Do quantum jumps occur at well-defined moments of time?

George Greenstein
Department of Astronomy, Amherst College, Amherst, Massachusetts 01002
Arthur G. Zajonc
Department of Physics, Amherst College, Amherst, Massachusetts 01002

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Shelved atom experiments appear to show clear evidence for quantum jumps. We use a gedanken interference experiment to demonstrate that a fundamental temporal ambiguity in the photon time-of-emission occurs in such transitions.

I. INTRODUCTION

The quantum jump, introduced by Bohr[1] in 1913, was one of the essential ingredients of the "old" quantum mechanics. With the development of the modern quantum theory, however, the concept was relegated to a far more problematical status, for as is well known the theory nowhere appears to describe such discontinuous transitions but rather speaks only of continuous evolution of the wave function. Until recently, no direct experimental evidence on jumps was available, for any such events would be averaged out in observations of the emission from large numbers of atoms.

Experiments involving so-called shelved atoms, however, first suggested by Dehmelt[2] and first realized in the laboratory by Nagourney, Sandberg, and Dehmelt,[3] have altered the situation. These experiments are often referred to as having provided us at last with direct evidence for something suspiciously reminiscent of Bohr's events: discontinuous atomic transitions, downward jumps occurring at well-defined moments in time. The first three published experimental papers[3,4] on the subject all bore the phrase "observation of quantum jumps" in their titles. Subsequent papers referring to them followed suit: by our count 12[5,6] papers have appeared since this seminal work, all citing it as evidence of the existence of jumps.

Unease over the concept has persisted, however. Numerous authors have elected to put the phrase "quantum jumps" in quotation marks, and a few papers have appeared in the literature arguing against so literal an interpretation of the experiments. It is revealing to note, however, that these papers advance radically differing reasons for rejecting the existence of quantum jumps. One author[7] has written of them as "knowledge-induced transitions;" another[8] as events arising purely from the Schrödinger equation without additional postulates; and a third[9] as artifacts from the process of decoherence.

In this paper we will also argue that the shelved-atom experiments do not constitute evidence for quantum jumps in the old sense. Indeed, we will argue that situations can be arranged in which no unique moment can be assigned to the transitions observed by these experiments. If jumps occur, their time of occurrence is ambiguous or "fuzzy."

Our method stems from a comment originally made by Schrödinger.[10] Schrödinger contrasted the supposed instantaneous character of a quantum jump with the duration of a coherent wave observed in an interferometer. How can these be reconciled? To be specific, imagine passing a photon emitted by an atom through a double-slit interference apparatus in an ideal thought-experiment. After trasversing the slits, the photon is detected at a screen at a well-defined moment of time. When, then, had it been emitted? Within *standard* interpretations of quantum mechanics the phenomenon of interference demonstrates that the photon must have passed through both slits. But the time of flight from the emitting atom to the detector differs between the two paths. We can only conclude that the single photon must have been emitted at two different times.

We can also take this argument a step further. Imagine a source of light that somehow announces the emission of each photon in an unambiguous way. Then pass the photon, whose emission time is well known, through a double-slit apparatus to a screen where it arrives at a well-defined time. By the above argument, this photon must not be able to produce interference. But why not?

The shelved atom is thought to provide the experimenter with the imagined system we want. In Sec. II we will briefly review the physics of shelved-atom experiments and, in Sec. III, pass to a consideration of thought experiments involving interference of photons emitted by these atoms. At no point do we discuss issues pertaining to turning our thought experiment into a real one.

II. SHELVED ATOMS

The so-called shelving of atoms arises in the three-level system schematically diagrammed in Fig. 1. Here "s" represents a high-lying state which strongly decays to a low-lying state "o." Similarly, "w" is a metastable high-lying state which weakly decays to "o" at a rate $\sim 10^{-8}$ that of the strong transition. Two lasers drive the $o \leftrightarrow s$ and $o \leftrightarrow w$ transitions simultaneously but not $w \leftrightarrow s$ because these transitions are forbidden. Current technology allows individual ions to be studied while trapped in, e.g., a Paul trap. Transition rates to and from the strong state of $\sim 10^8$ transitions/s can be achieved: under these circumstances the resulting fluorescence emission from the $s \rightarrow o$ transition is actually bright enough to be seen with the naked eye.

Experimentally, however, it is found that the emission is not continuous. Rather, the $s \rightarrow o$ emission is found to turn on and off. Figure 2, reproduced from Ref. 3, is a record of some actual data. It can be seen that the fluorescence radiation persists at a steady intensity for times on the order of a minute before randomly and apparently discontinuously dropping to approximately zero: this is the so-called "quantum telegraph."

The periods during which the strong fluorescence signal is detected represent times during which the system is rapidly shuttling back and forth between the ground state and the upper, strongly decaying state. But occasionally the system makes a transition to the weakly decaying state. Because this is a metastable state, the ion remains in it for a long time, during which time it is unavailable to produce the $s \rightarrow o$ fluorescence radiation. The strong intensity has been turned off: the system is said to be "shelved" in the metastable state.

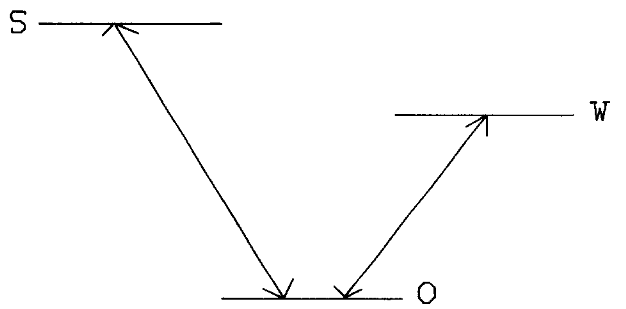

Fig. 1. Illustrating the level structure of the shelved atom.

The moments at which the dark periods commence, therefore, represent the times at which the $o \rightarrow w$ transition occurred. Similarly, the moments at which the fluorescence emission resumes mark the downward transitions $w \rightarrow o$. These two times (the beginning and end of a dark period) are to be identified with the times of the quantum jumps associated with the absorption and emission of weak photons. In this way, by monitoring the light produced by the strong transition, we can determine when the weak transition occurs.

The above account has been oversimplified in two ways. On the one hand, it leans heavily on semiclassical concepts such as that of a jump. The picture of the atom in the "old quantum theory" was one in which the atom was in one, and only one, of its energy eigenstates at a time. But this is in direct contrast to the principle of superposition, which permits the atom to be in a number of eigenstates simultaneously. Initially there was strong concern that the appearance of quantum jumps in the data was evidence in support of the old Bohr theory, but the work of Porrati and Putterman,[6] Cook,[7] and Cohen-Tannoudji and Dalibard,[11] has shown how the superposition principle is consistent with the quantum telegraph. Second, as we will now show, the moments of resumption of the strong intensity do not precisely mark the times of emission of the w photons. To see this, we now extend our initial argument to shelved atoms and interference experiments.

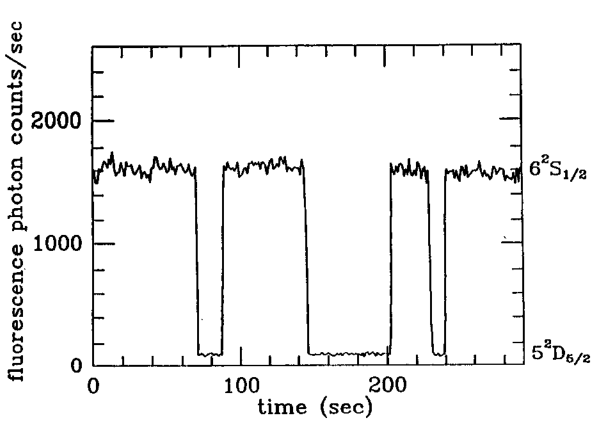

Fig. 2. A typical trace of fluorescence, adapted from Ref. 3.

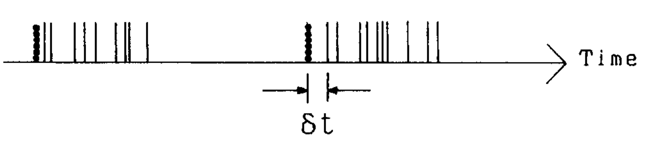

Fig. 3. A time line indicating times of emission of individual "strong" (solid lines) and "weak" (dotted lines) photons.

III. INTERFERENCE

We imagine a *gedanken* experiment in which an ensemble of three-level systems of the type described above is used, each producing a single weak photon from the $w \rightarrow o$ transition. The moment of production of the weak photon is marked by the resumption of the strong fluorescence signal, and is therefore known. Each weak photon passes through a double-slit interferometer. The place and time of arrival of each photon at the screen is determined in the usual manner. Under what conditions will interference be observed?

Experimental records such as shown in Fig. 2 in reality represent the detections of large numbers of individual s photons. In Fig. 3 we sketch a time line in which the times of arrival of these photons are indicated (solid lines). t_{obs} is the observed time at which the strong intensity resumes. But this does not precisely coincide with t_{jump}, the time of emission of the weak photon which we wish to determine. A lower limit to the error $\delta t \equiv t_{\text{obs}} - t_{\text{jump}}$, obtained by ignoring errors in the experimental determination of t_{obs}, is composed of (1) the time t_o the system remains in the o state before making the $o \rightarrow s$ transition, and (2) the time t_s it remains in the s state before making the $s \rightarrow o$ transition and emitting the first of the strong photons. Under the action of a strong laser pumping the $o \leftrightarrow s$ transitions, the system undergoes Rabi oscillations[12] between the o and s states. For resonant excitation, the Rabi flopping frequency is $\beta = \mu_{os}\epsilon/h$, where μ_{os} is the component along the electric field of the dipole matrix element connecting the two states, and ϵ is the electric field strength of the incident laser light. Within this picture, the rate of pump and decay transitions is proportional to the square-root of the laser intensity $\sqrt{I}$, and the times spent in the upper and lower states are equal when averaged over many cycles: $t_s = t_o = \delta t/2$.

This average uncertainty δt can be made smaller by turning up the power of the laser pumping this transition, thereby increasing the Rabi floppy frequency, β. But doing so broadens the s and o states, and so spoils the spectral purity of the weak photon via the energy-time uncertainty principle. This is the phenomenon of power broadening. The o state energy is uncertain by an amount $\Delta E_0 = h/t_0$; thus the frequency of the weak photon is uncertain by $\Delta \nu_w = \Delta E_o/h = 2/(\delta t)$ since the width of the w state is very small. It therefore has a coherence length $l = c/\Delta \nu_w$. As is well known,[13] interference will only occur when l exceeds the difference in path lengths between the two paths, which is $n\lambda$ for the nth-order interference fringe. It is readily shown that this condition implies

$$\delta t > 2nP, \tag{1}$$

where $P = 1/\nu_w$ is the period of oscillation associated with the weak photon.

Equation (1) is the condition for the breakdown of the concept of a quantum jump as being a single event occurring at a definite moment in time. This occurs for large uncertainty in time δt, i.e., weak pumping of the $o \rightarrow s$ transition. Conversely, for strong pumping the uncertainty δt is small and Eq. (1) is violated: interference will not be observed, and our argument against the concept of a well-defined time of the jump fails to go through.

Cook[7] has discussed in detail how frequent monitoring of the atomic state through the strong transition signal leaves little opportunity for the system to evolve into a superposition state and how therefore data such as that of Fig. 2 show what appear to be quantum jumps. Our point is that the act of accurately determining the time of a quantum jump destroys the possibility for the appearance of interference, which requires superposition.

Since shelved atoms announce their approximate times of emission of photons, and since the photons' times of arrival at the screen can also be determined, we have a means of measuring their time of flight and so obtaining which-path information. This information is available only if the uncertainty in time, δt, is less than the difference in times of flight between the two paths. This difference is nP for the nth order interference fringe. Thus we conclude that, when which-path information is available, Eq. (1) is violated and interference will not be observed. The well-known complementarity between which-path information and interference is related here to a complementarity between the possibility of assigning a well-defined time to the emission of a photon and interference.

In conclusion, we have seen that if the emission time is well-defined—a "sharp" quantum jump—interference disappears. Conversely, whenever interference exists, we have what might be called a fuzzy quantum jump, characterized by a fundamental ambiguity in the emission time, such that which-path information is lost. Such temporal ambiguity is a common feature of quantum mechanics, but it is usually hidden from view. In the case treated here, the extent of temporal ambiguity translates directly into fringe visibility.

ACKNOWLEDGMENT

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[13] See, for instance, M. Born and E. Wolf, "Principles of optics" (Pergamon, New York, 1964), p. 316.

GUIDANCE TESTS

I took several guidance tests at Columbia that were supposed to reveal my strengths and weaknesses. Interpretation of such tests was usually done cautiously, but not in my case: I was told that I did not have any ability for the sciences. In my over forty years of teaching since then, I have taken great care in advising a student who has poor grades in physics. I point out my own case, explain that such cases are very rare, but that if physics is what they *need* to do, they might well continue trying—that the odds are against them but that they are not nil. And that incredibly hard work, and luck, can beat a lot of odds.

Fay Ajzenberg-Selove, *A Matter of Choices—Memoirs of a Female Physicist* (Rutgers University Press, New Brunswick, New Jersey, 1994), p. 54.