Recoil-Limited Laser Cooling of ^{87}Sr Atoms near the Fermi Temperature

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A dynamic magneto-optical trap, which relies on the rapid randomization of population in Zeeman substates, has been demonstrated for fermionic strontium atoms on the $^1S_0 - {}^3P_1$ intercombination transition. The obtained sample, 1×10^6 atoms at a temperature of 2 μK in the trap, was further Doppler cooled and polarized in a far-off resonant optical lattice to achieve 2 times the Fermi temperature.

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The successful demonstration of the collisional cooling of fermionic alkali atoms [1] has triggered extensive studies on the collective quantum mechanical phenomena in a nearly degenerate fermionic system. Specifically, much attention has been paid to the Cooper pairing [2], which manifests itself as emerging from the macroscopic quantum coherence of the ensemble of cold fermions. This should lead to a crucial breakthrough in the understanding and exploitation of the many-body quantum effects, in particular, superconductivity. The recent cooling of ^{40}K [3] and ^{6}Li [4–7] atoms down to a quarter of the Fermi temperature has made it possible to observe a significant departure in the behavior of these Fermi gases from the predictions of classical thermodynamics, such as the Fermi pressure and the Pauli blocking effect.

The latter emphasizes the technological importance of degenerate fermions for atom interferometry because the quantum noise of the atom flux is expected to be reduced owing to the Pauli blocking [8]. In the cooling of the alkaline-earth atoms, the recently developed "narrow line cooling" method [9–13] has established a novel approach to reach quantum degeneracy [14]. Applying this method, a quantum mechanically dense ensemble of fermionic atoms will be created in one-tenth of a second, which offers a high-flux atom source that should be ideal for atom interferometers. Furthermore, the rich variety of optically accessible states in the alkaline-earth atoms allows the preparation of an atom population in the triplet metastable states, which can be used for various experiments such as magnetic-perturbation-free atom interferometers and ultraprecise atom clocks [12,13,15].

In this Letter, we report on the production of near-degenerate ^{87}Sr atoms in a quasi-2D optical trap by developing a dynamic magneto-optical trapping (DMOT) scheme to collect an ultracold atomic ensemble. In the 2D trap, we demonstrated Doppler cooling to the photon recoil temperature for the slow axis, while the atoms mostly occupied the vibrational ground state for the fast axis, thus achieving 2 times the Fermi temperature. These radiative cooling schemes can be especially advantageous for fermionic particles near degeneracy [16] since they are free from the Pauli blocking occurring in the collisional cooling of fermionic alkali atoms [1]. The cooling limit, therefore, will be solely determined by the degradation of radiative cooling efficiency at high atom density.

A standard textbook explanation of a magneto-optical trap (MOT) deals only with the position of resonances between a red-detuned trapping laser and Zeeman shifted transitions. An atom moving on one of three symmetric axes of a six-beam MOT [17] will experience a restoring force regardless of its magnetic substate m in the ground state if the position-dependent Zeeman shift

$$h\nu(x) = \{(m+1)\mu_e - m\mu_g\}B(x) \tag{1}$$

has the same sign for any m at position x, where the σ^+ transition is assumed and μ_e (μ_g) denotes the Zeeman shift coefficients for the excited (ground) state. Under this condition, an atom, moving in an inhomogeneous magnetic field of $B(x) = \beta x$ with the magnetic field gradient $\beta = dB/dx$, could go through resonance at some position x_0 for a negatively detuned (δ) trapping laser with specific polarization, as depicted in Figs. 1(a) and 1(b). This condition is given by

$$F/(F+1) < \mu_e/\mu_g < F/(F-1) \tag{2}$$

for the $F \to F+1$ transition, and

$$(F-1)/F < \mu_e/\mu_g < F/(F-1) \tag{3}$$

for the $F \to F$ transition. In those cases, the MOT will likely function three dimensionally, and most atoms trapped in MOTs to date satisfied the above conditions.

When Eq. (2) or (3) is not satisfied, as encountered in the laser cooling of fermionic alkaline-earth isotopes with $\mu_e/\mu_g \gg 1$, this position-dependent resonant condition does not guarantee stable trapping. However, as long as the population among magnetic substates is rapidly mixed by optical pumping, atoms can experience a restoring force on average for a $F \to F+1$ transition. With circularly polarized $\sigma^\pm$ light, the line strength

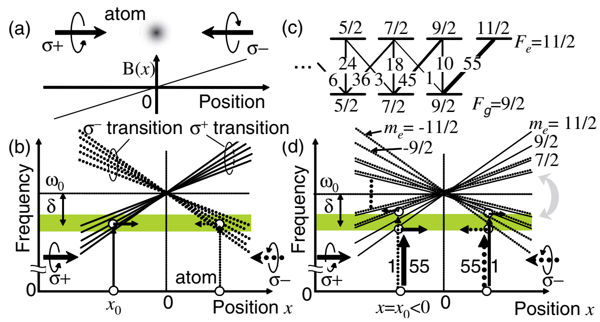

FIG. 1 (color online). (a) Configuration of the standard 1D magneto-optical trap. A pair of counterpropagating σ^+ and σ^- polarized lasers is applied in the presence of an inhomogeneous magnetic field, $B(x) = \beta x$. (b) Position-dependent transition frequencies for $m_g \to m_e = m_g \pm 1$ for the case of $\mu_e/\mu_g \simeq 1$. The sign of the frequency shift depends on the atom position and light polarization, independently of the ground Zeeman substates of m_g. Hence, a restoring force mechanism is discussed, as in the $F_g = 0 \to F_e = 1$ transition. (c) Relative transition probabilities for the larger m_g states in the $F_g = 9/2 \to F_e = 11/2$ transition. (d) For $\mu_e/\mu_g \gg 1$, the transition frequencies are solely determined by the Zeeman shifts of the magnetic substates m_e of the excited state. Therefore, the position-dependent resonant condition alone does not lead to a restoring force (see text).

for $m \to m \pm 1$ transition is maximum at the largest $m = \pm F$ magnetic substate in the ground state and decreases monotonically towards the opposite side of the $\mp F$ substate [see Fig. 1(c)]. This transition probability difference for $\sigma^\pm$ polarized light, instead of the Zeeman shifted resonant condition, can be used to cause a restoring force [18]. Figure 1(d) summarizes our scheme: Assisted by the spatial Zeeman shift and rapid mixing of the substates, atoms pumped to the outer Zeeman substate m can be hit back to the origin at the turning point of $x_0 \sim h|\delta_T|/(m+1)\beta\mu_e$, thus forming stable trapping.

One may expect randomization of magnetic substates through the optical pumping by the trapping laser itself, as observed in "strong transitions" [11,19] that do not satisfy Eq. (2). However, in the MOT operated on the "weak transition," where the linewidth γ is narrower than the single photon recoil shift of kv_R, such an optical pumping cycle is very limited and not enough to guarantee stable trapping, because only a few photon recoils can push atoms outside the narrow resonant linewidth of γ. Therefore it happens that the atoms leak out of the trap without being pumped to an adequate substate. In order to circumvent the difficulty, an optical pumping mechanism that does not cause excess heating of atoms is indispensable. We applied, in addition to the "trapping" laser that drove the $F_g = 9/2 \to F_e = 11/2$ transition, a "stirring" laser that was a slightly red-detuned from the $F_g = 9/2 \to F_e = 9/2$ transition [see Fig. 2(a)]. Because the latter transition has a 4.5 times smaller Zeeman shift than the trapping transition, the atom remains on resonance for an extended time in an inhomogeneous magnetic field. As a result, the stirring laser efficiently mixed magnetic-state populations while it functioned as an efficient molasses cooling, thus forming a DMOT.

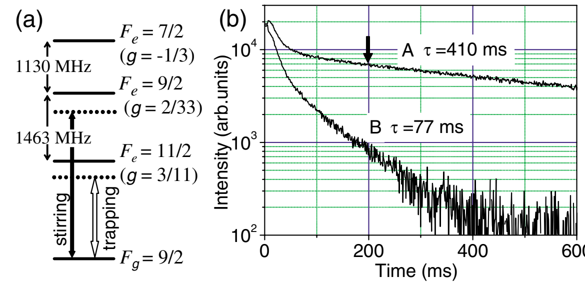

FIG. 2 (color online). (a) Hyperfine structure of the ^{87}Sr atoms in the $^1S_0 - {}^3P_1$ transition. The $F_g = 9/2 \to F_e = 11/2$ transition is used as a "trapping" cycle, while the $F_g = 9/2 \to F_e = 9/2$ transition with a smaller g factor is used as a "stirring" cycle. (b) Decay of atoms in the MOT. By applying the trapping and stirring lasers simultaneously (curve A), a stable operation of the DMOT is realized. The curve B shows the atom decay in the absence of a stirring laser.

In addition to the experimental setup described previously [10], a 1.5-cm-long atom collimator consisting of a two-dimensional optical molasses on the $(5s^2)\,^1S_0 - (5s5p)\,^1P_1$ transition was placed 4 cm downstream of an atom oven to enrich the ^{87}Sr isotope with a natural abundance of 7%. We employed a two-stage laser-cooling scheme: The $^1S_0 - {}^1P_1$ transition at 461 nm with a linewidth of 32 MHz was used for precooling, while the intercombination transition $^1S_0 - {}^3P_1$ at 689 nm with $\gamma_R = 2\pi \times 7.1$ kHz was used for further cooling. In the precooling, the cooled atoms were optically pumped into the metastable $^3P_2$ state via the $^1D_2$ state and were accumulated in the quadrupole magnetic trap, which functioned as an atom reservoir that shielded atoms from inelastic collisions caused by the cooling light. At the end of the loading period of 2 s, these magnetically trapped atoms were optically pumped back to the $^1S_0$ state via the $^3S_1$ state. This loading technique [20] allowed us to trap roughly 10^7 atoms, which was a factor of 7 increase in the number of atoms, at a temperature of a few mK.

In the subsequent cooling in the DMOT, two external-cavity loaded diode lasers, the trapping and stirring lasers, as shown in Fig. 2(a), were overlapped and introduced into the trap region with the same helicity. These two lasers, offset locked to a master oscillator that had a linewidth and frequency stability of less than 1 kHz [21], were initially frequency modulated at 15 kHz with a spectral bandwidth of 1.6 MHz to increase the velocity capture range of the narrow transition [10]. The magnetic field gradient was first set to $\beta = 1$ G/cm and then gradually increased up to 3 G/cm to compress the atomic cloud for better loading into an optical trap.

After the above broadband-cooling period of 120 ms, the frequency modulation of the two lasers was turned off to start the narrow line-cooling process to further reduce the temperature. The curve B of Fig. 2(b) shows the decay of atom fluorescence when the trapping laser alone was used. The observed lifetime of $\tau \simeq 77$ ms was significantly shorter than that measured for ^{88}Sr [10], indicating the presence of a leak in the MOT due to insufficient pumping among the Zeeman substates. By applying the stirring laser and activating the DMOT mechanism, the trap lifetime was dramatically extended to $\tau \simeq 410$ ms [curve A in Fig. 2(b)]. We note that by reducing the magnetic field gradient of β, which eased the adiabatic following requirement for atoms decelerated in an inhomogeneous magnetic field [10], the trap lifetime was further improved and approached the background-gas-collision limited one at the experimental condition of $p = 5 \times 10^{-10}$ Torr.

The number of atoms in the DMOT was measured as a function of the trapping and stirring laser frequencies δ_T and δ_S, respectively. Figure 3(a) shows the atom number at 200 ms after turning off the frequency modulation, as indicated by an arrow in Fig. 2(b). The total laser intensity was $I_T = 200I_0$ and $I_S = 200I_0$ for the trapping and stirring lasers, respectively, where $I_0 = 3\ \mu\text{W/cm}^2$ is the saturation intensity for the transition. In order to investigate the role of these two lasers, we have performed Monte Carlo simulations that calculate single-atom trajectories in a one-dimensional DMOT. Figure 3(b) shows the number of atoms remaining inside the trap region of $D = 5.6$ mm that are equal to the $1/e^2$ laser beam diameter used in the experiment. Since we simulated these atom trajectories as long as 200 ms, atoms that were not trapped were pulled by the gravity out of the trap region of D. Therefore the plot gives the stability region of the DMOT.

As shown in Figs. 3(a) and 3(b), the stability of the DMOT is sensitive to the stirring laser detuning, indicating that the Doppler cooling condition is crucial in the optical pumping process. On the other hand, the DMOT shows a stable operation for a rather wide detuning of δ_T, which is limited only by the condition $|x_0| < D/2$, i.e.,

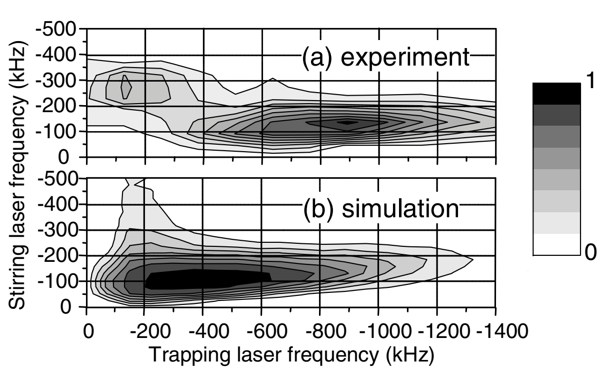

FIG. 3. Contour plot of the trapped atom number as a function of detunings of the trapping and the stirring lasers. The atom number is normalized by its maximum value. (a) Experimental results and (b) the Monte Carlo simulations.

the turning point locates inside the trap beam. This is in accordance with the fact that the detuning of the trapping laser only determines the turning point $|x_0| \propto |\delta_T|$ as discussed previously [10]. Although the simulation reasonably reproduced the experiment for larger $|\delta_T|$, the two plots showed significant disagreement for smaller detunings of $\delta_T \sim -200$ kHz and $\delta_S \sim -100$ kHz, where smaller trap volume was expected. This difference clearly indicates that cold-collision losses, which are seen in the rapid atom decay in Fig. 2(b) at $t < 50$ ms but not included in the simulation, strongly limit the atom number in the actual experiment.

The atom temperatures, measured by a time-of-flight (TOF) technique, were mainly dependent on the Doppler cooling condition of stirring laser δ_S and I_S. The temperatures were found to be in the range of 2–10 μK. A minimum temperature of 2.0 μK was observed for $\delta_S = -50$ kHz and $I_S = I_T \sim 50I_0$. This temperature was nearly 5 times higher than that observed for ^{88}Sr atoms because of the extra optical pumping processes required for ^{87}Sr. The atom number obtained for the lowest temperature was 1×10^6, with a typical $1/e$ cloud diameter of 240 μm.

In order to demonstrate the applicability of Doppler cooling near the Fermi temperature, these ultracold atoms were compressed into a far-off-resonant optical dipole trap (FORT) with a 1D lattice configuration. The FORT consisted of a standing-wave laser beam with its beam waist ($1/e$ radius of 24 μm) located in the atom cloud formed by the DMOT. The FORT laser with intensity of 300 mW/beam was operated at 840 nm to produce similar ac Stark shift potentials for the $^1S_0$ and $^3P_1$ states, enabling an efficient loading of atoms. Nearly 30% of the atoms were transferred into the FORT at a temperature of 2.2 μK in the narrow line DMOT period of 100 ms. This lattice FORT provided an anisotropic potential with an oscillation frequency of $\nu_r \approx 400$ Hz and $\nu_z = 60$ kHz for the radial and axial directions, respectively, enabling the separation of these two motional degrees of freedom. In addition, because of the tight axial confinement, 80% of the atoms were initially loaded into the vibrational ground state of $n_z = 0$, forming a quasi-2D system. In the following, we concentrate on the optical pumping and Doppler cooling with a laser beam propagating along the radial direction: The vibrational state $\langle n_z \rangle$ in the axial direction will remain unchanged in these processes, as the recoilless emission is expected for atoms confined in the Lamb-Dicke regime.

In order to optically pump the atoms into the $m_g = 9/2$ substate, we applied a weak bias magnetic field of $B_0 = 30$ mG perpendicularly to the lattice-FORT axis (see Fig. 4 inset) and irradiated a σ^+ polarized laser tuned to the $^1S_0(F = 9/2) - {}^3P_1(F = 9/2)$ transition for 30 ms. We then increased the magnetic field up to $B_0 = 1.7$ G and tuned the laser frequency 30 kHz below the $^1S_0(F_g = m_g = 9/2) - {}^3P_1(F_e = m_e = 11/2)$ transition in order to Doppler cool the atoms. Because the Zeeman

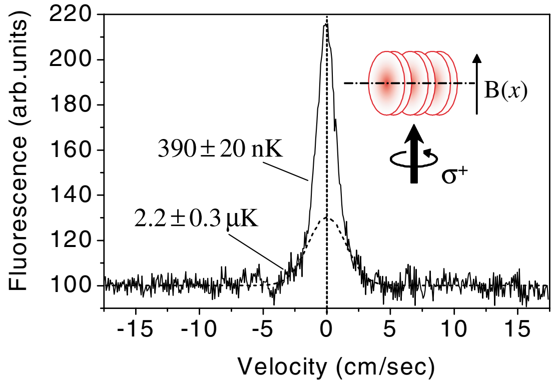

FIG. 4 (color online). Time-of-flight measurement of atoms in the lattice FORT. After polarizing and cooling the atoms, a bimodal velocity distribution appeared, indicating the atom population among several Zeeman substates. The dashed curve is a Gaussian fit to a background distribution corresponding to 2.2 μK. The experimental configuration is shown in the inset.

shift was sufficiently larger than the transition linewidth of γ_R, the Doppler cooling was effective only for atoms in the $m_g = 9/2$ substate, therefore the temperature of the atoms in the other substates remained unchanged.

By using the TOF technique, a bimodal velocity distribution was measured: It consisted of a 390 ± 20 nK narrow central peak of the recoil temperature and a 2.2 ± 0.3 μK broad background, as shown in Fig. 4. The population of atoms in the $m_g = 9/2$ state, or, the degree of atomic polarization was derived from the area of the central peak by fitting the profile using a double Gaussian function. Typically, we trapped 1×10^2 atoms in a single lattice site in which 80% of the atoms were polarized in the $m_g = 9/2$ state. Taking into account the occupation in the axial vibrational ground state as well, the Fermi temperature for the 2D system, $T_F = (h\nu_r/k_B)\sqrt{2N}$, was estimated to be $T_F \sim 0.2$ μK. We, therefore, achieved $T/T_F \sim 2$ for the 2D ensemble of fermionic atoms.

In conclusion, we developed a DMOT scheme for ^{87}Sr atoms and demonstrated a radiative cooling to twice the Fermi temperature in the quasi-2D optical trap. The DMOT scheme establishes time-averaged trapping forces through randomization of the population in the ground state Zeeman substates. This technique can be widely applied to alkaline-earth fermions and other systems, such as the carbon family atoms, where conventional MOT techniques are inapplicable. The long-lived metastable states of $(5s5p)\,^3P_{0,2}$ in Sr and in other alkaline-earth atoms will give us a unique opportunity to create more than one degenerate Fermi system simultaneously by using independent cooling transitions [20]. Controlling the radiative transition rate by employing the Pauli blocking effect [22] is an intriguing subject. By preparing the system in the state where atoms decay radiatively to the Fermi-degenerated ground state, a new type of metastable state caused by the particles' statistics will appear for a macroscopic number of atoms.

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[1] B. DeMarco and D. S. Jin, Science **285**, 1703 (1999).
[2] H. T. C. Stoof, M. Houbiers, C. A. Sackett, and R. G. Hulet, Phys. Rev. Lett. **76**, 10 (1996).
[3] B. DeMarco, S. B. Papp, and D. S. Jin, Phys. Rev. Lett. **86**, 5409 (2001).
[4] A. G. Truscott, K. E. Strecker, W. I. McAlexander, G. B. Partridge, and R. G. Hulet, Science **291**, 2570 (2001).
[5] F. Schreck, L. Khaykovich, K. L. Corwin, G. Ferrari, T. Bourdel, J. Cubizolles, and C. Salomon, Phys. Rev. Lett. **87**, 080403 (2001).
[6] Z. Hadzibabic, C. A. Stan, K. Dieckmann, S. Gupta, M. W. Zwierlein, A. Görlitz, and W. Ketterle, Phys. Rev. Lett. **88**, 160401 (2002).
[7] S. R. Granade, M. E. Gehm, K. M. O'Hara, and J. E. Thomas, Phys. Rev. Lett. **88**, 120405 (2002).
[8] B. Yurke, Phys. Rev. Lett. **56**, 1515 (1986); M. O. Scully and J. P. Dowling, Phys. Rev. A **48**, 3186 (1993).
[9] K. R. Vogel, T. P. Dinneen, A. Gallagher, and J. L. Hall, IEEE Trans. Instrum. Meas. **48**, 618 (1999).
[10] H. Katori, T. Ido, Y. Isoya, and M. Kuwata-Gonokami, Phys. Rev. Lett. **82**, 1116 (1999).
[11] T. Kuwamoto, K. Honda, Y. Takahashi, and T. Yabuzaki, Phys. Rev. A **60**, R745 (1999).
[12] E. A. Curtis, C. W. Oates, and L. Hollberg, Phys. Rev. A **64**, 031403 (2001).
[13] T. Binnewies, G. Wilpers, U. Sterr, F. Riehle, J. Helmcke, T. E. Mehlstäubler, E. M. Rasel, and W. Ertmer, Phys. Rev. Lett. **87**, 123002 (2001).
[14] T. Ido, Y. Isoya, and H. Katori, Phys. Rev. A **61**, 061403 (2000).
[15] H. Katori, in *Proceedings of the 6th Symposium on Frequency Standards and Metrology, 2002*, edited by Patric Gill (World Scientific Publishing Co., Singapore, 2002), p. 323.
[16] Z. Idziaszek, L. Santos, and M. Lewenstein, Phys. Rev. A **64**, 051402 (2001).
[17] E. L. Raab, M. Prentiss, A. Cable, S. Chu, and D. E. Pritchard, Phys. Rev. Lett. **59**, 2631 (1987).
[18] P. Bouyer, P. Lemonde, M. BenDahan, A. Michaud, C. Salomon, and J. Dalibard, Europhys. Lett. **27**, 569 (1994).
[19] T. Kurosu and F. Shimizu, Jpn. J. Appl. Phys. **29**, L2127 (1990).
[20] H. Katori, T. Ido, Y. Isoya, and M. Kuwata-Gonokami, in *Atomic Physics 17*, edited by E. Arimondo, P. DeNatale, and M. Inguscio (AIP, New York, 2001), p. 382.
[21] Y. Li *et al.* (to be published).
[22] T. Busch, J. R. Anglin, J. I. Cirac, and P. Zoller, Europhys. Lett. **44**, 1 (1998).