Stable, Tightly Confining Magnetic Trap for Evaporative Cooling of Neutral Atoms

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We describe a new type of magnetic trap whose time-averaged, orbiting potential (TOP) supplies tight and harmonic confinement of atoms. The TOP trap allows for long storage times even for cold atom samples by suppressing the loss due to nonadiabatic spin flips which limits the storage time in an ordinary magnetic quadrupole trap. In preliminary experiments on evaporative cooling of ^{87}Rb atoms in the TOP trap, we obtain a phase-space density enhancement of up to 3 orders of magnitude and temperatures as low as 200 nK.

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Laser cooling and trapping of neutral atoms can provide up to 15 orders of magnitude phase-space density compression in alkali vapors [1]; however, optical processes limiting density [2] and temperature [3] have obstructed efforts to optically cool an atom sample directly to the Bose-Einstein condensation (BEC) phase transition. Evaporative cooling [4] in a purely magnetic trap offers an appealing, nonoptical cooling mechanism that can enhance the phase-space density of an optically precooled sample by orders of magnitude [5]. The resulting atom clouds are ideally suited for high precision experiments, such as atomic fountain clocks, as well as quantum statistics studies in BEC and related degenerate phenomena. As high atom densities and long storage times are the key requirements for successful evaporative cooling, tight and stable confinement of the atoms is necessary.

The purpose of this Letter is threefold. We report the first measurements of the inherent storage time limitation on very cold atom clouds in an ordinary quadrupole magnetic trap [6]. We then demonstrate a new type of trap based on a time-averaged, orbiting potential (TOP) which, among other features, overcomes the storage time limitation of a quadrupole trap but nonetheless provides tight confinement. Finally, we discuss our initial results with evaporative cooling in this trap.

Magnetic trapping of atoms in static fields occurs in a local minimum of an inhomogeneous magnetic field. Traps such as the baseball trap [7] in which this local magnetic field minimum is different from zero must have a vanishing first derivative of the field at the trap center. As a general rule, traps with a nonzero field will confine an atom cloud of radius l with a confining potential that scales as $U \sim \mu B_0(l/R_c)^n$, where B_0 denotes the field produced by a trapping coil of radius R_c, μ is the atomic magnetic moment, and the multipole order is $n \geq 2$. On the other hand, if we allow for a zero magnetic field in the trap center as in a quadrupole trap, the first derivative need not vanish; it provides a confining potential $U \sim \mu B_0(l/R_c)$. Technical aspects such as optical access and vacuum considerations require that $R_c \gg l$. Thus for similar power dissipation and coil construction a quadrupole trap provides tighter confinement than higher-order traps by the large factor R_c/l which is typically on the order of 10 to 1000.

The quadrupole trap [Figs. 1(a) and 1(b)] is therefore ideal for tight confinement. On the other hand, a significant loss mechanism in the quadrupole trap rules out long storage times for cold (or, equivalently, small) clouds. Atoms passing too close to the zero field in the center can undergo a nonadiabatic spin flip and be lost from the trap [8]. The loss rate $1/\tau_0$ caused by this effect can eas-

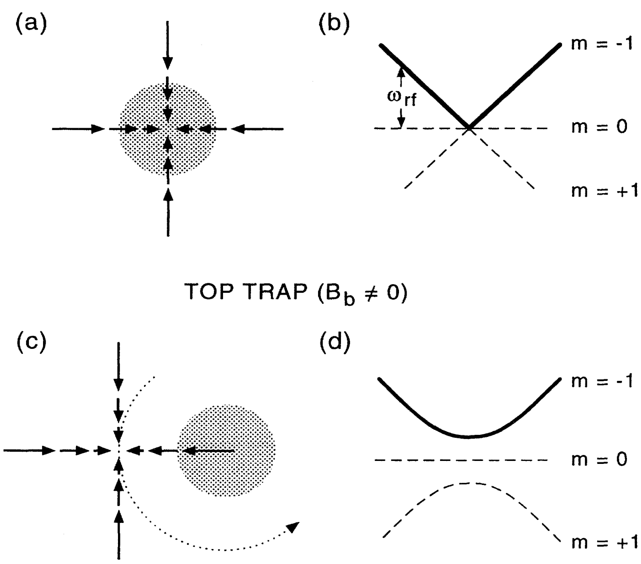

FIG. 1. The magnetic field configuration (a) and the cylindrically symmetric potential (b) of a quadrupole trap. The magnetic field at ω_{rf} for evaporation is shown schematically (b). The instantaneous horizontal field configuration of the TOP trap (c) is displayed together with the time-averaged, orbiting potential (d) of this new type of trap. In both the quadrupole potential and the TOP potential, an atom like ^{87}Rb is considered, which is trapped in a state with the total angular momentum quantum number $F = 1$ and the magnetic quantum number $m = -1$.

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ily be estimated: An atom with velocity v and mass m, passing within a minimum distance b of the center of the trap (with radial gradient $\partial B_r/\partial r = B'_q$), can undergo a nonadiabatic spin flip if the Larmor frequency $\sim \mu b B'_q/\hbar$ is smaller than the rate of change of the magnetic field direction v/b. Loss then occurs within an ellipsoid of radius $b_0 \sim (v\hbar/\mu B'_q)^{1/2}$. The loss rate is given by the flux through this ellipsoid, that is, the density of atoms N/l^3 times the area of the ellipsoid $\sim b_0^2$ times the velocity v, where N is the number of trapped atoms. The virial theorem then relates the mean velocity to cloud size $mv^2 \sim \mu l B'_q$ and it follows that $\tau_0 \sim (m/\hbar)l^2$. For ^{87}Rb atoms $m/\hbar$ is about 10^5 s/cm^2. The loss rate increases as the atoms are evaporatively cooled and spend more time at the bottom of the trap near the zero-field point; the loss eventually becomes so rapid that evaporation can no longer be sustained.

Our experiments in the quadrupole trap are performed with 3×10^6 ^{87}Rb atoms loaded from a modified magneto-optical trap [9] into a magnetic quadrupole trap. Efficient transfer is accomplished with a magneto-optical compression scheme [10], further cooling in an optical molasses, and optical pumping into the $^2S_{1/2}$ $(F = 1)$ ground state. When the magnetic trapping field is then suddenly turned on, the fraction of atoms in the $m_F = -1$ substate is trapped in a radial (axial) field gradient of 120 G/cm (240 G/cm). To measure the properties of the stored atoms we observe the spatial absorption profile of the cloud with a near-resonant 15 μs laser pulse. A bias field is turned on about 0.3 ms before the probe flash to ensure a uniform absorption cross section across the cloud. We measure the number of trapped atoms, the cloud size, and the optical depth and infer the density and the temperature. Residual background gas pressure ($<10^{-8}$ Pa) limits the lifetime for large clouds ($l \gg 1$ mm) to approximately 150 s.

We vary the temperature and thus the size of the cloud with an evaporative cooling technique [11]. Energy dependent transitions between trapped $m_F = -1$ and untrapped $m_F = 0$ and $m_F = 1$ substates are induced by a radio-frequency magnetic field [12]. As the radio frequency ($\omega_{\rm rf}/2\pi \sim 10$ MHz) is ramped down, higher-energy atoms are continuously removed, leaving the remaining atoms at lower mean energy and potentially higher phase-space density. (The increase in phase-space density is only realized after rethermalization of the remaining atoms.) The triangles in Fig. 2 indicate our measurements of lifetimes in the quadrupole trap after the atoms are cooled to various sizes. The dashed line is fit to the data assuming two parallel loss processes: collisions with background gases, independently measured to limit the lifetime of very large clouds to 150 s, and nonadiabatic loss limiting the lifetime of small clouds to $\tau_0 = \alpha l^2$, where l is the half width at half maximum and the fit value of α is $3.7(7) \times 10^4$ s/cm^2. As the cloud shrinks, the nonadiabatic loss rate eventually becomes faster than the rethermalization rate, limiting the density enhancement achievable with evaporation. In our quadrupole trap we see an evaporative increase in phase-space density of no more than 5.

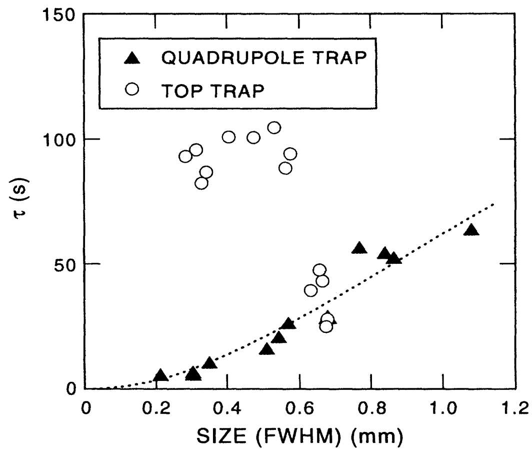

FIG. 2. The storage time of ^{87}Rb atoms as a function of trapped cloud size in the quadrupole and TOP traps. The fit to the quadrupole data (dashed line) indicates the scaling law expected from losses due to collisions with background gas and due to nonadiabatic spin flips in the center of the quadrupole trap.

Our TOP trap is designed to suppress the nonadiabatic losses by adding a transverse bias field to the quadrupole trap. Of course, adding a constant, uniform bias field results in a simple translation of the potential; within a trapped atom oscillation period ($2\pi/\omega_t \sim 10^{-2}$ s) the atom cloud will fall to the bottom of the new potential minimum and thus again will undergo loss via nonadiabatic spin flips. Our idea is to apply a continuously changing bias field that moves the location of the field zero around much faster than the atoms can respond. For a quadrupole trap with the axis in the $\hat{\mathbf{z}}$ direction, the applied bias field is a uniform magnetic field rotating in the x-y plane at frequency ω_b. As a result the zero of the total magnetic field orbits around the trapped atom cloud, as shown by the curved arrow in Fig. 1(c). The radius R_0 of the trajectory of the field zero equals the ratio of magnitude of the bias field B_b to the horizontal gradient of the quadrupole field, $R_0 = B_b/B'_q$. The instantaneous potential of the trap is given by

$$U(x,y,z,t) = \mu|(xB'_q + B_b \cos\omega_b t)\hat{\mathbf{x}} + (yB'_q + B_b \sin\omega_b t)\hat{\mathbf{y}} - 2zB'_q\hat{\mathbf{z}}|\,. \quad (1)$$

Here ω_b is chosen to be much less than the Larmor frequency (typically 7 MHz) for atoms in the bias field so that the projection of μ on the instantaneous direction of B is constant. On the other hand, ω_b is much larger than the atom oscillation $\omega_t \sim 100$ Hz so that the motion of the particle is then governed primarily by the time average (over one cycle of field rotation) of the instantaneous potential, Eq. (1). Averaged over one field rotation, the leading terms of the TOP are in cylindrical coordinates

$$U_{\mathrm{TOP}}(r,z) = \frac{\omega_b}{2\pi} \int_0^{2\pi/\omega_b} U(t)dt$$
$$\simeq -\mu B_b - \frac{\mu B_q'^2}{4B_b}(r^2 + 8z^2) + \cdots . \quad (2)$$

Figure 1(d) shows the potential of the TOP trap for an alkali atom in the $F = 1$, $m_F = -1$ state. Note that, unlike other traps which use time-dependent fields (such as the Paul trap for charged particles or the ac magnetic trap of neutrals [13]), the TOP trap is a straightforward time average rather than a pseudopotential arising from the interplay between the micromotion and a force gradient. A small amplitude circular motion at ω_b is superimposed on each atom's trajectory in the averaged potential. However, because the amplitude and phase of the circular motion are the same for all atoms, this motion does not lead to significant [14] viscous heating for $\omega_b \gg \omega_t$.

The trap is harmonic to lowest order and the magnetic field in the center of the trap is $B_b \neq 0$. The scaling laws for confinement in static magnetic traps discussed above are now modified. The potential confining a cloud of size l is given by the quadratic term in Eq. (2), i.e., it is proportional to $(B_0 l/R_c)^2/B_b = B_0 l^2/R_c R_0$, where B_0 and R_c as before are characteristic of the trapping coils and $R_0 \sim R_c B_b/B_0$ is the radius of the orbit of the field zero. In our setup R_0 ($\ll R_c$) is only slightly larger than l such that $l^2/R_c^2 \ll l^2/R_c R_0 \lesssim l/R_c$. Hence, the TOP trap confines atom clouds almost as tightly as a quadrupole trap and much more tightly than a baseball trap.

Another useful feature of the TOP trap is that at any given time the spins of the atoms are polarized in the laboratory frame. Moreover, the direction of polarization rotates synchronously with the rotation of B_b, which suggests a straightforward way of reducing systematic errors in trapped atom measurements of β-decay asymmetry [15].

As in the quadrupole trap, atoms in the TOP trap may be lost if they travel too close to the field zero. In a quadrupole trap, atoms are lost from an ellipsoidal volume, which includes the bottom of the potential well, whereas in a TOP trap the loss occurs in a toroid lying in the x-y plane a distance R_0 from the bottom of the potential well. Hence, the high-energy fraction of the cloud, i.e., the atoms with radial energy $\gtrsim \mu B_b/4$, is removed from the trap by the rapidly moving field zero. Evaporation is thus built into the TOP trap. Furthermore, as the cloud cools, the magnitude of the bias field B_b may be adiabatically decreased, which decreases R_0 and increases the spring constants [Eq. (2)]. As R_0 is decreased, evaporation is forced to continue and the increase in spring constant adiabatically increases the density and thus the rethermalization rate [16].

In our apparatus, the rotating horizontal-bias field $B_b = 10$ G is added to the static quadrupole field ($\partial B/\partial r = 120$ G/cm) by means of two coils mounted with axes at a 90° angle with respect to each other. The coils are driven at $\omega_b = 2\pi \times 7.5$ kHz with a relative phase shift of $\pi/2$. The laser absorption probe is synchronized with the rotation of B_b for a well-defined orientation of the probe bias field. The radial trap depth is on the order of 100 μK.

We load up to 3×10^6 atoms into the TOP trap. Using the identical diagnostic tools as in the quadrupole trap, we measure the atom cloud oscillation frequency in the TOP trap in the horizontal and vertical dimensions by monitoring the position of different atom samples at various times after the transfer. The radial and axial frequencies are 24(1) and 67(1) Hz, respectively, where Eq. (2) predicts 24(2) and 69(2) Hz.

When clouds of radial size greater than 0.06 cm FWHM are loaded into the TOP trap, they rapidly lose atoms and shrink in radius over a period of a few seconds as the zero-field point orbits through the outer edge of the cloud (see Fig. 2). Thereafter, evaporation may be forced to persist by one of three techniques—by ramping down the amplitude of the rotating bias field, by ramping down the frequency of an applied rf magnetic field (as with the quadrupole trap), or by doing both simultaneously. Our best results to date have been achieved by keeping the bias amplitude fixed and ramping the frequency of the rf evaporation drive smoothly downward over a period of about 150 s. This procedure cools a cloud from initial conditions of 7.5×10^6 atoms at 16 μK and peak density 3.3×10^{10} cm^{-3} to a final state of 2×10^4 atoms, at 200 nK and peak density 6.2×10^{10} cm^{-3}. This is a phase-space density increase of 3 orders of magnitude.

The measurement of lifetime as a function of cloud size in the TOP trap follows the same procedure as that for the quadrupole trap. Lifetimes of small clouds in the TOP trap show no dependence on size (Fig. 2) and are 20 times longer than those of small clouds in the quadrupole trap. The lifetime in the TOP trap is slightly shorter than the lifetime of very large clouds in the quadrupole trap. This is probably because the TOP trap is very shallow, such that collisions with room temperature gas atoms even at very large impact parameters can eject the trapped atoms.

We have measured the lifetimes for various densities and see no change, which rules out any major contribution from (density-dependent) intratrap collisions to the lifetime. The observations allow us to compute an upper limit to the rate of dipolar spin relaxation Γ_d between ^{87}Rb ($F = 1$, $m_F = -1$) atoms in the presence of a 10 G magnetic field. This rate is of interest with respect to recent theoretical studies on collisions between ultracold atoms in the presence of a magnetic field [17]. The lifetimes of 82(6) and 87(6) s for the two data points at 0.33 mm in Fig. 2 were measured at a temperature of 5μK and at peak densities of 1.5×10^{10} and 0.6×10^{10} cm^{-3}, respectively. For these conditions Γ_d is less than 10^{-12} $cm^3\,s^{-1}$ (95% C.L.). Our experimental upper limit is many orders of magnitude too high to seriously test recent theoretical predictions in the heavy alkalis [17].

In summary, we have identified nonadiabatic spin flips in the center of an ordinary quadrupole trap as a major loss mechanism. The TOP trap suppresses this loss while still providing very tight confinement. First experiments on evaporative cooling in the TOP trap yield 3 orders of magnitude increase in phase-space density and final temperatures as low as 200 nK. We are currently investigating the different evaporation schemes and their possible limitations.

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[1] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).

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

[3] For a recent optical cooling result see N. Davidson, H.-J. Lee, M. Kasevich, and S. Chu, Phys. Rev. Lett. **72**, 3158 (1994).

[4] N. Masuhara, J. M. Doyle, J. C. Sandberg, D. Kleppner, T. J. Greytak, H. F. Hess, and G. P. Kochanski, Phys. Rev. Lett. **61**, 935 (1988).

[5] C. Wieman, C. Monroe, and E. Cornell, in *Laser Spectroscopy X,* edited by M. Ducloy, E. Giacobini, and G. Camy (World Scientific, Singapore, 1992), p. 77.

[6] A. Migdall, J. Prodan, W. Phillips, T. Bergeman, and H. Metcalf, Phys. Rev. Lett. **54**, 2596 (1985).

[7] T. Bergeman, G. Erez, and H. Metcalf, Phys. Rev. A **35**, 1535 (1987); C. R. Monroe, E. A. Cornell, C. A. Sackett, C. J. Myatt, and C. E. Wieman, Phys. Rev. Lett. **70**, 414 (1993).

[8] For a quantum calculation of the loss rate at extremely low temperatures see T. H. Bergeman, P. McNicholl, J. Kyacia, H. Metcalf, and N. L. Balazs, J. Opt. Soc. Am. B **6**, 2249 (1989). See also A. Antillón, A. Góngora, and T. H. Seligman, Z. Phys. D **24**, 347 (1992).

[9] M. H. Anderson, W. Petrich, J. R. Ensher, and E. A. Cornell, Phys. Rev. A **50**, R3597 (1994), and references therein.

[10] W. Petrich, M. H. Anderson, J. R. Ensher, and E. A. Cornell, J. Opt. Soc. Am. B **11**, 1332 (1994).

[11] W. Petrich, M. H. Anderson, J. R. Ensher, and E. A. Cornell, in Abstracts of Contributed Papers, International Conference on Atomic Physics XIV, 1994 (to be published), p. 1M-7; K. B. Davis, M.-O. Mewes, M. A. Joffe, and W. Ketterle, *ibid.,* p. 1M-3.

[12] D. E. Pritchard *et al.,* At. Phys. **11**, 179 (1989).

[13] F. G. Major and H. Dehmelt, Phys. Rev. **170**, 91 (1968); E. A. Cornell, C. Monroe, and C. E. Wieman, Phys. Rev. Lett. **67**, 2439 (1991).

[14] Variations across the cloud in the phase and amplitude of the small-amplitude circular motion, coupled with the secular motion of atoms through the cloud, will give rise to a very small viscous heating associated with each intratrap collision. The scale of the velocity variation across the cloud is given by the ratio of the size of the cloud to the radius of the hole orbit, times the speed of the circular motion. As an atom moves across the cloud, there is a small amount of hysteresis, whose fractional scale is given by the trap frequency over the field rotation frequency, such that when short-range pairwise collisions take place the collision velocity will have an additive term of order $\delta v_{\mathrm{circ}} = (\omega_t/\omega_b)(l/R_0)\mu B'_q/m\omega_b$. This extra velocity, which gives rise to viscous heating, is for the present TOP parameters very small compared to (for instance) the zero-point motion of a hypothetical Bose condensate confined in the TOP trap.

[15] C. E. Wieman (private communication). See also V. Shapiro, TRIUMF Report No. TRI-PP-94-83, 1994.

[16] There are limits to the amount the bias field may be safely reduced. As the bias field is lowered, the oscillation frequencies in the TOP will no longer be much smaller than ω_b, calling into question the validity of time averaging the potential. Furthermore, for very low bias fields the Larmor frequency will no longer be much larger than ω_b, and the possibility of nonadiabatic flip loss is resurrected.

[17] E. Tiesinga, B. J. Verhaar, and H. T. C. Stoof, Phys. Rev. A **47**, 4114 (1993).