Demonstration of Neutral Atom Trapping with Microwaves

R. J. C. Spreeuw, C. Gerz, Lori S. Goldner, W. D. Phillips, S. L. Rolston, and C. I. Westbrook*
National Institute of Standards and Technology, PHY A-167, Gaithersburg, Maryland 20899

M. W. Reynolds† and Isaac F. Silvera
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138
(Received 4 November 1993)

We demonstrate trapping of neutral Cs atoms by the magnetic dipole force due to a microwave field. The trap is formed in a spherical microwave cavity tuned near the ground state hyperfine transition (9.193 GHz). With a microwave power of 83 W, the trap is ≈ 0.1 mK deep. It is loaded with Cs atoms laser cooled to ≈ 4 μK. We observe oscillatory motion of atoms in the trap at frequencies of 1–3 Hz. This type of trap has certain advantages for achieving the conditions for Bose-Einstein condensation in hydrogen or the alkalis, because it can confine atoms predominantly in the lowest energy spin state.

PACS numbers: 32.80.Pj, 42.50.Vk, 67.65.+z

Significant progress towards Bose-Einstein condensation of atomic hydrogen has been made by confining the gas in a static magnetic trap [1,2]. Unfortunately, this trap can only hold atoms in the excited (low-field seeking) spin states and as a result suffers from depletion of the atomic population by intrinsic dipolar spin relaxation to the ground state in binary collisions [3]. The ideal magnetic trap for atoms would have a magnetic field maximum that holds the ground state (high-field seeking) atoms, but Maxwell's equations do not allow for a maximum in a static field [4]. To solve this problem, Agosta and Silvera [5] proposed a microwave trap, the magnetic-dipole analog of the electric-dipole-force laser trap [6]. In a microwave trap the atoms can be essentially in the ground spin state, so that the dipolar decay mechanism is suppressed by a substantial factor [7]. As a result, higher densities should be obtained for longer times. In this Letter we present the first demonstration of the microwave trap, trapping laser-cooled cesium atoms.

The trap is formed in a spherical microwave cavity of radius 2.25 cm inside a UHV chamber (Fig. 1). The cavity is machined from nonmagnetic stainless steel, giving a decay time for eddy currents of 0.5 ms, so that we can rapidly switch magnetic fields during the loading of the trap. The cavity walls are gold plated to reduce microwave losses. There are 1 cm diameter access holes for the atomic beam, the laser beams, and for observation. Although these were beyond cutoff for microwave propagation, they decreased the cavity Q by increasing the surface area. To create the microwave trap we excite the TE_{11y} mode [8] at its resonant frequency of 9.44 GHz. This mode has a magnetic field maximum at the center of the cavity (see Fig. 1). Critically coupled to the coaxial input transmission line by a current loop, the measured Q is 5500. A frequency-locked oscillator, followed by a traveling-wave tube amplifier, provides microwave power up to 83 W. This power is dissipated in the cavity walls, which are water cooled.

The trapping force derives from the magnetic-dipole (electron spin flip) transition between the $|F,m_F\rangle = |3,3\rangle$ (lower) and $|4,4\rangle$ (upper) hyperfine sublevels of the electronic $6^2S_{1/2}$ ground state of cesium. The transition frequency is the hyperfine splitting (9.193 GHz) plus a small Zeeman shift which separates the trapping transition from other transitions to yield an effectively two-level system. The microwave field mixes these states and shifts the energies (ac Zeeman shift, the analog of the ac Stark shift). In a microwave field gradient this results in a force called the dipole force. An experimental complication is that, for practical microwave power levels, the dipole force is overwhelmed by gravity (for cesium $mg/k_B = 1.6$ mK/cm). To compensate, we apply a static magnetic field gradient of about 2.3 mT/cm to levitate atoms in the $|4,4\rangle$ state. Unfortunately, the levitating field introduces the new complication that a magnetic field gradient implies a gradient in detuning and hence a gradient in the admixture of the $|3,3\rangle$ state. This affects not only the microwave dipole force but also the static magnetic

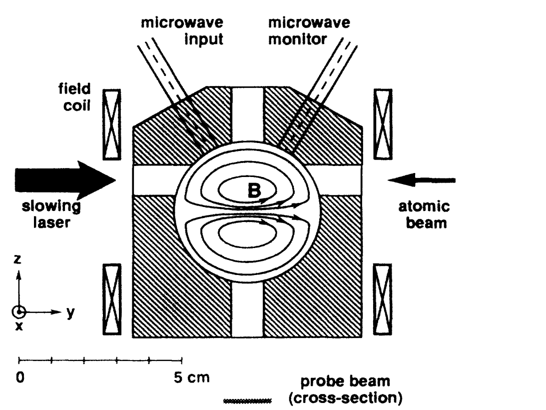

FIG. 1. Spherical microwave cavity (45 mm diameter) with holes for atomic beam, laser access, and observation. Not shown are three pairs of holes in the horizontal plane through the center. The coils serve both for the magneto-optic trap field and for the static field during the microwave trapping phase. The microwave input line is critically coupled and the power is monitored through an undercoupled output line. The magnetic field of the TE_{11y} mode is shown inside the cavity [8].

0031-9007/94/72(20)/3162(4)$06.00

force, since the magnetic moments of the $|3,3\rangle$ and $|4,4\rangle$ states have opposite signs.

The potential for the atoms in the trapping state, due to static magnetic, microwave, and gravitational fields, is

$$U(\mathbf{r}) = -\bar{\mu}B(\mathbf{r}) - \tfrac{1}{2}\hbar\Omega(\mathbf{r}) + mgz\,,$$

where mgz is the gravitational energy, $\Omega = (\omega_R^2 + \delta^2)^{1/2}$, with the Rabi frequency $\omega_R(\mathbf{r}) = \mu_\perp b_\perp(\mathbf{r})/\hbar$ and the detuning $\delta(\mathbf{r}) = 2\mu_z[B_{\rm res} - B(\mathbf{r})]/\hbar$, both functions of position; $b_\perp$ is the amplitude of the rf field transverse to the local static magnetic field $\mathbf{B}(\mathbf{r})$. Here $\bar{\mu} = \frac{1}{2}(\mu_{4,4} + \mu_{3,3}) \approx \frac{1}{8}\mu_B$ is the mean magnetic moment of the $|4,4\rangle$ and $|3,3\rangle$ states; $\mu_\perp \approx (\frac{7}{8})^{1/2}\mu_B$ is the transition dipole moment; and $\mu_z = \frac{1}{2}(\mu_{4,4} - \mu_{3,3}) \approx \frac{7}{8}\mu_B$ (μ_B is the Bohr magneton). $B_{\rm res}$ is the value of $B(\mathbf{r})$ that would tune the $|3,3\rangle \leftrightarrow |4,4\rangle$ transition into resonance with the microwaves ($B_{\rm res} \approx 10$ mT). We use $B(\mathbf{0}) = 7$ mT in the center of the cavity, so that the cavity frequency is ≈ 80 MHz above the transition ("blue detuning"). The Rabi frequency ω_R is proportional to the microwave magnetic field and reaches a maximum in the center of the cavity. For the highest power level used, 83 W, we calculate a central Rabi frequency of $\omega_R/2\pi = 36$ MHz. Given the detuning of 80 MHz in the center of the cavity, the Rabi frequency throughout the trapping region is small enough so that the population admixture of one state into the other stays below about 10%. For blue detuning, the upper level shifts downward due to the microwaves, so that the force is towards high microwave field. The lower level shifts upward, and the force is towards the low microwave field regions. Since for red detuning the forces point in the opposite direction, either state (upper or lower) can be trapped in a microwave field maximum. In the present experiment we work blue of resonance, so we trap the upper ($|4,4\rangle$-like) state. This provides the simplification of having nearly a two-level system. We have examined the possibility of trapping the lowest energy ($|3,3\rangle$) state by using a magnetic field such that the microwave frequency is red of the $|3,3\rangle \leftrightarrow |4,4\rangle$ transition. Levitation of the $|3,3\rangle$ state requires $-\frac{4}{3}$ times the magnetic field gradient that we use for the $|4,4\rangle$ state. As a result, complications arising from the associated detuning gradient are aggravated. Calculations show that with our present design of cavity and magnetic field coils we would have needed more microwave power than was available [9].

Figure 2 shows a typical calculated trapping potential in the Oyz plane, taking into account the microwave and static field profiles. The center of the resonator is at $r = 0$. The sharp drop in potential energy about 12 mm below the center occurs because the admixture of the $|3,3\rangle$ state becomes appreciable. Because the magnetic moment of this state has the opposite sign to that of $|4,4\rangle$, the levitation force is reduced. The more gradual increase in potential above the trap is due to nonuniformity of the levitating gradient. For the highest microwave power used, 83 W, we calculate a trap depth of 140 μK.

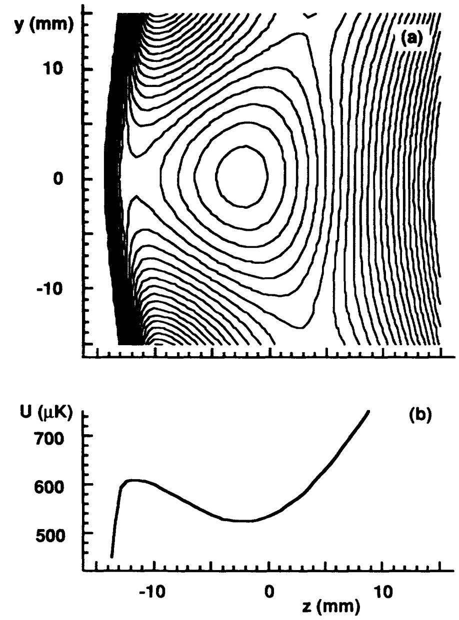

FIG. 2. (a) Calculation of the trapping potential in a vertical plane containing the symmetry axis of the microwave mode (Oyz plane; z is vertical). For this calculation the microwave power is 50 W. Contour lines are drawn 20 μK apart. (b) Cut of the same potential along the z axis ($y = 0$).

We load the microwave cavity with laser-cooled cesium atoms. A chirped laser slows a cesium atomic beam; the slowed atoms then fill a magneto-optic trap (MOT) [10] located in the center of the microwave cavity. After the MOT magnetic field is switched off, the atoms cool in optical molasses [11]. We then turn the lasers off and optically pump with a pulse of circularly polarized (σ^+) laser light to increase the population of the $|4,4\rangle$ state. After this, we have on the order of 10^7 atoms, with a temperature between 3 and 5 μK, that can be trapped by switching on the microwaves and the static magnetic field. The static field is created with the same set of coils that create the magnetic quadrupole field for the MOT. During the MOT phase, the upper and lower coils carry equal and opposite currents; during the microwave trapping phase, the lower coil carries more current, producing the necessary bias field and levitation gradient. After a variable trapping time we analyze the contents of the cavity by imaging the cloud of atoms with a charge coupled device (CCD) camera or by using a time-of-flight method in which the trapped atoms are released to fall through a probe region [11].

In order to obtain an image, we illuminate the atoms with a 4–10 ms "flash" from the molasses lasers immediately after turning off the microwave and static fields. We capture the synchronized video frame that contains the image of the fluorescence. In Fig. 3 we show a sequence where the trapping time increased by 67 ms for successive frames. Each frame represents a separate trap loading cycle, because the imaging technique is destruc-

FIG. 3. Sequence of images with 67 ms successive increase in trapping time. The bright ring is a 1 cm diameter observation hole in the side of the cavity. For this sequence the microwave power level was 42 W.

tive. We see that the atoms oscillate along the vertical direction. The reason is that the potential minimum is below the center of the cavity (see Fig. 2), which is where we release the atoms.

In the time-of-flight method we detect the fluorescence as the atoms fall through a probe beam located 57 mm below the cavity center. The arrival time at the probe depends on the position and velocity of the atoms at the time we switch off the trap. In Fig. 4(a) the oscillatory motion seen in Fig. 3 is evident in the dependence of the arrival time on trapping time. The oscillation in Fig. 4(a) is well fitted by the sum of two sine waves, the strongest of which corresponds to an oscillation with spatial amplitude of 1.5 mm and velocity amplitude of 18 mm/s. The frequencies obtained from such fits range from 1 to 3 Hz and increase with microwave power. This increase is expected because the trap depth, and therefore the curvature of the potential, increases with microwave power. A calculation of the trapping potential near the well bottom in fact yields three frequencies, two of which are nearly degenerate. The calculated frequency for the vertical motion agrees with either of the fitted frequencies to within 20%. One expects, however, the vertical direction to be a principal axis for reasons of symmetry and to see only one frequency in the time-of-flight signal since it is only sensitive to vertical motion. The fact that we see more than one frequency points to a coupling between the different modes. Trajectory calculations indicate that significant coupling can be caused by misalignment and imperfections in the magnetic field, due for example to the presence of magnetic materials.

The width of the time-of-flight signal, Fig. 4(b), is determined by the position and momentum spreads of the atoms. The width oscillates at twice the frequency of the arrival time, as one would expect for a harmonic potential well. This phenomenon is also observed in Fig. 3 as a "breathing" motion of the cloud as the spread in energy is periodically traded back and forth between kinetic and potential energy. From the "breathing" amplitude for the first 1.3 s in Fig. 4(b) we deduce that the effective temperature associated with the kinetic energy spread oscillates between 3.4 and 1.4 μK while the cloud diameter (full width at half maximum) oscillates between 1.9 and 3.0 mm. These diameters agree with the pictures in Fig. 3.

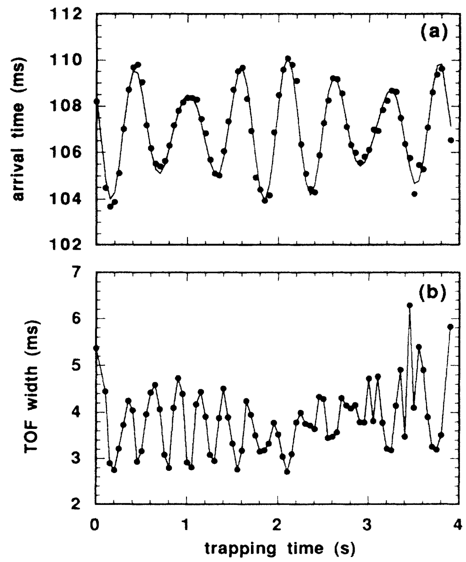

FIG. 4. (a) Time of arrival at the probe beam as a function of the time the atoms spent in the trap. The solid line is a fit to a sum of two sine waves. The oscillations correspond to the up-down motion visible in Fig. 3. (b) Width (FWHM) of the time-of-flight signal (TOF), showing oscillations corresponding to the breathing motion in Fig. 3. The solid line that connects the data is not a fit.

The integrated time-of-flight signal is proportional to the number of atoms that remain trapped. We find that this number decreases exponentially with trapping time, with a typical decay time ($1/e$) of 1 s. If we use no microwaves, but do switch on the levitating field, the decay time is only 0.1 s and no atoms can be detected after 0.4 s. This verifies that the levitating field does not produce a static magnetic trap. In order to see the influence of background pressure on the trap lifetime we varied the pressure by heating the cavity with microwaves. In Fig. 5 we show the number of atoms that survive 1 s of mi-

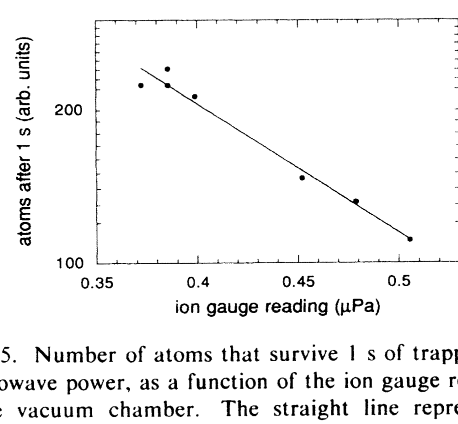

FIG. 5. Number of atoms that survive 1 s of trapping at 50 W microwave power, as a function of the ion gauge reading inside the vacuum chamber. The straight line represents exponential decay.

crowave trapping vs the ion gauge reading in the vacuum chamber. The strong dependence of surviving atoms on ion gauge reading can totally account for the typical lifetime of 1 s at a typical gauge reading of 0.4 μPa. We conclude that collisions with the background gas are the dominant trap loss mechanism.

Our experimental demonstration of trapping of neutral cesium atoms using the dipole force due to a microwave field opens up the possibility of confining the ground spin states of atomic hydrogen, which cannot be confined in static magnetic traps. This would reduce the spin-relaxation rate to much lower values. This mechanism in static magnetic traps limits the lifetime at high density, making it difficult to achieve Bose-Einstein condensation. (Static traps nevertheless achieve conditions close to Bose condensation [2].) Although the microwave trap is shallow, it can in principle be loaded with hydrogen atoms evaporatively precooled in a static magnetic trap, with the microwaves adiabatically transforming the atoms to the stable spin state [12]. For H it would be advantageous to operate the microwave trap in a strong static magnetic field (a few tesla) in order to reduce the trap size and power dissipation. This has the additional advantage that the sample approaches the fully (electron and proton) spin-polarized state so that it is more stable against recombination losses. For the alkalis the Zeeman substructure in the hyperfine ground state is more complicated, but considerations of spin-relaxation collisions are similar, although in the present experiment the density ($\approx 10^9$ cm^{-3}) is much too low for spin-relaxation losses to be a problem. Spin relaxation due to binary collisions makes it desirable to trap the lowest energy state so that spin relaxation is energetically unfavorable. This state could in principle be trapped in a number of different configurations, depending on the sign of the detuning, the cavity mode (field maximum or minimum), and magnetic field (high- or low-field limit). The microwave trap offers a promising alternative to other ground spin state confining traps, such as the laser dipole-force trap [6], detuned extremely far off resonance and the ac magnetic trap [13,14]. Detailed study should decide which of these traps holds the greatest promise for achieving and sustaining the conditions for Bose-Einstein condensation.

This work was supported by the Office of Naval Research (NIST) and the Department of Energy, Grant No. DE-FG02-85ER45190 (Harvard). Some of the authors acknowledge additional financial support: R.J.C.S. from the Niels Stensen Foundation, C.G. from the Alexander von Humboldt Foundation, and L.S.G. from an NRC/NIST fellowship.

*Present address: Institut d'Optique, Centre Scientifique d'Orsay, B.P. 147, 91403 Orsay, Cedex, France.

†Present address: Van der Waals–Zeeman Laboratory, University of Amsterdam, Valchenierstraat 65, 1018 XE Amsterdam, The Netherlands.

[1] A. Migdall, J. Prodan, W. Phillips, T. Bergeman, and H. Metcalf, Phys. Rev. Lett. **54**, 2596 (1985); H. F. Hess, Phys. Rev. B **34**, 3476 (1986).

[2] J. M. Doyle, J. C. Sandberg, I. A. Yu, C. L. Cesar, D. Kleppner, and T. J. Greytak, Phys. Rev. Lett. **67**, 603 (1991).

[3] A. Lagendijk, I. F. Silvera, and B. J. Verhaar, Phys. Rev. B **33**, 626 (1986).

[4] W. H. Wing, in *Laser-Cooled and Trapped Atoms*, Proceedings of the Workshop on Spectroscopic Applications of Slow Atomic Beams, edited by W. D. Phillips, NBS Special Publication No. 653 (U.S. GPO, Washington, DC, 1983).

[5] C. C. Agosta and I. F. Silvera, in *Spin Polarized Quantum Systems*, edited by S. Stringari (World Scientific, Singapore, 1989), p. 254.

[6] S. Chu, J. E. Bjorkholm, A. Ashkin, and A. Cable, Phys. Rev. Lett. **57**, 314 (1986).

[7] C. C. Agosta, I. F. Silvera, H. T. C. Stoof, and B. J. Verhaar, Phys. Rev. Lett. **62**, 2361 (1989).

[8] The holes in the cavity lift the threefold TE_{11m} degeneracy to give modes with the microwave magnetic field at the cavity center linearly polarized and aligned with the coordinate axes: TE_{11x} (9.428 GHz), TE_{11y} (9.436 GHz), and TE_{11z} (9.409 GHz).

[9] We note that while it is possible to trap the lowest state of Cs, in H it is much easier since the light mass would require only a 18 μT/cm gradient to levitate, greatly reducing the spatial detuning dependence.

[10] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).

[11] C. Salomon, J. Dalibard, W. D. Phillips, A. Clairon, and S. Guellati, Europhys. Lett. **12**, 683 (1990).

[12] I. F. Silvera and M. Reynolds, Physica (Amsterdam) **169B**, 449 (1991).

[13] R. V. E. Lovelace, C. Mehanian, T. J. Tommila, and D. M. Lee, Nature (London) **318**, 30 (1985).

[14] E. A. Cornell, C. Monroe, and C. E. Wieman, Phys. Rev. Lett. **67**, 2439 (1991).

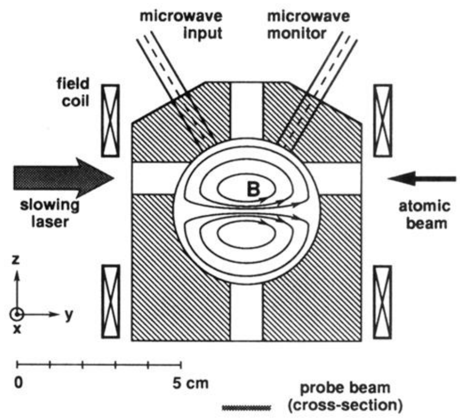

FIG. 1. Spherical microwave cavity (45 mm diameter) with holes for atomic beam, laser access, and observation. Not shown are three pairs of holes in the horizontal plane through the center. The coils serve both for the magneto-optic trap field and for the static field during the microwave trapping phase. The microwave input line is critically coupled and the power is monitored through an undercoupled output line. The magnetic field of the TE_{11y} mode is shown inside the cavity [8].

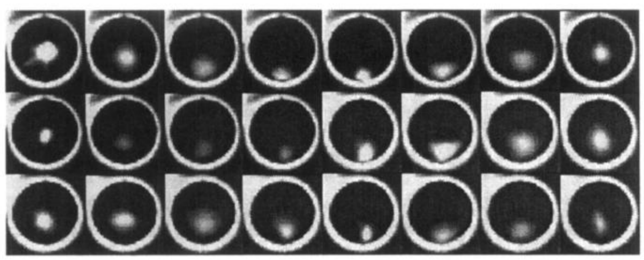

FIG. 3. Sequence of images with 67 ms successive increase in trapping time. The bright ring is a 1 cm diameter observation hole in the side of the cavity. For this sequence the microwave power level was 42 W.