Raman Cooling of Atoms in an Optical Dipole Trap

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We have Raman cooled sodium atoms below the photon recoil temperature in a novel type of blue-detuned optical dipole force trap. In this trap 4.5×10^5 atoms have been cooled to an effective three dimensional temperature of 1.0 μK at a final density of 4×10^{11} cm^{-3}. No atoms were lost during the cooling process. The phase space density increased by a factor of 320 over the uncooled sample. This is the highest phase space density achieved by an all-optical cooling method.

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In the field of laser cooling and atom trapping, the magneto-optic trap (MOT) [1] and polarization gradient molasses [2] represent the standard for atomic phase space density. These methods access typical densities and temperatures of $\sim 10^{11}$ cm^{-3} and $\sim 10T_{\mathrm{rec}}$, respectively, where $T_{\mathrm{rec}} = \hbar^2\mathbf{k}^2/mk_B$ is the single-photon recoil temperature, $\mathbf{k}$ is the wave vector of the cooling light, and m is the mass of the atom. Greater phase space densities are needed for experiments in quantum statistics, notably those seeking degenerate phenomena. Precision measurements and atom interferometry can also be greatly benefited: large numbers of atoms at temperatures far below the recoil temperature at low density can be prepared by adiabatically expanding a high phase space density sample.

At present evaporative cooling, first demonstrated on magnetically trapped hydrogen [3], is the only known method for advancing beyond the phase space density of the MOT. Recently evaporation of laser cooled atoms has led to independent observations of Bose-Einstein condensation (BEC) of magnetically trapped alkalis [4–6]. Despite this dramatic success, evaporative cooling does have drawbacks. It can be difficult to initiate, since efficient evaporation requires that ≥ 100 elastic collisions occur in one $1/e$ trap lifetime [7]. This condition requires that either the initial elastic collision rate and, thus, density be much higher than is typical for laser cooled samples [4,6] or the trap lifetime be extremely long [5]. In addition, the methods demonstrated in Refs. [4–6] implemented strong magnetic fields, thus virtually excluding precision measurement applications that require the atoms to have minimal internal level shifts or trapping of several hyperfine levels.

An alternative, all-optical cooling method can solve these issues. There are optical techniques which can subrecoil cool in free space: velocity selective coherent population trapping (VSCPT) [8] and Raman cooling [9]. Both have been extended to two and three dimensions [10]. Neither scheme has been implemented on magnetic traps. Raman cooling, however, has been applied to optical dipole traps. In low density red-detuned dipole traps, $\sim 10^4$ atoms have been cooled in one dimension to an effective temperature of $0.35T_{\mathrm{rec}}$ [11].

In this Letter we report on the application of Raman cooling to a new type far-off resonance dipole trap and have cooled sodium atoms in three dimensions to a temperature of 1.0 μK ($0.42T_{\mathrm{rec}}$) resulting in an atomic density of 4×10^{11} cm^{-3}. These results represent the highest atomic phase space density attained by any direct laser cooling technique, corresponding to a factor of ~ 250 improvement over the previous high [12]. The trap creates a free-space-like environment which captures all hyperfine ground states and can hold up to 4.5×10^5 atoms after Raman cooling, an unprecedented number for optical dipole traps. Atoms in far blue-detuned dipole traps are repelled from the trapping light maxima and spend most of their time in the dark [13], resulting in photon scattering rates and time-averaged light shifts which are much less than they would be in red-detuned traps of similar detuning and depth. Consequently, Raman cooling's spectral resolution and, therefore, compatibility with a dipole trap is primarily limited by the oscillatory motion of the atoms. If the atomic oscillation frequency approaches the two-photon Raman Rabi frequency, the velocity selective transitions used in Raman cooling become broadened by motional sidebands [14], thus reducing cooling performance. Other notable trap considerations are capture volume, storage time, and confinement. Our trap addresses all these issues by providing a large volume and tight confinement in three dimensions. Previous work [13] used a blue-detuned optical dipole trap that had weak parabolic confinement along one axis and was able to capture only a modest number (~ 4000) of atoms. The combination of volume and increased trap depth afforded by the present configuration lead to up to a 100-fold improvement in loaded atoms over the previous blue-detuned trap. The large volume also allowed a given atom to maintain a more constant velocity over the time scale of a typical Raman transition, leading to reduced, but still present, motional broadening effects. A final benefit from the trap is its ability to couple all three dimensions to one another through highly ergodic, chaotic atomic trajectories. This feature allowed all three dimensions to be cooled by Raman cooling only one of them. We investigated two

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trap geometries: a tetrahedral box configuration, where the atoms were confined by light in all dimensions, and an "inverted pyramid" configuration, which relied on gravity for vertical confinement. The inverted pyramid provided superior performance in the number of loaded atoms, lifetime, and Raman cooling compatibility.

The experimental details are similar to those described in previous work [15]. The formation of the MOT and loading of the dipole trap were accomplished as follows. Sodium atoms from a thermal source were cooled by a chirped slowing beam and loaded into a MOT. The intensity of the MOT beams was 3 $\mathrm{mW/cm^2}$ and the light was detuned 25 MHz below the $3S_{1/2}\,F = 2$ to $3P_{3/2}\,F = 3$ transition. The magnetic field gradient was 10 G/cm. The MOT beams passed through a 1.73 GHz electro-optic modulator (EOM) which produced a repumping sideband nearly resonant with the $3S_{1/2}\,F = 1$ to $3P_{3/2}\,F = 2$ state. The sideband intensity was 10% of the carrier. Throughout the loading period (typically 1 s), the MOT was intersected by the dipole trapping beams. Exactly 20 ms before the magnetic field and MOT beams were turned off, the intensity of the sideband was stepped down by a factor of 16 and held low for 19 ms. During this period the MOT's temperature and density became 60 μK ($25T_{\mathrm{rec}}$) and 6×10^{11} $\mathrm{cm^{-3}}$, respectively. The sideband was shut off for the remaining 1 ms in order to completely optically pump the atoms into the $3S_{1/2}\,F = 1$ state. The stepped sideband technique increased the number of atoms loaded into the dipole trap by more than an order of magnitude over the standard method, i.e., not stepping the sideband. We obtained comparable loading results ($\sim 1/2$ as many atoms) with a spatial dark MOT [16], but the present method is easier to implement.

The trap was constructed from four sheets of argon ion laser light that intersected to form a region of free space that was bounded by an inverted, square-based pyramid as depicted in Fig. 1. A 29 W argon ion laser operating all lines was used to produce the trapping beams. The beam passed through two prisms to spatially separate the lines. The 488 and 514 nm lines with powers of 6 and 10 W, respectively, were separated, focused with cylindrical lenses to produce elliptical sheets of light, and recombined with a dichroic mirror. The sheets were aligned with their long axes oriented $+25°$ and $-25°$ off from the vertical direction of gravity and were overlapped at their FWHM intensities. At the MOT's center the sheets had tight axes of 10 μm and long axes of 575 μm, thus forming a V-shaped, troughlike trap, similar to the one demonstrated in Ref. [13]. The sheets of light had parallel linear polarizations. After exiting the MOT, the light was redirected to cross the first trough trap at 90°. While being redirected, the light was reimaged twice to produce a noninverted, second trough at the MOT's center. The two troughs intersected to form the inverted pyramid. The polarizations of the troughs were set to be orthogonal to suppress standing wave effects. The trap depth, limited by the intensity of the weakest wall near the apex of the pyramid, was $9T_{\mathrm{rec}}$. Gravity provided confinement in the third dimension. As atoms cool, they are compressed by gravity into the pyramid's apex. We also trapped in a tetrahedral box configuration. By imaging the first trough only once, we could produce a second inverted trough which formed a lid to the first trap. The relative distance between the "lid" and the "floor" was adjusted to maximize the number of loaded atoms.

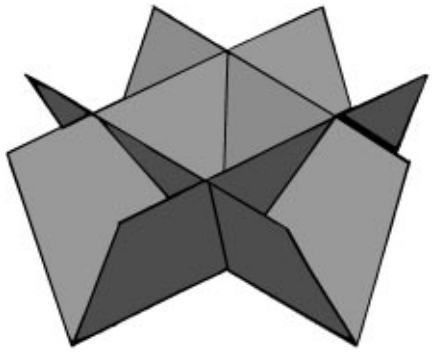

FIG. 1. Schematic of the far blue-detuned optical dipole trap geometry.

The size of the dipole trap was monitored by switching on the MOT beams and imaging the fluorescence onto a charge coupled device (CCD) array. The image was formed by an $f/2.5$ lens placed directly above the dipole trap. For the size measurements the light was pulsed on for 10 μs and detuned 25 MHz red from the $3S_{1/2}\,F = 2$ to $3P_{3/2}\,F = 3$ transition to minimize broadening effects introduced by ballistic expansion. The temperature of the atoms was measured either by a time-of-flight technique or by velocity selective Raman transitions. The density in the trap was determined by transferring the trapped atoms from the $3S_{1/2}\,F = 1$ to the $3S_{1/2}\,F = 2$ state by adiabatic passage [17] using a chirped microwave field, and then measuring the absorption of a weak, circularly polarized probe beam resonant with the $3S_{1/2}\,F = 2$ to $3P_{3/2}\,F = 3$ transition. The result was used to calibrate the CCD imaging system for subsequent density measurements. The total number of atoms was determined by measuring the atomic fluorescence with a calibrated photomultiplier tube. The density and number measurements had relative uncertainties of $\sim$30% and $\sim$20%, respectively.

We trapped 4.5×10^5 atoms in the inverted pyramid trap. The projected image of the atomic cloud, as viewed from above, appeared to be a square distribution, where a side had an rms length of 330 μm. The estimated initial peak density was 2×10^{10} $\mathrm{cm^{-3}}$ at a temperature of 7.7 μK.

Raman cooling was accomplished by a one-dimensional beam switching scheme using a setup similar to the one in Ref. [9]. The output from a second dye laser was divided into two 250 mW beams by a 30 MHz

acousto-optic modulator (AOM). The undeflected beam passed through a scannable 1.74 GHz EOM. The stimulated Raman transitions were excited by the upper sideband of the EOM beam and the downshifted AOM beam. Additional AOM's provided the amplitude modulation and beam switching. The axis defined by the Raman beams was set at 45° with respect to the trapping beams, i.e., parallel to one of the diagonals of the square atomic spatial distribution. The size of the trap allowed the beams to be focused to a 0.4 mm $1/e^2$ waist. The Raman light was detuned 230 GHz to the blue of the $3S_{1/2}$ to $3P_{3/2}$ transition in order to suppress spontaneous emission and photoassociative losses [18]. The optical pumping pulses were produced from the dye laser that provided the MOT beams and could be directed parallel or antiparallel (within 5°) to the Raman axis by reversing the optical pumping beam's direction with a Pockel's cell and polarizer.

The highest phase space densities occurred for a cooling sequence consisting of four Blackman pulses which had durations of 30, 30, 30, and 60 μs and red detunings of 500, 400, 300, and 200 kHz below the hyperfine resonance. The peak Rabi frequency was ~45 kHz. The closest detuned pulse excited atoms centered about velocities $\pm 2\hbar k/m$, substantially further away than would be typical in free space. Any attempt to detune closer than 200 kHz resulted in atoms near zero velocity being dramatically expelled, possibly because of residual motional sidebands which broadened the velocity width of the pulse. This conjecture is supported by hole burning experiments performed on the Doppler profile of trapped and untrapped atoms. We could burn holes with a FWHM of $\sim 0.25\hbar k/m$ for atoms in free space and yet with the same beams and parameters, could only observe a "hole" which had a width comparable to the initial velocity distribution, $\sim 1.0\hbar k/m$. Still, these holes were considerably better than the ones observed in single focus [11] and crossed [19] red-detuned dipole traps. A similar loss of atoms near zero velocity was observed when appropriately detuned square wave pulses were used [20]. Both of the aforementioned efforts lead to colder temperatures ($\sim 0.1 T_{\mathrm{rec}}$), but resulted in no additional gain in phase space density. The best optical pumping parameters were nearly identical to those used in free space Raman cooling [9]. A 1 μs long pulse followed every Raman pulse. The intensity of the optical pumping light was 100 mW/cm^2 and tuned 20 MHz red of the $3S_{1/2}\, F = 2$ to $3P_{3/2}\, F = 2$ transition. The optical pumping direction was chosen to always be in the same direction as the velocity kick of the Raman pulse. Unlike the findings of Ref. [9], reversing the direction of the optical pumping pulse with respect to the Raman kick for detunings of 200 kHz or less did not lead to any improvement.

After 180 ms of Raman cooling with the optimized parameters, the phase space density saturated. Figure 2(a) shows a velocity scan corresponding to a rms velocity of $0.65\hbar k/m$ along the Raman axis. The projected spatial distribution after cooling was still square, where the FWHM length of a side was reduced to 125 μm. Figure 2(b) shows the trap size along a diagonal of the square distribution after cooling. Because of the symmetry of the spatial distribution, the velocity along the direction orthogonal to the Raman axis in the plane of the trapping beams was assumed to also be $0.65\hbar k/m$. This velocity symmetry was verified by video time of flight. Assuming the dimension out of the plane also had a final velocity of $0.65\hbar k/m$, we find that the effective temperature, given by $T_{\mathrm{eff}} = m(v_x^2 + v_y^2 + v_z^2)/3k_B$, is 1.0 μK ($0.42 T_{\mathrm{rec}}$). The final density was 4×10^{11} cm^{-3}. Raman cooling increased the phase space density of the atomic sample by a factor of 320, a factor of ~400 from BEC [21].

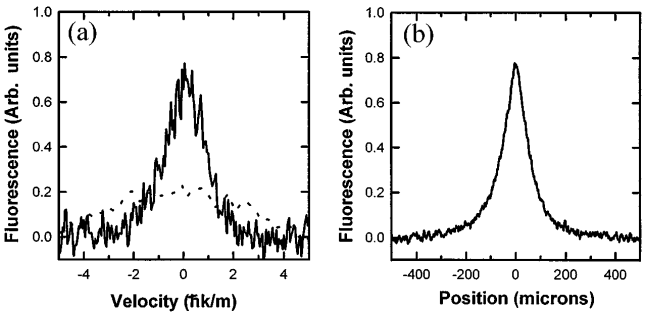

FIG. 2. (a) The velocity distribution before (thin line) and after (thick line) Raman cooling, as measured by stimulated Raman transitions. The final rms velocity was $0.65\hbar k/m$. Note the discrepancy in the areas of the velocity curves. Before cooling the Raman beams were of comparable size to the trap, hence, fewer atoms were detected. (b) Trap size along the diagonal of the square, spatial distribution after Raman cooling.

The lifetime of the Raman cooled pyramid trap is shown in Fig. 3. An initial rapid decay occurred in the first second after Raman cooling, reducing the number of atoms to 2.9×10^5. Afterwards, the decay tended to a single exponential with an extrapolated $1/e$ lifetime of 7.0 s. The lifetime was observed to be independent of background pressure from 7×10^{-11} down to 2×10^{-11} Torr. We measured a heating rate of $0.22 T_{\mathrm{rec}}$/s, which most likely limited the lifetime of the trap. The observed heating rate is a factor of ~30 higher than the estimated heating rate due to photons scattered from the trapping beams.

The box trap initially loaded 2.0×10^5 atoms at a temperature of 14.8 μK. We were able to Raman cool the box trap to 1.2 μK at a density of 0.5×10^{11} cm^{-3} using cooling parameters similar to the ones mentioned above. The trap after Raman cooling exhibited a very fast decay where 2/3 of the atoms were lost in 100 ms. After 700 ms and roughly an order magnitude loss in atoms, the extrapolated lifetime agreed with the inverted pyramid's lifetime. In view of this substantial and unexplained loss rate, we abandoned the box configuration.

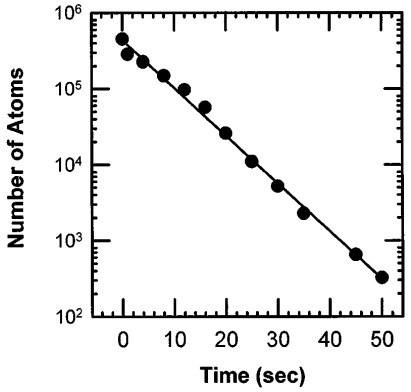

FIG. 3. Lifetime of the inverted pyramid trap at a background pressure of 2×10^{-11} Torr. The solid line is a fit by a single exponential neglecting the first data point.

The elastic collision rate of the inverted pyramid trap increased by a factor of 7 after cooling, corresponding to $\sim$20 collisions in one trap lifetime [22]. Efforts were made to further increase the collision rate to promote the onset of evaporation. Regardless of the cooling parameters or the trap conditions (relative beam alignment, angle, sheet width, etc.), we could not Raman cool the atoms to final densities above 10^{12} cm^{-3} [23]. There is strong evidence that ground state hyperfine changing collisions place a limit on the maximum density achievable with Raman cooling in dipole traps [24]. A number of active compression techniques that involve deflecting the trapping beams were attempted. Despite these efforts, we were unable to initiate evaporative cooling. For comparison, strong evaporative cooling was witnessed in a crossed red-detuned dipole trap [15] that had an initial collision rate and lifetime of $\sim$100 Hz and 0.8 s, respectively, despite an observed heating rate of $0.19 T_{\mathrm{rec}}/\mathrm{s}$. In the present case, evaporative cooling should be possible after elimination of the heating rate.

Raman cooling has been able to produce subrecoil temperature atomic samples at densities approaching 10^{12} cm^{-3} in optical dipole traps, corresponding to the highest phase space densities attained by nonevaporative techniques. The trap provides a near perturbation free environment for the trapped atoms and long storage times. Future efforts include extending the lifetime of the trap and pursuing evaporative cooling.

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[21] We assume equal distributions among the $F = 1\ m_F$ levels. The effective decrease in density (a factor of $\sim$3) has been included in the BEC estimate.
[22] The elastic cross section for $F = 1, m_F = -1$ state sodium atoms was reported to be 6×10^{-12} cm^{-2} in Ref. [6]. For our unpolarized atoms we expect the averaged cross section to be a factor of $\sim 2/3$ smaller due to issues related to the quantum distinguishability.
[23] Similar density limitations for Raman cooling were observed in Ref. [19].
[24] In the crossed red-detuned dipole trap of Ref. [19] at a density of $\sim 5 \times 10^{11}$ cm^{-3} with equal populations in the two ground states, atoms in the $F = 2$ (and $F = 1$) state decayed with a time constant of $\sim$100 ms, shorter than the typical saturation time for Raman cooling.