Gravitational Sisyphus Cooling of ^{87}Rb in a Magnetic Trap

N. R. Newbury, C. J. Myatt, E. A. Cornell, and C. E. Wieman

Joint Institute for Laboratory Astrophysics, National Institute of Standards and Technology and University of Colorado, and Physics Department, University of Colorado, Boulder, Colorado 80309-0440

(Received 17 October 1994)

We describe a method for cooling magnetically trapped ^{87}Rb atoms by irreversibly cycling the atoms between two trapped states. The cooling force is proportional to gravity. The atoms are cooled to 1.5 μK in the vertical dimension. We have extended this cooling method to two dimensions through anharmonic mixing, achieving a factor of 25 increase in the phase space density over an uncooled sample. This cooling method should be an important intermediate step toward achieving a Bose-Einstein condensate of Rb atoms.

PACS numbers: 32.80.Pj

There is an ongoing effort in the field of laser cooling and trapping to achieve lower temperatures and higher densities for a variety of purposes, particularly the attainment of Bose-Einstein condensation. In three dimensions, the lowest achieved temperature for a six-beam molasses is about $13T_r$ [1–3], where T_r is the photon recoil temperature [4]. Recently, temperatures as low as $3.5T_r$ have been reached using both a four-beam molasses [5] and Raman cooling [6]. These temperatures have been achieved in low density untrapped samples. A method of cooling a trapped atomic sample to comparable temperatures has obvious advantages since the cold and dense sample is preserved for subsequent experiments. The standard magneto-optical trap (MOT) [7] both confines and optically cools atoms. However, a variety of fundamental processes limit both the density and temperature of the atoms in a MOT [8–11]. We have developed a new method to cool large numbers of magnetostatically trapped atoms to temperatures near the recoil limit T_r. An important bonus of cooling magnetically trapped atoms is that the density increases as the atoms are cooled.

Currently, the only proven method of optically cooling atoms in a magnetic trap is doppler cooling [12,13], which reaches the relatively high temperatures of a few mK. Here we describe a new method called "gravitational Sisyphus cooling" which works by cycling the atoms between two parabolic potential wells whose minima are offset due to the gravitational force on the atoms and a slight difference in magnetic moments. The atoms are slowed by a force proportional to gravity, and the irreversibility is provided by the spontaneous emission of a photon during optical pumping. For temperatures above the recoil limit, the process is extremely efficient, removing >50% of the atom's potential energy per cycle. For technical reasons, we have worked in that regime and have cooled Rb in one dimension to the "submolasses" temperature of 1.5 μK $= 4T_r$. In principle, however, this technique will allow one to cool to below the recoil limit in one dimension in a manner completely analogous to Raman cooling [6]. Although this technique is inherently one dimensional, we have extended it to two dimensions through anharmonic mixing, and it could be extended to three dimensions using either collisional or anharmonic mixing. Unlike optical molasses [11], this cooling method is insensitive to optical thickness and therefore can cool very large dense samples to within a few recoil energies.

Similar ideas for cooling atoms in a magnetic trap have been proposed by Pritchard and co-workers, but never successfully implemented. In the original proposal [14–16], atoms were to be cooled by cycling between two harmonic potential wells with very different curvatures. However, as realized by Pritchard and Ketterle [17], gravity shifts the minima of two such potential wells vertically and for cold atoms completely foils the cooling. They then proposed a modified cooling scheme which, like gravitational Sisyphus cooling, used gravity as a slowing force. There are several technical but important distinctions between that cooling scheme and gravitational Sisyphus cooling. First, we use states with magnetic moments differing by $\lesssim 3\%$, rather than a factor of 2. For a given trap the final temperature will be a function of the difference in the magnetic moments of the two states. Second, while the proposal of Ref. [17] relied on a highly nonparabolic asymmetric potential, we use a parabolic magnetic trap which is simple to construct and provides better confinement of the atoms. Third, and most importantly, with gravitational Sisyphus cooling we have demonstrated how to efficiently drive real atoms (^{87}Rb) between two wells in the desired manner. This is the principle challenge to implementing most cyclic cooling schemes.

Gravitational Sisyphus cooling is shown schematically in Fig. 1. Initially there is a thermal distribution of cold magnetically trapped atoms in the "weak-field seeking" $|F = 1, m = -1\rangle$ ground state of ^{87}Rb ($I = 3/2$). To understand the cooling mechanism, we consider the magnetic trap potentials for the $|1, -1\rangle$ and $|2, +1\rangle$ states. The potential for the $|1, -1\rangle$ state is $V_{1,-1} = |\mu_{1,-1}||\boldsymbol{B}| + mgz$, where g is the gravitational acceleration and $\boldsymbol{B}$ is the total magnetic field. To cancel gravity, a pair of anti-Helmholtz coils supply a magnetic field gradient $dB/dz = mg/\mu_{1,-1} = -31$ G/cm. The mag-

 0031-9007/95/74(12)/2196(4)$06.00

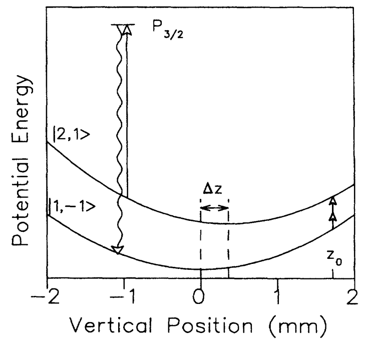

FIG. 1. Atoms are initially loaded into the $|1,-1\rangle$ state. A two-photon excitation, resonant at $z = z_0$, excites atoms to the upper $|2,1\rangle$ potential well. After one-half of an oscillation period, an optical pumping pulse drops the atoms back to the $|1,-1\rangle$ state. After a number of cooling cycles, the cloud is compressed spatially to a rms size of $\sim\Delta z$ and a rms velocity width of $\omega_z \Delta z \approx 2(\hbar k/m)$.

netic field of the remaining coils then produce a simple harmonic potential $V_{1,-1} = \mu_{1,-1}B_0 + m\omega_x^2 x^2/2 + m\omega_y^2 y^2/2 + m\omega_z^2 z^2/2$. To first order in B, the difference in the magnetic moment of the $|2,+1\rangle$ and $|1,-1\rangle$ states is $\Delta\mu \equiv \mu_{|2,+1\rangle} - \mu_{1,-1} = 2(QB_0 - \mu_N)$, where $Q = 431$ Hz/G^2, and $\mu_N = 1.4$ kHz/G is the nuclear moment. This slight difference in magnetic moments results in two differences between the potentials of the $|1,-1\rangle$ and the $|2,+1\rangle$ states. The first effect is a small and negligible difference in the three oscillation frequencies of atoms in the two potentials. The second effect [18] is to displace the minima of the two wells in the vertical direction by

$$\Delta z = \frac{\Delta\mu}{\mu_{1,-1}} \frac{g}{\omega_z^2}. \tag{1}$$

Gravitational Sisyphus cooling exploits this separation of the two wells to cool the atoms. A direct result of Eq. (1) is an almost linear variation with z in the energy difference between the two potential wells. Therefore, by selecting the frequency of a two-photon transition between these states, we can excite atoms at a specific vertical position from the $|1,-1\rangle$ to the $|2,+1\rangle$ state. Because of the bias magnetic field, this excitation is far off resonance for any other transitions. Consider a narrow slice of the distribution initially at $z = z_0$ which is excited to the upper well by a short two-photon excitation pulse. Since the excitation is velocity independent, the velocity distribution of the excited atoms is identical to the velocity distribution of atoms in the lower well [19]. After a half oscillation period $P/2$, the excited atoms will have oscillated to the opposite side of the upper parabolic well which is centered at Δz. These atoms are then optically pumped back to the lower well with laser light that does not excite atoms already in the $|1,-1\rangle$ state. After the cooling cycle, there is no change in kinetic energy (ignoring for now any effects of the optical pumping process), but the change in the potential energy is

$$\Delta U = -2m\omega_z^2 \Delta z(z_0 - \Delta z). \tag{2}$$

Because of the dependence on z_0, the larger the initial potential energy, the larger the decrease in the potential energy. For $1.2\Delta z < z_0 < 7\Delta z$, over 50% of the potential energy of the cycled atoms is removed in a single cooling cycle. In order to cool as many atoms as possible, the ideal cooling cycle would involve rapidly sweeping the two-photon excitation frequency so that all atoms at $z > \Delta z$ are excited to the upper well. This extended cloud will have an initial mean displacement which we identify as z_0. Equation (2) then describes the energy removed from the common or center-of-mass motion of the cycled atoms.

Depending on the experimental implementation, the optical pumping can impart some number n of directed momentum "kicks" ($= \hbar k$) to the atoms. In order to remove the most total (kinetic and potential) energy from the cycled atoms there is an optimum delay time $\tau_{\rm opt}$ between the two-photon excitation and the optical repumping of the atoms to the lower well. If the optical repumping involves n directed momentum kicks upward, one can show the optimum delay time is given by $\omega_z \tau_{\rm opt} = \arctan(-n\hbar k/m\omega_z \Delta z)$, and does not depend on z_0. The optimum delay time ranges from $P/2$ for $m\omega_z \Delta z \gg n\hbar k$ (the situation described above) to $P/4$ for $m\omega_z \Delta z \ll n\hbar k$. The general expression for the amount of energy removed is straightforward to derive but slightly more complicated than Eq. (2) and like Eq. (2) is negative, so that the atoms are cooled, only for sufficiently large z_0.

Because the atoms are in a harmonic trap, by repeating the cooling cycle at intervals of $3P/4$, all atoms regardless of the initial phase of their trajectories are cooled. Equation (2) shows the atoms can be cooled to a size $\sim\Delta z$ or, equivalently, $T_z \sim m(\omega_z \Delta z)^2$ for $n = 0$. Therefore, by either lowering the bias field or raising ω_z the distribution could be cooled to arbitrarily small Δz and temperature. Naively, the limiting temperature is set by the recoil heating in the optical pumping and hence will be no lower than T_r. However, for low density clouds, temperatures below T_r are possible through a diffusion to low energy states in a manner similar to that discussed in Refs. [6,15,20]. Of course, as in any subrecoil cooling scheme, the diffusion of the distribution toward lower and lower temperatures takes a progressively longer time. In a high density sample, elastic collisions will prevent any non-Boltzmann accumulation of atoms in very low energy states.

Our experimental implementation of gravitational Sisyphus cooling uses much of the apparatus and initial cooling techniques described in Ref. [21]. We use diode lasers and a standard vapor-cell MOT [2,7] to collect 10^7-10^8 atoms in about 1 min, as measured from the fluorescence detected by a photodiode. The atom sample is cooled further with an optical molasses [1] and then loaded *in situ* into the dc purely magnetic trap [21,22] with $\omega_x = (2\pi)9.30\ \text{s}^{-1}$, $\omega_y = (2\pi)14.4\ \text{s}^{-1}$, and $\omega_z = (2\pi)4.35\ \text{s}^{-1}$. The lifetime of atoms in the magnetic trap was limited to ~6 s by the background pressure in the cell.

The distribution and number of the trapped atoms can be measured (destructively) at any given time by suddenly turning off the magnetic trap and exciting the atoms with a 1 ms pulse of both the hyperfine repumping light $5s\ ^2S_{1/2}(F = 1) \rightarrow 5p\ ^2P_{3/2}(F' = 2)$ and laser light tuned three linewidths to the red of the $5s\ ^2S_{1/2}(F = 2) \rightarrow 5p\ ^2P_{3/2}(F' = 3)$ transition. To determine the spatial distribution of the trapped atoms, and equivalently the velocity distribution [21], the fluorescence is imaged with a charge-coupled-device camera and one raster of the image recorded by a PC.

The two-photon excitation is implemented by a microwave photon at 6833 MHz and an rf photon at 2 MHz. The microwave frequency is detuned by 15 MHz from the $|1,-1\rangle$ to $|2,0\rangle$ transition so that the $|1,-1\rangle$ and $|2,+1\rangle$ states can be regarded as a simple coupled two level system. The microwaves are generated by an HP8627A synthesizer, amplified using a 30 W traveling wave tube amplifier and directed at the atoms with an open-ended waveguide. The applied rf is linearly polarized resulting in nearly identical energy shifts of the two trapped states. The coupling of the microwave magnetic field to the actual trap region is poor so that the two-photon Rabi frequency of $\sim 10^4\ \text{s}^{-1}$ is on the order of the motional linewidth. Increasing the rf field to increase the Rabi frequency is undesirable because it distorts the trap potential and shortens the trap lifetime by heating the walls. For this low Rabi frequency, there is nothing to be gained by sweeping the frequency as described above, and we simply fix the microwave and rf frequency to excite atoms at a fixed vertical position z_0. After the cloud has been cooled to a size less than z_0, the microwave frequency is reduced to excite atoms at a lower vertical position. This approach reduces the cooling efficiency by about a factor of 2 over the ideal case discussed above.

We optically pump the atoms using two different laser beams. A 0.5 ms pulse of circularly polarized light propagating at ~30° with respect to the quantization axis in the $\hat{x}-\hat{z}$ plane drives the $5s\ ^2S_{1/2}(F = 2) \rightarrow 5p\ ^2P_{3/2}(F' = 2)$ transition, quickly pumping atoms into the $|2,-2\rangle$ state. This light will also excite those atoms to the $|F' = 2, m = -2\rangle$ state which decays into the $F = 1$ ground state, predominantly into the trapped $|1,-1\rangle$ sublevel. To retrieve the ~20% of atoms lost to the $|1,0\rangle$ and $|1,+1\rangle$ states, two circularly polarized 30 μs pulses of light drive the $5s\ ^2S_{1/2}(F = 1) \rightarrow 5p\ ^2P_{3/2}(F' = 1)$ transition at 795 nm during the 0.5 ms optical pumping pulse. The atoms receive $n \sim 4$ recoil kicks upward during this repumping. Therefore, we choose $\omega \Delta z \approx (n/2)\hbar k/m \approx 2\hbar k/m$.

A typical single cooling cycle begins with an 80 ms two-photon excitation pulse (defined by gating the microwave power), followed by a 40 ms pause, and then a 0.5 ms optical pumping pulse to return the atoms from the $|2,1\rangle$ to the $|1,-1\rangle$ state. To cool the cloud to 1.5 μK $\approx 4T_r$, we use eight cooling cycles at a two-photon frequency of 6834.91 MHz and then an additional eight cycles at 6834.92 MHz. The entire cooling process takes less than 2 s. Results of one-dimensional gravitational Sisyphus cooling are shown in Figs. 2(a) and 2(c). The temperatures quoted in Fig. 2 are calculated from the full width at the $e^{-1/2}$ points of the velocity distribution averaged over one oscillation period of the trap. We can further reduce the residual high velocity tails of the distribution by increasing the number of cooling cycles.

If the number of absorbed photons were reduced, we could lower Δz correspondingly and reach temperatures closer to T_r. This number could be reduced to one or two by using a technique for coherently transferring atoms between the $|2,+1\rangle$ and $|2,-1\rangle$ states. The attraction of our current scheme is that less than 2% of the excited atoms are lost to untrapped states in a cooling cycle and it requires only a single additional 20 mW laser.

Since gravitational Sisyphus cooling is restricted to the vertical dimension, we cool the sample in two dimensions (see Fig. 2) by anharmonically mixing the vertical and $\hat{x}$ dimensions. First the vertical distribution is cooled. Then, by adiabatically changing the trap parameters, we produce a degeneracy $\omega_x = \omega_z = (2\pi)3.5\ \text{s}^{-1}$. Anharmonicities

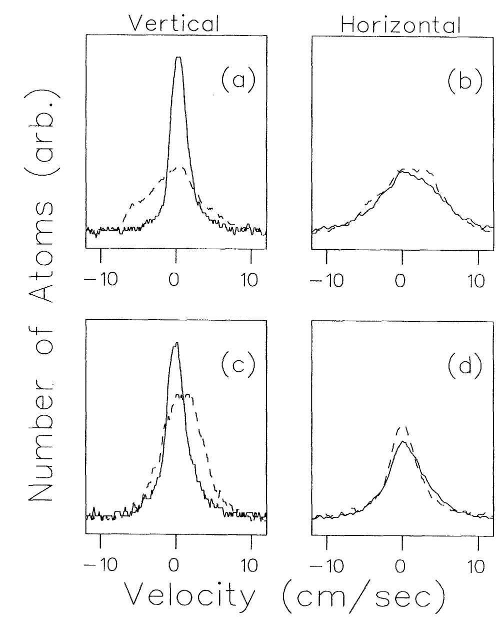

FIG. 2. The results of two-dimensional gravitational Sisyphus cooling. (a), (b) The vertical and $\hat{x}$ velocity distributions before cooling (dashed lines: $T_x = 19\ \mu$K, $T_z = 12.5\ \mu$K) and after cooling (solid lines: $T_x = 20\ \mu$K, $T_z = 1.6\ \mu$K). After anharmonic mixing of the vertical and $\hat{x}$ directions, the velocity distributions are given by the dashed lines of (c) and (d) ($T_x = 3.4\ \mu$K, $T_z = 8.3\ \mu$K). A final gravitational Sisyphus cooling gives the solid curves of (c) and (d) ($T_x = 6.4\ \mu$K, $T_z = 1.5\ \mu$K).

cause the atom cloud to rotate in the $x-z$ plane, exchanging the $\hat{x}$ and $\hat{z}$ distributions in ~ 0.65 s. After we adiabatically restore the trap to the initial field conditions, the one-dimensional phase-space density associated with the $\hat{x}$ direction is equal to the one-dimensional phase-space density of the cooled vertical direction before mixing. Since one-dimensional phase-space density, rather than energy, is exchanged, we expect a final horizontal temperature after mixing of $T_x^f = (\omega_x/\omega_z)T_z$, where T_z is the initial vertical temperature, which agrees well with Fig. 2(d). We then cool the vertical distribution again. The entire process is completed in ~ 5 s. The phase-space density, which goes as $(T_x T_z T_y)^{-1}$ for a simple harmonic trap, is increased by a factor of 25, compared to an uncooled sample after 5 s. Cooling in all three dimensions is also possible using anharmonic mixing but we cannot achieve the required condition $\omega_y = \omega_z$ with our magnet power supplies. The heating of $\sim 3T_r$ in the $\hat{x}$ direction during gravitational Sisyphus cooling results primarily from the velocity kick of $n \sin 30° \, \hbar k/m$ in the $\hat{x}$ direction during an optical pumping pulse and could be substantially reduced by the more advanced optical pumping schemes mentioned earlier.

In a denser sample, elastic collisions will mix the energy of the three dimensions so that $T_x = T_y = T_z$ in a time less than the trap lifetime. Anharmonic mixing, on the other hand, gives $T_x/\omega_x = T_y/\omega_y = T_z/\omega_z$ so the corresponding increase in phase space density will be greater for collisional mixing since $\omega_x, \omega_y > \omega_z$.

We have demonstrated gravitational Sisyphus cooling for a magnetic trap loaded *in situ* from a relatively small MOT ($\sim 10^7 - 10^8$ atoms). To take full advantage of gravitational Sisyphus cooling would require loading a large number ($\gtrsim 10^{10}$) of atoms into a long–lived magnetic trap. A large sample of magnetically trapped atoms loaded from a MOT would have a high initial potential energy, because of the fixed density of a MOT [8,9], and a high kinetic energy due to an elevated molasses temperature in large samples [11]. However, gravitational Sisyphus cooling and collisional mixing could cool and compress this distribution to ~ 1 μK in all three dimensions. Any heating effects associated with optical thickness of the sample could be greatly mitigated by optical pumping with light far detuned from resonance. After cooling, the thermalization rate of the sample would be very much larger than the trap loss rate and thereby permit efficient evaporative cooling to lower temperatures [23].

This work is supported by the Office of Naval Research and the National Science Foundation. We are pleased to acknowledge many useful discussions with M. Anderson and W. Petrich.

---

[1] See the special issue on laser cooling and trapping of atoms edited by S. Chu and C. Wieman [J. Opt. Soc. Am. B **6**, No. 11 (1989)].

[2] C. Monroe, W. Swann, H. Robinson, and C. Wieman, Phys. Rev. Lett. **65**, 1571 (1990).

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

[4] According to the equipartition theorem, the recoil temperature is properly defined as $k_B T_r = (\hbar k)^2/M$, where M is the atomic mass and $\hbar k$ is the laser photon momentum. This corresponds to twice the recoil energy $(\hbar k)^2/2M$.

[5] A. Kastberg, W. D. Phillips, S. L. Rolston, R. J. C. Spreeuw, and P. S. Jessen, Phys. Rev. Lett. **74**, 1542 (1995).

[6] N. Davidson, H.-J. Lee, M. Kasevich, and S. Chu, Phys. Rev. Lett. **72**, 3158 (1994).

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

[8] T. Walker, D. Sesko, and C. Wieman, Phys. Rev. Lett. **64**, 408 (1990).

[9] W. Ketterle, K. B. Davis, M. A. Joffe, A. Martin, and D. E. Pritchard, Phys. Rev. Lett. **70**, 2253 (1993).

[10] A. M. Steane, M. Chowdhurry, and C. J. Foot, J. Opt. Soc. Am. B **9**, 2142 (1992).

[11] G. Hillenbrand, C. J. Foot, and K. Burnett, Phys. Rev. A**50**, 1479 (1994); A. Clairon, Ph. Laurent, A. Nadir, M. Drewsen, D. Grison, B. Lounis, and C. Salomon (unpublished).

[12] D. E. Pritchard, K. Helmerson, and A. G. Martin, in *Atomic Physics 11,* edited by S. Haroche, J. C. Gay, and G. Grynberg (World Scientific, Singapore, 1989), p. 179; V. S. Bagnato, G. P. Lafyatis, A. G. Martin, E. L. Raab, R. N. Ahmad-Bitar, and D. E. Pritchard, Phys. Rev. Lett. **58**, 2194 (1987).

[13] I. D. Setija, H. G. C. Werij, O. J. Luiten, M. W. Reynolds, T. W. Hijmans, and J. T. M. Walraven, Phys. Rev. Lett. **70**, 2257 (1993).

[14] D. E. Pritchard, Phys. Rev. Lett. **51**, 1336 (1983).

[15] D. E. Pritchard, K. Helmerson, V. S. Bagnato, G. P. Lafyatis, and A. G. Martin, in *Laser Spectroscopy VIII,* edited by W. Persson and S. Svanberg, (Springer-Verlag, Berlin, 1987), p. 68.

[16] B. Hoeling and R. J. Knize, Optics Commun. **106**, 202 (1994).

[17] D. E. Pritchard and W. Ketterle, in *Laser Manipulation of Atoms and Ions,* edited by E. Arimondo, W. D. Phillips, and F. Strumia (North-Holland, Amsterdam, 1992), p. 473.

[18] This result holds even if the anti-Helmholtz field gradient does not exactly cancel gravity.

[19] We assume the initial mean velocity of the excited cloud is zero which will be true provided there are no correlations between position and velocity of the atoms in the lower well and there is no center-of-mass motion of atoms in the lower well.

[20] F. Bardou, B. Saubamea, J. Lawall, K. Shimizu, O. Émile, C. Westbrook, A. Aspect, and C. Cohen-Tannoudji, C. R. Acad. Sci. Paris **318**, II, 877 (1994).

[21] C. R. Monroe, E. A. Cornell, C. A. Sackett, C. J. Myatt, and C. E. Wieman, Phys. Rev. Lett. **70**, 414 (1993).

[22] T. Bergeman, G. Erez, and H. J. Metcalf, Phys. Rev. A **35**, 1535 (1987).

[23] J. M. Doyle, J. C. Sandberg, I. A. Yu, C. L. Cesar, D. Kleppner, and T. J. Greytak, Phys. Rev. Lett. **67**, 603 (1991); H. F. Hess, Phys. Rev. B **34**, 3476 (1986).