Multiply Loaded, ac Magnetic Trap for Neutral Atoms

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We have demonstrated an oscillating-gradient magnetic trap for confining cesium atoms in the lowest-energy spin state. In this state spin-flip collisions are energetically forbidden and thus the primary density- and temperature-limiting process for magnetic traps is eliminated. The atoms are initially collected in a vapor-cell optical trap, then repetitively tossed into a high-vacuum region, focused in three dimensions, and accumulated in the magnetic trap. An optical pumping scheme inserts each new batch of atoms into the magnetic trap without perturbing the atoms already trapped.

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Much of the recent rapid progress [1-3] toward colder and denser atomic vapors has been driven by the intrinsic interest of the processes involved. However, there are several external motivations as well, two of which we find particularly compelling: First, a cold gas of bosonic atoms is by far the cleanest system in which one could hope to observe Bose-Einstein condensation (BEC). The ability, in principle, to cross the phase boundary for BEC at several widely spaced points in the temperature-density plane offers the tantalizing prospect of studying the transition while varying the relative significance of interparticle interactions. Second, cold, dense samples of gas are ideal for the spectroscopy of weak transitions, such as those involved in the measurement of parity nonconservation in atoms.

In the past, cesium atoms have been confined in optical traps to a density of 5×10^{10} atoms per cm^3, then cooled in laser molasses to 2 μK [1]. However, several mechanisms limiting temperatures [2] and densities [4] are slowing further progress in optical traps. Magnetic trapping is a way to avoid these limitations. For example, the photon recoil energy, which is the primary limit for optical cooling, is not an obstacle to evaporative cooling in a magnetic trap. Spin-polarized hydrogen in a magnetic trap has been evaporatively cooled (allowing the highest-energy atoms to escape the trap) to a temperature 13 times below the photon-recoil limit [3], and to a density orders of magnitude larger than the present limit for an optical trap. However, traditional magnetic traps have a significant limitation of their own, namely, spin-flip collisions.

To date, all magnetic traps have been designed to work only for weak-field seekers, that is, for atoms or neutrons whose magnetic moment is antialigned with the magnetic field. These atoms are confined to a local minimum in the magnitude of a static magnetic field. Unfortunately, because weak-field-seeking states are not the lowest-energy configuration within the confining magnetic field, the atoms are susceptible to two-body collisions that change the hyperfine or Zeeman level of one or both of the colliding atoms. The energy released in these collisions heats the trapped sample and the spin-flipped atoms leave the trap. The loss rate due to these exothermic collisions scales as the density squared and thus provides an effective ceiling to the attainable density, and indirectly limits temperature as well [5]. However, if atoms were trapped in the lowest-energy spin state (magnetic moments aligned with the magnetic field), spin-flip collisions would be endothermic and, hence, greatly suppressed at low temperatures. Unfortunately, such "strong-field-seeking" atoms cannot be confined in a static configuration of magnetic fields because Maxwell's equations do not allow a local maximum in magnetic-field magnitude. However, there are time-varying field configurations which provide stable confinement.

Originally proposed for hydrogen atoms [6], our trap operates on the same dynamical principle as the Paul trap [7] for ions: Near the center of the trap, the potential is an axially symmetric quadrupole, oscillating at frequency Ω: $\phi=-\boldsymbol{\mu}\cdot\mathbf{B}=A(z^2-\rho^2/2)\cos\Omega t$. During each oscillation, the atoms are first confined axially and expelled radially, and then confined radially and expelled axially. For a range of values of the amplitude A, the net force averaged over a cycle of the oscillation is inward; the result is stable confinement in all three dimensions. For easily obtainable oscillating magnetic fields, the trap is extremely shallow (tens of microkelvins). However, using laser cooling we are able to produce atomic samples which are colder than this, and load them into the trap.

The loading procedure has a number of steps, as shown in Table I. First, cesium atoms are collected and cooled in an optical trap. The cold atoms are then launched into a differentially pumped vacuum region which contains the ac magnetic trap, as shown in Fig. 1. To reduce the spreading of the atoms they are magnetically focused as they move between the two traps. When they reach the magnetic trap the atoms are optically pumped into the state that is trapped. This approach allows multiple bunches from the optical trap to be transferred to the magnetic trap, thereby increasing the density.

The process of preparing room-temperature cesium atoms for magnetic trapping begins with a Zeeman-shift

TABLE I. Timing and laser detuning during one cycle of the multiple loading sequence.

Relative time (ms)	Laser detuning, function
−500 to − 2	−7 MHz. Atoms accumulate in optical trap.
−1 to 0	−30 MHz. Molasses cooling to 2 μK.
0 to 0.4	−7 MHz, and offset Δ ramped from 0 to 1.7 MHz. Atoms accelerate.
0.4 to 0.8	−30 MHz, and offset Δ constant at 1.7 MHz. Atoms cool to 4 μK in moving frame.
0.8 to 130	Main beams blocked. Optical trap off. Atoms rise to magnetic trap.
2 to 4	−250 MHz. Initial optical pumping.
60 to 62	Magnetic focusing pulse.
67 to 70	Magnetic focusing pulse.
128 to 130	−310 MHz. Final optical pumping as atoms reach magnetic trap.

optical trap (ZOT), which collects the low-energy tail from a vapor of room-temperature cesium atoms. This trap uses light from diode lasers which excites the $6S_{1/2}, F=4 \rightarrow 6P_{3/2}, F=5$ transition. In about 0.5 s, 10^7 atoms accumulate in the ZOT to form a ball 0.1 cm in diameter, with a temperature of a few hundred microkelvin. In the second stage of preparation, the magnetic fields for the ZOT are turned off and the laser frequency is red-shifted several linewidths, which allows the more effective molasses cooling mechanism to quickly reduce the temperature to ~ 2 μK. For details of the technique described thus far, see Ref. [1].

To toss the atoms up into the magnetic trap region, we use the technique of moving optical molasses [8]: We shift the frequency of the downward-angled molasses beams (Fig. 1) 1.7 MHz to the red, and the upward-angled beams 1.7 MHz to the blue, relative to the frequency of the horizontal beams. The standing-wave pattern at the intersection of the six laser beams now becomes a walking-wave pattern. To achieve the necessary acceleration ($200g$), while having the lowest possible final velocity spread, we vary the central laser frequency over time during the launch (Table I). After the atoms are accelerated, the molasses beams are shut off abruptly and a 2-ms pulse of σ^+ polarized light optically pumps the atoms to the $F=4$, $m_f=4$ state. The optical pumping beam is tuned to the $F=4 \rightarrow F'=4$ transition in order to minimize heating.

The tossed atoms begin their ascent with an internal velocity spread of about 3 cm/s rms. In the 130 ms it takes to reach the site of the magnetic trap, even this small velocity spread would result in a 100-fold decrease in cloud density. We avoid much of this decrease by focusing the atoms with magnetic lenses. Approximately halfway (in time) along their route, the atoms pass through two pulses of magnetic field, each around 3 ms long, separated by 8 ms. These pulses provide an impulse

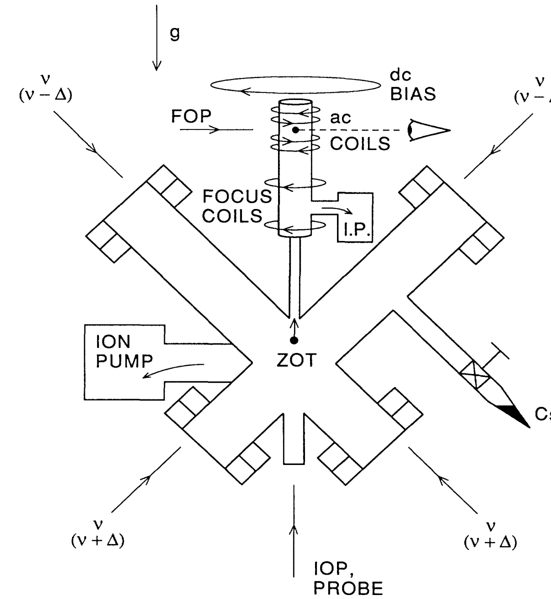

FIG. 1. Schematic of the apparatus, showing the upper and lower vacuum chambers, the configuration of key trapping and focusing coils, the paths of the initial optical pumping (IOP) and final optical pumping (FOP) laser beams, and the paths of four of the six laser beams defining the Zeeman-shift optical trap (ZOT) and the molasses. Frequencies of the molasses laser beams during the launch are shown in parentheses. Not shown are the paths of two horizontal laser beams which are perpendicular to the plane of the paper at the ZOT, the magnetic coils for tuning the optical trap, and a variety of shim magnetic coils.

which reverses all three components of the velocity. During the first focus pulse, the curvature of the magnetic field is such that the atoms are focused axially and defocused radially. During the second focus pulse, the curvature of the lenses is reversed. We adjust the timing and strength of the pulses (that is, the positions and effective focal lengths of the two magnetic lenses), in order to bring the atoms together to a focus axially and radially at the magnetic trap center.

As shown in Fig. 1, the magnetic trap is created by a combination of ac and dc coils and is located 14 cm above the optical trap. The 60-Hz ac field is generated by two pairs of coils which are arranged to produce maximum field curvature with relatively small oscillating field at trap center. The dc coil produces a field at trap center of 250 G, a gradient of 31 G/cm in the vertical direction, and very little curvature. This static gradient exactly balances the force of gravity, which the magnetodynamic forces are too weak to counteract. The peak amplitude of the ac component is 100 G at the center, with a curvature of 875 G/cm^2 in the axial direction and of 440 G/cm^2 in the radial direction. To make contact with the rf-ion-trap literature we note that the forces in our trap correspond to Paul-trap parameters $a_z=0$ and $q_z=0.40$, where a_z

and q_z are stability parameters, defined in Ref. [7].

Inserting the atoms into the magnetic trap requires some way of dissipating their energy. This is accomplished by optically pumping the atoms from the $F=4$ to the $F=3$ ground states. The trap will hold atoms in the $F=3$, $m_f=3$ state, but the atoms rising upward from the optical trap are in the $F=4$, $m_f=4$ state. Because this is a weak-field-seeking state, $F=4$ atoms approaching the magnetic trap are not only pulled downward by gravity but also repelled downward by the dc field gradient. The initial center-of-mass velocity of the atom cloud is adjusted so that this combination of forces brings the cloud to a stop just at the center of the trap. (The large time-dependent fringing fields from the trap make it somewhat difficult to achieve a stationary tightly focused cloud at exactly the correct position and time.) The stationary atoms are then illuminated with light linearly polarized along the magnetic field and tuned to the $F=4 \rightarrow F'=4$ transition. This optically pumps the atoms to the trapped, $F=3$, $m_f=3$ ground state. The $F=3$ atoms already loaded in the trap are transparent to the light used in this final optical pumping. The timing of the final optical pumping relative to the phase of the ac fields is critical. The micromotion (the small-amplitude, high-frequency oscillation induced by the ac forces [7]) of the weak-field-seeking atoms just arriving in the trap has an opposite phase from the micromotion of the trapped atoms. Unless the pumping occurs when the micromotion velocity is zero, the atoms are strongly heated.

While the atoms are in the magnetic trap, they do not interact with laser beams. To observe the trapped atoms, we abruptly turn off all the magnetic fields and then illuminate the trap region with a probe beam containing laser light which excites both $F=3 \rightarrow F'=4$ and $F=4 \rightarrow F'=5$ transitions. The resulting fluorescence from the atoms is imaged by a video camera and recorded on tape. Subsequent image processing reveals the spatial distribution and center-of-mass location of the atom cloud. Because the measurement is destructive—the photons from the probe beam blow the atoms away—time evolution of the trapped atoms can be studied only by repeating the load-probe cycle with varying time delays.

We study the magnetic trap by observing the shape and motion of the cloud of trapped atoms. Pulses of magnetic field from supplementary coils give the cloud any desired initial center-of-mass motion. From the evolution of the cloud motion we determine the frequency of the guiding-center oscillation in the effective potential. For an oscillation amplitude of 0.1 cm or less, we measure an axial frequency of 8.5(4) Hz and a radial frequency of 4.5(1.0) Hz. These agree with calculated [7] frequencies of 8.5 and 4.25 Hz.

The overall depth of the trapping potential is difficult to calculate or even to define precisely. The depth of the trap is determined mainly by the behavior of the trapped atoms away from the center of the trap. In those areas the field becomes anharmonic and the approximation that the ac fields simply provide an effective dc conservative potential is not valid. The harmonic region is quite small unless there is an axial dc bias field that is much stronger than the radial and axial components of the ac field everywhere in the trapping region. We confirmed experimentally that increasing the bias field improved the stability of the trap.

We have used a computer simulation to understand the behavior of the trap in the regions where the effective potential approximation is not valid. This simulation calculated the motion of clouds of noninteracting atoms with various temperatures in the trap. For clouds inserted with temperatures of 9 μK or less, nearly all the atoms remain trapped and the final spatial extent of the cloud is consistent with the initial velocity spread and a harmonic potential of the calculated spring constant. For clouds with higher initial temperatures, the final spatial distribution of trapped atoms is largely independent of initial temperature. The high-energy fraction of the atoms leaves the trap immediately, and the atoms remaining in the trap have an rms diameter of about 0.2 cm and an rms velocity of 5 cm/s (equivalent to a temperature of about 12 μK).

These simulation results match our experimental observations that a fraction of the atoms focused up into the magnetic trap region leave the trap within 0.15 s, and that those remaining form a ball about 0.2 cm in diameter. We conjecture, then, that the rms velocity of our trapped atoms is about 5 cm/s and that the depth of the trap is somewhat deeper than 12 μK. The trap has a $1/e$ lifetime which is typically about 5 s, as shown in Fig. 2. We believe that this is due entirely to collisions with the 1×10^{-9} torr of residual background gas. When we improved the vacuum by cooling some of the metal surfaces

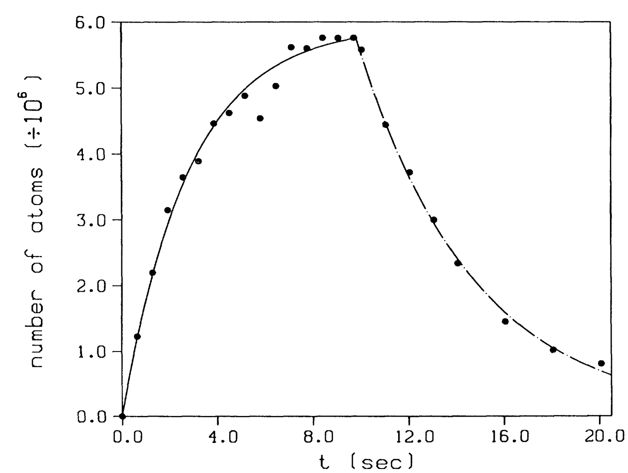

FIG. 2. Total fluorescence from the magnetically trapped atoms as a function of time. A new bunch was loaded every 0.65 s, for the first 10 s. The dot-dashed line is an exponential decay fit to the data, with 4.9 s $1/e$ time. The y axis has been calibrated to indicate the total number of trapped atoms.

of the upper vacuum chamber with liquid nitrogen, the lifetime nearly doubled.

The advantage of multiple loading is apparent in Fig. 2. By accumulating a number of loads, we were able to collect nearly 5 times as many atoms as from a single load. The factor-of-5 increase agrees well with our calculated value and is determined by the ratio of magnetic-trap lifetime to optical-trap fill time, by perturbations from the fringing fields of the magnetic focus, and by unintentional excitation of the trapped atoms during the initial optical pumping. Without great additional technical effort, this ratio could be a hundred or larger. As the density increases, viscous heating due to the micromotion may become a problem [6]. We have not yet seen any sign of such heating, and a simple estimate [9] of the heating rate leads us to believe that, with a suitable choice of experimental parameters, evaporative cooling can overwhelm the viscous heating.

We have demonstrated an ac magnetic trap for neutral atoms, and we have demonstrated how to load it optically on a quasicontinuous basis. The trap contains atoms in their lowest spin state, and thus avoids the effects that have previously limited the attainable phase-space densities in magnetic and optical traps. These techniques offer an appealing way to achieve the phase-space density necessary for Bose condensation in a dilute gas of neutral atoms.

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