First Observation of Magnetically Trapped Neutral Atoms

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We report the first observation of electromagnetically trapped neutral atoms. Laser cooled and stopped sodium atoms are confined in a magnetic quadrupole trap formed by two opposed, separated, coaxial current loops. The decay time constant for atoms in the trap is 0.83(7) s and is limited mainly by collisions with background gas atoms.

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Magnetic trapping of neutral atoms was proposed at least as early as 1960.[1,2] Despite considerable development in the theory of magnetic trapping,[3–6] the successful trapping of cold neutrons,[5] and serious attempts to trap atoms,[6] no such trapping has been reported until now. Furthermore, no other proposals[7] for electromagnetic trapping of neutral atoms have been realized.

Because electromagnetic forces applied to neutral atoms are generally quite small, practical atom traps are very shallow. The difficulty of obtaining atoms with low enough kinetic energy to be contained in such shallow traps has been a principal impediment to trapping. We use our previously reported[8] laser-cooling technique to stop a beam of Na atoms in the center of a magnetic trap which then confines them for long times. The observed time constant for the decay of the trapped atom population is 0.83(7) s, limited primarily by collisions with background gas.

Interest in magnetic trapping of atoms comes from intrinsic interest in the dynamics and stability of the trap itself as well as from the possible uses of trapped atoms, including the measurement of long, metastable-state lifetimes, refrigeration of atoms to energies as low as a few microkelvins,[9] and observation of quantum collective effects at low temperature and high density.[10,11] Highly refrigerated atoms could be released from a trap for use in ultrahigh-resolution spectroscopy, free of motional Doppler or transit-time effects, and in some instances spectroscopy might be performed on atoms held in the trap.

Magnetic trapping is possible because an inhomogeneous magnetic field exerts forces on atoms with a magnetic dipole moment. Atoms in quantum states whose energy increases with increasing field are trappable,[12] and if the Zeeman energy increases linearly (as for Na in the $3S_{1/2}$, $m_F=2$ state which we use), the potential energy is equal to the effective magnetic moment μ times the magnitude of the magnetic field B. For Na, where μ is approximately μ_B, a 2-T field change can form a trap 1.3 K deep which is only capable of containing atoms with velocities less than 30 m/s. This small trapping energy accounts for the difficulties in realizing a magnetic trap. Paul[3,4] has described a particularly simple class of magnetic traps formed by coaxial current loops. Although the three-loop "spherical hexapole" trap has received the most attention[4,6] because its potential is harmonic, we have chosen to use the two-loop "spheroidal quadrupole"[7] because of construction simplicity and easy optical access to the center.

Figure 1 shows our trap and its equipotentials and Fig. 2 shows the placement of the trap in the apparatus which is used to load it. The trap consists of two coaxial coils each having a mean radius of 2.7 cm and carrying 1900 At. With the currents in the coils in opposite directions the field is zero at the trap center and increases linearly in all directions away from the center. The force is constant along any line through

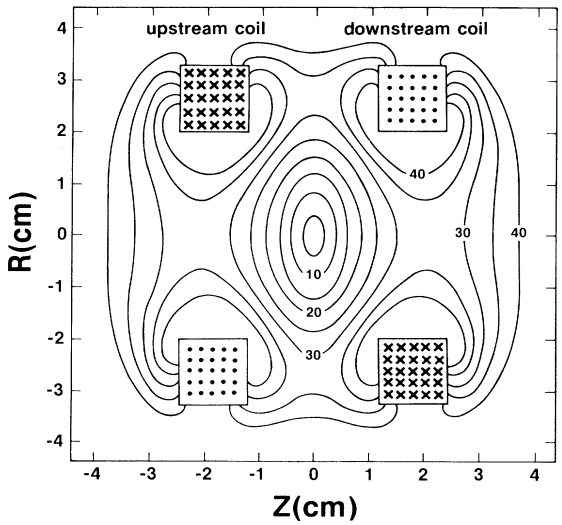

FIG. 1. Equipotentials (equal field magnitudes in millitesla) of our quadrupole trap in a plane containing the axis of symmetry (z axis).

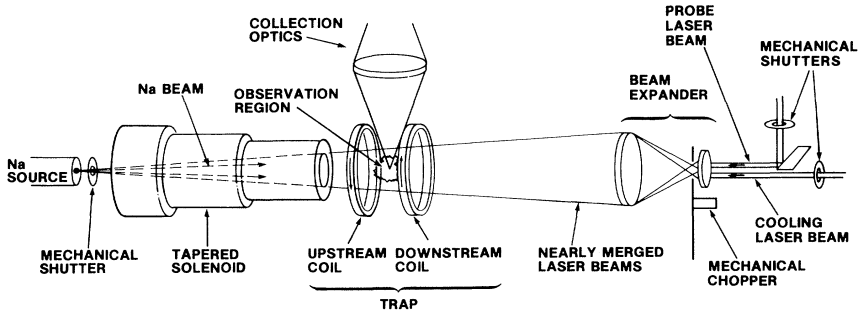

FIG. 2. Schematic of the apparatus. The solenoid is 1.1 m long and the trap is 40 cm from the end of the solenoid. The combination of shutters and chopping wheel allows the cooling and probe laser beams to be turned on and off rapidly and independently.

the center. This force is twice as large along the axis of symmetry of the trap as along the radial direction perpendicular to the axis. Approximately equal energy depth in the axial and radial directions is achieved by separation of the coils by 1.25 radii or ~ 3.4 cm. The maximum usable field (for which the equipotential surface intersects no part of the trap structure) is about 0.025 T for a potential-energy depth of 17 mK, equivalent to a Na velocity of 3.5 m/s. The volume of the trap is ~ 20 cm^3.

With such a shallow potential, successful magnetic trapping depends on loading of the trap with near-zero-velocity atoms. Our technique for stopping a beam of Na atoms is described in detail elsewhere[8] and is discussed here only briefly (see Fig. 2): Atoms in a thermal atomic beam with mean velocity of about 1000 m/s are decelerated and cooled as they scatter photons from a near-resonant, circularly polarized, counter-propagating laser. As the atoms in the beam slow down, their changing Doppler shift would take them out of resonance with the laser were it not for a spatially varying Zeeman shift provided by a tapered solenoid. In this way, nearly all atoms initially slower than 1000 m/s are decelerated and finally stopped near the exit end of the solenoid. Furthermore, all of these atoms are optically pumped into a state which is suitably oriented for magnetic trapping.

In order to allow the slow atoms near the end of the solenoid to reach the trapping region, free of any fast-atom background, we abruptly shut off both the cooling laser light and the atomic beam. Atoms with 100-m/s velocities reach the center of the trap and observation region after 4 ms. At this point a 400-μs pulse of light from the cooling laser stops them.

Only the upstream (nearest the Na source) trap coil is on during the pulse. This coil produces a spatially varying magnetic field which both shifts the atoms into resonance with the fixed-frequency cooling laser and partially compensates for the changing Doppler shift of the decelerating atoms in the same manner as the field in the main solenoid. (This last detail differs from the previously reported procedure[8] where a uniform field was used in the observation region. The nonuniform field produces a higher density of atoms per unit velocity interval at zero velocity and a wider final velocity distribution.)

After the 400-μs pulse, with the atoms at rest, the trap is completed by our turning on the opposing downstream coil, and is maintained for a selectable trapping time. In order to detect the trapped atoms, the trap field is turned off (about 5 ms are required for the field to fall to zero), the weak (2 mW/cm^2) probe laser is turned on for 100 μs, and the fluorescence induced by the probe in a volume of about 1 cm^3 is observed. Then the entire cycle (slowing, stopping, trapping, and probing) is repeated as the probe laser frequency is slowly scanned. In this way we determine the number and velocity distribution of the atoms which remain in the trap after a given trapping time. Observation in zero field eliminates any Zeeman shifts or broadening.

The fundamental limit to the storage time for atoms in the trap comes from nonadiabatic or Majorana transitions which reorient the atomic magnetic moment. While the initial orientation of the atoms produced by our Zeeman-tuned laser-cooling method is correct for trapping, that orientation must be preserved while the atoms move about in the trap even though the trap fields may change directions in a very complicated way. The magnetic moments precess about the field at the Larmor frequency $\omega_L = \mu B/\hbar$, and μ is approximately μ_B. As long as the atoms move slowly enough, they can follow the magnetic field adiabatically. This requires that $\omega_L >> \omega_T$, where ω_T is the instantaneous angular frequency of orbital motion in the trap. Violation of this adiabatic condition results in a large probability of a transition to a state of different orientation that may not be confined by the trap.[4]

The adiabatic condition is most severely violated by the fastest atoms (3.5 m/s) moving nearest the trap center where the field is smallest and changes direction most rapidly. With the smallest field gradient being

1.25 T/m in the radial direction, the most stringent requirement for adiabaticity is that the distance of closest approach to the center, r_c, satisfy $r_c >> 6\ \mu$m. By contrast, circular orbits in the $z=0$ plane, which are the least likely to violate the adiabatic condition, need only satisfy $r_c >> 0.3\ \mu$m.

Since the force confining the atoms in the trap is neither harmonic nor central, it is impossible to characterize a general orbit. Circular orbits of radius r in the $z=0$ plane have a period of $T=2\pi(r/a)^{1/2}$, where a is the centripetal acceleration supplied by the field gradient. For our trap $a \approx 300$ m/s^2 for $z=0$, and the fastest atoms in circular orbits have $v=2.5$ m/s at $r=2$ cm with periods $T=51$ ms. Atoms which oscillate linearly through the trap center have periods of $T=4v_{max}/a$, and the fastest atoms ($v_{max}=3.5$ m/s) have oscillation periods of 47 ms when oscillating perpendicular to z and 23 ms when oscillating along z where the acceleration is twice as big. In all of these cases, slower atoms have shorter periods, with the period being proportional to the maximum orbital velocity. We have done detailed numerical calculations of the orbital motion for more general cases, and have found that many orbits are irregular and aperiodic, although there are several special classes of nearly closed orbits. Since the nonadiabatic region of the trap is so small (less than 10^{-10} of the trap volume) nearly all of the orbiting atoms will behave adiabatically, and we expect that most atoms will stay trapped for many orbits.

Figure 3 shows the spectrum of atoms remaining in the trap after various trapping times. The observed full width at half maximum of ~ 20 MHz is consistent with a 10-MHz natural width power broadened to 11.5 MHz and convolved with the expected 12-MHz width corresponding to the ± 3.5-m/s range of trappable atoms. (Note that 1 m/s gives a Doppler shift of 1.7 MHz.) There is also about 4 MHz of laser frequency jitter, as well as a 2-MHz broadening and 8-MHz shift expected from the acceleration of atoms by the probe. Determination of the absolute velocity scale from frequency markers is uncertain by about 2 m/s for any one spectrum. Thus, the data are consistent with a sample of atoms distributed ± 3.5 m/s about zero velocity.

Figure 4 shows the observed atomic density as a function of trapping time before observation. The density follows an exponential decay curve with a time constant of 0.83(7) s. The absolute density scale is estimated from a comparison of the trapped-atom signals with those from the thermal atomic beam, whose density is determined from oven temperature and aperture size. This estimate is believed to be accurate within a factor of 3 and is consistent with that obtained from the observed signal strength, when we take into account all the collection and detection efficiencies.

We believe the decay time to be limited mainly by scattering of atoms out of the trap by collisions with background gas atoms. For a pressure of 1×10^{-8} Torr, measured close to the vacuum pump, an as-

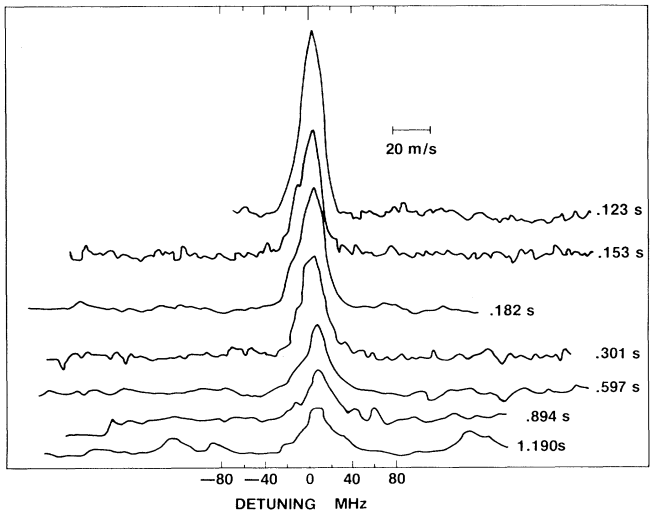

FIG. 3. Fluorescence from trapped atoms vs detuning of probe laser frequency from the $3S_{1/2},F=2 \rightarrow 3P_{3/2},F=3$ transition for atoms at rest in zero field, for various trapping times. Observation occurs 5 ms after the trap is turned off. Widths reflect velocity distribution as well as natural width, probe acceleration, and other effects (see text). The velocity scaling is obtained from $\Delta v = \lambda \Delta \nu$.

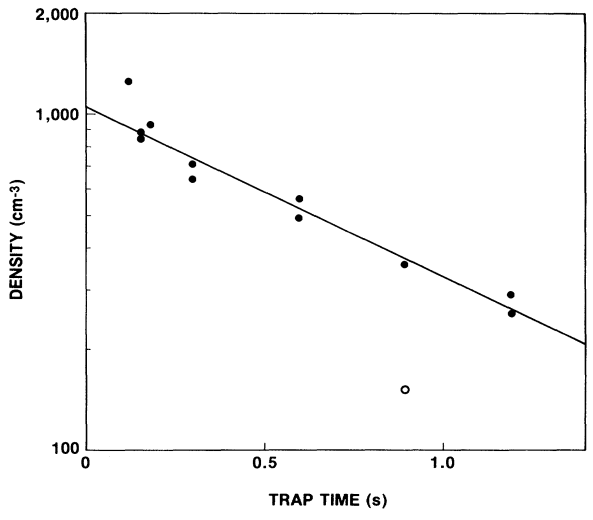

FIG. 4. Atomic density vs trapping time. A fit to all the filled points yields a decay time of 0.83(7) s. The filled points were taken at a measured background pressure of $\sim 1\times10^{-8}$ Torr; the open point was taken at $\sim 2\times10^{-8}$ Torr. Its decreased density reflects the fact that the pressure limits the lifetime.

sumed collision cross section of 10^{-14} cm^2, and a collision velocity of 5×10^4 cm/s, we obtain a mean time between collisions of 5 s. This estimate is higher than the observed 0.83 s mainly because the pressure in the trap is undoubtedly higher than at our gauge since the trap outgasses when heated by the current in its coils. We have repeatedly observed that the signal decreases as the pressure increases, which provides further evidence of the importance of the pressure in limiting trap lifetime. As a single example of this, the low, open point at 0.9 s in Fig. 4 was taken when the observed pressure was allowed to rise to 2×10^{-8} Torr. The point at 0.12 s is somewhat higher than the decay curve and may reflect the fact that some atoms in unstable orbits can circulate a few times in the trap before they escape.

We have performed several tests to determine whether the signals observed long after the atomic beam is shut off can be from anything other than trapped atoms. If we eliminate either the stopping laser pulse or the field of the downstream coil, the signals of Fig. 3 disappear. Also, we see very slow atoms which eventually drift into the observation region from the solenoid, but the signal from these disappears after about 75 ms. This disappearance is due to transverse and longitudinal spreading of the slow atoms as well as to the fact that they fall almost 3 cm in 75 ms under the influence of gravity. It shows that signals observed after 75 ms must be from trapped atoms. Furthermore, if we delay observation of the atoms after the trapping field is turned off, the signal disappears within 15 ms, consistent with atoms having velocities of a few meters/second drifting out of the observation region.

In conclusion, we have demonstrated the magnetic trapping of atoms with energies less than 17 mK for times longer than a second. This energy is comparable to the lowest energies reported[13] for laser-cooled trapped ions (5^{+15}_{-5} mK) and is achieved not by refrigeration but because the trap can contain no higher energies. The trapping time is limited mainly by collisions with background gas, so that substantial improvements in trapping time should be possible before the limits imposed by Majorana transitions are reached. We expect future developments to include further cooling of the trapped atoms and repeated or continuous loading of the trap to achieve high densities.

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