Microscopic Magnetic Quadrupole Trap for Neutral Atoms with Extreme Adiabatic Compression

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A microscopic magnetic quadrupole trap for neutral atoms has been realized with a combination of permanent magnets, coils, and ferromagnetic pole pieces. The attainable magnetic field gradients of 3×10^5 G/cm infer a spatial extension of the ground state much smaller than the wavelength of optical transitions. The field gradient can be varied over a wide range which allows for efficient loading of 4×10^5 lithium atoms from a shallow potential by adiabatic transport and compression. During compression the observed 275-fold density increase implies a collision rate increase by a factor of 1700. [S0031-9007(98)05383-6]

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The introduction of optical cooling methods as a means of loading magnetic traps with ultracold alkali atoms has opened a fascinating new field for experimental studies of which the recent realization of Bose-Einstein condensation is a most spectacular example [1]. Among the various trap designs those with steep potentials and correspondingly high atomic oscillation frequencies appear especially interesting. Steep traps allow for high collision rates in the magnetically compressed atomic gas which facilitates experiments that aim at atomic two- and three-body collisions in the regime above quantum degeneracy. The efficiency of evaporative cooling, for example, may be significantly improved in steep traps due to the enhanced elastic two-body collision rate [2]. This is particularly interesting for lithium which is a promising candidate for the preparation of a degenerate Fermi gas. Its small elastic scattering cross section, however, aggravates evaporative cooling of bosonic lithium [1] and potential cooling of fermionic lithium via collisions with a bosonic lithium buffer gas. In steep traps even samples with a small number of atoms will rapidly thermalize. Evaporative cooling of artificial or radioactive particles may thus become feasible. Fast thermalization will also reduce the preparation time for a conventional Bose-Einstein condensate which is desirable for experiments in which the condensate is used as a coherent atom source.

For very steep traps a qualitatively new regime is reached if the extension of the ground state wave function becomes smaller than the wavelength of an optical atomic resonance line. In such a microtrap an optical photon can be scattered by a trapped atom without changing the atomic momentum provided that only the low-lying vibrational states of the trap are occupied (Lamb-Dicke regime). This may open new possibilities to approach quantum degeneracy with optical cooling techniques alone. In particular, the problem of photon reabsorption by already condensed atoms may be circumvented [3]. Up to now, only single atoms have been loaded into three dimensional and so far purely optical microtraps [4]. A two dimensional confinement into the Lamb-Dicke regime has been reported for atomic hydrogen [5]. Magnetic microtraps based on microfabricated current loops have been proposed but not yet demonstrated [6]. Such traps made from miniaturized elements usually suffer from a small trapping volume that cannot be enlarged without substantially reducing the trap depth. Thus, it is difficult to compress the atoms into the tiny volume of the trap.

In this Letter we report on the realization of a magnetic quadrupole microtrap with a novel design that allows for efficient loading by adiabatic transport and compression of an optically precooled ensemble of lithium atoms. The trap is based on the implementation of miniaturized structures into the recently reported "tip trap" setup [7] and exploits the fact that for a given magnetic field B_0 the maximum possible field gradient scales like B_0/R, where R is the geometric size of the smallest relevant magnetic element. With $R = 10$ μm and $B_0 = 1000$ G the magnetic field gradient b of our "μ tip trap" exceeds 10^5 G/cm. At these extraordinary large field gradients the ground state oscillation frequency of the atoms or the corresponding trap energy unit [8] $\varepsilon_0 = (\mu b \hbar)^{2/3}/M^{1/3}$ reaches values of up to $\varepsilon_0/h = 1$ MHz (for lithium). M and μ denote the atomic mass and magnetic moment, respectively. As compared to conventional magnetic traps the density in the μ tip trap can be adiabatically increased by 3 orders of magnitude at constant phase space density resulting in an expected enhancement of the collision rate by a factor of 10^4.

The central element of the μ tip trap is a sharp steel pin that is magnetized by a small permanent magnet (expanded view in Fig. 1). An additional strong cylindrical electromagnet generates an opposite homogeneous offset field which at a certain distance from the tip exactly cancels the rapidly decreasing field of the pin. An expansion of the magnetic field around this point [9] is dominated by the spherical quadrupole term which establishes a magnetic quadrupole trap with its z axis along the symmetry

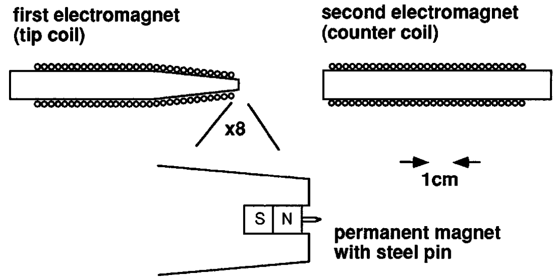

FIG. 1. Setup of the μ tip trap. A sharp steel pin is magnetized by a permanent magnet and exposed to a variable magnetic field that is generated by two electromagnets.

axis of the setup. The trap gradient is determined by the gradient of the pin field and becomes very large in the close proximity of the pin tip. Changing the offset field both shifts the minimum of the trap potential along the symmetry axis and changes the trap gradient. The maximum gradient is limited by the magnetization of the pin and the radius of curvature of its tip. If the current in the electromagnet is reduced the field minimum moves away from the pin and changes continuously into a comparably shallow quadrupole field. This transformation is supported by a second cylindrical electromagnet introduced along the symmetry axis of the setup and separated from the first magnet by several centimeters (Fig. 1). Its magnetization is opposite to that of the permanent magnet which preserves the quadrupole character of the field even if the first electromagnet is turned off. By inverting the current in the first electromagnet the field minimum can be shifted to the center between the two electromagnets where the small permanent magnet and the pin have negligible influence and the magnetic field is determined by the currents in the electromagnets alone.

To load the atoms into the steep potential we proceed as follows. By adjusting the currents in the coils to small values we achieve efficient operation of a magneto-optical trap (MOT) at the center between the electromagnets where a macroscopic number ($\sim 10^7$) of ^{7}Li atoms is cooled and collected [7]. Then a fraction of the atoms is transferred to a volume-matched but still relatively shallow magnetic potential by increasing the currents in both electromagnets and turning off the MOT light. When the current in the first electromagnet is subsequently ramped through zero to an appropriate value determined by the trap design the atoms are adiabatically transported by more than a centimeter towards the tip and then compressed into the steep potential of the trap. Adiabaticity during transport requires the acceleration of the trap center to be small compared to the acceleration produced by the trapping forces acting on the atoms. Adiabatic compression is guaranteed if the atomic oscillation frequency ω inside the trap obeys $d\omega/dt \ll \omega^2$. If both conditions are fulfilled, the occupations of the vibronic states remain unchanged and the loading procedure is fully reversible. Temperature, density, and collision rate increase strongly during the compression while phase space density is preserved. This scheme takes advantage of permanent magnets as simple sources of strong magnetic fields without sacrificing the option for time dependent experiments. The free expansion properties of the gas, for example, can still be studied by adiabatically transporting the atoms back to the shallow field that can be switched off rapidly [7] since the field of the small permanent magnet is negligible at this position. The described loading method is possibly also applicable to other recently discussed microtrap designs based on magnetic or optical forces [6] and may help to solve the general problem of loading miniaturized traps with a substantial number of atoms.

For our experiment we use a 0.65 mm long steel pin that is sharpened on a lathe to a radius of curvature of 10 μm. With its polished base surface (0.29 mm diameter) the pin is attached to the permanent magnet (Sm_2Co_{17}, remanence 1.0 T, 1.5 mm diameter, 3 mm long) and held in place by vacuum compatible cement. The permanent magnet is located inside a bore drilled into the pole piece of the "tip coil" (first electromagnet), which is made from magnetic steel and consists of a 60 mm long cylindrical part with a diameter of 12 mm and a conical part of 35 mm length with a final diameter of 4 mm. 443 turns of capton-isolated copper wire (0.6 mm diameter) are wrapped directly around the steel core in eight layers. The length of the pin in combination with the amount to which the permanent magnet is countersunk into the pole piece (0.27 mm) is a critical parameter since it determines the effective magnetization of the pin. A pin which exceeds the optimum length will be strongly demagnetized by the homogeneous offset field while a short pin which is too strongly magnetized by the permanent magnet would require a very large offset field for the field minimum to be shifted sufficiently close to the tip to make use of the highest gradients. For the present trap, the magnetization of the tip has been geometrically adjusted such that the trap center is positioned at 23 μm from the tip at an offset field of 1800 G that can be generated with a convenient current of 2.8 A inside the tip coil. The "counter coil" (second electromagnet) is separated from the tip coil by 33 mm and consists of a cylindrical pole piece (magnetic steel, 95 mm long, 12 mm diameter) that carries 405 turns of the same copper wire in nine layers. It is designed for a fixed current of 2.6 A which is reduced only during operation of the MOT. The entire magnetic field geometry is calculated numerically with a personal computer and commercial software.

As described elsewhere [6], the initial magnetic trap with an axial gradient of 165 G/cm is filled with about 10^6 atoms from a magneto-optical trap at a temperature of approximately 150 μK. By loading only a moderate number of atoms collisions can be avoided which allows us to study the trap without rapidly loosing the sample by Majorana spin flips. Only a minor fraction of atoms on trajectories with small angular momentum is lost within the first few milliseconds; however, these orbits are not repopulated by collisions such that the sample is stable for several seconds. The lifetime is eventually limited by collisions with the background gas which leads to an exponential decay with a measured time constant of 7.2 s. The atoms are then compressed into the microtrap by linearly ramping the current in the tip coil from -2 A to the final value of up to 3 A within 100 ms. We determine the number of remaining atoms by adiabatically returning to the initial shallow field and monitoring the fluorescence in a restored MOT. Among the four possible trapped hyperfine sublevels ($F = 2$, $m_f = 0, 1, 2$, and $F = 1$, $m_f = -1$) only two ($F = 2$, $m_f = 1, 2$) are suitable for being loaded into the steep potential. For the only weakly confined state with $m_f = 0$ the transport is not adiabatic while for the state with $m_f = -1$ the maximum trap depth is only 2.5 mK such that most of these atoms are heated out of the quadrupole potential at high compression. We thus keep only 30% of the magnetically trapped atoms when they are transported and compressed for the first time. However, if the same atoms are transported back and forth twice no further losses are observed. This suggests that 30% of the total number of atoms initially transferred from the MOT into the magnetic trap occupy the useful states with $F = 2$, $m_f = 1, 2$. In the following we consider only this fraction.

To monitor the shape and the position of the magnetically trapped atomic cloud conventional imaging techniques is not convenient since the large Zeeman broadening inside the microtrap distorts the image and reduces the signal. Instead we apply a thin light sheet perpendicular to the symmetry axis of the trap for a period (50 ms) much longer than the average oscillation period of the atoms (20 to 200 μs). The sheet with a thickness of 50 μm and an intensity of 20 mW/cm^2 passes the trapped cloud at a variable position along the symmetry axis. The light is resonant with the D_2 line (670.96 nm) and removes the exposed atoms from the trap by optical pumping into untrapped substrates of the ground state hyperfine multiplet. The number of atoms remaining in the magnetic trap is determined by monitoring the fluorescence of a restored MOT. Figure 2 shows the observed number of remaining atoms for various positions of the light sheet in the case of the initial shallow trap potential (a) and after compression (b). At the minimum of the data curve the light sheet intersects the center of the cloud. Then, all atoms oscillate through the light sheet and are removed from the trap. The compression factor is obtained by comparing the width of the observed curves before and after compression. By varying the current in the tip coil from -2 to $+1.2$ A the linear dimensions of the cloud are reduced by a factor of 6.5 from 1.3 to 0.21 mm resulting in a 275 times smaller cloud volume. For ideal adiabatic compression in a linear potential the occupied volume is inversely proportional to the magnetic field gradient. Hence the observed volume compression factor implies a lower limit of 45 000 G/cm for the trap's actual field gradient if all the atoms are in the state $m_f = 2$ and a lower limit of 28 000 G/cm if all the atoms are in the $m_f = 1$ state. Note that upon passing from the Zeeman to the Paschen-Back regimes during compression the effective magnetic moment of the state $m_f = 1$ increases. For the actual mixture of atoms in both states the observed gradient is consistent with the calculated value of 34 000 G/cm which indicates that the numerical calculation is reliable and that the magnetic transport is adiabatic. In the presence of an unwanted nonadiabatic heating during transport and compression the measured cloud size could be explained only by a magnetic field gradient significantly larger than predicted by the calculation.

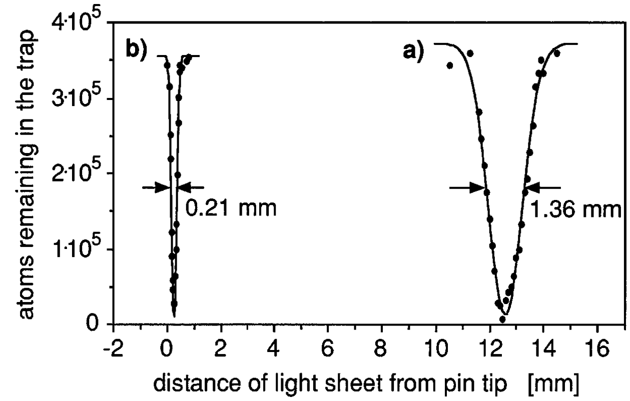

FIG. 2. Observed shape of the atomic cloud (a) in the shallow field after loading from a magneto-optical trap and (b) after compression in the steep potential of the μ tip trap at a current in the tip coil of 1.2 A.

To our knowledge the above values represent already the highest gradient reported for a magnetic trap, yet, even higher gradients are achieved by increasing the tip coil current above 1.2 A. Then, the atomic cloud shrinks to a size which approaches the spatial resolution of the observation method. However, the position of the potential minimum can still be monitored reliably which allows us to test the validity of the magnetic field calculation by comparing the observed and the calculated position of the trap center for currents up to 2.3 A (Fig. 3). Since the error for the experimental data is below 1% we interpret the small difference between experiment and simulation as an estimate for the uncertainty of the numerical calculation. It amounts to an average value of 12% for the predicted trap position which translates into an error of 9% for the magnetic field gradient at currents near 3 A. The reproducibility is limited by the temperature sensitivity of the remanence of the permanent magnet ($-0.04\%/{}^\circ$C). Because of heat dissipation in the electromagnets the temperature may vary up to 50 °C which translates into a reproducibility of 2% for the trap position and 6% for the magnetic field gradient.

The numerical result of the μ tip trap's axial field gradient is plotted in Fig. 4 for various currents in the tip coil. Between -2.2 and -0.1 A the trap moves towards the pin while the gradient remains almost unchanged.

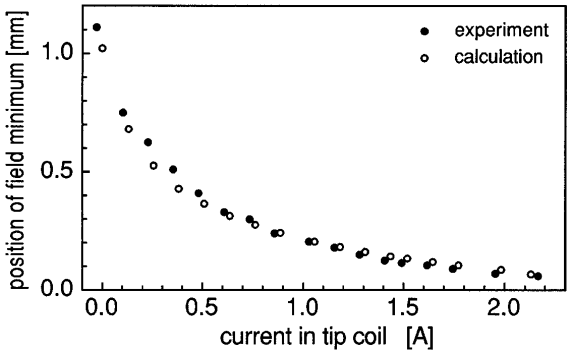

FIG. 3. Observed position (solid dots) of the trap center for various currents in the tip coil as compared to the results of the numerical calculation (white dots). The current in the counter coil is set to a fixed value of 2.6 A. The experimental errors are smaller than the size of the dots.

Above 0.1 A the cloud is mainly compressed and only little shifted. The "microtrap regime" (dotted line) where the optical wavelength exceeds the extension of the ground state wave function is entered at 60 mA and a maximum gradient of 3×10^5 G/cm is reached at the nominal design current of 3 A. In our experiment we achieve compression for gradients up to 1×10^5 G/cm. For larger currents the gas is adiabatically heated to temperatures on the order of several mK and is no longer exclusively trapped in the linear part of the potential. It is useful to define a "compression radius" r_c at which the radial field gradient does not change with current, i.e., $d^2B(r_c)/dr\,dI = 0$. Outside this radius the gradient decreases with increasing current and the atoms, although still trapped, are expanded rather than compressed. The compression radius at the various currents is determined only by the geometry of the setup and reaches a constant value of 100 μm in the vicinity of the tip. The full potential of the μ tip trap can thus be exploited by slightly cooling the atoms by either optical or evaporation techniques. This will reduce the cloud size below the compression radius and allow subsequent submission of the trapped gas to the full gradient of 3×10^5 G/cm. At these gradients the volume of the gas will be compressed by about a factor of 1000 as compared to the initial density in the shallow potential.

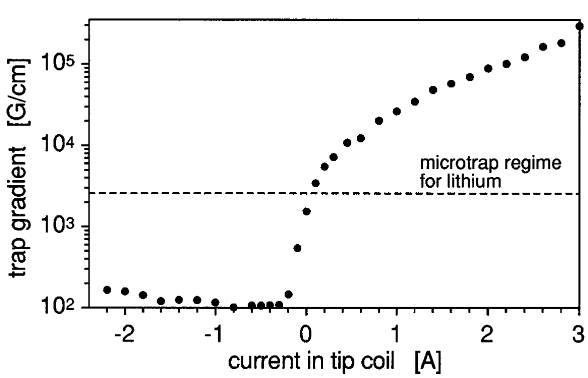

FIG. 4. Calculated magnetic field gradient of the trap for various currents of the tip coil. The current in the counter coil is set to a fixed value of 2.6 A.

The collision rate γ scales as nv, with n and v denoting, respectively, the number density and the average thermal velocity of the atoms. Assuming a constant phase space density $n\lambda^3 =$ const, and with the thermal de Broglie wavelength λ being proportional to $1/v$, γ scales as $n^{4/3}$ independent of the specific trap geometry. Consequently, an adiabatic density increase by a factor of 1000 results in 10 000-fold enhanced collision rate. Assuming initial collision rates on the order of 10 s^{-1} as reported for conventional traps and a required number of 1000 collisions for cooling the gas into the degenerate regime it seems possible to generate a Bose condensate within 100 ms.

The above estimation neglects the influence of Majorana spin flips as a major loss mechanism in a quadrupole trap. For future experiments it will thus be a promising challenge to adapt this trapping scheme to other trap geometries which do not suffer from spin flip losses. The extension of well known methods is conceivable as, for instance, adding a rotating offset field [10] or introducing an optical plug [1], but also recently proposed new trap designs based on microfabricated conductors [6] appear feasible. This may lead to novel and intriguing scenarios for trapping and guiding atoms in miniaturized structures where the atomic motion is dominated by its quantum aspects.

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[1] M. H. Anderson *et al.*, Science **269**, 189 (1995); K. B. Davis *et al.*, Phys. Rev. Lett. **75**, 3969 (1995); C. C. Bradley *et al.*, Phys. Rev. Lett. **75**, 1687 (1995).
[2] W. Ketterle and N. J. Van Druten, *Advances of Atomic, Molecular, and Optical Physics*, edited by B. Benderson and H. Walter (Academic Press, New York, 1996).
[3] U. Janicke and M. Wilkens, Europhys. Lett. **35**, 561 (1996); J. I. Cirac, M. Levenstein, and P. Zoller, Europhys. Lett. **35**, 647 (1996), and references therein.
[4] P. S. Jessen *et al.*, Phys. Rev. Lett. **69**, 49 (1992); A. Hemmerich and T. W. Hänsch, Phys. Rev. Lett. **70**, 410 (1993); G. Grynberg *et al.*, Phys. Rev. Lett. **70**, 2249 (1993).
[5] C. Cesar *et al.*, Phys. Rev. Lett. **77**, 255 (1996).
[6] J. D. Weinstein and K. G. Libbrecht, Phys. Rev. A **52**, 4004 (1995).
[7] V. Vuletic, T. W. Hänsch, and C. Zimmermann, Europhys. Lett. **36**, 349 (1996).
[8] T. H. Bergeman *et al.*, J. Opt. Soc. Am. B **6**, 2249 (1989).
[9] T. Bergeman, G. Erez, and H. J. Metcalf, Phys. Rev. A **35**, 1535 (1987).
[10] W. Petrich *et al.*, Phys. Rev. Lett. **74**, 3352 (1995).