Atoms on demand: Fast, deterministic production of single Cr atoms

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(Received 17 January 2003; accepted 17 March 2003)

We have realized a method for producing single Cr atoms on demand by suppressing the stochastic nature of the loading and loss processes of a magneto-optic trap. We observe single-atom trap occupation probabilities as high as $(98.7\pm0.1)\%$ and demonstrate ejection with greater than 90% efficiency at rates up to 10 Hz. Monte Carlo simulations agree well with extraction measurements and are used to predict ultimate performance. Such a deterministic atom source has potential applications in nanotechnology, quantum information processing, and fundamental quantum investigations. © *2003 American Institute of Physics.* [DOI: 10.1063/1.1572539]

Recently, there has been an explosion of research involving single atoms, ions, and molecules in diverse areas such as nanotechnology, molecular spectroscopy, quantum information processing, and quantum electrodynamics. While these studies originate from distinct disciplines, such as electronics, chemistry, and fundamental quantum physics, they all share a common thread in that they examine developing science and technologies that can be addressed by isolating and interacting with single quantum entities. Key to the advancement of this type of research is the development of techniques to controllably produce these isolated quantum objects. To date, the methods employed have relied on creating a sparse, random ensemble and then either hunting for a single particle (e.g., on a surface), or waiting until a single particle is captured randomly. With the present work, we overcome the obstacles imposed by this randomness by demonstrating a source in which a single, cold ($\lesssim 120\ \mu$K) atom is available in a small volume ($\approx 10^{-14}\ \mathrm{m}^3$) essentially whenever it is needed.

Our realization of a fast, single-atom source makes use of laser-atom manipulation techniques, in which atoms can be trapped and cooled to microkelvin temperatures and below.[1] Such techniques have previously been used to observe single atoms in a magneto-optical trap (MOT)[2–4] and transport them controllably once they have been trapped.[5,6] These methods have also been used in conjunction with collisionally-related loss processes of an optical-dipole trap to increase the maximum single-atom occupation probability from 0.37 (set by Poissonian statistics) to 0.50.[7]

The present work uses a MOT as the source of atoms, but differs significantly from previous single-atom studies in that we actively suppress nearly all of the stochasticity inherent in the load and loss processes of a MOT. Using high-efficiency fluorescence detection to determine the number of atoms in the trap, we employ feedback to maintain single-atom occupation by turning off the loading when one atom is detected, and dumping the trap if more than one atom is observed. These two feedback mechanisms suppress the random fluctuations in MOT atom number to the point at which the single-atom occupation probability is maintained quite close to unity. The fast response of this dynamic control to any perturbation in the trap atom number permits rapid, deterministic (e.g., periodic) extraction of single atoms.

A schematic of our experiment is shown in Fig. 1(a). A Cr MOT[8,9] is formed by six laser beams provided by a UV-pumped stilbene-3 dye laser tuned just below the ${}^7\mathrm{S}_3 \rightarrow {}^7\mathrm{P}_4^{\mathrm{o}}$ transition in Cr at 425.6 nm [see Fig. 1(b)]. Two repumping laser beams at 649.2 and 658.3 nm, provided by grating-stabilized diode lasers, are used to eliminate trap losses by spontaneous decay to the metastable ${}^5\mathrm{D}_3$ and ${}^5\mathrm{D}_4$ levels, respectively. The MOT diameter is on the order of 20 μm, and the lifetime ranges from 1 to 5 s, depending primarily on the stability of the repumping lasers. Although the MOT temperature is unmeasured, we presume it is at or below the Cr Doppler temperature of 120 μK.[10] Cr atoms are produced by an evaporator located 370 mm below the MOT center and maintained at a temperature between 1200 and 1400 °C, depending on the desired loading rate. The techniques for the fast control over loading and dumping are described in Fig. 1. The vacuum system containing the MOT consists of an ion-pumped central chamber [pressure typically $(0.5-1.0)\times10^{-6}$ Pa] and two reentrant flanges with water-cooled anti-Helmoltz magnetic coils [estimated field gradient (0.75–0.85) T/m]. To reduce detection of scattered light, the MOT laser beams are introduced through antireflection-coated viewports located on long arms and tilted 5° off normal to direct any retroreflected light onto blackened, cone-shaped baffles in the arms. Fluorescent light from the MOT is collected through a reentrant viewport with a solid angle of 0.2 steradians and imaged at 4× with a pair of achromatic doublet lenses onto a 0.2-mm diameter aperture. After passing through these optics and an optical bandpass filter centered at 425 nm (combined transmission ≈40%), the light is detected with ≈16% quantum efficiency by a low-dark-count single-photon-counting photomultiplier with a Na–K photocathode. The resulting pulses are then averaged by an analog ratemeter with variable time constant.

A figure of merit describing the low-extraction-rate performance of our feedback-controlled MOT is the probability P_1 of finding a single atom in the trap over some period of time. Generally speaking, we can write $P_1 = \tau_{\mathrm{single}}/(\tau_{\mathrm{single}} + \tau_{\mathrm{rec}})$, where τ_{single} is the average time spent with one atom

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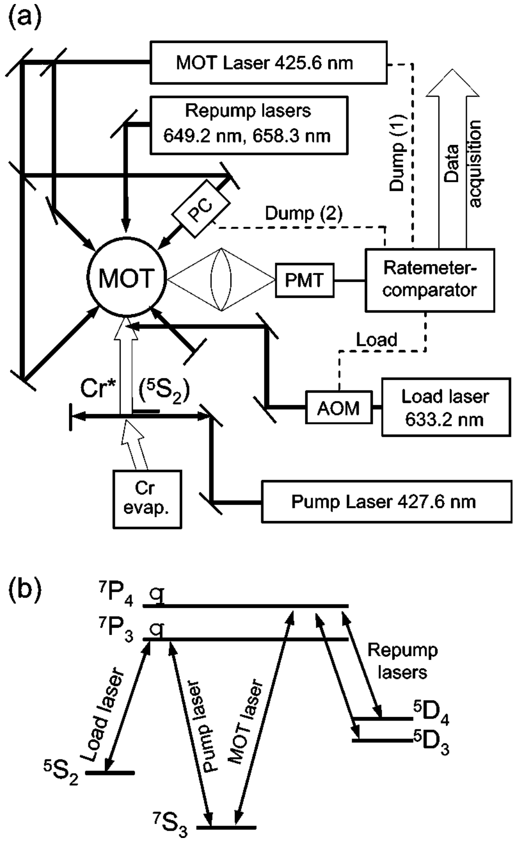

FIG. 1. (a) Schematic of the experiment. A MOT is formed by six beams (two axial beams not shown) from the MOT laser. Two repump lasers prevent trap loss to the metastable $^5D_3$ and $^5D_4$ levels. MOT fluorescence is detected by a photomultiplier (PMT), and then integrated and analyzed by a ratemeter-comparator that generates load and dump gates based on preset thresholds. Line-of-sight loading from a Cr evaporator is blocked. Instead, Cr atoms are deflected, collimated, and optically pumped into the metastable $^5S_2$ state via a pump laser tuned to the $^7S_3 \rightarrow {}^7P_3^o$ transition. When loading is desired, the $^5S_2$ atoms are optically pumped back to the ground state by a load laser gated with an acousto-optic modulator (AOM). The MOT is dumped by either of two methods: (1) momentarily (~ 1 ms) shifting the MOT laser frequency slightly above resonance; or (2) briefly (~ 5 ms) pulsing the MOT magnetic field off while simultaneously blocking one MOT laser beam with a Pockels cell (PC). (b) Energy levels of Cr (not to scale), showing laser transitions used for loading, pumping, trapping, and repumping.

in the MOT, and $\tau_{\rm rec}$ is the average time required for the feedback control to "recover" the stable single-atom state following a loss or other perturbation. The two times, $\tau_{\rm single}$ and $\tau_{\rm rec}$, are each determined by several time constants related to the dynamics of the MOT and control loop. $\tau_{\rm single}$ is predominantly governed by the intrinsic MOT loss lifetime $\tau_{\rm MOT}$, but is reduced because of dumping events triggered when a second atom is accidentally loaded despite feedback control. The two Poisson processes for trap loss and stray loading (at a mean rate of $R_{\rm stray}$) combine to give $\tau_{\rm single} = (\tau_{\rm MOT}^{-1} + R_{\rm stray})^{-1}$. The recovery time $\tau_{\rm rec}$ is in fact a composite time dominated by the longest of three time scales: (a) the inverse of the MOT load rate, $R_{\rm load}^{-1}$; (b) the averaging time used to measure the MOT fluorescence; and (c) the loading time delay $\tau_{\rm lag}$, which characterizes the time to fully cool and trap an atom once it enters the MOT capture region. Depending on the specific operating conditions of the MOT, any of these time scales may dominate $\tau_{\rm rec}$ and therefore P_1.

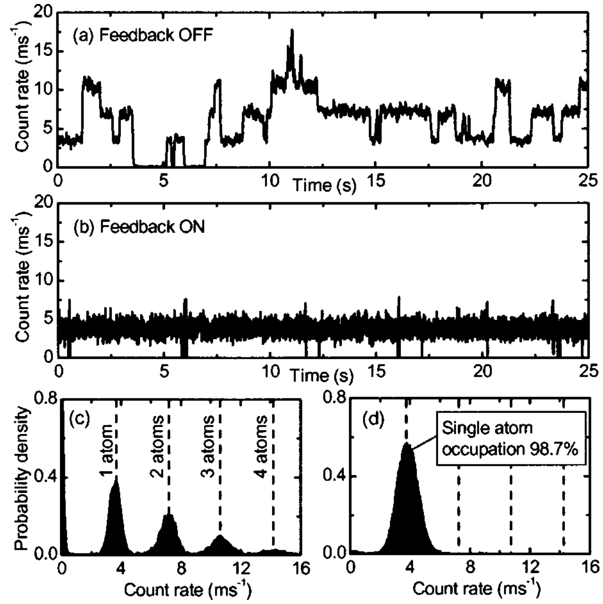

FIG. 2. MOT fluorescence. (a) Time series with feedback off; (b) time series with feedback on; (c) histogram of data in (a) with 100-s accumulation time; and (d) histogram of data in (b) with 200-s accumulation time. Without feedback, clear steps are seen as atoms enter and leave the trap randomly. With feedback the fluorescence is nearly constant at the one-atom level. (Note that a much smaller load rate and a longer ratemeter time constant were used in the no-feedback case.)

Measurements of P_1, $R_{\rm load}$, $R_{\rm stray}$, and $\tau_{\rm MOT}$ were carried out by analyzing fluorescence time series typically accumulated over 200 s. P_1 was obtained by dividing the total time spent in the single-atom state by the run time. $R_{\rm load}$ was measured by examining every loading event during a run and determining the average length of time the loading gate was on before a single atom was loaded. $R_{\rm stray}$ was estimated by measuring the mean time interval between MOT dumps that were triggered by the stray loading of a second atom. $\tau_{\rm MOT}$ was measured by first determining the average time spent in the single atom state, $\tau_{\rm single}$, and then using the relationship $\tau_{\rm MOT} = (\tau_{\rm single}^{-1} - R_{\rm stray})^{-1}$.

Figure 2 shows typical MOT fluorescence time-series measurements. Without feedback, atoms are stochastically loaded and lost from the trap, resulting in a random walk in MOT occupation number [Fig. 2(a)]. With feedback control, the MOT fluorescence is essentially constant at the single-atom level, with occasional fast dips to the background level and spikes to the two-atom level [Fig. 2(b)]. Histograms corresponding to these two cases are shown in Figs. 2(c) and 2(d). The feedback-on data in Figs. 2(b) and 2(d) is representative of the behavior under near-optimal conditions for our experimental configuration, and corresponds to a probability P_1 of finding a single atom in the trap of $(98.7 \pm 0.1)\%$.[11]

To be a viable deterministic atom source, our feedback-controlled MOT must have a single atom available with high probability while being continuously disrupted by the extraction process. To investigate this, we measured the response of our feedback-controlled MOT to periodic dumping which ejects the contents at some fixed rate. We plot in Fig. 3 the fraction of these intentional dump events that occur when only one atom is present. As expected, the single-atom ejection probability agrees with the measured single-atom occu-

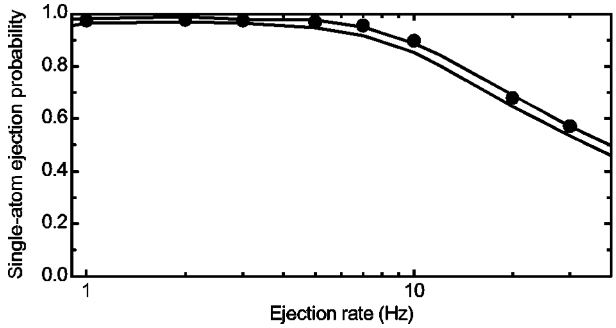

FIG. 3. Single-atom ejection probability vs ejection rate for $R_{\mathrm{load}} = 54.8–60.6\ \mathrm{s}^{-1}$, $\tau_{\mathrm{MOT}} = 1.8$ to 4.6 s, and $\tau_{\mathrm{lag}} = 3.5–5.3$ ms. Black circles indicate measurements, and the upper and lower solid lines define the upper and lower bounds of Monte Carlo simulations encompassing variations in experimental conditions. Uncertainties, estimated by combining in quadrature the standard deviations associated with the measurement uncertainty and the statistical sampling uncertainty, are smaller than the plotting symbols.

pation probability at low ejection rates, but begins to degrade as the ejection rate approaches τ_{rec}^{-1}. Nevertheless, a single-atom ejection probability near 0.9 is still obtained up to ejection rates of 10 Hz.

Also shown in Fig. 3 are the results of Monte Carlo simulations of the single-atom ejection probability. As input parameters we used measured values for τ_{lag} (3.5–5.3 ms), R_{load} ($54.8–60.6\ \mathrm{s}^{-1}$), R_{stray} ($0.1\ \mathrm{s}^{-1}$), τ_{MOT} (1.8–4.6 s), the mean detected fluorescence rate ($3500\ \mathrm{s}^{-1}$), and the background count rate ($350\ \mathrm{s}^{-1}$). For the load threshold, dump threshold, and measurement time, we used the experimentally set values of $1050\ \mathrm{s}^{-1}$, $7670\ \mathrm{s}^{-1}$, and 5 ms, respectively. The excellent agreement between simulations and measurements indicate that this model captures the essential physics of the feedback-controlled MOT and the effects of extraction.

Using the simulations as a guide, it is of interest to investigate the fastest extraction rate possible assuming best-case operating conditions. With some care in optimizing the MOT and the collection of its fluorescence, it is reasonable to presume that the detected photon count rate can be as high as $10^7\ \mathrm{s}^{-1}$, τ_{lag} can be reduced to 0.1 ms, τ_{MOT} can be as large as 100 s, and R_{stray} can be made negligible. In this scenario, simulations suggest that with $R_{\mathrm{load}} = 3333\ \mathrm{s}^{-1}$, single atoms can be extracted with 99% certainty at a rate of 400 Hz. Since τ_{lag} becomes the limiting time scale in this scenario, it is interesting to note that setting $\tau_{\mathrm{lag}} = 0$ in the simulation allows single-atom extraction rates as high as 10^4 Hz with 99% certainty.

With these experiments, we have shown that a single atom can be made available with high confidence essentially whenever it is required. The next step is to reliably transfer the atom to a specific experiment. Several options exist for this purpose, including ejection with light pressure, capturing and transferring the atom with optical tweezers,[12] or photo-ionization followed by electrostatic extraction. With further research, any of these could in principle be used in conjunction with our source to rapidly provide a large but precise number of single atoms on demand to an experiment or device for which isolated quantum objects are desired.

The authors wish to thank R. Celotta, S. Leigh, J. Yen, A. Rukhin and the members of the Electron Physics Group for stimulating discussions.

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