The Quantum Zeno Effect in Trapped Ions

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Abstract. The quantum Zeno effect is the slowing down of the rate of a quantum mechanical transition by the frequent application of measurements to the system. Following the original suggestion of an experiment to test this in trapped ions, Itano *et al* performed an experiment in 1990. This was followed by several detailed theoretical treatments of the problem, making new predictions and giving a better understanding of what was happening. Also since then, suggestions for new types of experiment to test the quantum Zeno effect have been made. At Imperial College we are currently setting up an experiment to study the quantum Zeno effect on a single ion, incorporating some of these new ideas. Details of this experiment are discussed in the paper.

INTRODUCTION

Ion traps are well suited to the measurement of long coherent processes in atomic systems because of the long interaction time which is possible, the excellent isolation from the environment, and the stable trapping conditions which can be achieved (see, for example, [1–3] for general reviews). It is possible to use long coherent pulses of radiation to couple two atomic levels together and then to study the evolution of the system under these conditions. It is also possible to isolate single atomic particles, and many significant experiments have been performed on single ions, which have increased our understanding of the way that single particles interact with radiation.

The quantum Zeno effect was first introduced by Misra and Sudarshan in 1977 [4]. These authors pointed out that, in a quantum mechanical system that decays from one state to another, a measurement taking place during the decay collapses the wave function into either the initial state or the decayed state. Now in the very early stages of the decay the probability of such a measurement resulting in the particle ending up in the final (decayed) state rises *quadratically* with time, even though for longer times the decay proceeds exponentially (which can be approximated as a *linear* decay for short times). Since the effect of a measurement is to destroy all the coherences in the system, in effect it restarts the decay process. Now if the decay is continually put back onto the quadratic part of the curve, the end result is that the overall rate of decay is slowed down from the rate expected from the exponential curve.

This was termed the *quantum Zeno effect* by analogy with the classic paradox due to Zeno about an arrow in flight. The point is that if we make many measurements on a decaying system (such that they probe this early quadratic region) we can slow down the decay. In the limit of continuous observation, we can expect the decay to slow to zero. This is a classic example of the measurement of a quantum mechanical system having an effect on the subsequent behaviour of the system.

The trouble with the observation of this phenomenon for spontaneous decay in real atomic systems is that the time period over which the decay is quadratic is extremely short and inaccessible experimentally. The length of this period is related to the bandwidth of the reservoir of states into which the system can decay, which is extremely large for a normal decay of an excited atomic state.

In 1988 Cook suggested that the quantum Zeno effect could in fact be studied experimentally, but by choosing a driven transition instead of a natural decay [5] (see also [6]). The advantage of using a driven transition is that this also has a quadratic phase at the start, but the length of this phase is under experimental control and is much longer than in a natural decay.

Consider a three-level system with a ground state (1) coupled by a microwave transition to a metastable level (2) and by a strong optical transition to an excited atomic state (3) which can only decay back to level 1. Cook suggested taking a π-pulse of microwave radiation between levels 1 and 2 and showed that if this pulse were interrupted by a series of short measurement pulses (a burst of laser radiation coupling level 1 to level 3) then the overall probability of completing the microwave transition, measured at the end of the π-pulse, was reduced dramatically. He suggested that this experiment could be carried out on a single ion in a Paul trap, taking advantage of the ideal conditions offered by the use of trapped ions, in particular the long interaction times possible.

EXPERIMENTAL OBSERVATION

Itano *et al* [7] performed an experiment in 1990 to observe the quantum Zeno effect. In their experiment they worked on a driven radiofrequency transition between hyperfine Zeeman sublevels in a cloud of Be^+ ions in a Penning trap. In this way they avoided the problem of the very small signal which would be available in a single ion experiment. In this case the length of the quadratic period depends on the rate at which the transition is driven, which is under experimental control (they chose a π-pulse with a length of the order of 1 second). Of course the effect is now not quite the same as in the original paper [4], but the principle is very similar.

Since Itano *et al* used a π-pulse of radiofrequency radiation to drive the transition, in the absence of any measurements the probability of the transition taking place is nearly equal to unity. However, if the coherent transition is interrupted by short measurements, they show that the overall transition probability is reduced dramatically in both theory and experiment [7]. Here the measurement, which consists of a brief laser pulse which is tuned to a transition out of *one* of the two hyperfine Zeeman levels involved, could in principle be used to detect whether the ions were in that state (by the observation of at least one fluorescent photon) or the other one (by the failure to observe any photons). The laser pulse has to be sufficiently long and intense to ensure that an ion in that state has a high probability of being excited by the laser. Since in a large cloud the ions are not inside the laser beam all the time, the length of the pulse must therefore be several times the oscillation period in the trap, in order to ensure that every ion is subjected to the effect of the measurement.

Assume that the ions start in state 1. Then the wave function at time t is given by

$$|\psi(t)\rangle = \cos(\Omega t/2)|1\rangle - i\sin(\Omega t/2)|2\rangle \tag{1}$$

where Ω is the Rabi frequency, and 1 and 2 are the initial and final states. For a π-pulse, the length, T, is given by $T = \pi/\Omega$, and this transfers all the population from state 1 to state 2. If the π-pulse is interrupted at a time $t_1 = \pi/n\Omega$, then we find that the probabilities of the ion being found in the two states are now:

$$P_1(t_1) = \cos^2(\pi/2n) \tag{2}$$

$$P_2(t_1) = \sin^2(\pi/2n). \tag{3}$$

At this point the decay restarts and the calculation can be repeated for each of the $(n-1)$ remaining measurement pulses. In practice the state of the ions is only determined in this experiment at the end of the π-pulse, when the fraction of ions that have made the transition is determined by measuring the amount of fluorescence on a cycling transition which yields a signal of many photons per ion in the first few ms of irradiation. It can be shown by an extension of the arguments above that the fraction of ions in the two states at the end of the π-pulse, after n measurement pulses, is given by

$$P_1(T) = \frac{1}{2}[1 + \cos^n(\pi/n)] \tag{4}$$

$$P_2(T) = \frac{1}{2}[1 - \cos^n(\pi/n)] \tag{5}$$

Itano *et al* used this simple wavefunction collapse model to predict the fraction of ions to complete the transition from state 1 to state 2 as a function of the number of measurement pulses n (with some small modifications) and the experiment verified these predictions to within the experimental error. They concluded that this wavefunction collapse model gave a good description of the process.

DETAILED THEORETICAL MODELS

Many theorists were unhappy with the approach outlined above, in particular the idea of the collapse of the wavefunction which was employed, and the publication of these experimental results gave rise to much theoretical work which aimed to give a more detailed and more rigorous description of what was going on in this experiment.

One treatment of this problem is given by Frerichs and Schenzle [8] (see also [9]). They treat the system of 3-level ion, radiofrequency radiation and laser radiation as a single system using a Bloch equation approach. The evolution of the complete system can then be calculated both during the periods when just the microwave radiation is present, and also when both radiations are simultaneously present. This gives predictions for how intense the laser pulse has to be for it to count as a measurement. This was something that had to be introduced in an *ad hoc* manner in the treatment of Itano *et al.* The Bloch equation approach shows that the effect of the laser pulse is to destroy the coherences (i.e. the off-diagonal elements of the density matrix) which are built up by the radiofrequency radiation. This is the mechanism for the collapse of the wavefunction in this case. Other treatments of the problem are given, for example, in references [10] and [11].

These treatments show that the measurement pulse can be properly described using standard techniques of quantum optics, so it is not necessary to introduce the idea of the wave function collapse separately. They also show that, for a sufficiently intense measurement pulse, the effect is the same as that obtained by using the wave function collapse model, so this is a good working model under these circumstances.

PROPOSED EXPERIMENT

At Imperial College we are in the process of building an experiment to test the predictions of these theoretical models. We will perform an experiment which is similar to that of Itano *et al* [7] but we need to perform the experiment on a single ion so that we can have a closer control of the experimental conditions. This will also be closer to the original suggestion of Cook [5] (though the experiment will still be performed in a Penning trap rather than a Paul trap). This will clearly reduce the signal level and the experiment will therefore need to run in a stable manner for a long time to collect data. However, it gives us the advantage of being able to make a direct comparison with the predictions of recent formulations of quantum mechanics which calculate single particle trajectories directly (see for example [12,13]).

One point we wish to investigate is the variation of the effect of the measurement pulses with the strength of the pulses in an attempt to verify the theoretical predictions for what constitutes a measurement. This comes naturally out of the Bloch equation treatment of the three level system, including the effects of both radiations. Here the use of a single ion has an advantage because a single ion experiences more of a uniform laser intensity than an ion in a cloud, due to the much reduced amplitude of its motion. There is therefore a more definite relationship between the applied laser intensity and the intensity experienced by the ion.

We will also look at variations in the experiment which should allow us to introduce some decay by coupling to an excited state of the ion in the manner proposed by Plenio *et al* [14]. This will take the experiment closer to the scheme originally proposed by Misra and Sudarshan [4]. In this scheme, the microwave transition takes the system from the ground state (1) to a metastable excited state (2) as before, but this time the metastable state is itself coupled (for example, with a second laser) to a third level (3) which can decay back to the metastable level (2) or down to another excited state (4). The measurements are performed, as before, with a laser pulse coupling state (1) on a strongly allowed transition to an excited state (5). The effect of this is to introduce decay into the system in a controlled manner. The time evolution of the population without the measurement pulses now becomes an exponential at long times, but the early quadratic phase is still there, with its length under experimental control. Both of these schemes suggested by Plenio *et al* can be implemented with trapped ions of Be or Mg using two lasers.

Another possibility is to perform a quasi-continuous measurement, as proposed by Beige and Hegerfeldt [15] for the original three-level system. In this scheme, there is no π-pulse, but the measurement pulses are applied in a continuous stream on a single trapped particle. As the interval between these pulses reduces, the system starts to execute quantum jumps between the ground state and the metastable level. The length of the jumps is proportional to $(\Delta t)^{-2}$, where Δt is the interval between measurements. These quantum jumps are well defined for $\Delta t \approx T/6$ or less [15]. Careful selection of the laser pulse integrated intensity and the values of Ω and Δt should enable a clear quantum jump signal to be obtained. Care has to be taken because in our system

(^{9}Be$^+$ or ^{25}Mg$^+$) the laser pulses can also drive the system into a different atomic state (the state involved in conventional quantum jump measurements in this system: see, for example, [13,16]) so the pulses should not be too intense. On the other hand, the pulses have to be sufficiently intense for us to be able to detect which state the ion is in. This means that we need to detect an average of about 10 photons per pulse for an ion in state (1), leading to a pulse length of the order of 1 ms with our laser.

The trap for this experiment has been constructed and tested. It is a 5-electrode cylindrical Penning trap which is placed in a superconducting magnet with a field of 1.3 T. The experiment is expected to run with Be$^+$ ions, but it is also possible to use Mg$^+$ if required (for example, if sympathetic cooling is required). The laser beam enters the trap at a small angle to the radial plane to give cooling in the axial direction as well as in the radial plane. The ion fluorescence is imaged with a ×25 magnification lens system, specially designed for this trap, onto the photocathode of a photon counting photomultiplier.

We have been able to trap and cool large and small clouds of Be$^+$ ions in this trap, and to drive the microwave resonances between the Zeeman levels in the magnetic field. Quantum jump signals have been seen from single ions, and we expect to make preliminary studies of the Zeno effect in the near future.

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