PROPOSED QUANTUM-BEATS, QUANTUM-ERASER EXPERIMENT

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Received 7 March 1983

An experiment is proposed which demonstrates that quantum-interference effects are contingent on the presence or absence of residual information in the atom or scattered radiation field. The experiment may also be operated in a delayed-choice mode.

1. Introduction. Interest in experiments which demonstrate the non-local nature of quantum measurement has been expressed by several authors [1]. In such experiments the presence or absence of a quantum-interference effect may be triggered by the experimenter even after the photon has interacted with the apparatus. Most recently Scully and Drühl [2] have proposed a type of two-slit interference experiment in which the slits are replaced by two 4-level atoms. Interference between the two possible scattering histories can only occur if the atom is left in a final state devoid of information as to which path the photon has taken. Otherwise at some time, conceivably much later, one could probe the atom to determine whether the photon scattered from atom 1 or atom 2. In their proposal the information remaining in the atoms after scattering the first photon, is "erased" by application of a second light pulse and coincidence detection.

Although conceptually elegant there are certainly technical problems associated with realizing an interference experiment on a two-atom system. Any normal experiment will likely deal with large numbers of atoms from which each light pulse will be scattered. One then confronts the problem of interference arising from a randomly arranged n-atom gas. Under such conditions the desired fringes will certainly wash-out. There exists, however, a very well-studied area in which system single-atom, quantum-interference effects exist: namely quantum beats.

In the following I propose a type of quantum beats, coincidence experiment which appears feasible and which demonstrates the non-local nature of quantum measurement. It may also be operated in a "delayed-choice" mode by delaying the erasing pulse until well after the first light pulse has interacted with the system. The experiment makes use of a distinction already recognized by Breit in 1933 between so-called type I and type II atoms [3]. Following the usual notation, a type I atom is one in which there is a single ground state and two or more upper states, while a type II atom has a single upper state and two or more lower states (fig. 1). If the upper states of a type I atom are coherently excited, quantum beats in the fluorescence intensity are predicted and for the last decade these have been the subject of many experiments [4]. On the other hand, no beats are predicted from excitation and decay of type II atoms. This is easily understood since the two photon scattering histories are distinguishable by a subsequent experiment. The experiment proposed below suggests a means of "erasing" just this distinguishability and restoring quantum beats at a frequency equal to a ground-state splitting. As in ref. [2] this is done by a second pulse and coincidence detection.

In section 2, I recall the results of the QED treatment of normal quantum beats in type I and type II atoms. I then show in section 3 how beats may arise in a suitably designed coincidence experiment on type II atoms.

2. QED derivation of quantum beats. For purposes

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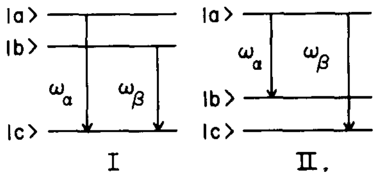

Fig. 1. Energy-level structure for type I and type II atoms.

of comparison and completeness I briefly rederive the QED results concerning single-atom quantum beats [4,5]. First consider a type I atom as shown in fig. 1. At time $t = 0$ we assume that a short broadband light pulse prepared the system in a coherent superposition of states so that its state vector at $t = 0$ is given by

$$|\psi(0)\rangle = A(0)|a0\rangle + B(0)|b0\rangle + C(0)|c0\rangle .$$

Here $|\psi(t)\rangle$ is the total wavefunction and $|a0\rangle$ for example, represents the system in atomic state $|a\rangle$ and no photon present. The constants $A(0)$, $B(0)$, and $C(0)$ are just the probability amplitudes that the system was prepared in the corresponding atomic state. Assuming the transitions $|a\rangle \to |c\rangle$ are dipole allowed, the state vector will quickly evolve into one reflecting decay to atomic state $|c\rangle$ and the emission of a photon into either mode α or β. We may then write the state vector as a function of time as

$$|\psi(t)\rangle = A(t)|a0\rangle + B(t)|b0\rangle + C(t)|c0\rangle$$
$$+ A_1(t)|c1_\alpha\rangle + B_1(t)|c1_\beta\rangle . \qquad (1)$$

Clearly the time dependence of the coefficients will reflect the exponential decay of the excited state and resulting increase in the ground-state population according to the Wigner–Weisskopf theory of spontaneous emission. The detailed expressions for each of these can be found in the literature [4].

Photons from an ensemble of such atoms fall on a detector at the point $\boldsymbol{r}$. Glauber has shown that the average photon-counting rate is simply related to the first-order correlation function of the operator $\hat{E}^+(rt)\hat{E}^-(rt)$ [6]. Here $\hat{E}^+(rt)$ and $\hat{E}^-(rt)$ are the positive- and negative-frequency components of the electric field. They are given by [7]

$$\hat{E}^+(rt) = \mathrm{i} \sum_k (\hbar\omega_k/2\epsilon_0 v)^{1/2}\, \boldsymbol{\varepsilon}_k \hat{a}_k$$
$$\times \exp(-\mathrm{i}\omega_k t + \mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}) \qquad (2a)$$

and

$$\hat{E}^-(rt) = -\mathrm{i} \sum_k (\hbar\omega_k/2\epsilon_0 v)^{1/2}\, \boldsymbol{\varepsilon}_k \hat{a}_k^\dagger$$
$$\times \exp(\mathrm{i}\omega_k t - \mathrm{i}\boldsymbol{k}\cdot\boldsymbol{r}) . \qquad (2b)$$

The two independent directions of mode polarization $\boldsymbol{\varepsilon}_k$ must be included in the sum over $\boldsymbol{k}$. In the above $\hat{a}_k^\dagger$ and $\hat{a}_k$ are the creation and annihilation operators. The photon counting rate is then given by

$$S(rt) = \langle\psi(t)|\hat{E}^-(rt)\,\hat{E}^+(rt)|\psi(t)\rangle . \qquad (3)$$

If we consider the idealized case represented by eq. (1) of only two modes, present in the radiation field (α and β), then quantum beats follow immediately upon substituting eqs. (1) and (2) into eq. (3). In the case of two modes, eqs. (2a) and (2b) become

$$\hat{E}^+(rt) = \hat{E}_\alpha^+(rt) + \hat{E}_\beta^+(rt)$$

and

$$\hat{E}^-(rt) = \hat{E}_\alpha^-(rt) + \hat{E}_\beta^-(rt) .$$

The resulting expression for the photocurrent contains several terms. Of interest to us is the cross-term which gives rise to beats,

$$\langle\psi(t)|\hat{E}_\alpha^-(rt)\hat{E}_\beta^+(rt)|\psi(t)\rangle$$
$$\propto A_1^*(t)\, B_1(t) \langle c1_\alpha|\hat{a}_\alpha^\dagger a_\beta|c1_\beta\rangle$$
$$\times \exp(\mathrm{i}\omega_\beta t)\exp(-\mathrm{i}\omega_\alpha t) .$$

Since $\langle c1_\alpha|\hat{a}_\alpha^\dagger a_\beta|c1_\beta\rangle = 1$, the photocurrent clearly shows beats at the frequency $(\omega_\beta - \omega_\alpha)$.

If one instead considers a type II atom (fig. 1), its state vector as a function of time can be written [5]

$$|\psi(t)\rangle = A(t)|a0\rangle + B(t)|b0\rangle + C(t)|c0\rangle$$
$$+ A_1(t)|b1_\alpha\rangle + A_2(t)|c1_\beta\rangle .$$

Following an identical procedure leads to cross-terms such as the following:

$$\langle b|c\rangle\langle 1_\alpha|\hat{a}_\alpha^\dagger \hat{a}_\beta|1_\beta\rangle \exp[-\mathrm{i}(\omega_\beta - \omega_\alpha)t] .$$

But because the ground-state sublevels are orthogonal, $\langle b|c\rangle = 0$, no beats are predicted. This was to be expected as residual information exists after the interaction as to which transition the atom made, $|a\rangle \to |b\rangle$ or $|a\rangle \to |c\rangle$.

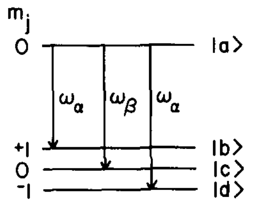

Fig. 2. Energy-level structure for a four-level atom with a single upper state and three Zeeman sublevels in the ground state.

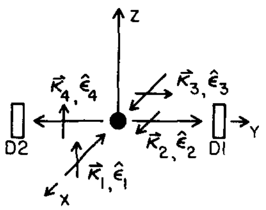

Fig. 3. Schematic diagram of the proposed experiment showing incoming and scattered photons. Detectors D1 and D2 are sensitive only to the polarizations shown.

Of course, this does not imply that it is impossible under all circumstances to create and detect hertzian coherences in the ground-state sublevels of type II atoms. Using a high-power laser one can establish ground-state coherences which may be detected, for example, by a weak probe laser [8]. The following experiment, however, is not of this type.

3. Quantum beats and quantum erasers. Consider a four-level atom (fig. 2) in which there is a single upper state and three lower levels. To be specific let $|a\rangle$, the upper state, be a singlet $J = 0, m_J = 0$, and let the lower state possess three Zeeman sublevels $m_J = 0, \pm 1$ of a $J = 1$ state. For the reasons described in section 2, QED predicts no beats in fluorescence after illumination by a single sudden excitation. However, if all residual information in the ground state is erased by a second pulse and subsequent detection we may expect an interference signal to arise. In order to show that this is indeed the case it is sufficient to consider the following specific example.

Let the four-level atom of fig. 2 be placed in a weak magnetic field. We will take the quantization axis to be along the magnetic field. Two short pulses of light are prepared with wave vectors $\boldsymbol{k}_1$ and $\boldsymbol{k}_3$, and polarizations $\hat{\boldsymbol{\varepsilon}}_1 = \hat{z}$ and $\hat{\boldsymbol{\varepsilon}}_3 = \hat{y}$. For convenience we take the beams to be counterpropagating along the x axis so that $-\boldsymbol{k}_1 = \boldsymbol{k}_3 = k\hat{x}$. Two detectors are arranged with linear polarizers orthogonal to one another, so that $\hat{\boldsymbol{\varepsilon}}_4 = \hat{z}$ and $\hat{\boldsymbol{\varepsilon}}_2 = \hat{x}$ (fig. 3). The detectors respond to decay photons $\boldsymbol{k}_2, \hat{\boldsymbol{\varepsilon}}_2$ and $\boldsymbol{k}_4, \hat{\boldsymbol{\varepsilon}}_4$. There now exist two *distinguishable* histories which the scattered photons may follow. Fig. 4 shows the two histories separately. For clarity let the atom be prepared in quantum state $|c\rangle$ ($J = 1, m_J = 0$). Since $\boldsymbol{k}_1$ is π-polarized, $\Delta m_J = 0$ for that transition in both history 1 and history 2. Photon $\boldsymbol{k}_1, \hat{\boldsymbol{\varepsilon}}_1$ therefore always takes $|c\rangle$ to $|a\rangle$. At this point a split takes place in that $|a\rangle$ can decay to any of the three ground-state sublevels. Decay to $|c\rangle$ is uninteresting since $\boldsymbol{k}_3, \hat{\boldsymbol{\varepsilon}}_3$ will not be able to excite the atom from $|c\rangle$ to $|a\rangle$ due to dipole selection rules. I ignore that decay channel henceforth. Decay from $|a\rangle$ to $|b\rangle$ distinguishes history 1, from $|a\rangle$ to $|d\rangle$, history 2. Once again no beats will be seen between these two channels because a later experiment could still probe the ground-state sublevels to determine, in fact, which history was followed. Quantum interference, however, can be restored by "erasing" this information. Simply sending in a second laser pulse to scramble the information will not be sufficient. In general the information will only be transferred, for example, to the scattered second photon. If one detects *both* photons we will see that all information can be erased as to which history was followed and one must then add the quantum amplitudes for each separate history. The system of two photons plus atom is a *single* quantum system after the interaction. The resulting interference is a clear example of non-separability in quantum mechanics.

The second light pulse $\boldsymbol{k}_3, \hat{\boldsymbol{\varepsilon}}_3$ can be thought of as $\pm\,\sigma$-polarized which will pump $|b\rangle$ to $|a\rangle$ and $|d\rangle$ to $|a\rangle$ by dipole-allowed transitions. We are interested in those decay photons ($\boldsymbol{k}_4, \hat{\boldsymbol{\varepsilon}}_4$) which bring the atom back to its original state $|c\rangle$. Clearly no further experiment on the atom can be performed to determine which scattering history was followed. It is possible, on the other hand, to detect the photons in such a way, either through polarization or frequency analysis, so as

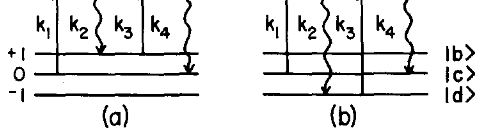

Fig. 4. The two scattering histories (a) and (b) whose amplitudes superpose to yield the beats described.

to determine which history was followed. Hence, it is important to use broadband detection and to orient the polarizers properly so the histories are in fact indistinguishable. The choice made in fig. 3 satisfies these requirements. Photon k_4, $\hat{\varepsilon}_4$ falls on detector 2. The polarizer on detector 2 has its transmission axis parallel to the quantization axis. It will never register a signal for k_2, $\hat{\varepsilon}_2$. Detector 1 has its polarizer a along the x axis so that it will be equally sensitive to *either* $k_{2a}\hat{\varepsilon}_{2a}$ *or* $k_{2b}\hat{\varepsilon}_{2b}$. Once both photons have been detected *all* information has been erased regarding the scattering histories and one would expect a quantum interference signal to reappear. To show that this is the case, I perform a QED calculation similar to those above with the exception that we are now interested in the coincidence signal from detectors 1 and 2. We will need to use Glauber's second-order correlation function to predict the signal.

We may write the second-order correlation function as

$$G^2(r_1t_1;r_2t_2)$$
$$=\langle\psi(t)|\hat{E}^-(r_1t_1)\hat{E}^-(r_2t_2)\hat{E}^+(r_2t_2)\hat{E}^+(r_1t_1)|\psi(t)\rangle\,,$$

where r_1 and r_2 are the positions of detectors 1 and 2, and t_1 and t_2 label the time at each detector. As before we need the state vector just before detection $|\psi(t)\rangle$. The two terms of importance superpose to give

$$|\psi(t)\rangle\sim C_1(t)|\mathrm{c},1_\alpha 1_\beta\rangle+C_2(t)|\mathrm{c},1_\gamma 1_\beta\rangle\,.$$

Other terms will also be present but will either not contribute due to orthogonal polarization, or will give only a dilution of the beat signal. The positive- and negative-frequency components of the quantized electro-magnetic field can be expressed as in eq. (2) with, for example,

$$\hat{E}_2^-(r_2t_2)=\hat{E}_\beta^-(r_2t_2)\,,$$

$$\hat{E}_1^-(r_1t_1)=2^{-1/2}[\hat{E}_\alpha^-(r_1t_1)+\hat{E}_\gamma^-(r_1t_1)]\,.$$

Use has been made of the short-hand notation employed in fig. 2 for the three decay modes α,β,γ.

Cross-terms once again appear, for example

$$\langle\psi(t)|\hat{E}_\alpha^-(r_1t_1)\hat{E}_\beta^-(r_2t_2)\hat{E}_\beta^+(r_2t_2)\hat{E}_\gamma^+(r_1t_1)|\psi(t)\rangle$$
$$=\langle 1_\alpha 1_\beta|\hat{a}_\alpha^\dagger\hat{a}_\beta^\dagger\hat{a}_\beta\hat{a}_\gamma|1_\beta 1_\gamma\rangle\langle\mathrm{c}|\mathrm{c}\rangle\,C_1^*(t)\,C_2(t)$$
$$\times\exp[\mathrm{i}\omega_\alpha t_1-\mathrm{i}k\cdot r_1]\exp[-\mathrm{i}\omega_\gamma t_1+\mathrm{i}k\cdot r_1]$$
$$=C_1^*(t)\,C_2(t)\exp[\mathrm{i}(\omega_\alpha-\omega_\gamma)t]\,.$$

We expect therefore that a beat signal will reappear at the difference frequency $\omega_\alpha-\omega_\gamma$ in coincidence detection.

4. Conclusion. In the above, no particular assumption was made with regard to the details of order or timing of the four events: two incident light pulses and two detections. Conceptually we perhaps may best conceive of the experiment as involving initially an atom and two incident photons, separately. After the first photon interaction but before detection there is a single atom-plus-one-photon quantum system. The second photon scatters off that "composite" system giving a single quantum system, atom-plus-two-photons. Delays can be inserted as appropriate to permit the experiment to run in a "delayed-choice" mode. One could in that case even imagine an electro-optic shutter which isolates detector 1, for example, from the atom shortly after the first interaction of $k_1\hat{\varepsilon}_1$. Such an experiment would be a lovely demonstration of non-separability.

In conclusion, we have described an experiment which is a clear analog of the Young's double-slit experiment in which quantum-interference effects will appear contingent on the erasure of residual information in the atom or photon field concerning scattering histories. This experiment should be more feasible than an earlier proposal by Scully and Drühl [‡1]. Finally, the experiment can also be configured to run in a delayed-choice mode.

I would like to thank the Laboratoire de Spectroscopie Hertzienne of the Ecole Normale Supérieure and especially Dr. M.A. Bouchiat for hospitality and support during the time this work was performed.

[‡1] I understand that a similar calculation has been undertaken by Scully and co-workers independently and that an experiment is underway at the Max-Planck-Institut for Quantum Optics in Garching (personal communication).

I also gratefully acknowledge the receipt of a Trustee-Faculty Fellowship from Amherst College. Conversations with R. Krotkov, S. Haroche and M. Scully helped clarify the questions which I address in this article. Support for this research came in part from Research Corporation and the National Science Foundation under Grant No. PRM-812789.

References

[1] M.O. Scully, R. Shea and J.D. McCullen, Phys. Rep. 43 (1978) 486;
J.A. Wheeler, in: Problems in the formulations of physics, ed. G.T. di Francia (North-Holland, Amsterdam, 1979).
[2] M.O. Scully and K. Drühl, Phys. Rev. A25 (1982) 2208.
[3] G. Breit, Rev. Mod. Phys. 5 (1933) 91.
[4] S. Haroche, in: High-resolution laser spectroscopy, ed. K. Shimoda (Springer, Berlin, 1976) pp. 253–313.
[5] W.W. Chow, M.O. Scully and J.O. Stoner, Phys. Rev. A11 (1975) 1380.
[6] R.J. Glauber, in: Quantum optics and electronics, eds. B. DeWitt, A. Blandin and C. Cohen-Tannoudji (Gordon and Breach, New York, 1964) pp. 65–107.
[7] R. Loudon, The quantum theory of light (Oxford Univ. Press, London, 1973) p. 135.
[8] J. Mlynek and W. Lange, Opt. Commun. 30 (1979) 337.