Very Cold Trapped Atoms in a Vapor Cell

C. Monroe, W. Swann, H. Robinson,[a] and C. Wieman

Joint Institute for Laboratory Astrophysics, University of Colorado and National Institute of Standards and Technology, and Department of Physics, University of Colorado, Boulder, Colorado 80309-0440

(Received 31 May 1990)

We have produced a very cold sample of spin-polarized trapped atoms. The technique used dramatically simplifies the production of laser-cooled atoms. In this experiment, 1.8×10^7 neutral cesium atoms were optically captured directly from a low-pressure vapor in a small glass cell. We then cooled the $<1\text{-mm}^3$ cloud of trapped atoms and loaded it into a low-field magnetic trap in the same cell. The magnetically trapped atoms had an effective temperature as low as 1.1 ± 0.2 μK, which is the lowest kinetic temperature ever observed and far colder than any previous sample of trapped atoms.

PACS numbers: 32.80.Pj, 42.50.Vk

In recent years there has been dramatic progress in the use of laser light to cool[1] and trap[2] neutral atoms. We and others[3,4] have previously reported using optical traps to produce cold atomic samples with high densities and optical thicknesses beyond that attainable in most beams. Such samples would be ideal for a variety of experiments which are currently done with atomic beams. However, in previous optical traps, a substantial vacuum apparatus was required to slow an atomic beam prior to trapping. The ability to trap atoms directly and efficiently from a room-temperature vapor means that for many experiments, this apparatus can be replaced with a small cell.

Such an optically trapped sample is useful for many applications, but it has some inherent limitations; the atomic spins are randomly oriented, perturbing light fields must be present, and it is difficult to achieve temperatures lower than 300 μK. We have overcome these limitations by loading the optically trapped atoms into a magnetostatic trap. Because the atoms are very cold when first loaded, we can trap them with relatively small magnetic fields. By properly cooling the atoms before turning on the magnetic trap we have produced a sample which is more than 100 times colder than any previously trapped neutral atoms.

In our experiment the atoms are initially captured using the Zeeman-shift spontaneous-force optical trap (ZOT) reported first by Raab *et al.*,[3] and used by us in a variety of recent studies.[4,5] This trap uses the light pressure from six orthogonal intersecting laser beams. A weak magnetic-field gradient acts to regulate the light pressure in conjunction with the laser frequency to produce a damped harmonic potential. In previous work we found that the trap could capture cesium atoms from a cooled beam with speeds up to ≈ 12 m/s and substantial numbers of atoms from an uncooled beam.[5] Similar observations were made by Cable, Prentiss, and Bigelow for sodium.[6] This suggested the possibility of capturing atoms directly from a room-temperature vapor.

The number of atoms contained in a trap which is in a dilute vapor is determined by the balance between the capture rate into the trap and the loss rate from the trap. Given the maximum capture speed of the trap, v_c, the number of atoms per second entering the trap volume with low enough velocities to be captured is easily calculated.[7] This rate is $R=0.5nV^{2/3}v_c^4(m/2kT)^{3/2}$, where n is the density of cesium atoms, m is the mass, T is the temperature, and V is the trapping volume (about 0.1 cm^3 for our trap). For cesium at a temperature of 300 K, approximately one atom in 10^4 is slow enough to be captured. The loss rate from the trap, $1/\tau$ (τ=lifetime), is primarily due to collisions with atoms in the vapor. If we assume the density of noncesium atoms is negligible, then $1/\tau=n\sigma(3kT/m)^{1/2}$, where σ is the cross section for an atom in the vapor to eject a trapped atom. The number of atoms in the trap, N, is then given by the solution to the simple rate equation $dN/dt=R-N/\tau$. Assuming $N(t=0)=0$, we obtain $N(t)=N_s(1-e^{-t/\tau})$, where the steady-state number N_s is given by

$$N_s=R\tau=(1/\sqrt{6})(V^{2/3}/\sigma)v_c^4(m/2kT)^2. \quad (1)$$

Note that N_s is independent of pressure. However, the lifetime τ, which is also the time constant for filling the trap, does depend on pressure.

Because N_s is very sensitive to v_c, we should note which parameters of the ZOT determine v_c. The primary stopping force comes from the imbalance in the radiation pressure due to the differential Doppler shift between the two counterpropagating beams. This force decreases rapidly with velocity once the Doppler shift gets so large that the atom is out of resonance with both beams. Since the frequency of the laser is typically 1 linewidth to the red of the atomic resonance, $v_c\approx 2\Gamma\lambda$, where $\Gamma\lambda$ is the velocity at which the Doppler shift equals the natural linewidth Γ (5 MHz for our transition).

The actual construction of the cell trap was quite simple. Shown in Fig. 1, the cell is a vertical cylinder of fused silica 12 cm long with windows on each end and four windows mounted in a cross at the top of the

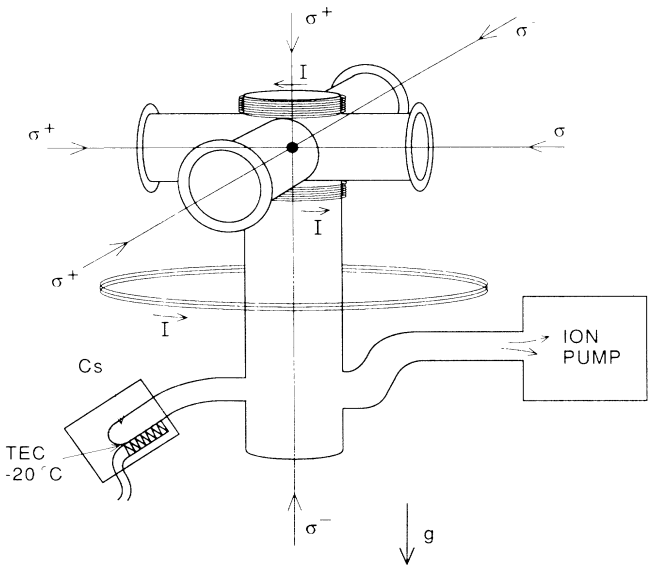

FIG. 1. Vapor cell used for optically and magnetically trapping and cooling cesium atoms. For the optical trap, the small coils are operated in the anti-Helmholtz configuration. The six laser beams are indicated by arrows. For the magnetic trap, the current to the small coils is turned off and the large coil turned on. The four vertical current bars providing horizontal confinement are not shown.

cylinder. Attached to the main cylinder are two smaller tubes. The first is a "cold finger" which contains a reservoir of cesium whose temperature determines the vapor pressure in the cell. It can be cooled to $-23\,^{\circ}$C using a small thermoelectric cooler. The second tube leads to a 1-ℓ/s ion pump which removes any residual gas (mostly helium) that may diffuse through the cell walls. The ZOT setup was the same as in our previous work: The light from a diode laser tuned to the $6S_{1/2},F=4 \rightarrow 6P_{3/2},F=5$ cycling transition was split into three beams 0.5 cm in diameter with ~ 2 mW per beam. The beams were circularly polarized and aligned to intersect perpendicularly in the center of the cell. After leaving the cell each beam went through a quarterwave plate and was reflected back on itself. Light from a second laser tuned to the $6S_{1/2},F=3 \rightarrow 6P_{3/2},F=4$ transition also illuminated the intersection region and prevented the atoms from accumulating in the $F=3$ ground state. A magnetic-field gradient of ~ 10 G/cm was produced by an anti-Helmholtz pair which was wound on the cylinder. The fluorescence from the center of the cell was observed using a charge-coupled-device television camera as well as a calibrated photodiode.

When the trapping laser was tuned between 1 and 10 MHz to the red of the transition (~ 6 MHz was optimal), a bright cloud of trapped atoms < 1 mm^3 appeared in the center of the cell. By measuring the fluorescence we determined that the cloud contained as many as 1.8×10^7 atoms, in agreement with the value predicted by Eq. (1) with $v_c = 15$ m/s. As we observed in our previous work,[2] the density of atoms in the cloud was limited by radiation trapping to about 5×10^{10} atoms/cm^3, and the temperature was about 30 μK. The trapped atom cloud was more than 1000 times brighter than the background fluorescence in the cell at a cesium pressure of 6×10^{-9} Torr. The growth in the number of atoms with time agreed well with the predicted form. The lifetime of atoms in the trap was 1 s at a pressure of 6×10^{-9} Torr. The steady-state number of atoms in the trap changed by less than 30% as the cesium pressure was varied between $\sim10^{-7}$ Torr ($\tau=0.06$ s) and $\sim1.5\times10^{-9}$ Torr ($\tau=4$ s). Lifetimes of 1–2 s were attained using the thermoelectric cooler, and lifetimes up to 10 s were reached by immersing the cesium reservoir in a dry ice and alcohol solution. For lower cesium pressures, the number of trapped atoms decreased, presumably because the loss rate from collisions with noncesium atoms became important. At very high pressures the attenuation of the trapping laser beams caused the number of trapped atoms to decrease.

From the lifetime and the pressure we find $\sigma=2\times10^{-13}$ cm^2. The lifetime at a given pressure is about a factor of 5 shorter than what we previously measured for optically trapped cesium atoms in a stainless-steel UHV chamber. This difference is reasonable since the background gas (mostly H_2) in that case was much lighter than cesium.

Perhaps the most striking aspect of this trap is its insensitivity to nearly all optical parameters. Although the detailed shape of the cloud changes, the number of atoms is nearly unaffected by changes in alignment, attenuation of the return beams, or quality of the laser wave fronts. Sending the trapping beams directly through the curved glass walls of the cell rather than through windows made little difference in the performance; the trap even worked when a lens tissue was placed in one of the incident beams. Zhu and Hall have trapped sodium in a similar cell, and they have achieved results comparable to ours for cesium.[8]

With additional laser power it should be possible to increase v_c significantly and thereby dramatically increase N. This could be done by enlarging the diameter of the trapping beams (keeping the intensity near saturation) to allow the stopping force to act over a larger distance. Adding red-shifted sidebands on the laser would give further improvement.

We have used these optically trapped atoms to carry out a variety of experiments within the vapor cell. First, the atoms were further cooled by switching off the anti-Helmholtz coils to leave the atoms in optical molasses. This technique produces a dense sample of very cold but untrapped atoms, as was demonstrated in Ref. 9. When the laser light was shut off, these samples fell ~ 10 cm to the bottom of the cell with very little expansion. Alternatively, after turning off the light, we loaded these very cold atoms into a magnetostatic trap or bowl where they

were held by magnetic $\mathbf{V}(\boldsymbol{\mu}\cdot\mathbf{B})$ and gravitational forces at the same location as in the optical trap. This produced a very cold, 100% polarized sample which was not subjected to the perturbing fields of the laser.

To trap the $|F,m_F\rangle=|4,4\rangle$ weak-field-seeking state, four vertical bars, each carrying a current with direction opposing that of its nearest neighbors, were placed around the cell. In the horizontal (x,y) plane, they provide a quadrupole field distribution having zero field in the center along the vertical (z) axis. In addition, a horizontal coil below the atoms gives a vertical bias field as well as a vertical field gradient.[10] This gradient $(\partial B_z/\partial z)$ supplies the levitating force to support the atom against gravity. At the trap, $B_z\approx 100$ G and $\partial B_z=-24$ G/cm. The x and y field gradients, depending on the current through the bars, were 20–80 G/cm. Since B_z is much greater than the horizontal components (B_x,B_y) over the trap volume, the trapped atoms see only very small changes in the direction of $\mathbf{B}$.

The combination of the magnetic field and gravity produces a very nearly harmonic confining potential within the trap volume in all three dimensions. The vertical spring constant (κ_z), fixed by gravity and our coil geometry, was 0.5 mK/cm^2 corresponding to an oscillation period of 360 ms. The horizontal spring constants, determined by the corresponding field gradients, were $\kappa_x=0.5$–5 mK/cm^2 and $\kappa_y=0$–5 mK/cm^2.

The following sequence was used to load the atoms into the magnetic trap: (1) The optical trap was turned on and filled for 3 s. (2) For additional cooling, all magnetic fields were turned off, the laser frequency was shifted 50 MHz to the red, and the intensity was reduced by a factor of 4. After 5 ms, the trapping laser was quickly turned off (20 μs). (3) A 10-G vertical field was applied and a weak circularly polarized vertical laser beam was pulsed on (duration 0–1 ms) to pump the atoms into the $|4,4\rangle$ state. (4) At the end of this pulse, the magnetic fields for the trap were switched on in 20 μs.

We observed the distribution and number of magnetically trapped atoms at later times by waiting (0–3 s), then quickly (20 μs) switching the magnetic fields off and the laser beams back on. A television camera recorded the image of the clouds as the laser came on. With a 1-ms optical pumping time in step 3, essentially all the optically trapped atoms $[(1-2)\times 10^7)]$ were loaded into the magnetic trap. However, the scattering of photons during the optical pumping heated the atoms. We avoided this by adjusting the alignment and intensities of the trapping-molasses light beams to enhance the population of the $m=4$ state in the molasses. We were able to obtain nearly a factor-of-3 enhancement (30% of the atoms in $m=4$ without external optical pumping) without significantly affecting the number of trapped atoms or the final temperature. With this enhancement, the additional optical pumping required to put more than 50% of the atoms into $m=4$ produced only slight heating. This will be discussed in a later publication. The lifetime in the magnetic trap was $\approx\frac{1}{4}$ that of the optical trap, and depended very weakly on the depth of the trap.

We studied the temperature of the cooled and magnetically trapped atoms by observing their motion in the known trapping potentials. For large spring constants the magnetically trapped atoms were confined to much the same volume as they occupied in the optical trap and quickly reached a static distribution. With weaker spring constants, however, the cloud expanded and contracted as each atom oscillated sinusoidally in three dimensions. We reduced the spring constants until the maximum diameter of the cloud was 3 or more times the minimum (initial) diameter. Under these conditions the initial velocity distribution is mapped into the spatial distribution after $\frac{1}{4}$ of the oscillation period T to within 10%. They are related by $v_i=(\kappa_i/m)^{1/2}r_i$, where v_i is a component of initial velocity, and r_i is the component of displacement at $T/4$. Thus, we find the velocity distribution by measuring the spatial distribution of the atom cloud at the time of largest expansion. We found the velocity distribution depended on the alignment of the trapping-molasses beams. In general, the distributions were different in the x, y, and z directions, and could deviate from a thermal Maxwell-Boltzman distribution. For conditions where the initial distribution was thermal to within our 10% uncertainty, we can characterize the distribution of velocities in each direction by a temperature, $T_i=\kappa_i r_i^2/2k$. This kinetic-energy spread oscillated as a function of time between the initial value (a few μK) and a minimum value which we estimate is about 100 nK. The time-average kinetic energy of the trapped atoms is described by an effective temperature which is the average of these two, or essentially $\frac{1}{2}$ the initial value. With no optical pumping we obtained effective temperatures as low as $T_x=T_y=1.1\pm 0.2$ μK, and $T_z=1.3\pm 0.2$ μK. As expected, these effective temperatures are about $\frac{1}{2}$ the temperature recently observed with cesium atoms in optical molasses.[11] They are more than a factor of 100 lower than has previously been obtained for a sample of trapped atoms.

There are many potential uses for samples of magnetically or optically trapped atoms which can be produced and precisely manipulated with such a simple apparatus. They are useful targets for many scattering experiments and ideal samples for precision spectroscopy. We have demonstrated one example of the latter by dropping the optically trapped and cooled sample and observing the cesium clock hyperfine transition with good resolution as it fell.[12] Another unique characteristic of these samples is the large optical thickness with negligible Doppler or collision broadening. It should be possible to obtain an optical thickness of 10. Because this is much larger than can be achieved in a collimated atomic beam, it will allow significantly improved measurements of weak optical processes such as parity-nonconserving transitions.[13] When combined with the ability of the optical trap to

efficiently collect the atoms of a very dilute species, rare short-lived radioactive isotopes can be captured and used for such measurements. As an example, this will allow the precise measurement of parity nonconservation in a large number of isotopes of cesium. This set of measurements will provide an extremely stringent test of the standard model which does not require precise calculations of atomic structure. Trapped polarized samples of other radioactive isotopes collected in this manner will also allow more precise studies of β decay.[14] Finally, by moving the magnetic trap into a lower pressure region located above the optical trap and propelling many balls of atoms into it, it should be possible to obtain much higher densities. This would improve all of the above experiments. When combined with additional cooling of the magnetically trapped atoms,[2,15] this approach also offers a potential route toward achieving Bose condensation in an alkali-metal vapor.

This work is supported by the Office of Naval Research and the National Science Foundation. We are pleased to acknowledge beneficial discussions with T. Walker and D. Sesko. One of us (H.R.) was a Visiting Fellow at the Joint Institute for Laboratory Astrophysics.

---

[a]Permanent address: Physics Department, Duke University, Durham, NC 27706.

[1]See special issue on laser cooling and trapping of atoms, edited by S. Chu and C. Wieman [J. Opt. Soc. Am. B **6**, No. 11 (1989)].

[2]D. Pritchard, in *Atomic Physics 11*, edited by S. Haroche, J. Gay, and G. Grynberg (World Scientific, Singapore, 1989).

[3]E. Raab, M. Prentiss, A. Cable, S. Chu, and D. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).

[4]T. Walker, D. Sesko, and C. Wieman, Phys. Rev. Lett. **64**, 408 (1990).

[5]D. Sesko, T. Walker, C. Monroe, A. Gallagher, and C. Wieman, Phys. Rev. Lett. **63**, 961 (1989).

[6]A. Cable, M. Prentiss, and N. Bigelow, Opt. Lett. **15**, 507 (1990).

[7]F. Reif, *Fundamentals of Statistical and Thermal Physics* (McGraw-Hill, New York, 1965).

[8]M. Zhu and J. Hall, JILA, University of Colorado (private communication).

[9]M. Kasevich, E. Riis, S. Chu, and R. DeVoe, Phys. Rev. Lett. **63**, 612 (1989).

[10]D. Pritchard, Phys. Rev. Lett. **51**, 1336 (1983).

[11]C. Salamon, J. Dalibard, W. Phillips, A. Clarion, and S. Guellati, Europhys. Lett. (to be published).

[12]C. Monroe, H. Robinson, and C. Wieman, Joint Institute for Laboratory Astrophysics report (to be published).

[13]M. Noecker, B. Masterson, and C. Wieman, Phys. Rev. Lett. **61**, 310 (1988).

[14]Stuart Freedman, University of Chicago (private communication).

[15]H. Hess, G. Kochanski, J. Doyle, N. Masuhara, D. Kleppner, and T. Greytak, Phys. Rev. Lett. **59**, 672 (1987).

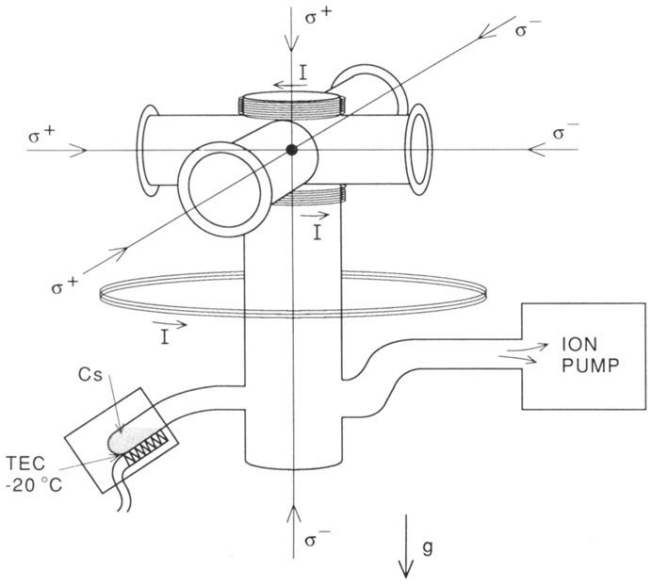

FIG. 1. Vapor cell used for optically and magnetically trapping and cooling cesium atoms. For the optical trap, the small coils are operated in the anti-Helmholtz configuration. The six laser beams are indicated by arrows. For the magnetic trap, the current to the small coils is turned off and the large coil turned on. The four vertical current bars providing horizontal confinement are not shown.