Degenerate Raman Sideband Cooling of Trapped Cesium Atoms at Very High Atomic Densities

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We trap 10^7 cesium atoms in a far red detuned 1D optical lattice. With degenerate Raman sideband cooling we achieve a vibrational ground state population of 80% for the steep trapping direction. Collisional coupling enables us to cool the spin-polarized gas in 3D without loss of atoms to a peak phase space density of $1/180$ at a mean temperature of 2.8 μK and a density of 1.4×10^{13} cm^{-3}. [S0031-9007(98)08002-8]

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Evaporative cooling of an optically precooled atomic gas in a magnetic trap to Bose-Einstein condensation (BEC) has become a well-established technique [1]. Although laser cooling methods contribute the bulk of the phase space compression in these experiments, severe limitations at densities approaching one atom per cubic wavelength [2] make it necessary to use evaporative cooling to reach the degenerate quantum regime. In spite of the great success of evaporative cooling in this role, however, the attainment of BEC by optical means remains an important goal. Optical cooling can be much faster than evaporation and does not remove the majority of the originally trapped atoms, which should allow more atoms to be condensed faster. In addition, evaporative cooling relies heavily on a favorable ratio of elastic to inelastic collision rates, which may preclude the production of a condensate by evaporative cooling in a magnetic trap altogether for some elements [3,4]. Finally, for the purpose of sympathetic cooling [5], a dense, continuously optically cooled atomic gas in thermal contact with the sample of interest would constitute a powerful refrigerator, with a cooling power as large as one quantum of vibration energy per oscillation period. For a trap oscillation frequency of 200 kHz and equal numbers of "coolant" and "thermal load" atoms, the cooling rate corresponds to 1 K/s.

The density limitations associated with conventional polarization gradient cooling are believed to be due to the reabsorption of spontaneously emitted photons at high optical densities and to light-induced atom-atom interaction effects [2]. While it had previously been suggested that these effects would prevent Bose-Einstein condensation by laser cooling in weakly confining traps [6], recent theoretical works have explored ways to overcome these limitations. Apart from using strongly anisotropic traps with larger surface area-to-volume ratios and therefore larger photon escape probabilities, it has been proposed that the reabsorption problem could be overcome by making the photon scattering rate smaller than the trap vibration frequency [7]. In that case most of the scattering processes are elastic and do not heat the sample.

Lamb-Dicke traps, where the ground state spread is much smaller than the wavelength of the cooling light, are particularly promising in this context since their high vibrational frequencies permit a fast optical cooling rate. These traps offer the additional advantage that the condensation temperature can easily be higher than the recoil energy. Since the critical temperature for BEC in a 3D harmonic trap is proportional to the geometric mean of the oscillation frequencies in the three spatial dimensions [8], even a trap with just one tightly bound direction, e.g., a 1D optical lattice, can have a significantly higher condensation temperature than conventional magnetic traps. However, this higher critical temperature comes only at the expense of a higher critical density. It is therefore particularly important to suppress density-dependent heating mechanisms such as inelastic two-body collisions, and to develop a laser cooling method that remains efficient at very high atomic densities.

In steep traps where the vibrational structure can be spectrally resolved it is possible to cool the center-of-mass motion using sideband cooling techniques. Single ions have been cooled to the motional ground state in traps where the vibrational frequencies exceed the natural linewidth of the atomic transition [9]. For neutral atoms and the correspondingly weaker trapping forces, the vibrational levels can be resolved with two-photon Raman transitions, and Raman sideband cooling has recently been demonstrated in 2D and 1D [10,11].

In this Letter we present a Raman sideband technique with which we have cooled trapped neutral atoms to 3D temperatures similar to those achieved in free space using polarization gradient cooling, but at densities almost 2 orders of magnitude higher. Our method uses only the two lowest-energy atomic ground states, resulting in an enormous suppression of the heating and trap loss normally caused by inelastic two-body collisions. Although this is particularly important for Cs, which has exceptionally large spin-exchange and dipolar cross sections [3], limitations on the laser cooling of other atoms due to hyperfine-changing collisions have also been observed [12]. Our cooling technique works at densities of 10^{13} cm^{-3} and we observe no cooling-induced loss of atoms. The strong collisional coupling at these high densities allows us to cool all three dimensions using

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Raman sideband cooling only along a single tightly bound Lamb-Dicke direction.

Our cooling method is similar to that used in Ref. [10]. We begin with a spin-polarized atom in the state $|F = 3, m_F = 3; \nu\rangle$, where $\nu > 0$ denotes an excited vibrational state in the Lamb-Dicke direction (Fig. 1). An external magnetic field **B** is applied to shift this level into degeneracy with $|3, 2; \nu - 1\rangle$; since the vibration frequencies of the $m = 3$ and $m = 2$ potentials are approximately the same, this condition holds for all ν in the harmonic region of the trap [13]. A cooling cycle then consists of a degenerate Raman transition from $|3, 3; \nu\rangle$ to $|3, 2; \nu - 1\rangle$, followed by optical pumping back to $|3, 3\rangle$. Since the atom is tightly bound, the recoil momentum from the scattered photon is unlikely to change its vibrational state, and the atom is preferentially returned to $|3, 3; \nu - 1\rangle$, with one quantum of vibration energy removed. After subsequent cooling cycles $|3, 3; \nu - 1\rangle$ to $|3, 2; \nu - 2\rangle$, etc., the atom reaches the vibrational ground state which is dark to both the optical pumping and degenerate Raman transitions.

Since the Raman transitions use two isoenergetic photons, they can be driven by the trapping light itself, whose large intensity and detuning allow a sizable coupling in combination with low heating by spontaneous Raman processes. The coupling strength is given by the off-diagonal matrix element of the light shift operator [13], $\langle 3, 2; \upsilon - 1|U(\mathbf{r})|3, 3; \upsilon\rangle$, which for general polarization is nonzero only when the external magnetic field **B** is oriented at a nonzero angle β relative to the wave vector **k**. Different center-of-mass wave functions are coupled by the two-photon recoil associated with the spatial dependence of U, whose parity with respect to the Lamb-Dicke potential wells is determined by the polarization configuration of the standing wave. To drive transitions with $\Delta\nu = -1$, we use two counterpropagating running waves whose linear polarizations subtend an angle α [14]. The coupling strength for this configuration is approximately $\langle 3, 2; \nu - 1|U|3, 3; \nu\rangle = \nu^{1/2}(6^{1/2}/2)\varepsilon U_0 \eta \sin\alpha \sin\beta$, to leading order in the Lamb-Dicke parameter $\eta = kx_0$ [15]. Here U_0 is the trap depth for linearly polarized light, $\varepsilon = 2.34 \times 10^{-2}$ characterizes the relative strength of the Raman transitions for our detuning, and x_0 is the rms width of the ground state in position space. Note that both the radial and axial vibration frequencies are also functions of the angle α.

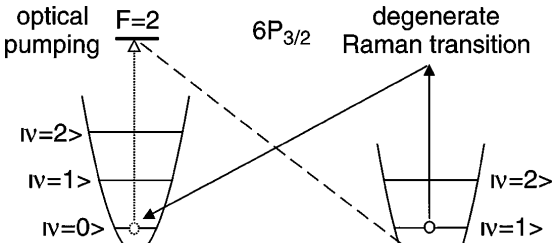

FIG. 1. Degenerate Raman sideband cooling in a Lamb-Dicke trap using the two lowest-energy magnetic levels. One cooling cycle consists of a vibration-changing Raman transition followed by optical pumping back to the $m_F = 3$ sublevel. The atoms accumulate in the vibrational ground state of the $m_F = 3$ level (black dots) which is dark to both the optical pumping light and the Raman transitions.

Our 1D lattice trap is produced by the TEM_{00} output of an optically injection-locked Nd:YAG laser system which we constructed. It produces a single frequency output power of 21 W at $\lambda = 1064$ nm that is used to form a vertical standing wave with a beam waist of 260 μm and a running wave power of 17 W at the position of the atomic cloud. For a linearly polarized standing wave the calculated trap depth [16] is $U_0/h = 3.2$ MHz or 160 μK, while the calculated axial and radial vibration frequencies are $f_{\mathrm{ax}} = 130$ kHz and $f_r = 120$ Hz, respectively. The estimated scattering rate induced by the trapping light is 2 s^{-1}.

We begin with a magneto-optical trap (MOT) that is loaded from a background cesium vapor with a time constant of 4.5 s. We collect 3×10^7 atoms in 500 ms in the MOT and then decrease the total repumping light intensity to 3.2 mW/cm^2 for 38 ms to compress the cloud. Subsequently, blue detuned Sisyphus cooling [16] is performed in the trap for 5 ms on the $6S_{1/2}$, $F_g = 3$ to $6P_{3/2}$, $F_e = 2$ transition with a detuning of $2\pi \times 18$ MHz. The MOT laser here serves as a repumper from the $F_g = 4$ ground state on the $6S_{1/2}$, $F_g = 4$ to $6P_{3/2}$, $F_e = 4$ transition. In the 1D lattice we trap a total of 1.0×10^7 atoms in a cigar-shaped cloud with a vertical FWHM of 2.5 mm. This length corresponds to 4700 individual pancake shaped traps each with an aspect ratio of 1000, spaced by 532 nm. The vertical density distribution is approximately Gaussian, yielding a population of 2.0×10^3 atoms per trap in the central region.

The lifetime of the trapped gas depends strongly on the hyperfine level. For atoms prepared in the lower hyperfine level $F = 3$ the decay is purely exponential with a background-pressure limited time constant of $\tau = 2.0$ s. For the upper hyperfine level we observe a much faster density-dependent loss due inelastic two-body collisions. Figure 2 shows the decay for an unpolarized sample prepared by optical pumping at $t_0 = 400$ ms in the upper hyperfine state $F = 4$ at $T = 14$ μK and $n = 1.1 \times 10^{12}$ cm^{-3}. The data are well described by a two-body loss process with a rate coefficient in agreement with a previously published value [17]. For atoms in the lower hyperfine level at zero magnetic field there are no exothermic two-body collisions.

We measure the axial and radial kinetic energy distributions of the trapped atoms using a time-of-flight method. The atoms are dropped by extinguishing the trapping light

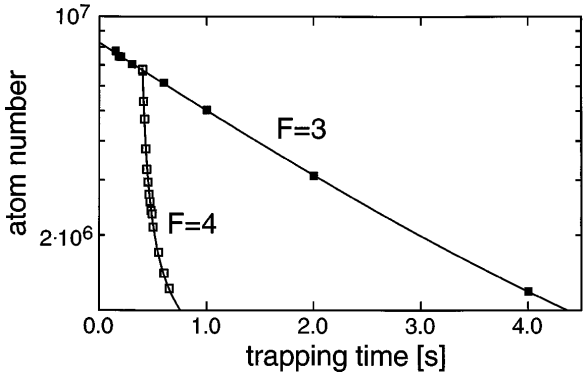

FIG. 2. Decay of the trapped gas for different hyperfine ground states. The open squares show the atom number upon preparation in the upper hyperfine state at the time $t_0 = 400$ ms. The initial density is 1.1×10^{12} cm^{-3}. The solid lines are fits including a two-body loss.

in 2 μs with an acousto-optic modulator. A light sheet is located 12 cm below the trap and the fluorescence from the falling cloud is imaged onto a photodiode and a CCD camera. From the temporal and spatial widths of these two signals, the axial and radial velocity distributions are extracted. By varying the turn-off time of the trapping light, we have verified that negligible adiabatic cooling occurs during the release. To measure the trap vibration frequencies, we use a parametric excitation technique similar to the one used in Ref. [18]. A 0.2% modulation is applied to the intensity of the trapping light, and a small heating is observed when this modulation is tuned to twice the atomic oscillation frequency. This procedure yields frequencies that agree to better than 10% with the calculated values, and gives accurate results for atoms near the bottom of the trapping potential. From the measured frequencies we calculate the potential curvatures, which in combination with measurements of temperature, atom number, and vertical cloud size are used to calculate the spatial and phase-space densities for the trapped gas.

Immediately after filling the trap, the axial temperature is 3 μK. The radial directions each have an initial mean kinetic energy of $W/h = 33$ kHz, and cannot be assigned a temperature for storage times shorter than the radial oscillation period. Within 150 ms the axial and the radial temperatures take on steady-state values of 15 μK. We believe that the observed increase is mainly due to the addition of trap potential energy during loading which is subsequently converted into kinetic energy.

For the degenerate Raman sideband cooling we apply a magnetic field of magnitude $B = 4hf_{\mathrm{ax}}/\mu_{\mathrm{B}}$, typically 230 mG, where μ_{B} is the Bohr magneton. The optical pumping beam is applied along the z direction with elliptical polarization such that it has both σ^+ and π components along the quantization axis defined by the external magnetic field. This mixture is necessary because the optical pumping is performed on the $6S_{1/2}$, $F_g = 3$ to $6P_{3/2}$, $F_e = 2$ transition to minimize excitation to the $F_g = 4$ ground state. We have experimented with cooling on the $F_g = 3$ to $F_e = 3$ transition, and have observed a strongly reduced efficiency, most likely because of the longer time the atoms spend in this state. In both cases, an additional repumping beam is applied on the $F_g = 4$ to $F_e = 3$ transition. We observe cooling for large ranges of parameters, however, the lowest 3D temperatures were obtained for $\alpha = 70°$ and $\beta = 8°$, which corresponds to a Rabi frequency of $\Omega/2\pi = 1.4$ kHz for the Raman transitions. The optical pumping rate from $F = 3$, $m_F = 2$ to $m_F = 3$ was $\Gamma_{32} = 70$ s^{-1} at an intensity of 8 μW/cm^2. Figure 3 shows the cooling resonance as a function of the Zeeman splitting for 200 ms of cooling time. The asymmetric shape is due to inhomogeneous broadening of the axial vibrational levels in the Gaussian beam profile of the trap. The second peak corresponds to twice the axial vibration frequency and represents cooling on the degenerate $|3, 3; \nu\rangle$ to $|3, 2; \nu - 2\rangle$ transition.

The evolution of the axial and radial temperatures vs cooling time is shown in Fig. 4. The initial cooling rate in the Lamb-Dicke direction is 11 mK/s. This rate increases with optical pumping intensity, but only at the expense of a less efficient radial cooling, probably resulting from increased radial recoil heating. When the axial temperature is cooled below the radial, the latter follows with a time constant of 50 ms. This coupling has been observed directly by heating the axial direction for a short time and monitoring the subsequent rethermalization. When the density is reduced this time constant becomes longer, and we therefore conclude that the coupling is due to collisions rather than to anharmonic mixing of the axial and radial motion. It should be noted, however, the thermalization time is much longer than the estimated collision time of 1 ms at our highest densities. One possible explanation is that at temperatures comparable to or smaller than the axial vibrational spacing it may take a larger number of collisions to repopulate higher axial vibrational states.

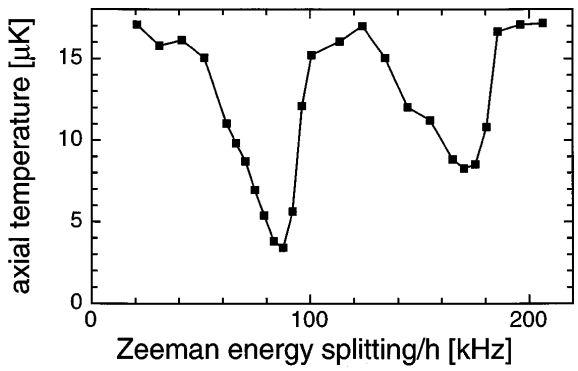

FIG. 3. Axial temperature after 200 ms of degenerate Raman sideband cooling as a function of the Zeeman energy difference between $m = 2$ and $m = 3$.

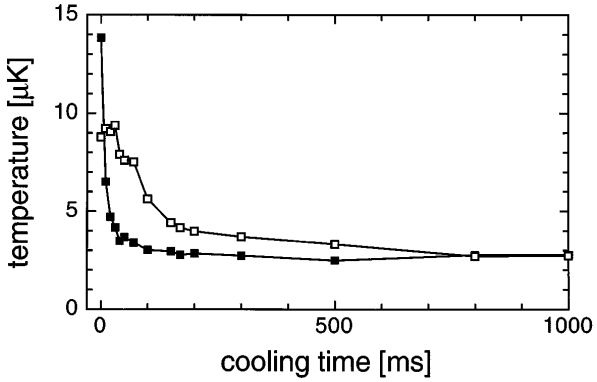

FIG. 4. Evolution of the axial (solid squares) and radial (open squares) temperatures. The degenerate Raman sideband cooling is applied only along the steep axial direction.

The lowest axial and radial temperatures obtained are $T_z = 2.5\ \mu$K and $T_\rho = 3.0\ \mu$K, respectively, after 500 ms of cooling. With the directly measured values for the vibration frequencies of 80 kHz and 115 Hz we calculate 80% population in the ground state of the Lamb-Dicke direction and a peak phase space density of $1/180$ for the traps in the central region. To our knowledge, this is the highest phase space density yet obtained by an optical method. The final peak spatial density is $1.4 \times 10^{13}\ \mathrm{cm}^{-3}$. The estimated uncertainties for the temperature, phase space density, and spatial density are 10%, 40%, and 25%, respectively. Finally, the axial motion can be further cooled to 340 nK by adiabatic expansion with a turn-off time constant of 130 μs.

Atoms were previously sideband cooled in a 2D lattice without confinement or temperature measurement in the third dimension, yielding a 2D kinetic temperature of 0.97 μK and a 2D ground state population exceeding 95% [10]. In a 1D lattice trap a 1D temperature of 3.6 μK has been achieved, at the expense of heating the two radial directions to 24 μK [11]. In contrast, relying on collisional coupling at high densities, we cool all three dimensions to 2.8 μK by 1D sideband cooling. Our cooling performance may therefore be limited by density-related processes such as reabsorption of spontaneous photons that compromise the optical pumping and thus the sideband cooling. In addition, we observe a small heating rate of 4 μK/s independent of the cooling, which in conjunction with our low final cooling rates might be determining our present temperature limit. We have investigated possible heating sources associated with trapping light fluctuations [19]. All of the heating rates as calculated from measured noise spectra are smaller than 0.1 μK/s. We are currently investigating higher-order contributions form noise at subharmonics of the trap frequencies.

In conclusion, we have cooled a tightly trapped gas of neutral atoms in 3D at a density for which the calculated elastic collision rate exceeds 1 kHz. The optical cooling of a very dense, spin-polarized gas may represent an important step towards attaining BEC by all-optical means and provides favorable starting conditions for evaporative cooling.

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