Shelved Optical Electron Amplifier: Observation of Quantum Jumps

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We demonstrate here the direct observation of quantum jumps between the $6^2S_{1/2}$ state and the $5^2D_{5/2}$ state of an individual laser-cooled Ba$^+$ ion contained in a radio-frequency trap. The state detection and cooling are performed by two lasers which cause $6^2S_{1/2}$-$6^2P_{1/2}$-$5^2D_{3/2}$ transitions. Incoherent excitation to the $5^2D_{5/2}$ state (via the $6^2P_{3/2}$ level) causes the fluorescence from the $6^2P_{1/2}$ state to be suppressed for the > 30-sec lifetime of that state, after which the fluorescence reappears. The resulting "telegraph signal" provides a direct monitor of the atomic state.

In 1975, one of the authors briefly described a scheme[1] in which the strong resonance fluorescence of an individual atomic ion confined in high vacuum serves as a monitor which determines whether or not the ion is in its electronic ground state. The usefulness of the scheme as a millionfold amplifier of the very weak *optical* fluorescence from one of the ion's metastable levels was pointed out. Concepts of both the simple quantum electrodynamics of Planck and Einstein as well as concepts following from Rabi's and Bloch's treatment of transitions in coherent electromagnetic fields were important in this description. Recently, in this and other journals a number of other workers[2-7] have analyzed the proposal in much detail and confirmed its essential correctness. However, no experimental demonstration of the shelved optical electron amplifier, or "shelving" for short, appears to have been published so far. We now report the demonstration of shelving in the metastable $5^2D_{5/2}$ level of the barium ion with a lifetime > 30 sec.

These experiments have a special fascination, as, in the language of modern quantum mechanics, they allow one to watch the reduction of the wave function by the measurement process on the oscilloscope screen. The reduction process here is demonstrated in a fashion even more striking than the 1976 geonium experiments for spin flips of a single electron via the continuous Stern-Gerlach effect.[8]

The technique requires an atom with two excited states, both of which are radiatively coupled to the same ground state but with vastly different transition rates. In a 1-sec interval, the strong transition results in the scattering of $\approx 10^8$ photons from the ion, of which $\approx 0.1\%$ can be conveniently collected and counted. (The strong transition would also be used for cooling.) If the highly metastable level has a lifetime of ≈ 1 sec, a transition to it will result in the complete suppression of the strong resonance fluorescence for a period of 1-sec average length. The resulting *loss* of some 10^8 fluorescence photons produces an easily observed signal, even with poor photon-collection efficiency. Thus, the transition to the metastable level

can be detected with unity quantum efficiency. This process can be thought of as a form of amplification akin to photomultiplier gain, which allows one to observe the presence of individual photoelectrons with very little uncertainty. A similar technique has already been employed[9] in a microwave-optical double-resonance experiment on an ion cloud. Our observations are the first known application of this scheme in the detection of forbidden *optical* transitions in an individual ion, as originally proposed.

The apparatus is essentially similar to that used in the two-photon spectroscopy of a single laser-cooled barium ion and is described elsewhere.[10] The principal difference is that the vacuum enclosure is a stainless-steel block with the windows, pump, and electronics feedthrough attached via conflat flanges; the advantage of this over the glass enclosure is that the system can be readily modified. Also, the ion is exposed to the ambient magnetic field; no magnetic shielding or coils are used in this experiment. The vacuum is maintained with a 20-liters/sec ion pump; after a ≈ 48-h bakeout, the low pressures of about 8×10^{-11} Torr are readily achieved, which are absolutely necessary to suppress collisional deactivation of the excited $D_{5/2}$ state.

The ion is cooled and thereby localized to < 1 μm with two collinear laser beams provided by stabilized, single-frequency dye lasers. The $6^2S_{1/2}$-$6^2P_{1/2}$ transition at 493 nm is driven by a laser which uses LD 490 dye and the $5^2D_{3/2}$-$6^2P_{1/2}$ transition at 650 nm is driven by a laser which uses DCM dye. In order to observe the quantum jump phenomenon, it is necessary to excite the ion into the $5^2D_{5/2}$ level. This is done by focusing a filtered commercial barium hollow cathode lamp onto the ion. The interference filter removes all but the 455.4-nm line from the output of the lamp. As can be seen from Fig. 1, after at most several excitations to the $6^2P_{3/2}$ level, the ion will fall into the $5^2D_{5/2}$ level in which it is trapped until it can spontaneously decay to the ground state. The lamp intensity is adjusted until the average time to excite the ion into the shelf level is ≈ 30 sec. The use of a branching ra-
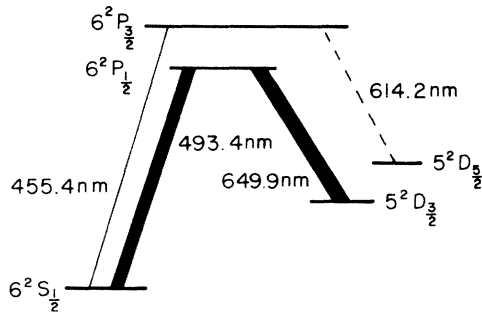
FIG. 1. Level structure of Ba$^+$. The shelf level is the $5^2D_{5/2}$ state. The laser excitation is shown by the bold lines; the lamp excitation is indicated by the light solid line while the subsequent decay into the shelf level is indicated by the dashed line.

FIG. 2. A typical trace of the 493-nm fluorescence from the $6^2P_{1/2}$ level showing the quantum jumps after the hollow cathode lamp is turned on. The atom is definitely known to be in the shelf level during the low fluorescence periods.

tio[11] of $\frac{1}{3.2}$ into the shelf level implies a lamp intensity of about 0.1 photons/sec per $\lambda^2/2\pi$ within the ≈ 20-MHz natural breadth of the $6^2P_{3/2}$ state or $\approx 6.8 \times 10^{-9}$ W/cm^2 over the ≈ 1-GHz Doppler breadth of the lamp. By use of a photomultiplier of known quantum efficiency, the measured lamp intensity at the position of the ion is $\approx 4.4 \times 10^{-9}$ W/cm^2.

The usual ion loading procedure is followed until it is thought that a single ion has been loaded. After this, the hollow cathode lamp is turned on and the blue fluorescence from the $6^2P_{1/2}$-$6^2S_{1/2}$ transition is monitored by a computer programmed as a signal averager with an averaging time for one data point of 1 or 2 sec. As can be seen from Fig. 2, after the lamp is turned on, the fluorescence changes randomly between the value it had when the ion was loaded and the background. The average "shelving time" (the duration of the "dark" intervals) can be seen from Fig. 2 to be ≈ 30 sec, almost the radiative lifetime $(47 \pm 16$ sec) [12] of the $5^2D_{5/2}$ level. This fluorescence trace also confirms that only a single barium ion is present in the trap; if more than one ion were present, the fluorescence trace would display intermediate "steps" as each ion is individual shelved.

In describing the barium-ion signals, we rely on the simple quantum electrodynamics of Planck, Einstein, and Bohr. In this method,[13] a two-level atom in the thermal radiation field is pictured as instantaneously emitting and absorbing a photon and jumping between the two levels (labeled as 0 and 1) in which it remains with the respective randomly varying dwell times t_0 and t_1. For a spectral density of radiation field u at the transition frequency, the rate for upward jumps $0 \rightarrow 1$ is given by Bu. The rate for $1 \rightarrow 0$ downward jumps is $A + Bu$, where A and B are the Einstein coefficients for spontaneous and induced processes. In the limit of weak light, the downward jump rate, $A + Bu$, is much greater than the upward jump rate, Bu. Therefore, the
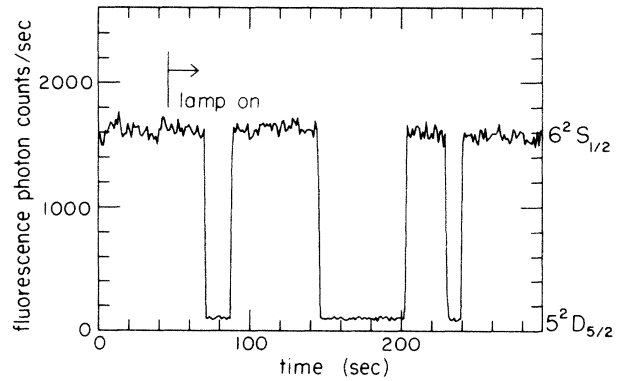
term Bu may be neglected in the sum which thereby reduces to A. Now it is well known[13] that in this situation the dwell times t_1 in the upper level have a probability distribution proportional to

$$\exp(-At_1), \tag{1}$$

yielding an average dwell time

$$\langle t_1 \rangle_{av} = 1/A \equiv \tau_1. \tag{2}$$

Analogously, because of the complete correspondence of the probabilities A and Bu, the distribution of dwell times in the lower level 0 must be proportional to

$$\exp(-But_0), \tag{3}$$

yielding an average dwell time

$$\langle t_0 \rangle_{av} = 1/Bu \equiv \tau_0. \tag{4}$$

To put it another way, the process by which the atom jumps from one level into another cannot depend on what happens after the instantaneous jump. Thus, it must be irrelevant whether the atom remains in the ground state 0 after jumping into it from level 1 at rate A because of spontaneous emission or whether it jumps back to state 0 spontaneously after having been excited by means of radiation at rate Bu into state 1 from the ground state. For the three-level ruby laser system, the exponential decay of the ground-state population due to the optical pump process has even been demonstrated experimentally.[14] The very weak monitoring processes in our experiment leave this picture essentially unchanged because they remove the atom from the ground state only for a small fraction of the time. These results are in agreement with the more refined discussions in the literature.[2-7]

Our current experiment differs somewhat from the

above scheme in the way the shelf level of the barium ion is excited. In our case the excitation proceeds via a mostly empty intermediate P level; the excitation rate then if Buf, where B is the Einstein coefficient for the $6^2S_{1/2}$-$6^2P_{3/2}$ transition and f is the branching ratio for the very rapid decay from the $6^2P_{3/2}$ level to the $5^2D_{5/2}$ shelf level. Thus, it is a fair conjecture that the probability distribution for "on times" t_0' of the fluorescence (i.e., times during which the ion is in the ground state, with very brief interruptions) is proportional to

$$\exp(-Buft_0').\tag{5}$$

The very slow spontaneous decay from the shelf level is unperturbed by the lamp radiation, is obviously exponential, and presents no problem.

A comparison of the experimental data with the theoretical expectation can be made by the plotting of a histogram of observed shelf-level dwell times (t_1). Figure 3 is such a histogram plotted for 203 observed "off intervals." The fitted lifetime, τ_1, is 30 ± 3 sec. To estimate the contribution of collisional quenching to this lifetime, the ion pump is turned off and the pressure is allowed to rise from 8.2×10^{-11} to 4.5×10^{-10} Torr. This results in a $\approx 25\%$ reduction in the fitted lifetime (for a small sample of 43 dwell times). Extrapolating to zero pressure increases the measured lifetime to 32 ± 5 sec; this lies just within 1 standard deviation (16 sec) of the published lifetime[12] of 47 sec.

The application of this technique to high-resolution spectroscopy of a single trapped ion should now be clear. If, instead of our using the hollow cathode lamp, a laser capable of generating narrow-band radiation at 1.762 μm were used, it would be possible to perform extremely high-resolution spectroscopy on the $5^2D_{5/2}$ level[15] of 0.005-Hz natural width. As originally proposed[1] and subsequently verified by theoretical calculations,[3,6] it would be necessary to alternate the cooling-interrogation lasers and the clock laser in order to avoid ac Stark broadening of the narrow transition. The clock-laser pulse would ideally approximate[1,6] a π pulse (on resonance) to invert the population. The cooling-interrogation lasers would then (with the clock laser off) determine whether the ion is in the metastable state or ground state in essentially the same way as it does for the case of continuous incoherent excitation, as described in this work. Such spectroscopy would be free from Doppler shifts to all orders (because of the laser cooling) and would not be subject to collisional or transit time broadening. In fact, with adequate magnetic shielding, the principal broadening mechanism for the foreseeable future would be the breadth of the laser. This experiment demonstrates that, even with an extremely low optical transition
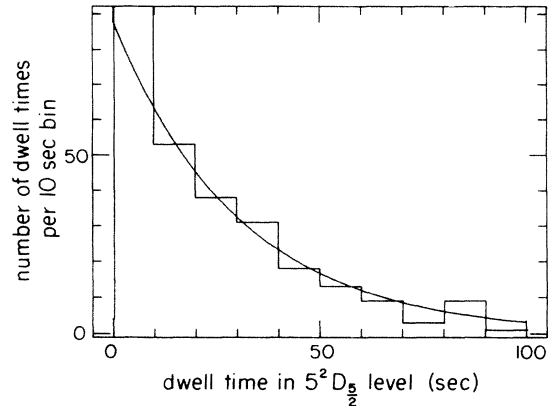

FIG. 3. Histogram of distribution of dwell times in the shelf level for 203 "off" times. A fitted theoretical (exponential) distribution for a metastable lifetime of 30 sec is superposed on the experimental histogram.

rate, virtually every transition to the metastable level would be detected.

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