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QUANTUM MECHANICS WITH ONE, TWO, AND MANY ATOMS*

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Abstract

Trapped ions can be used in interesting demonstrations of quantum mechanics. Ions can be observed individually, so that transitions between their internal quantum states (quantum jumps) can be clearly seen. The fact that coherent superposition states can be readily created and destroyed makes possible a demonstration of the quantum Zeno effect. The ability to observe light scattered from two ions whose separation is held constant to less than a wavelength makes it possible to realize a version of Young's two-slit experiment, a well-known paradigm of quantum mechanics.

1. Introduction

When one of us (W.M.I.) was invited to speak at this Colloquium, he accepted, but asked the organizers what they wanted to hear, since he had published only one paper relating to an application of group theory to physics,[1] and this paper has probably not been read or cited for years (until just now). He was told that, over the last 20 years, the subject matter of the Colloquium had expanded to include areas such as quantum field theory, statistical physics, nuclear physics, mathematical physics, and the foundations of quantum mechanics. He was asked to talk on atomic physics and issues related to the foundations of quantum mechanics.

Three topics were chosen for the talk: (1) quantum jumps of a single atom, (2) the quantum Zeno effect, and (3) Young's interference of light scattered from two atoms. The publication of a transcript of the actual talk would serve little useful purpose, since most of the content has been published previously in three articles.[2–4] However, there have been some new developments since these articles were published, and it might be useful to summarize them. The following amounts to a series of addenda to these three articles. The discussion of the experiments is very brief and is not meant to be self-contained.

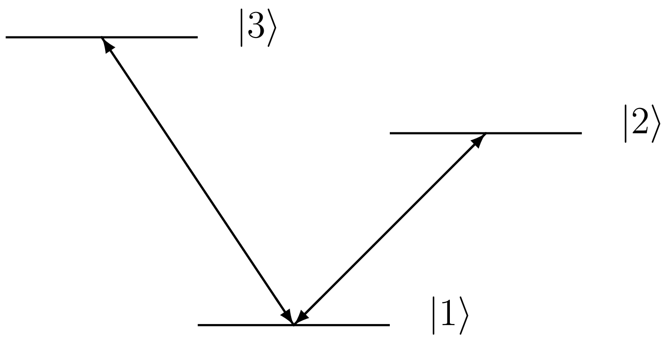

Figure 1: Simplified atomic level diagram for discussion of quantum jumps and the quantum Zeno effect.

2. Quantum jumps

The work on quantum jumps in a single Hg^+ ion, which was reported at the Colloquium, has been published previously.[2] Ensemble averages were computed from observations of quantum jumps of a single atom, and radiative decay rates and decay branching ratios were derived. Quantum mechanics predicts the behavior of ensembles, not of single systems (like single atoms). When a single atom is studied, ensemble averages are generated by repeating the experiment.

In this context, a quantum jump is a sudden change in the state of an individual quantum system, such as a single atom. A simple case[5,6] in which quantum jumps can be observed is a three-level atom having a metastable state $|2\rangle$ and a short-lived state $|3\rangle$, both of which decay only to the ground state $|1\rangle$ (see Fig. 1). If the atom is initially in the ground state and is subjected to laser radiation resonant with the transition from $|1\rangle$ to$|3\rangle$, it emits fluorescence photons at a high rate. If the atom is induced to make a transition to $|2\rangle$, for example by a second laser, the fluorescence suddenly stops. After the atom returns to $|1\rangle$, the fluorescence returns to its previous level. These sudden changes in the fluorescence are called quantum jumps.

The first observations of single-atom quantum jumps were made by several experimental groups at about the same time.[7–10] At the time of these experiments, there was much theoretical interest in the subject, since it was not clear whether we would observe bistable, discontinuous fluorescence, as just described, or something more continuous, as would be observed with an ensemble of atoms. Several review papers on single-atom quantum jumps have appeared.[11–13]

The Hg^+ system is more complex than the simple example just given. As a result, we could measure the total radiative decay rates for two metastable states by analyzing the quantum jumps. One of these states can decay to two different states, and we were able to measure the branching ratio for these two decay modes. The measurements were later confirmed by other, more conventional, methods.[14] (There was a misprint in Ref. 2, where the lifetime calculations of Garstang[15] and Al-Salameh and Silfvast (AS)[16] were quoted. The values for the decay rates $f_1\gamma_1$ and $f_2\gamma_1$ were reversed. The corrected text is: "Garstang has calculated the decay rate $f_2\gamma_1$ to be 54 s^{-1}, in very good agreement with the present value. The other decay rate $f_1\gamma_1$ has been calculated by Garstang to be 42 s^{-1} and by AS to be 75.6 s^{-1}." We thank M. Wilson for bringing this to our attention.) Others have used quantum jumps to measure radiative decay rates in Ba^+,[7,9,17] Sr^+,[18,19] Ca^+,[20] and In^+.[21]

The single-atom quantum jump data of Refs. 2 and 8 have been subjected to various statistical tests of randomness.[13,22–24] Nothing other than the expected random behavior has been found.

3. Quantum Zeno effect

The publication of our experimental demonstration of the quantum Zeno effect[3] generated a great deal of controversy, with many authors discussing and in some cases criticizing our interpretation of the experiment. (None, however, questioned the results.) The quantum Zeno effect, or quantum Zeno paradox as it is sometimes called, is the inhibition of the unitary evolution of a quantum system that is subject to frequent measurements. It was first discussed under this name by Misra and Sudarshan.[25]

Cook[26] proposed a feasible experimental demonstration on a three-level atomic system like that in Fig. 1. Here, $|1\rangle$ is the ground state, $|2\rangle$ has a lifetime long enough that it does not decay during the experiment, and $|3\rangle$ decays radiatively only to $|1\rangle$ with a short lifetime. The system whose evolution is to be studied is the pair of states $|1\rangle$ and $|2\rangle$. A resonant field is applied, and causes the population to oscillate between $|1\rangle$ and $|2\rangle$ if the system is not disturbed. A laser pulse, resonant with the transition between $|1\rangle$ and $|3\rangle$, and long enough to scatter at least a few fluorescent photons constitutes the "measurement." If the atom is in $|1\rangle$, it scatters photons; if it is in $|2\rangle$, it does not. Frequent measurement pulses tend to "freeze" the atom in either $|1\rangle$ or $|2\rangle$. This effect was observed in an experiment on trapped $^9Be^+$ ions and was in agreement with the results of a simple calculation.[3]

Some authors deny that the quantum Zeno effect exists at all. Fearn and Lamb[27,28] carried out a numerical simulation of a particular quantum measurement, concluded that the quantum Zeno effect was not present, and argued against the existence of the quantum Zeno effect in general. Others have disputed their conclusions.[29,30] Since the simulation specifically involved position measurements, it is not applicable to our experiment in any case. Other authors have carried out calculations that show a quantum Zeno effect for position measurements for appropriate ranges of parameters.[30,31]

Some authors have criticized our use of the word "measurement" in cases where the scattered photons are not actually detected.[32–37] In our experiment, the photons emitted during the frequent, short intermediate “measurements” were not observed. At the end of the process, a long laser pulse was applied, and the photons were actually detected. According to some authors, our experiment was not an example of the “true” quantum Zeno effect, because photons were not detected at the intermediate steps.[34–37] According to them, it *would* have been a good example if the photons *had* been detected. However, these authors agree that the same final experimental results for the atomic state populations would be obtained whether or not the photons were detected at the intermediate steps.

Inagaki *et al.*[36] regard this as “a very peculiar property.” We do not consider it to be surprising. The fact that the photons are not detected at the intermediate steps does not change the fact that an irreversible process has taken place.[38] Each intermediate laser pulse causes a splitting of the wavefunction into different branches having different numbers of scattered photons. The branches do not interfere with each other, since the final states of the electromagnetic field are orthogonal. It is possible to keep all of the branches of the wavefunction (2^N for N intermediate laser pulses) and reduce the wavefunction only at the time of the final photon detection. This is the method used by Petrosky *et al.*[34,35] It seems natural, though, to carry out the reduction at each step, as soon as there is no more possibility of interference between branches. The same final result for the atomic state populations is obtained in either case. Similar conclusions have been reached by others.[37,39]

Our use of the concept of wavefunction reduction or collapse has been criticized.[32,33] This seems to us to be a matter of taste. In this case, “wavefunction collapse” is merely a shorthand for “setting to 0 the off-diagonal matrix elements of the reduced density matrix describing the measured system.” As long as the experimental predictions are the same, there is no real difference. Calculations which go beyond the approximation in which the density-matrix elements are set to 0, for example for the case of weak laser pulses, have been published by others.[40–44]

Some authors have attempted to distinguish different kinds of quantum Zeno effects, although they do so in different ways. Block and Berman[42] refer to the inhibition of *induced* transitions (as in our experiment) as the quantum Zeno *effect* and to the inhibition of *spontaneous* transitions as the quantum Zeno *paradox*. The paradox would be very difficult to observe, since the measurement would have to be made within an extremely short period. Home and Whitaker[39,45] reserve the term quantum Zeno paradox for those cases in which the mere presence of a *macroscopic* observation apparatus affects the behavior of a system, while calling other, formally analogous processes examples of the quantum Zeno *effect*. They regard our experiment as an example of the quantum Zeno *effect*, since they do not regard the interaction of the atoms with the electromagnetic field as being equivalent to an interaction with a *macroscopic* apparatus.

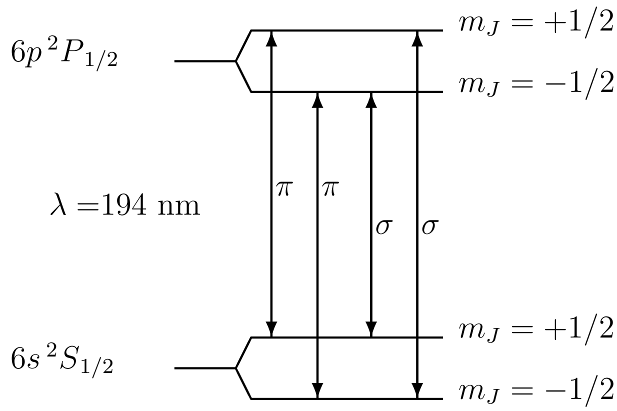

Figure 2: Zeeman sublevels involved in the 194 nm, $6s\,^2S_{1/2}$-to-$6p\,^2P_{1/2}$ transition of $^{198}Hg^+$. The allowed π and σ transitions are labeled. The Zeeman splitting of the levels is exaggerated.

4. Young's interference experiment

We have observed Young's interference fringes in the light scattered from two trapped atoms. Two $^{198}Hg^+$ ions were held a few micrometers apart and irradiated with laser light near the 194 nm $6s\,^2S_{1/2}$-to-$6p\,^2P_{1/2}$ resonance transition (see Fig. 2). The intensity of the scattered light was measured as a function of the scattering angle. This experiment has been described previously.[4,46] The fact that interference fringes appear only when it is impossible in principle to determine which atom scattered the photon was emphasized. This is true even if the measurement is not actually made. Interference fringes were observed in the scattered light when it was π-polarized (electric field vector in the plane containing the electric field vector of the incident light and the wavevector of the outgoing light). In this case, scattering can be viewed as a π-transition upward followed by a π-transition downward (see Fig. 2). It is impossible to tell which atom has scattered the photon, since it returns to the same state. Interference fringes were not observed in the σ-polarized light, which is polarized perpendicularly to the π-polarized light. In this case, the atom which scatters the photon changes its state, and in principle this could be measured. We note that this experiment is similar in principle to some thought experiments discussed by Scully and Drühl.[47]

Recently, there have been theoretical discussions of the old topics of complementarity and wave-particle duality in the context of double-slit interference experiments. While there is general agreement that interference fringes disappear if it is possible to tell which of the two paths the system took, there is disagreement regarding the mechanism by which the interference is lost. According to some, a random phase resulting from an uncertainty relation between conjugate variables, such as the position and momentum[48] or the angular momentum and angular orientation[49] is *always* the cause of the loss of interference whenever the path can be determined. Complementarity is then a consequence of the uncertainty relations. According to others,[50–52] this is not necessarily the case, and complementarity is an independent postulate of quantum mechanics. Our two-atom Young's interference experiment is a case in which complementarity is enforced in a manner which does not require the position-momentum uncertainty relations.

5. Acknowledgments

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