Continuous Stopping and Trapping of Neutral Atoms

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Neutral sodium atoms have been continuously loaded into a 0.1-K-deep superconducting magnetic trap with laser light used to slow and stop them. At least 1×10^9 atoms were trapped with a decay time of $2\frac{1}{2}$ min. The fluorescence of the trapped atoms was studied as a function of time; possible loss mechanisms from the trap are discussed.

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Trapping neutral atoms and cooling them to microkelvin temperatures will make possible a variety of experiments including precision spectroscopy, atomic collision studies in the s-wave-only regime, and studies of collective behavior including, possibly, Bose condensation. This Letter reports several important advances toward the accomplishment of such experiments. We have continuously stopped thermal sodium atoms with laser light and continuously loaded them into a 0.1-K-deep superconducting magnetic trap. The continuous loading process has allowed us to accumulate up to 1×10^9 trapped atoms. This is 4 orders of magnitude more than for the previous magnetic trapping results of Migdall *et al.*,[1] and 6 orders of magnitude more than Chu *et al.*[2] obtained with use of an optical trap. We have observed trapping times of up to $2\frac{1}{2}$ min.—2 orders of magnitude greater than in these previous experiments—and studied the fluorescence of the trapped atoms. These increases in trapping time and number of trapped atoms will permit useful experiments with the trapped atoms for the first time. The trap has the added feature of having a uniform magnetic field at its bottom, opening up the possibility of precision spectroscopy of the trapped atoms.

The arrangement of longitudinal magnetic fields, laser beams, and fluorescence detectors used in our experiment is shown in Fig. 1. The magnetic fields are generated by superconducting magnets operated in a persistent mode. A beam of sodium atoms from a $\simeq$550 °C oven ($v_{\text{thermal}}\simeq800$ m/s) is slowed to a stop in two stages. In the first stage, an arrangement similar to that described by Phillips and Metcalf[3] is used to slow the atoms to about 200 m/s. The atoms are repeatedly excited from the $^2S_{1/2}$, $F=2$, $m_F=2$ state to the $^2P_{3/2}$, $F'=3$, $m_F'=3$ state by a counterpropagating laser beam which is right circularly polarized and tuned to be resonant with this "cycling" transition. For each photon an atom absorbs, it receives a velocity "kick" of 3 cm/s in the direction of the laser beam; the momentum from the spontaneously emitted photons averages to zero. Slowing to 200 m/s requires about 20000 photons to be scattered. The tapered "slower" magnet shown in Fig. 1 keeps the atoms resonant with the laser by inducing a changing Zeeman shift of the cycling transition to compensate exactly for the changing Doppler shift of the light seen by the decelerating atoms. A Coherent Inc. type-699 ring-dye laser provided about 120 mW of 589-nm light for the slowing laser beam.

Slow atoms pass into the trap region where they are stopped with use of a second laser beam and a second tapered magnetic field, actually located within the trap. This "stopping" laser beam is tuned to the red of the cycling transition for stationary atoms at the bottom of the trap, and retroreflected back on itself to produce a one-dimensional version of "optical molasses."[4] Atoms are Doppler shifted closer into resonance with the laser beam opposing their motion, so that their velocity is damped, and the atoms are cooled. The stopping laser beam ($\sim$12 mW in each direction) is also right circularly polarized and was produced by a Coherent Inc. type-599 standing-wave dye laser. Both the slowing and the stopping laser beams are about 1 cm in diameter as they pass through the trap, and converge to a focus close to the sodium oven.

Magnetic traps can confine atoms whose electronic

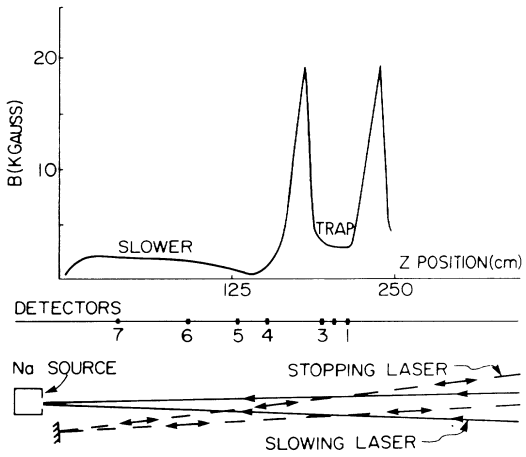

FIG. 1. Arrangement of the longitudinal magnetic fields, laser beams, and fluorescence detectors used in the experiment.

spins are oriented in the direction of the magnetic field, so that their energy increases with the magnitude of the field. These atoms can therefore be trapped in local minima of the field magnitude (maxima do not exist in current-free regions[5]). The trap itself is similar to one described by Pritchard,[6] with a finite magnetic field at its minimum. Axial confinement is provided by a solenoid whose field is sketched in the right half of Fig. 1. A bias field of 1600 G at the trap's minimum inhibits Majorana transitions to untrapped m_F states (a loss mechanism for spherical quadrupole traps[1]), and decouples the two stages of slowing by Zeeman shifting the transition frequency of atoms in the trap out of resonance with the slowing laser. The tapered field for stopping atoms within the trap is produced by a shim coil located between the peaks of the trap magnet.

Radial confinement in the trap is provided by an octopole magnet whose pole pieces are parallel to the trap axis. The trap is shallowest ($\sim$0.12 K) in the radial direction. The field from the octopole, whose magnitude varies radially as r^3, adds in quadrature with the much larger axial field, giving a total field magnitude which varies as r^6 near the center of the trap. This relatively uniform field at the trap center is well suited to spectroscopy of the trapped atoms and gives a trapping volume $\sim 10^2$ cm^3. A different field configuration can be used to achieve substantially smaller trapping volumes if atom-atom interactions are to be studied.

Continuous stopping of sodium atoms was demonstrated by the charging of all the magnets except for the radially confining octopole. The velocity of the atoms leaving the first slowing region and entering the trap is determined by the slowing laser frequency: "Bluer" light produces slower atoms. Measurements were made by our fixing the frequency of the slowing laser and scanning the stopping laser. Seven photodiodes were used to monitor the fluorescence of the atoms in the slowing and trap regions (see Fig. 1). The fluorescence seen by detector 1, located at the minimum of the magnetic field in the trap region, is shown in Fig. 2, for a series of such scans. The topmost scan [Fig. 2(a)] shows fluorescence from atoms which have left the slower but which were too fast to be slowed in the trap region by the stopping laser. There are two peaks, as first the incident and then the retroreflected laser beams are Doppler shifted into resonance with the moving atoms. When the slowing laser is blue shifted so that slower atoms enter the trap region, these peaks move together [Fig. 2(b)]. With the slowing laser tuned to produce atoms with a mean velocity of less than $\sim$250 m/s, a third peak appears exactly halfway between the other two [Figs. 2(b) and 2(c)]. This peak comes from continuously stopped atoms, i.e., atoms with zero axial velocity. As still slower atoms are extracted from the slowing region, the three peaks ultimately merge into one [Fig. 2(c)].

The signal seen in the central peak is consistent with

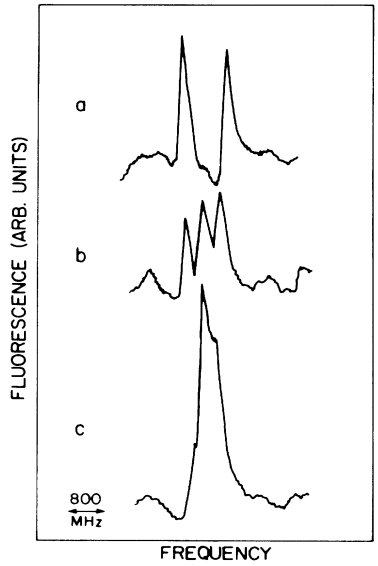

FIG. 2. Fluorescence from atoms in the trap region as a function of stopping laser frequency for three different velocities of atoms leaving the slower: (a) 280 m/s, (b) 200 m/s, and (c) 130 m/s. The outer peaks correspond to atoms not slowed by the stopping laser; the central peak corresponds to stopped atoms.

stopping of only $\sim$1% of the atoms seen in the "fast atom" peaks. This low efficiency probably resulted from the magnetic field gradient in the second slower field being insufficient to slow all but the very slowest atoms provided by the first slower. Increasing the slowing field within the trap, and hence its ability to slow faster atoms, should improve this fraction substantially.

Upon charging the radially confining octopole magnet we observed manifestations of trapped atoms. For certain laser frequencies the fluorescence seen by the detectors in the trap region increased dramatically, building up over time scales of about 1 sec: The trap was filling. To determine how long atoms could be trapped for, measurements were made for the following sequence: (a) lasers on to fill the trap, (b) lasers off for a variable period of time, and (c) stopping laser back on to probe the remaining trapped atoms. Figure 3 is a composite of the fluorescence observed from trapped atoms upon turning back on the stopping laser after waiting different amounts of time. For these runs, a $1/e$ trapping time of 1.7 ± 0.3 min is observed, while trapping times of up to 2.7 ± 0.4 min were observed during later runs, 2 orders of magnitude longer than for previously reported traps.[1,2] The observation of trapping times of several minutes in our magnetic trap, and also for spontaneous-force light traps,[7] suggests that the only limit to trapping times for neutral atoms is collisions between the trapped atoms and residual molecules in the vacuum system.

The number of atoms in the trap may be estimated

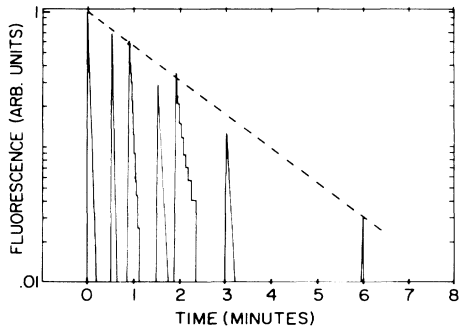

FIG. 3. Fluorescence from trapped atoms produced by unblocking of the stopping laser for various trapping times. The trap was first loaded, and both the slowing and stopping lasers were blocked at $t=0$.

from the absolute fluorescence measured by the photodiodes. It is necessary to make some assumptions about the spatial distribution of the atoms in the trap, and to estimate the laser's detuning from their resonance frequency. The former is fairly straightforward. Gravity's force on the atoms is nearly equal and opposite to that of the field gradient produced by the stopping magnet within the trap. The net result is a relatively flat-bottomed (within $\simeq 2$ mK) mechanical potential which is cylindrical in shape, $\simeq 4$ cm in diameter and $\simeq 25$-cm long, with steep sides and ends. For our detuning, the stopping laser should cool atoms to temperatures between 4 and 20 mK, which will lead to a relatively homogeneous distribution of atoms within this cylinder. On the bases of the relative size of the signals seen by the detectors in the trap, and of fluorescence studies described below, we estimate the detuning for the stopping laser to be about 80 MHz to the red of the cycling transition for atoms at the magnetic field minimum. The signal intensities we measure then correspond to $\sim 1\times 10^9$ trapped atoms in the $^2S_{1/2}$, $m_F=2$ state. We suspect that there may have been trapped atoms in the other states of the $^2S_{1/2}$, $m_s=\frac{1}{2}$ ground-state manifold, but no quantitative estimate can be made for such atoms since we observed no fluorescence from them.

The number of atoms trapped was limited by the trap loading time. This was determined by the time taken for the strong, off-resonant, slowing laser to remove an atom from the strongly fluorescing $m_F=2$ state of the $^2S_{1/2}$, $m_s=\frac{1}{2}$ manifold. Consequently, runs with longer filling times showed a larger fluorescence signal due to the larger number of atoms accumulated. We measured the characteristic trap loading time by fixing the frequencies of both lasers, blocking and unblocking the atomic beam, and recording the (roughly equal) decay and rise times of the fluorescence signal. From run to run, this characteristic time varied from one second to less than 50 ms, and presumably reflects the presence of $\Delta m_F=0$ and $\Delta m_F=-1$ transitions to "wrong" excited-state hyperfine levels (i.e., other than $m_F'=3$). Atoms excited in this manner can subsequently decay to states other than the $F=2$, $m_F=2$ ground state, and will thereafter cease to fluoresce. $\Delta m_F=0$ transitions can result from a misalignment between the laser beam and the magnetic field; their rate is very sensitive to the alignment of the laser beam through the trap because of the r^3 dependence of the radial field near the trap axis. Transitions with $\Delta m_F=-1$ may be induced by light of the incorrect (left circular) polarization, and therefore depend sensitively on the polarization purity of the laser beams. The variability of the observed rate suggests that we should be able to reduce this rate substantially. Certainly "wrong transitions" like these are not a fundamental limit to the accumulation of atoms in the trap; for example, even after decay to an untrapped level an atom may be "recovered" by off-resonant excitation, or excitation by another laser beam, which transfers it back to a trapped level.

Finally, we studied the time dependence of the fluorescence of the trapped atoms as a function of stopping laser frequency, with the slowing laser off. The stopping laser's frequency was measured with respect to the frequency, f_{peak}, that produced maximum fluorescence at the trap minimum (i.e., detector 1) with the slowing laser on. The atoms were illuminated with the full 12 mW of the stopping laser beam. For frequencies to the blue of f_{peak}, the fluorescence signal from the trapped atoms decayed rapidly once the slowing laser was turned off. Time constants of less than half a second were observed. For frequencies to the red of f_{peak}, the fluorescence lasted much longer; typically, time constants of five to ten seconds were measured for red detunings of between 20 and 60 MHz (the range we investigated). The intensity of the fluorescence signal for even the largest red detuning, 60 MHz, was found to be only about half of the intensity measured at f_{peak}, confirming our estimate that f_{peak} is ~ 80 MHz to the red of the resonant frequency for stationary atoms at the bottom of the trap.

The observed strong dependence of the fluorescence decay-time constant on stopping laser frequency may result from excitation of atoms near the trap minimum to the $F'=3$, $m_F'=1$ excited state, which was 60 MHz to the red of the cycling transition for our experimental conditions. Atoms in this state decay mainly to the $F=2$, $m_F=0$ level of the ground-state manifold which, although trapped, will not contribute to the fluorescence signal, and may well constitute a major unseen population of trapped atoms. The (5–10)-sec time constants measured for the larger red detunings probably reflect some other limiting process, such as off-resonant excitation to excited-state levels which can decay to the untrapped $m_s=-\frac{1}{2}$ ground-state manifold.

Summarizing, we have demonstrated the first continuous stopping and trapping of neutral atoms: This has resulted in confinement of $\simeq 1\times 10^9$—an increase of 4 or-

ders of magnitude over previous observations. The trapping times of $\simeq 2\frac{1}{2}$ min, 2 orders of magnitude greater than previous observations, result mainly from a better vacuum due to the cryogenic nature of our apparatus. These increases in numbers and trapping times, together with the uniformity of the magnetic field at the trap bottom, should permit experiments, such as high-resolution spectroscopy, to be performed on the trapped atoms. Continuous stopping represents an important advance over pulsed stopping schemes[8] because it should enable the accumulation of large numbers of atoms, ultimately limited only by collisions or absorption of the stopping light.

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