be exactly the same sampling windows as those used to count N(AB).

Otherwise it is trivial to create a perfect interference (a)−(b) and a perfect anticorrelation (c), if one misaligns the sampling windows used for counting N(AB) in (c) so that the signal peaks of A and B are partially shifted (for the N(AB) coincidence unit) from the center of the sampling window, in opposite directions. That will reduce N(AB). If one simultaneously does use well centered (on the signal peaks of A and B) sampling windows for counting N(A) and N(B), one can obtain an apparent violation of (1) (which is a perfectly classical 'violation').

In practice one would create the sampling windows using photon pairs, such PDC or atomic cascade pairs, where one photon of the pair defines the EM field sampling window (usually 1−3 ns centered around its trigger), while the other photon is used for measurements (a)−(c). See [1] for how this can be done.

2. In order to measure the relevant counts N, N(A), N(B) and N(AB) one cannot discard cases when neither DA nor DB trigger in the sampling window (see [1]). Otherwise, a perfectly classical sequence of pair results (A,B), such as the results obtained by tossing a pair of coins A and B (and assuming large enough N, so that the statistical fluctuation ~sqrt(N) is negligible compared to N, when the counts are used in (1)):

#(0,0)=N/4
#(1,1)=N/4
#(1,0)=#(0,1)=N/4

where N is the number of sampling windows (or pair tosses) and #(A,B) is the number of occurrences of the result pair (A,B), will violate the classicality condition (1). Namely, with all sampling windows properly counted (and defining heads=1 and tails=0 as trigger and non−trigger):

N(A) = #(1,1) + #(1,0) = N/2
N(B) = #(1,1) + #(0,1) = N/2
N(AB) = #(1,1) = N/4

which satisfies (1) as equality: N(AB)*N / N(A)*N(B) = 1. On the other hand, with rejection of (0,0) events, we have a new count of sampling windows: N' = N − #(0,0) = 3*N/4, while the other 3 counts #(1,1), #(0,1) and #(1,0) remain unchanged. Using this adjusted N' as the total count of sample N in (1), we get: N'*N(AB)/N(A)*N(B)= 3/4 < 1. Hence by discarding (0,0) events, we can get a "violation" of classicality by tossing a pair of coins. Therefore, QO experiments aiming to show the violation of classical inequality (1) cannot discard the (0,0) results either, otherwise even the plain coin tossing yields a non−classical statistics.

Your suggestion to observe single gamma photon detections shows nothing that would surprise a 19th century physicist. If P(A) and P(B) are small enough (weak source or low yield detectors or short sampling window), and you discard (0,0) data, you can have g2 arbitrarily close to 0 i.e. you get an apparent perfect particle−like anticorrelation (whenever there is a trigger, it is almost always a single trigger), while still getting a perfect interference in the (a)−(b) experiment.

Note that PDC source cannot, even in principle, violate (1), since the laser pump used is at best a Poissonian source, hence the number of pairs in each sampling window is at best Poissonian (cf. [3],[4] for actual PDC pair statistics, experiment and theory). For the same reason, PDC source cannot produce violation of Bell inequality (as demonstrated in a series of papers by T. Marshall, E. Santos, et al, [5]), or do anything non−classical in Quantum Computing/Encryption.

More general problem is that a classical laser pump which yields photon pairs via some interaction Hamiltonian (modeling some non−linear optical medium), cannot even in principle (due to the linearity of the interaction Hamiltonian operator acting on a coherent state) produce sub−Poissonian pair statistics. Blotting out events randomly from a sequence of Poissonian events, always yields another Poissonian sequence, just sparser.

One needs to read carefully the claims by Quantum Opticians, though, since they use different concept of "photon" than QED photon (the one used to mediate the fermion interaction in QED perturbation expansion). While QED Photon is a quantized mode of free EM field with sharp energy−momentum values, the QO photon is any superposition of infinitely many QED photons with the same value of photon number operator (and otherwise arbitrary energy−momentum). Thus when Quantum Opticians claim they have demonstrated "single photon" source which uses classical pump (laser), that single QO photon is still at best a coherent superposition of infinitely many QED photons. Since the photon relevant for describing the results of the interaction (such as photo−ionisation, or generally any detection) is the QED photon, the actual detector counts remain at best Poissonian, hence anything deduced from these counts or their correlations is classical. The term "non−classical" in QO thus refers to violation of classical inequalities, such as (1) or Bell inequality, by the adjusted counts (via post−selection i.e. after seeing the results), such as N' in the coin tossing example. Even though the coincidence counts are adjusted after seeing the outcomes (from remote detectors), the Quantum Opticians specializing in the "non−classicality" demonstrations have declared that this procedure represents a "fair sampling" (cf. [6] on absurdity of such wishful labeling), hence they are free to extrapolate the actual Poissonian results to the hypothetical "ideal" setup in which the EM field states have sharp number of QED photons (hence, yield the sub−Poissonian detector counts).

Hence, at best, one should take QO "non−classicality" as a convenient term of art describing certain states of EM field, but which has no relation to the genuine non−classicality, as understood by physicists.

Generally, though, these QO non−classicality claims are ambiguous, relying on omissions in describing the counting & subtraction procedure, and publishing only the adjusted figures without a caveat, or even a mention of subtractions/adjustments or the "fair sampling" assumption, rationalized (when questioned) that it is all a well known QO counting convention. Unfortunately, if you're a student or a physicist not specializing in QO, trying to learn what the actual empirical facts on quantum "non−classicality" are, you don't know the "well known QO counting conventions". You take that "counts" are what you get when you count the detector triggers and then end up wondering how can that be. The simple answer is, once the peculiar QO terminology is translated into the language of conventional physics −− it indeed can't be and it is not what is being observed in Quantum Optics.

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