Trapping of Neutral Sodium Atoms with Radiation Pressure

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We report the confinement and cooling of an optically dense cloud of neutral sodium atoms by radiation pressure. The trapping and damping forces were provided by three retroreflected laser beams propagating along orthogonal axes, with a weak magnetic field used to distinguish between the beams. We have trapped as many as 10^7 atoms for 2 min at densities exceeding 10^{11} atoms cm^{-3}. The trap was $\simeq 0.4$ K deep and the atoms, once trapped, were cooled to less than a millikelvin and compacted into a region less than 0.5 mm in diameter.

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The ability to cool and trap neutral atoms has recently been demonstrated by several groups.[1-3] Their traps utilized the intrinsic atomic magnetic dipole moment or the induced oscillating electric dipole moment to confine sodium atoms about a local-field strength extremum. We report the first optical trap which relies on near-resonant radiation pressure (also called *spontaneous* light force, in contrast to *induced* light forces[4]) to both confine and cool the atoms. The trap has an effective depth of about 0.4 K, about 10 times deeper than the deepest traps previously reported.[3] It is the first trap which exploits an atom's internal structure to induce a greater absorption probability for light moving toward the center of confinement.[4,5]

The basic principle of the trap can be illustrated by considering a hypothetical atom with a spin $S=0$ ($m_s =0$) ground state and a spin $S=1$ ($m_s = -1,0,+1$) excited state. In a weak inhomogeneous magnetic field $B_z(z) = bz$, the energy levels are Zeeman split by an amount $\Delta E = \mu m_s B = \mu b m_s z$ [Fig. 1(a)]. Now illuminate the atom with weak, collimated σ^- light propagating in the $-\hat{z}$ direction and σ^+ light propagating towards $+\hat{z}$. If the laser is tuned below the $B=0$ resonance frequency, the atom at $z > 0$ will absorb more σ^- photons than σ^+ photons (since the laser frequency is closer to the $\Delta m = -1$ transition frequency) and consequently will feel a net time-averaged force toward the origin. For an atom at $z < 0$, the Zeeman shift is reversed, and the force will again be directed to $z=0$. Tuning the low-intensity laser to the red of resonance also provides damping, as in the "optical molasses" demonstrated previously.[6]

The scheme is readily extended to three dimensions by adding counterpropagating beams along the x and y axes, and a "spherical quadrupole" magnetic field as shown in Fig. 1(b). The field is of the type used by Migdall *et al.* to confine spin polarized atoms magnetically,[1] though the field magnitudes in the light trap are about 100 times smaller and contribute negligibly to the confining force. If the x and y axis beams are polarized as shown, the conditions for confinement will be satisfied independently along each of the three axes.

The method can also work for atoms with a more complicated hyperfine structure. In the case of the sodium $3S_{1/2}$-$3P_{3/2}$ transition, e.g., the ground states have total
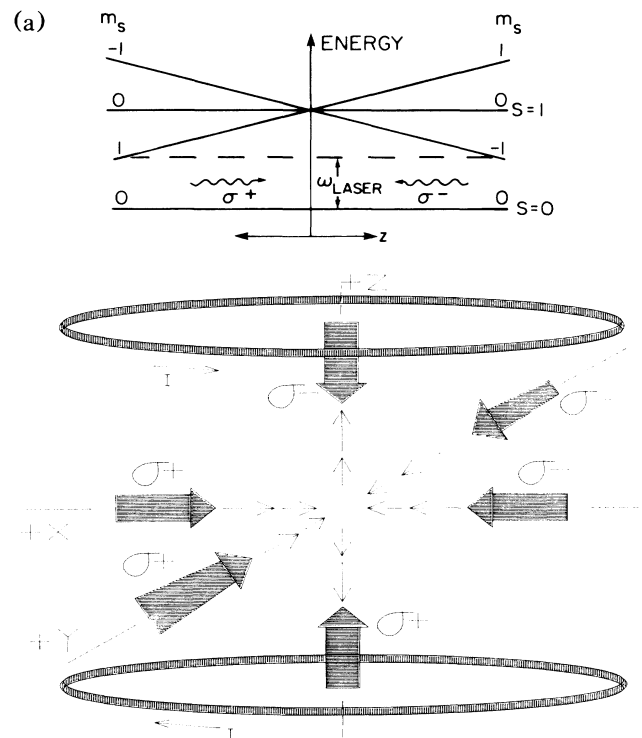

FIG. 1. (a) Energy-level diagram of hypothetical atom having spin $S=0$ ground state and spin $S=1$ excited state, immersed in a magnetic field $B_z(z) = bz$. The frequency and polarization of the counterpropagating laser are chosen to produce damping and restoring forces for the atom's z-axis motion. (b) Trapping scheme in three dimensions. The "spherical quadrupole" field is generated by two coils of opposing current placed along the z axis approximately as shown. The field along the axes, indicated by the light arrows, is parallel to its respective axis. Laser light, indicated by the heavy arrows, counterpropagates along x, y, and z, and is polarized as shown with respect to the axis of propagation.

angular momentum $F = 2,1$ and the excited states have $F' = 3,2,1,0$. Figure 2 shows the results of a computer model of the trap where the average force in one dimension was calculated for several magnetic field strengths and atomic velocities. Two laser frequencies are used in the model to avoid optically pumping the atom into an inaccessible ground hyperfine state. The results show the presence of both restoring and damping elements of the force. If we consider small displacements and velocities, we may write $F \approx -\kappa x - \alpha \dot{x}$; the model in this regime gives $\kappa = (dB/dz)2.67 \times 10^{-16}$ dynes cm^{-1}, and $\alpha = 6.07 \times 10^{-18}$ dynes/cm s^{-1}. The equation of motion for small oscillations about the origin is simply that of a damped harmonic oscillator: $\ddot{x} + 2\beta\dot{x} + \omega_0^2 x = 0$, where $\omega_0^2 \equiv \kappa/m$, $\beta \equiv \alpha/2m$, and m is the mass of the atom. If we assume a nominal field gradient of 5 G/cm, we obtain $\omega_0 \approx 6 \times 10^3$ s^{-1}, and $\beta \approx 8 \times 10^4$ s^{-1}. Thus, the motion is strongly overdamped; the relaxation to the origin (at this gradient) is governed by a time constant $\tau_{simul} \approx 2\beta/\omega_0^2 \approx 4$ ms. The model was also used to examine the case when the atom ventures off from the principal axes, where the additional complication of $\Delta m = 0$ transitions arises. It was found that the trap was indeed restoring for small displacements in any direction.[7]

The spontaneous–light-force trap described above was demonstrated in the same apparatus previously used to generate optical molasses,[6] with only a few modifications. Six antireflection-coated quarter wave plates were placed adjacent to the six windows to generate circularly polarized light and to reverse the polarization of the reflected beams. Also, a pair of coils with opposing current was positioned within the vacuum chamber to
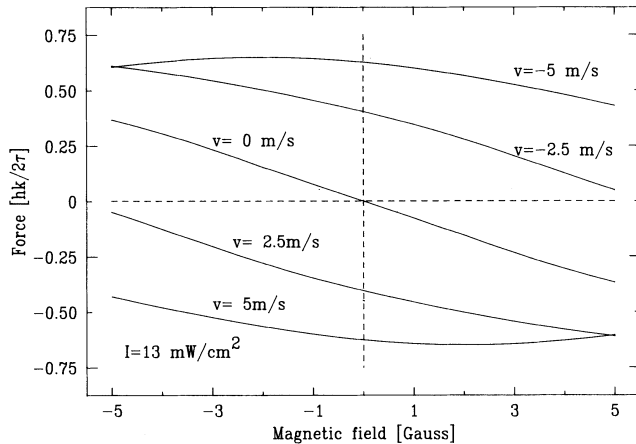

FIG. 2. Result of computer model for the forces felt by a sodium atom along the z axis in the light trap. The lasers are tuned 10 MHz to the red of the $F = 2$ to 3 and 1 to 2 transitions in the $D2$ line, with an intensity of 13 mW/cm^2 per sideband. $k = 2\pi/\lambda$, $\tau = 16$ ns is the natural lifetime for the sodium $D2$ line; $\hbar k/2\tau = F_{max} = 3.5 \times 10^{-15}$ dynes, the maximum theoretical spontaneous force attainable with this transition.

generate the desired magnetic field. Each 5-cm-diam coil consisted of three turns of $\frac{1}{8}$-in.-o.d. copper refrigerator tubing sheathed in fiberglass insulation. Water was passed through the coils for cooling.

Improvements were made in the remaining apparatus to increase its reliability and repeatability. The ring dye laser was actively locked to a crossover resonance of the Na $3S_{1/2}$-$3P_{3/2}$ transition in a saturated absorption cell. This allowed us to determine the laser frequency accurately and to provide the frequency stability necessary to observe atoms that remain in the trap for half an hour or more. A 5-m single-mode optical fiber was used as a spatial filter for the trapping beams; this also improved their pointing stability (and day to day alignment) since spatial drift of the dye laser output could be compensated by minor changes in the input coupling of the fiber. We used a larger $1 \times 1 \times 20$-mm^3 LiTaO$_3$ crystal as an electro-optic modulator to provide optical sidebands with a minimum of beam distortion. The crystal was driven by a resonant circuit tuned to 856 MHz with $Q \approx 100$, allowing us to maximize the fraction of light in the two first-order sidebands ($\approx 70\%$ total) with an rf drive power of less than 0.5 W.

The trap was loaded with atoms evaporated by a pulsed yttrium-aluminum-garnet laser and cooled by a frequency-swept laser beam as previously described.[6] Once slowed to velocities less than 2×10^3 cm s^{-1}, the atoms drifted into the molasses region and were trapped. The combination of restoring and damping forces compressed the trapped atoms into a small bright ball. Since the storage time of the atoms in the trap was considerably longer than the 10-Hz rate of the pulsed atomic beam, many (≈ 100) pulses of atoms could be injected into the trap before an equilibrium density was achieved.

Trapping was observed over a wide range of conditions. With a fixed 1712.4-MHz optical sideband splitting, the laser frequencies were tuned to the red of the $F = 2 \rightarrow 3$ and $1 \rightarrow 2$ transitions or the $F = 2 \rightarrow 2$ and $1 \rightarrow 0$ transitions. The former tuning produced a much more compact ball of atoms than the latter. For a fixed light intensity and a variety of laser detunings and magnetic field strengths, the size of the atom cloud, measured with a video camera and video wave-form analyzer, is shown in Fig. 3. The resolution of the camera system was better than 200 μm. We found that the diameter of the trapped atom cloud varies inversely as the square root of the current, consistent with our model of a harmonic trap potential and an atomic temperature independent of the current. Using a independent measure of the temperature (described below), we obtain a force constant of $8.8B' \times 10^{-17}$ dynes cm^{-1}; When $B' = 5$ G cm^{-1}, this implies an oscillation frequency $\omega_0 = 3.4 \times 10^3$ s^{-1} when trapping with the stronger transition. The results are thus in accord with the predictions of the model.
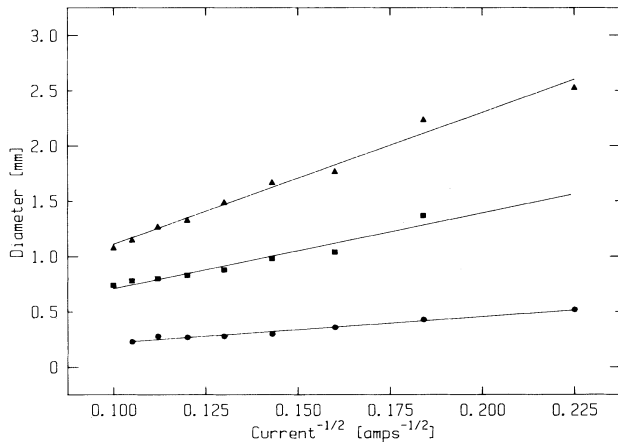
The restoring and damping forces were studied by

FIG. 3. The trap size (FWHM) as a function of the current through the magnets, for various laser tunings. The circles represent tuning 8 MHz to the red of the $F=2$ to 3 and 1 to 2 transitions, with an intensity of 13 mW/cm^2 per sideband. The squares and triangles represent tuning 8 and 20 MHz to the red of the $F=2$ to 2 and 1 to 0 transitions, respectively, with an intensity of 15 mW/cm^2.

FIG. 4. Decay of atoms from the trap. The magnetic field gradient was $\simeq 12$ G cm^{-1}, and the laser intensity was $\simeq 20$ mW/cm^2 per sideband. The pressure was $\simeq 5 \times 10^{-11}$ Torr. The line indicates an exponential decay having a time constant of 95 s, which we observed at lower densities.

pushing the atoms from the center of the trap, then releasing them and allowing them to reequilibrate. Their relaxation to the origin was detected by placing an aperture around the image of the trap at equilibrium. Light passing through the aperture was detected by a photomultiplier tube; when the atoms were displaced from equilibrium, the signal from the photomultiplier tube would decrease. Two methods were used to displace the atoms: Either a neutral density filter was placed in one of the retroreflected beams (the trap was stable for a total attenuation of 0.6), or a cw probe laser was introduced (stability was destroyed for $I > 0.1I_{sat}$). The maximum displacement was $\simeq 1$ mm. With a field gradient of 5 G cm^{-1}, both measurements yielded a restoring force of $\simeq 10^{-14}$ dynes cm^{-1} when $I = 10$ mW/cm^2 per beam (in each sideband) and $\delta = -10$ MHz, giving an oscillation frequency of $\omega_0 = 1.5 \times 10^4$ s^{-1}. This is approximately 2 times larger than ω_0 obtained from the model results at the higher intensity, which is fair agreement considering the experimental uncertainty and theoretical simplifications.

Once the trap was fully loaded, the yttrium-aluminum-garnet laser and chirped laser pulses were turned off, and the decay of the trap fluorescence was recorded as shown in Fig. 4. The longest lifetimes ($1/e$ $\simeq 2$ min) were recorded at pressures of 5×10^{-11} Torr, achieved by cooling a cooper shroud inside the vacuum chamber to liquid-nitrogen temperatures. For low densities or later times ($t > 5$ s), the decay curve approached a simple exponential whose time constant decreased with increasing background pressure. This indicates that atoms were being expelled from the trap by collisions with the background gas. The initial decay for higher
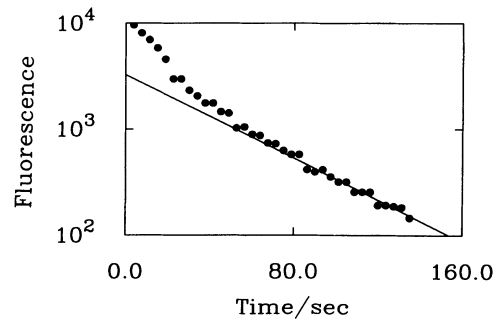
densities was dominated by a loss which can be fitted to the square of the density of the trapped atoms. A detailed study of this loss mechanism will be presented in a future publication.

By measuring the absorption of a weak, resonant probe beam with the trapping light both on and off, we determined the ratio of the average excited-state population to the average ground-state population under various experimental conditions. With a magnet current of 50 A (corresponding to $B' \simeq 10$ g cm^{-1} along z) and tuning to the red of the stronger ($F = 2 \rightarrow 3$, $1 \rightarrow 2$) transitions, e.g., we found this ratio to be $\simeq 3:4$. Measurements of the absolute fluorescence from the trapped atoms with a calibrated photomultiplier tube and lens assembly then implied that 3×10^6 atoms could be confined to a region $\simeq 320$ μm in diameter (FWHM). Thus the atomic density is 1.8×10^{11} atoms cm^{-3}. When the laser was tuned to the red of the $F = 2 \rightarrow 2$ transition, the number of atoms trapped was $\simeq 1.2 \times 10^7$ with a trap diameter of 1 mm, giving a density of $\simeq 2 \times 10^{10}$ atoms cm^{-3}. The absorption of the probe beam was also used as an independent measure of the density. The peak absorption observed was 80% through $\simeq 300$-μm path which, with the assumption of a simple two-level atom, corresponds to a density of roughly 5×10^{10} atoms cm^{-3}. It is important to note that the rapid nonexponential loss mechanism seen at higher densities is responsible for keeping the atomic densities below 10^{12} atoms cm^{-3} under the present loading conditions. By adjustment of experimental parameters to limit the density of atoms (misalignment of the trapping beams, the tuning to the weaker transition, and the use of weak light intensities and field gradients), up to 10^8 atoms have been contained.

The effective depth of the trap was measured by giving the trapped atoms an impulse from an additional beam while the trapping lasers were momentarily off. We find that with an intensity per side band of 30 mW/cm^2, a

light pulse of 18 μs was necessary to eject $\simeq$80% of the atoms from the trap. Thus, atoms at the center of the trap require a velocity of $\simeq$1600 cm s^{-1} to escape, implying a trap depth of $\simeq$0.4 K.

We have also measured the fraction of atoms that remain in the trap after the molasses beams have been shut off for various times. At early times, the loss is dominated by atoms that leave the trapping region ballistically before the light is turned back on. We can estimate the mean atomic velocity $\bar{v}$ by observing that half the atoms are lost in the first 15 ms of darkness; if we assume a capture radius of 1 cm, we obtain a $\bar{v}$ of 45 to 85 cm s^{-1}, corresponding to a temperature of 300 to 1000 μK. Trapping with the $2 \rightarrow 2$ transition produced a gas 2 orders of magnitude hotter than trapping on the $2 \rightarrow 3$ transition.

The trap is very robust and does not critically depend on balanced light beams, purity of the circular polarization, or laser frequency (the trap worked over a 25-MHz tuning range). Trapping was observed for peak magnetic fields as low as 5 G and laser intensities ranging from 30 to 0.4 mW/cm^2. We were able to load the trap without the use of the chirped slowing laser by capturing atoms in the slow velocity tail of the pulsed atomic beam. When the laser beams were slightly misaligned, the potential well was no longer simply harmonic, causing the atoms to swirl around in rings or form irregular shapes. The atoms would sometimes settle into one of several local potential minima, and could be made to oscillate between them.

To summarize, we have trapped over 10^7 neutral atoms for over 2 min. We utilized a magnetic field to tune the atomic resonance, enabling radiation pressure to provide both cooling and damping forces. The confinement volume is several cubic centimeters and the effective depth is $\simeq$0.4 K. The density of atoms is $\simeq$2$\times$10^{11} atoms cm^{-3} at a temperature of $\simeq$600 μK.

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

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

[3]V. Bagnato, G. Lafyatis, A. Martin, E. Raab, and D. Pritchard, Phys. Rev. Lett. **58**, 2194 (1987).

[4]D. E. Pritchard, E. L. Raab, V. Bagnato, C. E. Wieman, and R. N. Watts, Phys. Rev. Lett. **57**, 310 (1986).

[5]S. Chu, M. Prentiss, J. Bjorkholm, and A. Cable, in *Laser Spectroscopy VIII,* edited by S. Swanberg and W. Pearson (Springer-Verlag, Berlin, 1987).

[6]S. Chu, L. Hollberg, J. Bjorkholm, A. Cable, and A. Ashkin, Phys. Rev. Lett. **55**, 48 (1985).

[7]Proceedings of International Laser Science Conference II, October, 1986 (to be published).