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State Vector Reduction and Photon Coincidences

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The paper contains a discussion on two kinds of coincidence experiments. First, a standard two-photon coincidence experiment is considered and it is shown that its outcomes are incompatible with any classical radiation theory because of the role of the state vector reduction phenomenon in such an experiment. In the second part of the paper a proposed new kind of photon coincidence experiment is discussed. The classical and quantum predictions for the outcomes of this experiment differ dramatically and therefore the experiment should constitute a new limitation to the classical radiation theories. The proposed experiment should also yield information about the kinematics of the reduction of the state vector process.

1. INTRODUCTION

It is well known that quantum electrodynamics (QED) has been encumbered from its very beginnings with several technical difficulties and that the roots of these are probably inherent in the foundations of quantum theories or at least in their interpretation. In an attempt to find an escape from these technical difficulties and also in order to look for suggestions to overcome the deeper problems, Jaynes and co-workers[(1)] proposed an essentially classical scheme (so-called neoclassical, NCT, scheme) for the description of elementary electrodynamical phenomena. A number of these phenomena, e.g., the photoelectric effect, the Lamb shift, blackbody radiation,[(1)] can indeed be rederived classically.[2] There are cases, however, where the results of NCT differ from those of QED and of experiment.[(2,3)] The numerical discrepancies do not undermine seriously NCT, since in view of its flexibility there is

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[2] For a bibliography concerning NCT see references quoted by Jaynes.[(1)]

always the possibility of improving the theory. But, as was shown by Clauser,[4] there is at least one case where NCT is essentially unable to give account of an actually occurring phenomenon: the Einstein–Podolsky–Rosen one.[(5),3]

The aim of the present paper is to point out that there is another phenomenon which cannot be described by any classical radiation theory, namely that of the reduction of the state vector. This phenomenon plays a crucial role in any coincidence experiment in which coincidences from an at least two-step cascade are observed. In order to connect this with NCT, we are going to discuss the standard two-photon coincidence experiment. In the second part of our paper a possible different coincidence experiment will be suggested, namely an experiment in which one of the detectors can be regarded as an emission detector.

2. THE STANDARD TWO-PHOTON COINCIDENCE EXPERIMENT

Consider a three-level system with nonequidistant spectrum, e.g., an atom or a nucleus, such that radiative transitions from the second excited level occur in two steps: $2 \to 1$ and $1 \to 0$ (0 denotes the ground level, and the energies satisfy $E_2 > E_1 > E_0$). Assume that the transition $2 \to 0$ is forbidden, say, for parity reasons.

The standard coincidence experiment consists in measuring the radiation with two detectors, one which records only the radiation from the transition $2 \to 1$, the second which detects only the radiation from $1 \to 0$. An electronic setup enables one to determine the time correlations of the counts of both detectors. One can fit the experimental conditions in such a way that the number of decays per unit time is low, so that we can consider the simplified situation with only one radiating atom present.

Let us now consider this experiment from the classical point of view. By "classical" we understand any theory which treats the radiation as a classical electromagnetic wave. The photons corresponding to the transitions $2 \to 1$ and $1 \to 0$ are then to be regarded as short pulses of classical radiation, i.e., as classical wave packets centered about frequencies ω_{21} and ω_{10}, respectively.

We are interested in the probability $P(\tau)$ that the detector D_2 will record the wave packet $1 \to 0$ after a time interval τ (τ needs not be > 0) which elapses after the recording of the packet $2 \to 1$ by the detector D_1.

[3] In the Kocher–Commins (KC) experiment the correlated particles were optical photons. There are also experiments which make use of annihilation photons (see, for example, Refs. 6 and 7). However, Yoshihuku[8] pointed out that only the KC experiment constitutes a complete experimental proof of the existence of an EPR phenomenon. Recently Faraci *et al.*[9] reported that the results of their experiment with annihilation photons do not agree either with quantum mechanical or with classical predictions.

Classical theories usually assume that the probability $P(t)$ of recording a low-intensity electromagnetic pulse in some moment t by a detector is a function of the field intensity absorbed by the detector. We postulate accordingly

$$P(t) = \eta f[E(t)] \tag{1}$$

Here η denotes an instrumental constant and $f(E)$ is a function of the field E at the detector such that, roughly speaking $f(E) > 0$ for nonvanishing E. The function $f(E)$ may also be of the form

$$\int_t^{t+\vartheta} dt\, E^2(t) \tag{2}$$

where ϑ is the resolving time of the detecting device.[10]

When emitted, the classical wave packet is an independent entity in the sense that its absorption by the detector does not affect the state of both the source and the second wave packet. The recordings of both the detectors D_1 and D_2 are thus independent and we can write for $P(\tau)$

$$P(\tau) = \int_{-\infty}^{+\infty} dt\, P_1(t)\, P_2(t + \tau) \tag{3}$$

where $P_1(t)$ and $P_2(t)$ denote the probabilities of recording the first wave packet by D_1 and the second by D_2, respectively.

Any classical theory that is subject to an assumption like the one expressed by Eq. (1) has then two important features. First, as is shown by Eq. (3), $P(\tau)$ depends upon $P_1(t)$, i.e., upon the shape of the first wave packet. Second, the beginning moment of the coincidence curve depends upon the kind of classical theory considered, and this moment can only incidentally fall on $\tau = 0$. Generally, the coincidence curve begins earlier or later than $\tau = 0$, as is seen from Eq. (3). These two points are inconsistent with the experimental data. It is well known, indeed, that the shape of the coincidence curve does not depend upon the lifetime of the second excited level and, furthermore, that the curve always begins at $\tau = 0$ (if the detectors are equidistant from the source).

Note, by the way, that in NCT the initial state of the source (the radiating atom) is generally a mixture of all three stationary levels. This does not affect the present argument, although it leads to a better correspondence with the exponential decay law.[11] The reproduction of the exponential decay is, however, only a quantitative problem for NCT while both mentioned points constitute an essential qualitative inconsistency with experiment.

Now, let us consider the problem from the quantum point of view. The independence of $P(\tau)$ of the first photon distribution is a well-known result of QED (see, e.g., Agarwal[12]). We focus therefore on the problem of the beginning of the coincidence curve.

If one assume that the state of the system "field + atom" can be described by a state vector $\Psi(t)$ which is the superposition of the stationary states of the system, one can write

$$\Psi(t) = b_2(t)|\, 2, \{0\}\rangle + b_1(t)|\, 1, \{k\}\rangle + b_0(t)|\, 0, \{k, l\}\rangle \tag{4}$$

$b_i(t)$ denotes the time-dependent amplitudes of the stationary states $|\, , \{\ \}\rangle$. The first argument in the ket labels the atom's levels, the second (in the curly brackets) denotes the number of photons in the field modes. We have assumed that the first photon $2 \to 1$ is emitted in the kth mode and the photon $1 \to 0$ in the lth mode.

The initial conditions are usually assumed to be

$$b_2(0) = 1, \qquad b_1(0) = b_0(0) = 0 \tag{5}$$

At the moment of the emission of the photon $2 \to 1$ into the mode k, the state vector $\Psi(t)$ undergoes the reduction process and is transformed into the reduced state vector $\Psi'(t)$. Denote this moment by t_k. We have the following conditions for the amplitudes $b_i'(t)$, which are the coefficients of the expansion of $\Psi'(t)$:

$$b_2'(t \geqslant t_k) \equiv 0, \qquad b_1'(t_k) = 1, \qquad b_0'(t_k) = 0 \tag{6}$$

Thus, for $t \geqslant t_k$, $\Psi'(t)$ has the form

$$\Psi'(t) = b_1'(t)|\, 1, \{k\}\rangle + b_0' \,|\, 0, \{k, l\}\rangle \tag{7}$$

The emission of the first photon $2 \to 1$ then has to be regarded as a preparation of the system and the information that the system has been prepared is yielded by the record of the detector D_1. Equation (7) and the conditions (6) show that the moment $\tau = 0$ corresponds to the emission moment of the first photon. The reduction of the state vector $\Psi(t) \to \Psi'(t)$ is therefore a necessary condition for the moment $\tau = 0$ to be the beginning of the second photon's emission process: not too early and not too late as is possible in classical theories.

3. PROPOSED COINCIDENCE EXPERIMENT WITH AN EMISSION DETECTOR

Let us consider the principle of an experiment, the schematic arrangement of which is shown in the Fig. 1. A low-intensity monochromatic beam

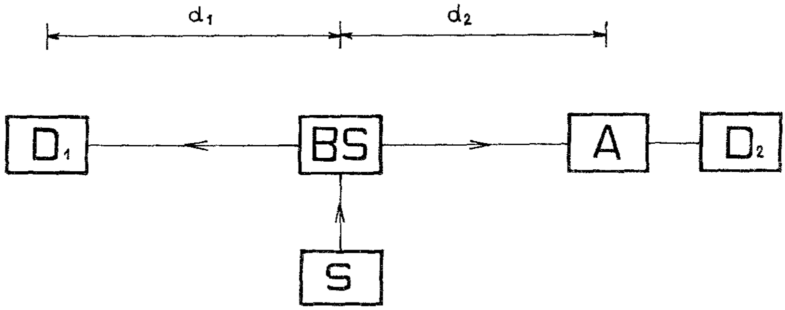

Fig. 1

from the light source S is split by a semitransparent mirror BS. One part of the beam is detected by D_1, the second part by D_2. In front of D_2 a two-level atom A is placed. Its excitation energy corresponds to the energy of the photons emitted by S.

One measures the delayed coincidences of the recordings of D_1 and D_2. The distances d_1 and d_2 are variable. We are going to consider two preparations [referred to as (g) and (e)] of the system:

(g) One photon from S present in the field, atom A in the ground state.

(e) One photon from S present, A excited.

In order to discuss the possible outcomes of the experiment, we have to consider the following probabilities pertinent to the problem:

$P(n)$ The probability of detecting n photons by D_2 if D_1 detects one photon.

$P_s(n)$ The probability of detecting, by D_2, n photons emitted spontaneously by A if D_1 detects one photon.

$P_i(n)$ The probability of detecting, by D_2, n induced photons from A if D_1 detects one photon.

$P(n)$, $P_s(n)$, $P_i(n)$ can be determined, in principle, experimentally. In order to select from the total $P(n)$ the contribution $(P_s + P_i)$, one has to compare $P(n)$ measured for (e) with the one measured for (g), since we can assume, to a good approximation, that, for (g), $P_s = P_i = 0$. P_s can be measured if a black screen is placed before the atom A when the system is prepared according to (e). Thus P_i is simply $(P_s + P_i) - P_s$.

We are now interested in the probability $P_i(1)$. From both the classical and the quantum points of view the wave packet (photon) emitted by S is split by BS and the situation is similar in both theories as long as the detector D_1 does not record the photon. After it does, the quantum and classical descriptions differ dramatically. Classically, the detection of the wave packet by D_1 does not affect in any way the second part of the wave packet, i.e., the radiation propagating in the direction of D_2. Now, in quantum mechanics the recording of the photon by D_1 causes an immediate vanishing of the inducing field propagating toward D_2 because of the reduction of the photon's state vector. Thus, the photon emitted by S is able to induce an emission from A only until it has not been detected by D_1. The dependence of $P_i(1)$ upon the coincidence delay-time and/or upon the distances d_1 and d_2 is then the main point of the information the experiment is supposed to yield.

Note that, in principle, this dependence should also give direct information about the time development of the state vector reduction process.

Recently Scarl and Smith[13] have performed an experiment in order to measure the time correlations of induced and inducing photons. They used a beam of light which passed through a gas laser's gain tube operating below threshold. Behind the gain tube the beam containing both inducing and induced photons was split into two parts by a semitransparent mirror and the coincidence rate between the two beams was measured by photomultipliers. Note, by the way, that unexpectedly they did not find correlations exceeding the Hanbury Brown–Twiss background.

Now, the experimental arrangement used by Scarl and Smith can be used for the purpose of the experiment proposed here if the light beam is split not behind the gain tube but before it passes through the tube (the tube replacing the atom A in our experiment).

Finally, let us note that the general idea of our experiment was suggested in a paper by Selleri,[14] who considered the possibility of experiments in which the "reality" or "physical existence" of the wave function could be tested. According to Selleri, such experiments would consist in measuring the lifetime of an unstable (fluorescent, radioactive, etc.) substance σ covering a screen. A source emits photons that can reach a region R of the screen. Photons will arrive randomly at different points of R, but their waves will interact with all the region of R, perhaps changing the lifetime of σ distributed over R.

We close with the following comments. Experimental evidence has shown two points. First, one photon cannot be split into two parts, both of which are able to excite a detector; second, these parts of the split field of one photon are, however, able to interact in some way leading to interference effects. The latter is shown by the well-known experiments performed by Jánossy and Náray.[15] The experiment proposed here pushes the question one step further: It should yield evidence of the interaction of the photon's field not with the second part of the same field but with an atom by inducing an emission from this atom. From the orthodox point of view, however, this does not provide any new argument in favor of the "reality" of the wave function. It would be so only if the inducing part of the photon field would not vanish immediately after the photon has been recorded by D_1.

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