Beyond Optical Molasses: 3D Raman Sideband Cooling of Atomic Cesium to High Phase-Space Density

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We demonstrate a simple, general purpose method to cool neutral atoms. A sample containing 3×10^8 cesium atoms prepared in a magneto-optical trap is cooled and simultaneously spin polarized in 10 ms at a density of 1.1×10^{11} cm^{-3} to a phase space density $n\lambda_{\mathrm{dB}}^3 = 1/500$, which is almost 3 orders of magnitude higher than attainable in free space with optical molasses. The technique is based on 3D degenerate Raman sideband cooling in optical lattices and remains efficient even at densities where the mean lattice site occupation is close to unity.

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Optical molasses has for some time been the mainstay of atomic physics experiments requiring ultracold temperatures [1]. Although other techniques, such as evaporative cooling [2], velocity-selective coherent population trapping [3], or free-space Raman cooling [4] are superior in some respects, none thus far combine the speed, ease-of-use, efficiency, and versatility of optical molasses. However, at densities high enough for atoms within the sample to exchange photons, light-induced atom-atom interactions [5–8] cause density-dependent heating and loss that severely limit the phase space density; this puts strong constraints on the optical preparation of high-density samples for subsequent evaporative cooling or studies of collisional and many-body effects.

At densities where the absorption length becomes smaller than the sample size, reabsorption of scattered photons [9,10] produces heating and outward radiation pressure [5]. Although the contribution from incoherent scattering is suppressed at low saturation [11], reabsorption in this limit becomes dominated rather by a stimulated Raman process where the atom reemits a photon into the cooling beam [12]. This process is considered to be the fundamental obstacle to obtaining Bose-Einstein condensation using only optical cooling [9]. At higher densities where the interatomic distance becomes comparable to the optical wavelength, the light-induced interaction is dominated by the dipole-dipole force [13], which can accelerate a pair of atoms excited by the light to a large relative kinetic energy before they decay to the ground state. This process, known as a "radiative collision" [6–8], has been observed to limit the lifetime of a magneto-optical trap (MOT) [8], and places strong constraints even on the use of far-detuned lasers to trap or manipulate high density samples [7].

These processes are suppressed in "dark state" cooling [3,4,14,15], where atoms are collected in states with a reduced coupling to the light field. An example is blue-detuned Sisyphus cooling or "grey molasses," which at a given density cools to lower temperatures than ordinary or "bright" molasses [14,15]. Even in this case, however, the "dark" state is still weakly coupled to the light, and a linear increase of temperature with density of 600 nK/10^{10} cm^{-3} has been observed for cesium [14]. Another strategy is to confine the atoms tightly in an optical lattice, where optical molasses has been used to cool at much higher densities than is possible in free space [16,17]. Indeed, it has been suggested theoretically that the detrimental heating effects associated with reabsorption should be reduced for trapped atoms if the vibration frequency exceeds the optical pumping rate [10]. Furthermore, radiative collisions are strongly suppressed in lattice traps, where the atoms are tightly bound at separate lattice sites. However, a fundamental upper bound on the density then is set by the requirement that lattice sites not be multiply occupied, since two atoms together in a single site are quickly lost [16].

An additional advantage of optical lattices is that dissipative cooling can be followed by adiabatic release from the trapping potential [16,18], trading in peak density for a reduced kinetic energy at fixed bulk density. Molasses cooling in optical lattices followed by adiabatic release has produced 3D free-space kinetic temperatures for cesium atoms as low as 650 nK [18] and 350 nK [16]. These results were strongly limited by the performance of molasses cooling, and it was suggested in Ref. [18] that a resolved-sideband cooling technique could provide a substantial improvement. Such a technique has recently been demonstrated in 2D [19] and 1D [20,21].

In this Letter, we demonstrate for the first time 3D degenerate Raman sideband cooling, which combines the advantages of dark-state cooling and tight confinement to achieve a strong suppression of the limiting processes encountered in conventional molasses. In a total time of only 10 ms we transfer 95% of the atoms from a cesium MOT into a 3D far-detuned optical lattice, cool 80% of those into the lowest vibrational band, and after subsequent adiabatic release attain free-space kinetic temperatures as low as 290 nK. The observed density dependence of the final temperature is almost 100 times weaker than that measured for optical molasses, and the cooling simultaneously spin polarizes the sample, resulting in a phase-space density for

3×10^8 atoms as high as $1/500$ at a density of 10^{11} cm^{-3}. In addition, we observe only a small loss of atoms at densities up to 1×10^{12} cm^{-3}, which is comparable to the density of 3D lattice sites. Finally, the technique is experimentally very simple, can be implemented using the same optical access as the MOT, and requires only a relatively weak laser to produce the optical lattice.

Our degenerate Raman sideband cooling [19,21] scheme is shown in Fig. 1(a). A cooling cycle begins with an atom initially polarized in the $F = 3$, $m_F = 3$ ground state in a high-lying vibrational level ν of the lattice. A small magnetic field is used to bring this state $|F = 3, m_F = 3; \nu\rangle$ into degeneracy with $|3, 2; \nu - 1\rangle$ and $|3, 1; \nu - 2\rangle$. Two-photon degenerate Raman transitions induce a coupling between these states that rotates the atomic polarization while simultaneously reducing the vibrational quantum number. Optical pumping with a strong σ^+ polarized component and a very weak π component is applied on the $6S_{1/2}$, $F = 3 \rightarrow 6P_{3/2}$, $F' = 2$ transition. Since the Raman coupling is much faster than the slow π pumping, the atom is quickly transferred to $m_F = 1$ where it is pumped by the strong σ^+ light. The subsequent decay favors $m_F = 3$, and in the Lamb-Dicke regime is unlikely to change the vibrational state, resulting in a cooling by two vibrational quanta. The fast cooling is repeated until the atom reaches $|3, 3; 1\rangle$, after which it is pumped into the dark $|3, 3; 0\rangle$ state only very slowly by the weak π light. This provides a suppression of reabsorption heating in the final cooling stage where it is most needed [10], and produces lower temperatures than pumping on an $F \rightarrow F$ transition with pure σ^+ light.

The degenerate Raman transitions are induced by the far-detuned optical lattice which also provides the trapping potential, and is derived from a 100 mW distributed Bragg reflector (DBR) diode laser (SDL-5712-H1 from SDL). We use four linearly polarized beams, two counterpropagating along the z axis, and two directed along x and y, which requires only the same optical access as the MOT. The linear polarizations of the counterpropagating beams subtend angles $\pm\alpha$, typically $\pm 10°$, with the line bisecting the x and y axes. The other two beams are also polarized in the x-y plane, which maximizes the Raman coupling for a magnetic field in that plane. The beams along z are typically 3 times stronger than those along x and y. This intensity ratio and the angle α were optimized experimentally at fixed detuning, typically -16 GHz from the $F = 3 \rightarrow F' = 4$ transition, and at a fixed total power as small as 20 mW for e^{-2} beam waists of 1 mm, slightly larger than our typical MOT. The optical pumping beam propagates along x, and is typically detuned $+10$ MHz from the $F = 3 \rightarrow F' = 2$ transition. In order to obtain both σ^+ and π polarizations along the magnetic field **B**, we orient **B** in the x-y plane at a small angle $\beta \approx 5°$ to the optical pumping beam, whose ellipticity we adjust to eliminate the σ^- component. Its intensity is typically 0.4 mW/cm^2, corresponding to 1 μW/cm^2 for the π component with $\beta = 5°$. An additional copropagating repumping beam on the $6S_{1/2}$, $F = 4 \rightarrow 6P_{3/2}$, $F' = 4$ transition quickly recycles atoms off-resonantly pumped to the upper hyperfine manifold, whose Landé g factor of opposite sign yields heating rather than cooling [19]. The pumping and repumping beams are derived from the same two DBR lasers which generate our MOT, and are locked relative to Cs sub-Doppler resonances.

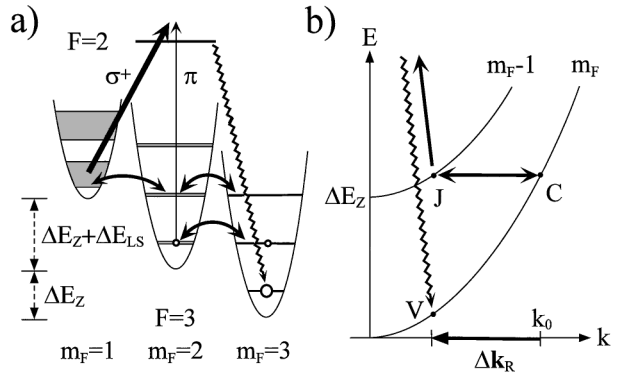

FIG. 1. (a) Vibrationally excited atoms are cooled quickly by degenerate Raman transitions (double-sided arrows) and fast σ^+ optical pumping, while the final cooling stage uses only weak π pumping. This scheme strongly suppresses reabsorption heating. (b) Initially unbound atoms are transferred from $m_F(C)$ to $m_F - 1(J)$ when a two-photon degenerate Raman transition satisfies energy and momentum conservation. Optical pumping back to $m_F(V)$ cools the atoms by one Zeeman energy splitting ΔE_Z.

We begin with 10^8 to 10^9 cesium atoms collected in a MOT from a room-temperature vapor. The cloud is compressed by increasing the detuning and reducing the intensity of the MOT beams, and increasing the magnetic field gradient. After 20 ms, the quadrupole field is turned off and the MOT and repumping lasers are extinguished. The optical pumping and repumping beams are then applied on the $3 \rightarrow 2$ and $4 \rightarrow 4$ transitions, respectively, and the 3D lattice is switched on, along with a bias field of 150 mG for optical pumping. After 2 ms of pumping into the $m_F = 3$ state, the magnetic field is switched to the value nominally resonant with the vibrational spacing, typically 50 mG, and the atoms are subsequently Raman cooled in the lattice for 8 ms, after which the optical pumping and repumping beams are extinguished. For adiabatic cooling, the lattice power P is decreased according to $P(t) = P(0)[1 + t/t_0]^{-2}$ for 1 ms [18], where t_0 is typically chosen to be 100 μs, before the light is turned off completely.

The kinetic energy of the atoms is measured with a time-of-flight technique [1] using a thin sheet of light located 12 cm below the lattice. We extract the temperature of the atoms in two orthogonal directions from the temporal and spatial widths of the fluorescence from the falling cloud, applying a small correction on the 10% level to account for the initial cloud size. After a few ms of fast initial cooling a steady-state temperature of $kT = 0.7\hbar\omega$ is consistently reached, where $\omega/2\pi = 18$ kHz is the typical average vibration frequency, as measured independently

using parametric excitation [21]. We have verified that the cooling is limited neither by impurity of the optical pumping polarization nor by off-resonant depletion of the dark state by the strong Raman coupling.

To measure the peak density the atoms are illuminated for 300 μs with resonant light, and the resulting fluorescence is imaged onto a CCD camera and collected by a calibrated photodiode. The measured widths of the approximately spherical Gaussian-shaped cloud with typical aspect ratio of 1.1:1 in combination with the atom number derived from the photodiode signal are used to calculate the peak density. This result consistently agrees to 20% or better with an independent resonant absorption measurement using a weak, collimated probe beam.

Our lowest 3D kinetic temperature observed after adiabatic release is 290 nK or 1.5 recoil temperatures, attained with a sample of 10^8 atoms at a density of $n = 1 \times 10^{10}$ cm^{-3}. To characterize the density-dependent heating, we vary the density by changing the magnetic field gradients used during MOT loading and compression. The resulting phase space density $n\lambda_{\mathrm{dB}}^3$ is shown in Fig. 2 as a function of atomic density. The temperature is plotted in the inset, along with a linear fit whose residual slope is only $T' = 8$ nK/10^{10} cm^{-3}, 75 times smaller than the value of $T' = 600$ nK/10^{10} cm^{-3} obtained with optical molasses in Ref. [14]. The solid, dashed, and dotted lines in Fig. 2 show the phase-space density calculated using the observed density-dependent temperatures of the form $T = T_0 + T'n$ for our cooling method, grey molasses, and bright molasses, respectively. Our low final temperatures, combined with the fact that our sample is spin polarized by the cooling process, produce phase-space densities as high as $n\lambda_{\mathrm{dB}}^3 = 1/500$ at a density of only

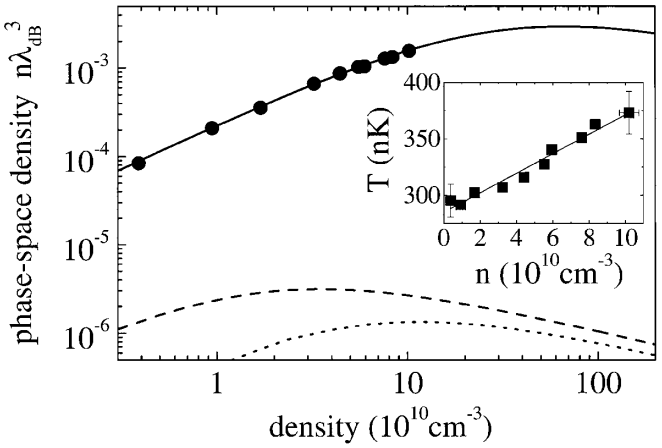

FIG. 2. Phase-space density $n\lambda_{\mathrm{dB}}^3$ and temperature after cooling as a function of density, shown with circles and squares, respectively. The solid lines are a linear fit to the temperature, whose slope is 8 nK/10^{10} cm^{-3}. For comparison, the phase-space density obtained in Ref. [14] with grey and bright molasses is shown with dashed and dotted lines, respectively. All three curves eventually decrease when extrapolated to higher density, since $n\lambda_{\mathrm{dB}}^3 \propto nT^{-3/2}$.

10^{11} cm^{-3}. We have also cooled higher density samples prepared in a very far-detuned trap at 1064 nm, and we observe free-space temperatures consistent with the same weak density dependence at densities up to 10^{12} cm^{-3}. At even higher densities, closer to the 3×10^{12} cm^{-3} density of lattice sites, substantial loss of atoms is observed during the 10 ms cooling time. This decay is due to radiative collisions induced by the lattice itself [7,16], and consequently blue-detuned or very far-detuned lattices exhibit a smaller loss [22].

The large Raman coupling in our configuration is comparable to the average vibration frequency. This allows us to cool efficiently in a 3D lattice where the trapping potential is neither isotropic nor harmonic. In contrast to previous work [19,21], neither the individual vibration frequencies nor their second harmonics are resolved, as is evident from the magnetic field dependence of the final temperature, which for optimum parameters displays only a single broad feature. We observe that the shape of this cooling spectrum is independent of the atomic cloud size, indicating that it is not caused by the spatial variation of the vibration frequencies across the intensity envelope of the lattice.

The number of atoms captured and the temperature to which they are cooled are strongly asymmetric in the optical pumping detuning from the $F = 3 \rightarrow F' = 2$ resonance. This is a result of the light shift ΔE_{LS} of the $m_F = 1$ level caused by the intense σ^+ light, as indicated in Fig. 1(a) for a blue detuning. In this case, the $m_F = 1$ level is shifted upward, and consequently the cooling performance is only weakly dependent on detuning and intensity. Since the levels are broadened by the fast pumping and the Raman coupling strength is large, the energy mismatch between adjacent levels induced by the $m_F = 1$ light shift has little effect on the cooling. For small red detuning, however, the $m_F = 1$ level shifts below $m_F = 2$ and the cooling turns into heating, ejecting even initially bound atoms from the lattice.

For MOT cloud sizes smaller than our lattice volume, we cool almost all atoms into the lattice even though initially only about 30% are bound. This loading is completed after only 2 ms, much too quickly for elastic collisions to be responsible. Instead, we believe that it is due to the free-space analog of degenerate Raman sideband cooling, shown in Fig. 1(b). An unbound atom initially in the $m_F = 3$ state is accelerated by the optical potential until it reaches the point C where a degenerate Raman transition to $m_F = 2$, which changes its momentum by one two-photon recoil, will satisfy both momentum and energy conservation. Optical pumping with π light from this state (point J) or a second Raman transition to $m_F = 1$ followed by σ^+ pumping then cools the atom by one or two Zeeman energy splittings ΔE_Z (point V). This process is repeated until the atom binds to a lattice site, and sideband cooling takes over. We have demonstrated this free-space Raman cooling experimentally in 1D by decelerating freely falling atoms.

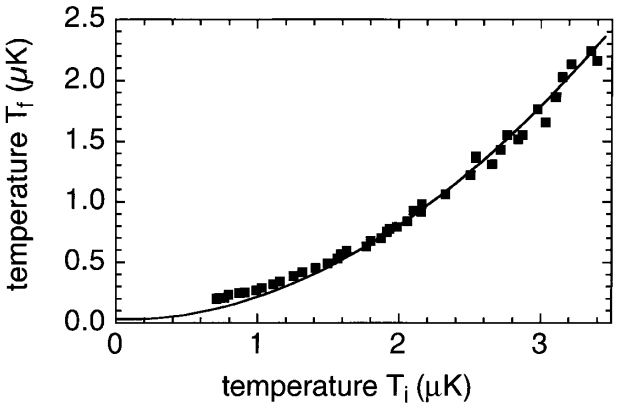

FIG. 3. Temperature T_f after adiabatic release vs initial temperature T_i in a 2D isotropic lattice. The line is calculated from a band model with no free parameters using the measured vibration frequency $\omega/2\pi = 22$ kHz.

Finally, the large vibrational ground state populations accessible with our cooling allow us to directly verify the band model for adiabatic release originally developed in Ref. [18]. In this model, the Bloch states within each vibrational band are assumed to be equally populated, corresponding to random phases of the wave functions at different lattice sites. Adiabatic release maps the nth band onto free-space momenta between $n\hbar q/2$ and $(n + 1)\hbar q/2$, where q is the reciprocal lattice vector, resulting in a quadratic dependence of kinetic energy on band index n and nonzero final kinetic energy even for atoms prepared purely in the ground vibrational state. Figure 3 shows the observed kinetic temperature after adiabatic release as a function of initial temperature in a 2D lattice, with which we could easily obtain isotropic lattice sites. The line is calculated using the band model with no free parameters, based on the measured vibration frequency of $\omega/2\pi = 22$ kHz and the known 2D lattice periodicity. Different initial temperatures were obtained by varying the detuning of the optical pumping. The minimum observed 2D temperature is 210 nK.

In conclusion, we have developed a simple, spin-polarizing, 3D optical cooling method that goes far beyond the temperature and density limitations of optical molasses, and produces high phase-space density at temperatures near the single-photon recoil limit. This may be used to greatly increase the brightness of atomic fountains by cooling in a moving frame, or can be transformed into a high peak density using adiabatic compression after optimized loading into a magnetic or optical trap. Atomic samples thus prepared are ideally suited for collision studies, and also provide excellent starting conditions for evaporation. The cooling can also be performed directly inside very far-detuned optical traps, and we have recently achieved peak phase-space densities as high as $1/100$ using interspersed cooling and dark periods. (A similar value of $1/190$ has been reported in Ref. [16] with 5×10^7 atoms.) The resulting densities produce high lattice site occupancy, but at the present detuning lead to strong trap loss due to radiative collisions. However, laser cooling in multiply occupied sites may still be possible in very far-detuned lattices, and may be a promising method for achieving quantum degeneracy with purely optical means.

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[1] See, for instance, *Laser Manipulation of Atoms and Ions*, edited by E. Arimondo, W. Phillips, and F. Strumia (North-Holland, Amsterdam, 1992).
[2] W. Ketterle and N. J. van Druten, in *Advances in Atomic, Molecular, and Optical Physics* (Academic Press, San Diego, 1996), Vol. 37, p. 181.
[3] A. Aspect, E. Arimondo, R. Kaiser, N. Vansteenkiste, and C. Cohen-Tannoudji, Phys. Rev. Lett. **61**, 826 (1988).
[4] M. Kasevich and S. Chu, Phys. Rev. Lett. **69**, 1741 (1992); J. Reichel *et al.*, Phys. Rev. Lett. **75**, 4575 (1995).
[5] T. Walker, D. Sesko, and C. Wieman, J. Opt. Soc. Am. B **8**, 946 (1991); A. M. Steane, M. Chowdhury, and C. J. Foot, J. Opt. Soc. Am. B **9**, 2142 (1992).
[6] V. Sanchez-Villicana, S. D. Gensemer, and P. L. Gould, Phys. Rev. A **54**, R3730 (1996).
[7] K. Burnett, P. S. Julienne, and K.-A. Suominen, Phys. Rev. Lett. **77**, 1416 (1996); V. Vuletic, C. Chin, A. J. Kerman, and S. Chu, Phys. Rev. Lett. **83**, 943 (1999).
[8] M. H. Anderson, W. Petrich, J. R. Ensher, and E. A. Cornell, Phys. Rev. A **50**, R3597 (1994).
[9] M. Olshanii, Y. Castin, and J. Dalibard, in *Proceedings of the 12th International Conference on Laser Spectroscopy*, edited by M. Inguscio, M. Allegrini, and A. Lasso (World Scientific, Singapore, 1996).
[10] J. I. Cirac, M. Lewenstein, and P. Zoller, Europhys. Lett. **35**, 647 (1996); Y. Castin, J. I. Cirac, and M. Lewenstein, Phys. Rev. Lett. **80**, 5305 (1998).
[11] B. R. Mollow, Phys. Rev. **188**, 1969 (1969).
[12] B. Lounis and C. Cohen-Tannoudji, J. Phys. II (France) **2**, 579 (1992).
[13] Yu. A. Vdovin and V. M. Galitskii, Sov. Phys. JETP **25**, 894 (1967) [Zh. Eksp. Teor. Fiz. **52**, 1345 (1967)].
[14] D. Boiron *et al.*, Phys. Rev. A **53**, R3734 (1996).
[15] C. Triché, P. Verkerk, and G. Grynberg, Euro. Phys. J. D **5**, 225 (1999).
[16] S. L. Winoto, M. T. DePue, N. E. Bramall, and D. S. Weiss, Phys. Rev. A **59**, R19 (1999); M. T. DePue, C. McCormick, S. L. Winoto, S. Oliver, and D. S. Weiss, Phys. Rev. Lett. **82**, 2262 (1999).
[17] D. Boiron *et al.*, Phys. Rev. A **57**, R4106 (1998).
[18] A. Kastberg, W. D. Phillips, S. L. Rolston, R. J. C. Speeuw, and P. S. Jessen, Phys. Rev. Lett. **74**, 1542 (1995).
[19] S. E. Hamann, D. L. Haycock, G. Klose, P. H. Pax, I. H. Deutsch, and P. S. Jessen, Phys. Rev. Lett. **80**, 4149 (1998).
[20] H. Perrin, A. Kuhn, I. Bouchoule, and C. Salomon, Europhys. Lett. **42**, 395 (1998).
[21] V. Vuletic, C. Chin, A. J. Kerman, and S. Chu, Phys. Rev. Lett. **81**, 5768 (1998).
[22] At detuning δ larger than the fine structure splitting Δ_{fs}, the Raman coupling decreases faster than the trap depth by a factor of order $\delta/\Delta_{\mathrm{fs}}$.