Improved magneto-optic trapping in a vapor cell

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We have captured 3.6 x 10^10 cesium atoms in a magneto-optic trap loaded from a vapor cell. The 300-fold increase in the number of trapped atoms compared with that of previous research was accomplished by using larger laser intensities and 4-cm-diameter laser beams. The loading time constant was as short as 0.2 s.

A sample of trapped atoms is an ideal starting point for many experiments. For example, precision microwave spectroscopy\(^1\) and atom interferometry\(^2\) based on an atomic fountain begin with the collection of a large number of atoms in a magneto-optic trap.\(^3\) Similarly, studies of collisions of ultracold atoms with each other\(^4\) and with surfaces,\(^5\) and efforts to reach Bose condensation of a weakly interacting gas, would benefit if the number of trapped atoms could be increased.

In the first demonstration of the magneto-optic trap,\(^3\) ~10^7 atoms were trapped. The atoms were first precooled by slowing atoms in an atomic beam to velocities of ~20 m/s before they were captured. Recently Monroe et al.\(^6\) have shown that atoms can be trapped without the precooling step by embedding the magneto-optic trap in a vapor cell and capturing atoms in the low-velocity tail of the thermal distribution. In their experiment as many as 1.8 x 10^7 Cs atoms were trapped. More recently Grison et al.\(^7\) have trapped 10^6 Cs atoms. Here we show that 3.6 x 10^8 Cs atoms can be loaded directly into a vapor cell trap in a time as short as 0.2 s.

In the vapor-cell trap, atoms with velocities less than a capture velocity \(v_c\) are slowed sufficiently after entering the intersecting laser beams so that they can be loaded into the magneto-optic trap. The rate at which these slow atoms enter this volume is\(^8\)

\[
R = \frac{n d^2 v_c^4}{u^3}. \tag{1}
\]

Here \(n\) is the background Cs density, \(d\) is the circular laser beam diameter, and \(u = (2 kT/m)^{1/2}\) is the most probable speed (190 m/s for Cs at \(T = 300\) K). The \(v_c^4\) dependence occurs on integrating the Boltzmann flux distribution, which is proportional to \(v^3\) for \(v \ll u\).

The capture velocity and the laser beam diameter in relation (1) are related. Atoms are decelerated by scattering \(r\) photons/s, where each scattered photon slows the atom by a recoil velocity \(v_r\), 3.5 mm/s for our case. The distance required to stop an atom of velocity \(v_c\) is then \(d = v_c^2/2rv_r\). Thus the loading rate \(R\) is proportional to \(d^4\). The scattering rate is \(r = p/[2(1 + p)n_r]\), where \(n_r\) is the excited-state natural lifetime \((1/n_r = \gamma_r = 2\pi \times 5\) MHz\) and \(p\) is the saturation parameter given by \(p = (I/I_s)/(1 + 4\Delta^2/\gamma_r^2)\). Here \(I\) is the laser intensity, \(I_s\) is the atomic saturation intensity, 1.1 mW/cm\(^2\) for the case of the Cs 6S\(1/2\leftarrow F = 4, m_F = 4\) \(\rightarrow 6P_{3/2}\leftarrow F = 5, m_P = 5\) transition, and \(\Delta\) is the laser detuning that includes the Doppler shift. Because the laser must be nearly resonant with atoms at velocity \(v_c\), the detuning must be increased if the beam diameter is increased. To maintain the same saturation parameter for the trapped atoms, \(I\) must be increased as \(I \propto v_c^2 \propto d\). Hence, for the loading rate to remain proportional to \(d^4\), the required laser power must increase as \(d^3\).

Monroe et al.\(^6\) have shown that the number of trapped atoms is independent of the background density \(n\). This occurs because both the loading rate and the dominant loss mechanism, collisions with background Cs atoms at a rate \(\Gamma_c = n \sigma u\), are both proportional to \(n\). Thus solving the steady-state rate equation \(dN/dt = R - \Gamma_c N\), we get the steady-state number of trapped atoms,

\[
Nss = \frac{R}{\Gamma_c} = \frac{d^2 (v_c^4)}{\sigma (u)^4}. \tag{2}
\]

Here \(\sigma\) is the cross section for a background gas collision that ejects a trapped atom. Because atoms scattered by weak collisions may be again slowed by the laser beams and recaptured, \(\sigma\) is expected to have a slight dependence on \(v_c\); \(\sigma \propto v_c^{-2/3}\) for a trapped atom in an excited state.\(^8\)

Our Cs vapor cell was similar to that described in Ref. 6, except that larger windows with a 4-cm clear aperture were used. A Ti:sapphire laser supplied three sets of orthogonal laser beams to the cell with 1/e\(^2\) diameters of 5.5 cm and peak intensities of 25 mW/cm\(^2\). A diode laser was combined with the three trapping beams and supplied 20 mW of light resonant with the 6S\(1/2\leftarrow F = 3 \rightarrow 6P_{3/2}\leftarrow F = 4\) transition to repump atoms from the \(F = 3\) to the \(F = 4\) ground-state level. After traversing the cell, the circularly polarized trapping and repumping laser beams were focused by \(\approx 30\)-cm focal-length lenses and retroreflected by a mirror placed slightly before the focus to compensate for the reflection losses from the cell windows. Quarter-wave plates were inserted before the mirrors to maintain the helicity of the light after retroreflection. Both lasers had

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linewidths <2 MHz and were frequency locked to sub-Doppler Cs resonances. We controlled the laser-beam intensities with acousto-optic modulators and mechanical shutters. We also used a tunable diode laser to probe the trapped atoms.

By varying the trap parameters, we trapped $3.6 \times 10^{10}$ atoms (see Fig. 1). By using a CCD camera, we measured the FWHM of the trap fluorescence to be 1.1 cm. The trap was spherical, with a nearly uniform density distribution of $3.6 \times 10^{10}$ cm$^{-3}$ and an on-resonance optical transmission of $\exp(-40)$. The trapped atoms emitted 16 mW of fluorescent power, and the trap loading followed the expected time dependence $N_{\text{sat}}(1 - \exp(-\Gamma_d t))$.

We used three methods to determine the trap population. In the first method, we used a 1-ms pulse of the six trapping beams and measured the trap fluorescence versus intensity. The fluorescence was detected within a known solid angle by using a calibrated photodiode and preamplifier. By assuming an effective saturation parameter for all the $F = 4$ magnetic sublevels, we calculated the number of atoms in the trap.

In the second detection method, we measured the absorption of a weak probe beam versus detuning from the $F = 4 \rightarrow F' = 5$ transition. By using the average photon absorption cross section $(1.5 \times 10^{-19}$ cm$^2$) for all of the ground-state sublevels and the measured trap size, we calculated a trap population.

In the third and most precise method, we optically pumped the atoms into the $F = 4$ ground state. By using a 1–2-ms pulse of light nearly resonant with the $F = 4 \rightarrow F' = 4$ transition, we hyperfine-pumped the atoms from the $F = 4$ to the $F = 3$ ground state and detected the fluorescent pulse emitted by the atoms during this optical pumping. Because the spontaneous emission branching ratio $\Gamma_{F' = 4 \rightarrow F = 3}/\Gamma_{F' = 4 \rightarrow F = 4} = 7/5$, each atom emits an average of 2.4 photons during this hyperfine-pumping process, and hence the integral of the fluorescence photodiode signal is proportional to the number of atoms. The integrated signal was independent of laser polarization, intensity, and detuning over more than an order-of-magnitude change in power and a frequency range of ±80 MHz. As an additional check, we have also hyperfine pumped the atoms using the $F = 4 \rightarrow F' = 3$ transition, which causes the atoms to emit an average of 1.33 photons.

The optimal trap parameters depended on the laser beam diameters. By increasing the laser power and going towards larger beam diameters, we measured the scaling law $N_{\text{sat}} \propto d^d$ and determined that $\beta = 3.65$ with a fitting uncertainty of ±0.14. For beam diameters of <2 cm, 10-G/cm gradients and detunings of 10–15 MHz gave the most trapped atoms, which is consistent with previous results.\(^{37}\) For larger beams, however, larger detunings and smaller gradients trapped the largest number of atoms. With 4-cm-diameter laser beams, a 7.7-G/cm magnetic field gradient, a 20-MHz detuning corresponding to $4\gamma_c$, and a trapping intensity of 22 mW/cm$^2$ in each laser beam (see Fig. 1) gave the most trapped atoms.

The capture velocity for our trap was considerably higher than that of previous traps. With a background Cs density of $n = 2.1 \times 10^8$ cm$^{-3}$ (maintained by a cold finger at ~20°C) and a background collision rate of $\Gamma_\text{c} = 2.5$ s$^{-1}$, relations (1) and (2) gave $v_c = 35$ m/s, which corresponds to a Doppler shift of 41 MHz. Uncertainties in the background Cs density and unknown geometric factors in relation (1) may change the calculated loading rate by a factor of ~2. This, however, only produces an ≈20% uncertainty in the calculated $v_c$.

The magnetic field gradient affected both the loading time constant $\Gamma_d^{-1}$ and the steady-state population of the trap. With the large laser beams, $\Gamma_d$ increased for smaller field gradients (i.e., smaller trap depths), which implies a larger loss rate from the trap owing to background gas collisions. At higher field gradients, the loading rate $R$ decreased, which decreased the steady-state number of trapped atoms while the density remained constant. The large field gradients impede the slowing mechanisms because, several centimeters from the trap center, the Zeeman shifts of the magnetic sublevels are larger than the laser detuning. To allow a period of slowing in zero magnetic field followed by a period of trapping with a field gradient, we modulated the magnetic field gradient. However, we observed no increases in trap population.

From relation (1) it might seem as if the loading rate would continue to increase with increasing laser power and detuning. We believe that the observed finite optimal detuning and power (for a given $d$) are partially a consequence of the three-dimensional nature of the cell trap. Atoms that are being slowed from velocity $v_c$ to 0 are excited not only by the counterpropagating laser beam but also by the transverse laser beams, which do not slow the atoms. Increasing the intensities above those shown in Fig. 1, or increasing the detuning, raises the relative rate of transverse-to-counterpropagating excitations. Consequently atoms are slowed less efficiently, $v_c$ decreases, and the number of atoms decreases. Further experimental and theoretical investigation is needed to understand fully the three-dimensional slowing process.

In addition to increasing transverse excitations, the detuning also affects the optical thickness of the
gradient cooling occurs in a magneto-optic trap.

As an atom is slowed to zero velocity, it shifts out of resonance with the slowing beam. It has been suggested that sidebands might increase the number of trapped atoms in a vapor cell. We have tried adding sidebands and chirping the laser frequency to keep light on resonance with the atoms as they are slowed in an effort to decrease the slowing distance, increase $v_r$, and collect more atoms. We added one and two sidebands to the trapping laser beam by using an acousto-optic modulator and an electro-optic modulator, respectively. For all parameter regimes explored, including frequency differences $\delta$ as large as 40 MHz, the sidebands only significantly decreased the number of trapped atoms.\(^{11}\) Chirping the frequency to keep the laser on resonance with atoms as they were slowed also only decreased the number of trapped atoms.

Steane and Foote\(^{12}\) have shown that polarization-gradient cooling occurs in a magneto-optic trap. Polarization gradients with multiple-frequency components have not yet been studied, and we speculate that the coherent beating of the standing waves at the sideband frequency may inhibit the polarization-gradient cooling of atoms to $v = 0$. We note that a single sideband causes a temporal modulation of the ac Stark shifts at any point in space. Also, for sidebands created by an electro-optic phase modulator and frequency-difference wavelengths $c/\delta$ on the order of the distance from the trap center to the retroreflection mirror, the standing wave spatially oscillates on the scale of the optical wavelength at the sideband frequency $\delta$. Experimentally, when the frequency of the two laser beams along the coil axis was detuned by $\approx 100$ kHz from the four beams in the perpendicular plane, the trap size increased and the population fell dramatically. This may further suggest the importance of polarization-gradient cooling because the frequency difference of the axial trapping beams produces a rapid modulation of the three-dimensional polarization gradients.

A vapor-cell magneto-optic trap with a high background Cs density could be used as a source of cold atoms. In Fig. 1, $3.6 \times 10^{10}$ atoms were collected with a time constant $T^{-1}$ of 0.19 s. If the trap were repeatedly loaded for 0.19 s and the atoms launched into a high-vacuum chamber, these results indicate that this pulsed atomic beam would produce a flux of $10^{13}$ cold atoms/s. This would be a bright source of cold atoms that would be useful for pulsed atomic-beam experiments and for loading a second magneto-optic trap in high vacuum.\(^{13}\)

Similarly, an atomic funnel\(^{14}\) could also be constructed in a vapor cell. The loading rate and hence the flux of cold atoms could be greatly increased by increasing the background Cs density [see relation (1)]. The optimal flux should be obtained at the highest background Cs density for which most of the cold atoms did not undergo a background gas collision before entering a high-vacuum chamber.

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References

8. Here we assume an interatomic potential $V(R) = \pm C_6 / R^6$ for a ground-state/excited-state Cs-Cs interaction and small-angle scattering.
11. M. Zhu, C. W. Oates, and J. L. Hall have observed similar behavior in a Na vapor-cell trap (Joint Institute for Laboratory Astrophysics, University of Colorado, Boulder, Colo. 80309, personal communication, 1991).