Quantum Beats

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As noted before,[1] one of the most durable of all beliefs about QED is that it endows light with "granular" properties that somehow wipe out the interference effects of classical electromagnetic theory.

In 1954, Forrester, Gudmundsen, and Johnson[2] proposed to observe microwave beats between Zeeman components of a spectral line. The existence of the effect was promptly denied by some on grounds of quantum theory—as everybody knows, "a given photon interferes only with itself." Yet the photoelectric klystron worked, the beats were seen, and an important lesson was learned about the meaning and correct application of quantum theory.

But not for long. In 1956, Hanbury Brown and Twiss[3] proposed to measure stellar diameters by interference measurements involving fourth-order spatial correlation functions of the field. Again, quantum theorists denied the existence of the effect. I myself, at a seminar talk by E. M. Purcell, witnessed the reaction of one Nobel laureate who thought a hoax was being perpetrated. Yet the experiment worked—just as classical EM theory predicted—and again an important lesson was learned.

But not for long. With the appearance of the laser in the early 1960s, we were told that it was fundamentally impossible to observe beats between independently running lasers—a given photon interferes only with itself. Naturally, the beats appeared on schedule—just as classical EM theory predicted.

But this time Roy Glauber[4] produced a detailed theoretical analysis showing in great generality just *why* QED allows beats to be seen in photoelectric detection experiments, and what property of the field state vector determines this. For example, whether beats can or cannot be

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seen in the photocurrent induced by the light is not determined by any two-point correlation function of the field (such as the expectation of the Poynting vector), because the state vector of the field may leave the phase of those beats completely indeterminate. Rather, the observable spectral density of the photocurrent is an instrumental constant times the Fourier transform of the fourth-order correlation function,

$$\phi(\tau) = \langle E^2(t) E^2(t + \tau) \rangle$$

at the photocathode. So the lesson was learned still another time and, thanks to Glauber, one might have thought it would now stay learned.

This lesson was learned, independently, at about the same time by many others. One of the most interesting documents recording this fact is the article of Gordon, Louisell, and Walker[5] on "Quantum Fluctuations and Noise in Parametric Processes." They state in the abstract:

> We find that a classical description of the input fields and of the amplification process is completely valid provided we take correctly into account the response of the amplifier to the input zero-point fields. This result is valid for inputs of arbitrarily small power.

Their evident surprise at finding this from a QED analysis is shown by the number of times essentially the same remark is repeated in the article. And indeed, their result conflicts with what we have all been told about QED in undergraduate physics courses.

One can then imagine my dismay on receiving, in February 1974, a paper coauthored by one of my own former students with the title "Missing Interference Effects in Multi-Level Fluorescence." Ten years after Glauber's explanation, this most durable of all views about QED had returned still another time. Of course, with each resurrection it had appeared in a more subtle form; this time it was vastly more subtle and even seemed, at first glance, to be backed up by a specific QED calculation. However, this work[6] calculated only the expectation of the Poynting vector in the radiation from a single atom, and was thus, on two counts, inadequate to determine what QED predicts for a real experiment to observe beats in the photocurrent.

Some of these limitations were recognized and removed by Chow, Scully, and Stoner,[7] and a still more realistic treatment was given by Senitzky,[8] whose conclusions are, I think, a reliable guide to what should and should not be observable in a real experiment according to QED.

But all these analyses still leave untouched the basic point of principle about the difference in physical content of QED and classical electromagnetic theory, as it pertains to interference. So some pedagogy is still needed if erroneous ideas about interference effects in QED are not to crop up still another time in the future.

Deferring a more complete analysis of the specific experiments that might now be attempted and what value they would have as further tests of QED, this short note tries to explain only that basic point of principle. In view of my previous strong criticisms[1,9] of the Copenhagen interpretation of quantum theory, I must now step rather far out of character and expound that interpretation as it applies to this problem. Fortunately, one need not believe a theory in order to understand it and teach it. Quite the contrary, I am convinced that many who defend the Copenhagen interpretation most fervently do so only because they have never thought deeply enough to realize its full implications.

An atom can decay from an excited state $|a\rangle$ to a lower level $|b\rangle$, with emission of a photon $\hbar\omega_\alpha$, or to a different lower level $|c\rangle$ by emission of a photon $\hbar\omega_\beta$ of a different frequency. The point at issue was stated originally as: if the atom is allowed to decay spontaneously, choosing its own way through these decay modes, can we then see "lower-level beats" between the two photons? But of course, if a single atom can produce at most only a single photoelectron, then no matter how it decays, we can hardly expect to see anything that could properly be called "beats." So let us frame the question less presumptively: "Is it possible to see interference effects between the two photons?"

In classical theory it is enough to ask merely: "Does the atom emit waves of both frequencies simultaneously?" If the answer is "yes," this is taken to be a statement of physical fact—that electromagnetic waves of frequencies ω_α, ω_β *exist* in the space around the atom. This being the case, there is no reason why an experimenter could not, by one means or another, verify this by causing them to induce oscillations of the beat frequency $\omega_\alpha - \omega_\beta$ in some detection device. But whether these beats can or cannot be seen is entirely a question of the skill and ingenuity of the experimenter and does not concern the theoretician, whose job is finished when he has described, by calculation, the *real physical situation*. Or to put it more strongly: in classical physics, it is simply not in his area of competence for the theoretician to make pronouncements about what can and cannot be measured in the laboratory, any more than for the experimenter to proclaim what can and cannot be calculated in the theory.

As both Bohr and Heisenberg have stressed strongly and repeatedly, the situation in quantum theory is entirely different. Present (Copenhagen) quantum theory cannot, as a matter of principle, answer any question of the type, "What is really happening when . . . ?" because there is no longer any such thing as a "real physical situation." It can answer only: "What will be the result of this particular experiment?" Even then it usually gives, not a definite answer, but a set of possible answers, with their probabilities. As Bohr stressed over and over again, a physical phenomenon is defined *only* by specifying the entire experimental arrangement used to observe it. (Bohr even added the stricture that the experimental arrangement must be described in classical terms, although Wigner[10] asked, plaintively, "But *why* must I describe it in classical terms? What will happen to me if I don't?")

Bohr's point still has to be stressed today, in spite of the fact that we have all heard it so many times, because of an irresistible tendency to accept it in principle—and immediately ignore it in practice. This is seen in all the aforementioned discussions of "lower-level quantum beats." But it is not merely an observation to which one can give lip service and then, as practical people, proceed as if it had never been uttered. For in quantum theory you cannot carry out a practical calculation of a real experimental result unless you know what experimental arrangement is to be used.

In quantum theory, then, the theoretician and experimenter are forced into a much closer collaboration—in principle, the theoretician's problem cannot even be formulated until the experimenter tells him exactly what apparatus and procedure he proposes to use. Whether "lower level quantum beats" can or cannot be observed according to QED depends on what experiment you perform and how you perform it.

In the notation of Chow, Scully, and Stoner (hereafter referred to as CSS), an initial state $\Psi(0) = |a0\rangle$ (i.e., atom in state a, field in vacuum state) evolves with time into lower states with emission of two photons, $\hbar\omega_\alpha$, $\hbar\omega_\beta$:

$$\Psi(t) = A_0(t)|a0\rangle + A_1(t)|b1_\alpha\rangle + A_2(t)|c1_\beta\rangle \tag{1}$$

where $|b1_\alpha\rangle$ denotes an atom in state $|b\rangle$, one photon $\hbar\omega_\alpha$ in the field, etc. Suppose the two transitions are equally rapid: $|A_1| = |A_2|$. Then, after the emission is over, we may write the final state $\Psi(\infty)$ as

$$\Psi(\infty) = (|b1_\alpha\rangle + e^{i\theta}|c1_\beta\rangle)/2^{1/2} \tag{2}$$

where θ is a phase factor determined by the equations of motion. This is the correlated state.

If now a measurement finds the atom to be in state $|b\rangle$, then according to present quantum mechanics the "reduction of the wave packet" occurs, and we know that the field must be in state $|1_\alpha\rangle$. Then, as noted by CSS, there can be no interference between ω_α, ω_β for any subsequent experiment, because to put it colloquially, the photon $\hbar\omega_\beta$ was "never emitted." More specifically, if F represents any field observable, its expectation is $\langle F\rangle = \langle 1_\alpha|F|1_\alpha\rangle$, and ω_β is not involved at all. On these grounds, it has been held that lower-state interferences do not occur in QED.

But we can write the final state $\Psi(\infty)$ equally well as

$$\Psi(\infty) = (|\Psi_+\rangle|\alpha\beta_+\rangle + |\Psi_-\rangle|\alpha\beta_-\rangle)/2^{1/2} \tag{3}$$

where the field state $|\alpha\beta_\pm\rangle$ and atom states $|\psi_\pm\rangle$ are

$$|\alpha\beta_\pm\rangle = (|1_\alpha\rangle \pm e^{i\phi}|1_\beta\rangle)/2^{1/2} \tag{4}$$

$$|\Psi_\pm\rangle = (|b\rangle \pm e^{i(\theta-\phi)}|c\rangle)/2^{1/2} \tag{5}$$

and ϕ is a phase that we may choose arbitrarily. If now measurement shows the atom to be in state $|\psi_+\rangle$, then we know the field must be in the linear combination

$$|\alpha\beta\rangle = (|1_\alpha\rangle + e^{i\phi}|1_\beta\rangle)/2^{1/2} \tag{6}$$

in which both photons are present after all!

Any field observable F then has expectation value

$$\langle F\rangle = \tfrac{1}{2}(\langle\alpha|F|\alpha\rangle + \langle\beta|F|\beta\rangle + e^{i\phi}\langle\alpha|F|\beta\rangle + e^{-i\phi}\langle\beta|F|\alpha\rangle) \tag{7}$$

in which contributions from both photons, and interference terms between them, are present. So, it seems a little hasty to conclude that QED does not predict lower-level interference effects.

But is the measurement of $|\psi_\pm\rangle$ really possible? If a determination of the states $|b\rangle, |c\rangle$, as assumed by CSS, is possible, then a measurement of $|\psi_\pm\rangle$ is surely also possible. In the Bloch sphere representation, $|\psi_\pm\rangle$ are points lying on the equator, diametrically opposite, with longitude determined by our choice of ϕ. Application of a suitable 90° pulse (via the quadrupole moment matrix element $\langle b|Q|c\rangle$, if the dipole moment vanishes), will then bring about the transformation $|\psi_+\rangle \to |b\rangle$, $|\psi_-\rangle \to |c\rangle$, after which we use the apparatus of CSS.

We have, then, the full EPR paradox—and more. By applying or not applying the 90° pulse before measuring the atomic state we can, at will, force the radiation field into either: (1) a state with a known one of the photons $\hbar\omega_\alpha$, $\hbar\omega_\beta$ present, and no possibility of interference effects in any subsequent measurement; (2) a state with both $\hbar\omega_\alpha$, $\hbar\omega_\beta$ present with a known relative phase. Lower-level interference effects are then not only observable, but predictable. And we can decide which to *do* after the emission is over and the radiation is far from the atom, so there can be no thought of any physical influence on the radiation!

But that is not the end, because this radiation can still be recaptured totally and used to initiate a second experiment. Place the emitting atom A at one focus of a perfectly reflecting ellipsoidal cavity of major diameter D. After a time D/c the radiation converges, in a spherical wave of just the original intensity, onto the other focus, where we have placed a test atom A'.

Let A' have the inverted level scheme, i.e., it waits in its ground state $|a'\rangle$ from which it can be excited to $|b'\rangle$ or $|c'\rangle$ by absorption of $\hbar\omega_\alpha$, $\hbar\omega_\beta$, respectively. Immediately after the radiation has fallen on A', we measure its state, and we can at our option either use or not use a 90° preparatory pulse on A', independently of whether we used it on A.

We can, of course, measure the state of atom A while the radiation is en route, and since the distance $A - A'$ is less than the distance D traveled by the light, the result of the measurement can be transmitted to an experimenter E' stationed at A', reaching him before the light from atom A does. So E' can still decide which experiment to perform on A' *after* he knows which measurement was made on A, and its result.

QED then predicts the following. If atom A was found in state $|b\rangle$, then we know in advance that A' can be found later in $|b'\rangle$, but not in $|c'\rangle$, and vice versa. If we use the 90° pulse and find A in $|\psi_+\rangle$, then we know in advance that a similar measurement on A' can find it in $|\psi'_+\rangle$. The observable and predictable interference effect is then that A' cannot be found in $|\psi'_-\rangle$.

And bear in mind that all this holds even though, by the analog of (5), the relative phase with which $|b'\rangle$ and $|c'\rangle$ are combined in this state $|\psi'_-\rangle$, which becomes impossible, can be chosen arbitrarily by us. That is, by choosing[1] fine details of how the 90° pulse is applied to atom A, *after* it has decayed, we can force atom A' into a known linear combination of states $|b'\rangle$ and $|c'\rangle$ with any relative phase we please, and *the results of subsequent experiments on A' depend on that phase.*

From this, it is pretty clear why present quantum theory not only does not use—it does not even dare to mention—the notion of a "real physical situation." Defenders of the theory say that this notion is philosophically naive, a throwback to outmoded ways of thinking, and that recognition of this constitutes deep new wisdom about the nature of human knowledge. I say that it constitutes a violent irrationality, that somewhere in this theory the distinction between reality and our knowledge of reality has become lost, and the result has more the character of medieval necromancy than of science. It has been my hope that quantum optics, with its vast new technological capability, might be able to provide the experimental clue that will show us how to resolve these contradictions.

References and Notes

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