Observation of a single atom in a magneto-optical trap

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Fluorescence from Cs atoms in a magneto-optical trap is detected under conditions of very low atomic density. Discrete steps are observed in the fluorescent signal versus time and are associated with the arrival and departure of individual trapped atoms. Histograms of the frequency of occurrence of a given level of fluorescence exhibit a series of uniformly spaced peaks that are attributed to the presence of $N = 0, 1, 2$ atoms in the trap.

A variety of fundamental investigations in optical physics require a sample consisting of an individual atom that is spatially localized with small kinetic energy. For example, there has been considerable interest in the possibility of spectroscopy with squeezed and other forms of nonclassical light, for which coherent illumination over 4π sr (and hence localization to better than the optical wavelength) is important.[1,2] Likewise, investigations in the area of cavity quantum electrodynamics have achieved strong coupling for a single atom interacting with the field of an optical cavity, but these investigations are hampered by fluctuations in the number of intracavity atoms provided by a conventional atomic beam.[3] Apart from the atom as an optical sample, there are opportunities for the study of the quantized motion of the trapped atom itself, as, for example, in the generation of squeezed states of a mechanical oscillator[4] or quantum nondemolition detection of its motion.[5]

Motivated by these considerations, in this Letter we report the observation of the cooling and trapping of individual Cs atoms in a magneto-optical trap (MOT). Our work follows in the tradition of the ion-trapping community, where trapping of a single ion was first reported in 1980.[6] Beyond this work with ions, single localized molecules have also been studied optically by matrix isolation[7] and by near-field microscopy.[8] Relative to these and other techniques, a significant factor that drives our current effort is the availability of nonclassical sources of light tailored to the optical transitions of Cs.[2,9]

Turning now to our actual experiment as depicted in Fig. 1, we note that the apparatus is similar to that employed in our previous spectroscopic experiments[10] and follows well-documented principles.[11–13] The trap is driven with radiation from a Ti:sapphire laser, which is split into five beams, and is tuned 1–2 linewidths below the atomic transition employed for cooling and trapping ($F = 4 \rightarrow F' = 5$ component of the D_2 line at 852 nm). The laser frequency is locked to an auxiliary Cs cell with FM saturation spectroscopy (linewidth ~60 kHz). A semiconductor diode laser repumps population from $6S_{1/2}$, $F = 3$ back to $F = 4$. A field gradient of 7 G/cm along the z axis provides the quadrupole magnetic field required for the MOT. The vacuum vessel is an ultrahigh-voltage all-metal chamber with a pressure of roughly $p_0 \approx 6 \times 10^{-9}$ Torr. A Cs ampoule in a side arm of the chamber is cooled to approximately −34 °C and is the atomic source for the trap. The collection optics provide a resolution of ~150 μm, as limited by aberration, which matches the useful aperture of our photodetector.

In a standard regime with a high number of atoms, we examine the trap using a CCD camera and find that it has roughly 10^6 trapped atoms and a diameter of ~400 μm, which are typical of a MOT. After initial alignment and characterization of the standard trap, the camera is replaced by an avalanche photodiode (APD) operating in a photon-counting mode. An aperture to control the size of the trapping beams is next closed down, yielding beams with a waist of approximately $\omega_0 = 2$ mm at the trap. A valve V that separates the main chamber from the source is then closed to reduce the background Cs pressure in the main chamber. Typically, after operation of a normal MOT, which fills principally from atoms in the broad atomic beam from the source, it takes several hours to pump away the residual Cs vapor in the main chamber. During this period we observe the fluorescence from the trap as detected by the APD and as recorded and stored by a photon-counting system and a computer. As the background Cs pressure drops, the observed signal from the trap diminishes, but, more importantly, the relative variance of the trapping signal increases. After subtraction of a nonresonant scattered component, we infer from a plot of signal size versus signal variance that the mean number of trapped atoms $\overline{N} \lesssim 10^2$.

When the background Cs pressure falls yet lower we are finally able to record traces of detected counts versus time as displayed in Fig. 2. From the figure we see that the counting rate exhibits distinct steps above a background level C_0, where C_0 is associated with (nonresonant) scattering from various optical components. Indeed, if we assert that the well-separated jumps in Fig. 2(a) are caused by fluorescence from single trapped atoms, then the duration τ_{on} of these steps should be exponentially distributed with τ_{on} governed by the collision (and hence ejection) rate of the trapped atom with the residual background gas. Following the analysis of Ref. 12, we take $1/\tau_{on} = n_{BG}\sigma u$, where n_{BG} is the density of background gas, $\sigma \sim 2 \times 10^{-13}$ cm^2 is the

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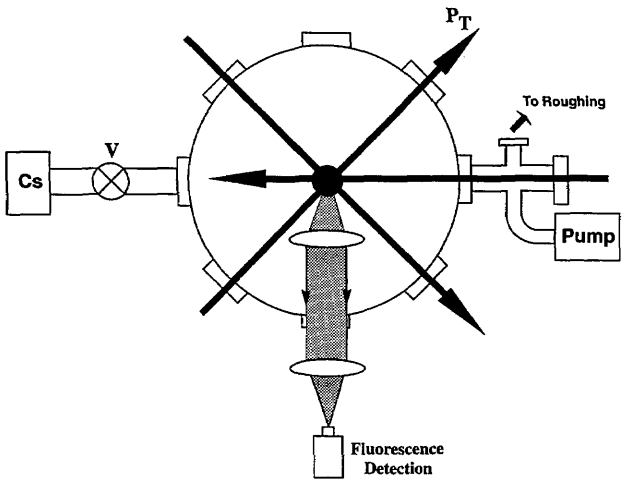

Fig. 1. Schematic of the apparatus used in the single-atom trapping experiment. Two z beams for trapping propagate into and out of the page.

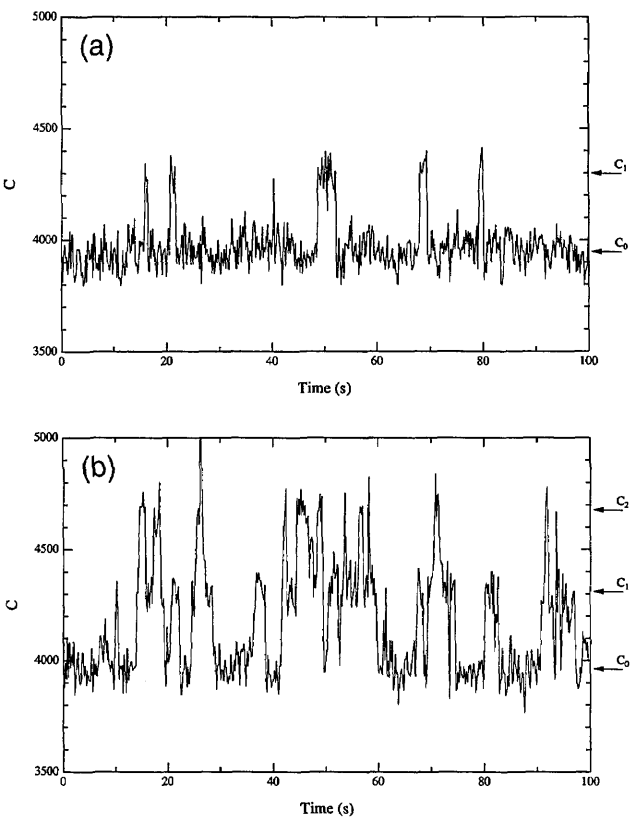

Fig. 2. Trap signal C (counts/0.1 s) versus time under conditions of very low Cs background pressure. The discrete steps evident in the figure are interpreted as arising from the arrival and departure of individual Cs atoms in the trap. In moving from (a) to (b), the background Cs pressure has been increased by injection of a small amount of Cs through the V valve (Fig. 1).

cross section for the collision of a trapped Cs atom with the (non-Cs) background,[12] and $u \sim 400$ m/s is the approximate thermal velocity appropriate to the collision (e.g., N_2 at 300 K). For $p_0 = 6 \times 10^{-9}$ Torr we thus deduce that $\tau_{on} \sim 0.6$ s. In fact, from a histogram constructed from a long record of which Fig. 2(a) is but one segment, we find that the distribution of on times is approximately exponential with time constant $\tau_{on}' \simeq (0.9 \pm 0.2)$ s.

The distribution of dwell times τ_{off} between two successive jumps of the fluorescence should likewise be exponential. However, to determine τ_{off} theoretically requires a bit more effort since we must treat in detail the processes by which the trap is filled. We employ the simple model presented in Refs. 12 and 13 in which any atom entering the volume enclosed by the laser beams with velocity below a certain capture velocity v_c is slowed and eventually trapped. The dwell time τ_{off} is then taken to be the inverse of the associated capture rate,

$$1/\tau_{off} = \frac{1}{4} n_{Cs} v_{Th} \frac{1}{\sqrt{\pi}} \left(\frac{v_c}{v_{Th}}\right)^4 \left(\frac{3}{2} \pi \omega_0^2\right), \qquad (1)$$

where n_{Cs} is the background Cs density with thermal velocity v_{Th}. The term $(v_c/v_{Th})^4$ arises from our requirement that the initial velocity be less than v_c. The effective trapping area presented by the laser beams to this flux is $3\pi\omega_0^2/2$, where we assume a uniform circular distribution with diameter ω_0. From the requirement that an atom having velocity v_c be stopped within distance ω_0, we find that $v_c^2 \approx 2 v_{rec} \Gamma \omega_0$, where $v_{rec} = 3.5$ mm/s is the recoil velocity and $\Gamma = (1/2\tau)\{(I/I_s)/[1 + I/I_s + (2\tau\delta)^2]\}$ is the total scattering rate. In our case the total intensity $I = 10$ mW/cm^2, the detuning $\delta/2\pi = -6$ MHz, the excited-state lifetime $\tau = 32$ ns, and the saturation intensity I_s lies in the range $1 \lesssim I_s \lesssim 2.5$ mW/cm^2 (with the lower value corresponding to the $F = 4$, $m_F = 4 \rightarrow F' = 5$, $m_{F'} = 5$ transition, while the upper value is for an average over the Zeeman sublevels of $F = 4 \rightarrow F' = 5$). Thus $5 \times 10^6/\text{s} \lesssim \Gamma \lesssim 9 \times 10^6/\text{s}$, from which we calculate $9 \lesssim v_c \lesssim 11$ m/s.[12] For this range of v_c we can then estimate τ_{off} from Eq. (1) given a knowledge of the Cs background density n_{Cs}. Unfortunately we have no independent monitor of n_{Cs}, so instead we use the observed values of τ_{off} to infer n_{Cs}. For example, from the data in Fig. 2(a) we find that the duration of the off intervals is approximately $\tau_{off} \sim 10$ s, which suggests that $n_{Cs} \approx 20 - 50/\text{cm}^3$.

Next we turn to the actual magnitude N_1 of the jumps in fluorescence associated with a single trapped atom, which is given by $N_1 = \Gamma f T_0 \alpha \Delta t$, where Γ falls in the range given above, $f \approx 1\%$ is the fraction of the 4π solid angle collected by our imaging system, $T_0 \approx 70\%$ is the total transmission of the collecting optics, $\alpha \approx 25\%$ is the overall quantum efficiency of the APD, and Δt is the counting interval. Thus we expect a value of $0.9 \times 10^3 \lesssim N_1 \lesssim 1.6 \times 10^3$ counts/0.1 s, which is roughly a factor of 3–4 times larger than we actually observe in Fig. 2 ($N_1 = C_1 - C_0$). A possible source for this large discrepancy is a potential mismatch between the size of the trap image and of the active area of the APD, which we estimate reduces the expectation for N_1 by roughly a factor of 2. Another possible cause for this discrepancy is that the trap may not have been well centered with respect to the intersection of the trapping beams. Again, since we

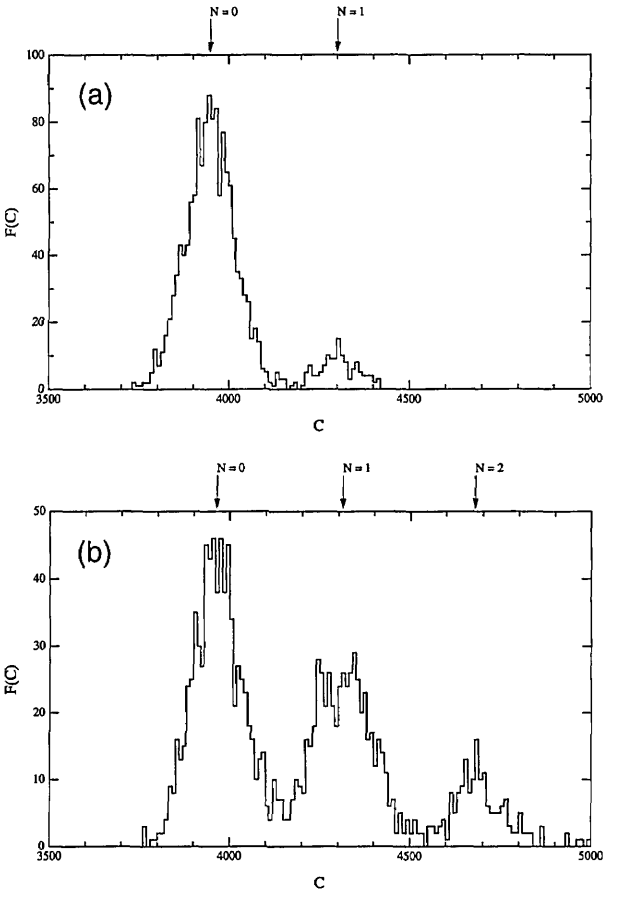

Fig. 3. Histogram of the frequency occurrence $F(C)$ of a given number of detected counts in a 0.1-s interval. (a) Low Cs background pressure as in Fig. 2(a), (b) slightly higher pressure, as in Fig. 2(b). The arrows mark the counting levels C_0, C_1, C_2 associated with $N = 0, 1, 2$ trapped atoms. The mean number of trapped atoms is $\overline{N} = 0.1$ in (a) and $\overline{N} = 0.6$ in (b).

have no imaging capability in the photon-counting regime, it may be that the actual intensity at the trap site is lower than that given by the peak intensity of the five trapping beams. These and other possibilities are currently being investigated.

Finally, from traces as in Fig. 2, but from much longer time series, we have constructed histograms of the frequency of occurrence of a given count rate versus count rate. At low pressure, as in Fig. 3(a), one sees predominantly two peaks, with the larger peak associated with the absence of trapped atoms ($N = 0$), whereas the smaller peak corresponds to a jump in fluorescence with one trapped atom ($N = 1$). At higher background Cs density, as in Fig. 3(b), the relative weight of the $N = 1$ peak increases, and a new peak corresponding to two trapped atoms emerges ($N = 2$). Note that the separation of the $N = 0, 1, 2$ peaks is approximately constant, consistent with the interpretation of the trapping of individual atoms. Also note that the widths of the peaks arise from Poisson counting fluctuations principally from the large component of nonresonant scattered light. Efforts are in progress to reduce this background component and hence to resolve more clearly the individual peaks.

In summary, we have recorded discrete jumps in fluorescent light emitted by a small number of atoms trapped in a MOT and have compared the duration and size of the jumps to values predicted by simple models. Although there is a quantitative disagreement between theory and experiment as to the absolute magnitude of the individual jumps, other evidence from the experiment strongly supports the conclusion that we have observed the trapping of individual neutral atoms. Straightforward improvements in the optical system (for enhanced signal-to-noise ratio) and in background pressure (for increased trap lifetime) should lead to a relatively stable sample consisting of a single trapped neutral atom for a variety of future applications. Beyond the confinement of atomic position provided by the MOT, it will also be of interest to explore other trapping schemes, such as a far-off resonance trap,[14] for greatly improved atomic localization.

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