Magneto-Optical Trapping and Cooling of Strontium Atoms down to the Photon Recoil Temperature

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We report narrow-line laser cooling and trapping of strontium atoms down to the photon recoil temperature. ^{88}Sr atoms precooled by the broad $^1S_0$-$^1P_1$ transition at 461 nm were further cooled in a magneto-optical trap using the spin-forbidden transition $^1S_0$-$^3P_1$ at 689 nm. We have thus obtained an atomic sample with a density over 10^{12} cm^{-3} and a minimum temperature of 400 nK, corresponding to a maximum phase space density of 10^{-2} which is 3 orders of magnitude larger than the value that has been obtained by magneto-optical traps to date. This scheme provides us an opportunity and system to study quantum statistical properties of degenerate fermions as well as bosons. [S0031-9007(98)08352-5]

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Laser-cooling techniques have opened up new opportunities to perform precision measurements of individual atoms with reduced thermal motion and to study atom-photon mechanical interactions and atom collisions at ultracold temperature. Another landmark for these techniques is to get into a quantum degenerate regime where the phase space density $\rho = n\lambda_{\mathrm{dB}}^3$ is of the order of unity, by further cooling atoms with simultaneous increase of atom density n, where λ_{dB} is the thermal de Broglie wavelength of atoms. The realization of Bose-Einstein condensation (BEC) in alkali atoms in 1995, which has triggered a vast research field [1,2], enables us to study the fundamental aspects of degenerate Bose gas in dilute atomic vapors experimentally and theoretically. Extending atomic species would be an important step for a future investigation, because the nature of the degenerate atoms strongly depends on their internal states or statistics, which leads to intriguing studies such as the study of bosons with attractive interactions [2], degenerate Fermi gas, and boson-fermion mixture.

In view of a better handling of the condensates [3], as well as the challenge for an ultimate optical manipulation of atoms, there were tremendous efforts toward BEC by purely optical means [4–6] although they were not completely successful. This Letter demonstrates laser cooling of ^{88}Sr atoms down to the photon recoil temperature in a magneto-optical trap (MOT) using an intercombination line. The use of the narrow transition with the linewidth less than the photon recoil shift drastically altered the radiation trapping effects occurring in the conventional MOT's [7,8], allowing us to achieve the phase space density as high as 10^{-2}. This scheme can be a promising route to obtain quantum-degenerate gases of either boson or fermion, by all-optical means.

The study of ultracold alkaline earth atoms has several advantages over alkali atoms: (1) Since the ground state is a closed shell of the $^1S_0$ state, fewer inelastic collision channels are expected, which is crucial to achieve high density trapping. (2) Using a spin-forbidden line of $^1S_0$-$^3P_1$ allows us to Doppler-cool atoms down to the nanoKelvin regime [9]. (3) Because of abundant fermionic isotopes and their simple hyperfine structure in the ground state, those isotopes can also be easily laser cooled to explore the features of degenerate fermions. Among alkaline earth atoms, we find an adequate transition moment for cooling and trapping in the strontium intercombination line [10]; the Doppler cooling limit, $\sim\hbar\gamma$ [9,11], is close to the photon recoil energy $E_R = \hbar^2k^2/2m$, while the acceleration due to photon recoils $\sim\hbar k\gamma/2m$ is large enough to hold atoms against the gravitational acceleration g, where γ, k are the linewidth and the wave number of the transition, respectively, and m is the mass of the atom.

Laser cooling essentially relies on the spontaneous emissions for energy dissipations. However, the reabsorption of these spontaneously emitted photons, on the other hand, causes serious obstacles in obtaining cold and dense samples [12]. These radiation trapping effects, giving rise to the repulsive forces between cold trapped atoms [8], put a stringent limit on the attainable phase space density. In conventional MOT's [7] or polarization gradient molasses [13] using dipole-allowed transitions $\gamma \gg E_R/\hbar$, the phase space density is typically less than 10^{-5}. A lot of attempts have been made to overcome this restriction by reducing the excitation of atoms once they are cooled and trapped: Ketterle *et al.* invented a dark-SPOT [14] to achieve the density close to 10^{12} cm^{-3} with $T \sim 1$ mK. Later, Raman cooling was applied for sodium and cesium atoms [4,5] trapped in far off resonant optical dipole traps to increase the phase space density up to $\sim 10^{-3}$. Similar phase space density was obtained using gray molasses [6]. However, the drawback in their schemes is that they cannot suppress the reabsorption of the spontaneous photons emitted in the course of the laser cooling because of their broad cooling transitions. In striking contrast with these approaches, we used a spin-forbidden transition, even narrower than the single photon recoil shift of $\hbar k^2/m$, to substantially minimize the reabsorption process. In addition, a position-dependent Zeeman shift in a MOT further keeps the atoms from radiation trapping by reducing the photon scattering rate in the trap center.

We have employed two laser-cooling stages to achieve the recoil temperature. The broad transition $5s^2\,{}^1S_0{-}5s5p\,{}^1P_1$ with the wavelength $\lambda_1 = 461$ nm and the linewidth $\gamma_1/2\pi = 32$ MHz was used for preliminary cooling. A stilben-3 dye laser (COHERENT 899) was employed as a light source. Strontium atoms from an oven were decelerated in a 30-cm-long tapered solenoid [15] by a laser detuned 270 MHz below the resonance. The slowed atoms were fed into a MOT formed by a pair of anti-Helmholtz coils and three pairs of counterpropagating laser beams in orthogonal directions with opposite circular polarization [7]. Each trapping beam typically has an intensity of 5 mW with an e^{-2} radius of 6 mm and a frequency detuning of -70 MHz from the resonance. This blue-MOT collected 8×10^7 atoms in a typical loading time of 20 ms. This loading time suggests the blue-MOT lifetime that is limited by an optical pumping loss to the long-lived metastable ${}^3P_2$ state via the ${}^1D_2$ state [10,16].

These precooled atoms were transferred into a second stage red-MOT for further cooling, by switching over the laser to the $5s^2\,{}^1S_0{-}5s5p\,{}^3P_1$ transition at $\lambda_2 = 2\pi/k_2 = 689$ nm with $\gamma_2/2\pi = 7.6$ kHz and the saturation intensity $I_2 = 3\ \mu\text{W/cm}^2$. The cooling laser was generated by laser diodes: An extended cavity loaded laser diode, electronically stabilized to a high-finesse reference cavity made of an Invar spacing, was used to injection-lock a slave laser to increase laser power up to 10 mW [17]. The stability of the laser frequency was estimated to be less than 50 kHz in 5 min, a typical time during which we did series of measurements. The laser, passed through an acousto-optic modulator in a double pass configuration to manipulate the laser spectrum, was superimposed on the blue-MOT laser with the same circular polarization to form a red-MOT as well.

To design a loading procedure for the red-MOT, we performed Monte Carlo simulations to consider the following issues: (1) an improvement of the limited velocity capture range imposed by the narrow linewidth γ_2, (2) the cooling time required to push most of the atoms into a narrow phase space, and finally (3) an optimum magnetic field gradient to compress the atom cloud while satisfying the adiabatic requirement $\mu_2 dB/dz < \hbar k_2^2 \gamma_2/2mv$ for stable trapping [15,18], where $\mu_2 = 2\pi \times 2.1$ MHz/G is the Zeeman shift coefficient for ${}^1S_0$-${}^3P_1$ and v is the velocity of the atom. To compensate the velocity capture range $v_c \sim \gamma_2/k_2$ that is narrower than the photon recoil velocity, we broadened the laser line shape to cover the Doppler shift $k_2 v$ of the atoms from the blue-MOT. 1D semiclassical simulations showed that 30 sidebands, with a spacing of 50 kHz and an intensity of 10 μW/cm^2 for each sideband, cooled and trapped 90% of the atoms with an initial temperature of 2 mK in 40 ms. The optimum field gradient dB/dz was around 5 G/cm that gave a trap lifetime of 1 s. Further increase of dB/dz reduced the trap lifetime dramatically, although it allowed compression of the cloud's size z_0, which will be discussed later. The designed loading procedure is depicted in Fig. 1(a): Strontium atoms collected by ${}^1S_0$-${}^1P_1$ are cooled further by a red-broadband laser for 90 ms, which is longer than the 1D simulation considering the increased dimensionality. A weak magnetic field $dB/dz \sim 3$ G/cm is used to well satisfy the adiabatic requirement in the early stage; then the field gradient is gradually increased to compress the cloud and achieve higher density.

For the experimental realization of broadband cooling, the laser frequency tuned 1.6 MHz below the ${}^1S_0$-${}^3P_1$ resonance was sinusoidally modulated at 50 kHz with a maximum frequency shift of 1.5 MHz (or the modulation index of 30), which was wide enough to cover the entire Doppler shift of initial velocity distribution. The total laser intensity was 7 mW/cm^2 at the center of the trap. Figure 1(b) shows the fluorescence intensity from the trap that is proportional to the number of atoms inside the 3 mm diameter observation region. The ratio of the intensity just after the loading ($t = -90$ ms) and at the end of broadband cooling ($t = 0$ ms) indicates the transfer efficiency ($\sim$30%) of atoms into the red-MOT. The behavior of the florescence intensity in the range $-90 < t < 0$ ms is explained by cooling dynamics: The initial sample, with an energy of a few mK, expanded outside the observation region causing the decrease in total fluorescence. Laser cooling in the red-MOT then compresses the sample, producing the gradual increase in the fluorescence. In the final stage ($t > 0$ ms), the frequency modulation was turned off to operate at a single frequency, and the laser detuning δ_s and the total

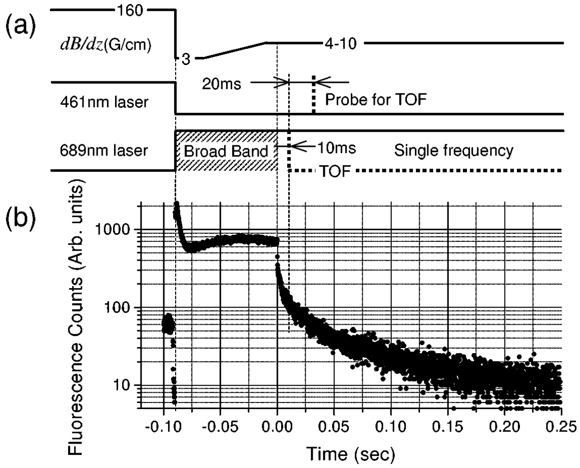

FIG. 1. (a) Sequence of the experiment; the control of the magnetic field gradient dB/dz for the MOT, ${}^1S_0$-${}^1P_1$ cooling laser, and ${}^1S_0$-${}^3P_1$ cooling laser, respectively. The horizontal axis corresponds to the plot below. The timing for time-of-flight (TOF) measurement is shown by the dotted line. (b) Change of ${}^1S_0$-${}^3P_1$ fluorescence from the red-MOT.

laser intensity I_s in the trap were adjusted to optimize the final phase space density. For $t \gg 50$ ms, the fluorescence decay became closer to exponential as an asymptote [19], which inferred the trap lifetime of 600 ms that reasonably agreed to the collision limited lifetime at the background pressure 10^{-8} Torr.

To perform time-of-flight measurements, the laser was turned off to free the atoms at $t = 10$ ms as indicated in Fig. 1(a). The falling and expanding atom cloud was probed 20 ms later by a 50-μs-long laser pulse near resonant to ${}^1S_0$-${}^1P_1$. Figure 2(a) shows a charge-coupled device (CCD) image exposed during $5 < t < 31$ ms; the upper disk shows the atom cloud in a red-MOT (fluorescence observed at λ_2) and the sphere below the expanded cloud (observed at λ_1), respectively. Since the confining force of the trap was comparable to that of gravity, the shape of the atom cloud was deformed considerably; the atoms sank to the lower boundary where the Zeeman shift in the quadrupole field balanced the laser detuning. The temperature of atoms was determined by the width of expanded cloud with the initial trap size taken into account. The temperatures calculated from the horizontal and the vertical expansions in Fig. 2 were $0.68 \pm 0.01\ \mu$K and $0.83 \pm 0.01\ \mu$K, respectively. This difference, which was within 20%, can be attributed to a large oscillatory motion of trapped atoms in the horizontal direction. Thus in the following we discuss the temperature by the vertical one.

Figure 3 summarizes the temperature of atoms in the red-MOT. The temperatures were rather insensitive to the laser detunings δ_s as shown in the inset, which can be explained by the radiation pressure that depends on the Doppler shift and the position-dependent Zeeman shift [20]. The effective detuning $\delta'_\pm$ for atoms moving along a particular axis in a quadrupole field is written as $\delta'_\pm = \delta_s \pm [k_2 v + \mu_2 B(z)]$, with $\beta = dB(z)/dz = 4-10$ G/cm and $\pm$ corresponding to circularly polarized light from right and left with opposite helicities, respectively. Assuming large negative detuning $\delta_s \ll -\gamma_2$, as used in the experiment, simplifies the discussion. Atoms moving toward their turning points rebound at $z_0 \sim \pm\delta_s/\mu_2\beta$ with nearly zero velocity. These atoms are then accelerated toward the origin until their Doppler shifts exceed the transition linewidth, i.e., $k_2 v = \gamma_2$, which provides the MOT temperature $k_B T$ on the order of $m(\gamma_2/k_2)^2 = (\hbar\gamma_2)^2/2E_R$. This gives 300 nK independent of δ_s, where we used the Doppler limit $\hbar\gamma_2/k_B = 360$ nK and the recoil limit $2E_R/k_B = 440$ nK. Note that the trap width $2z_0$ is proportional to $|\delta_s|$ or β^{-1}. By reducing the laser intensity, the temperature was decreased down to 400 nK as shown in Fig. 3, which is due to the reduced saturation of the cooling transition. However, for intensity $I_s < 10\ \mu\mathrm{W/cm^2}$, the radiation force could no longer hold atoms against the gravity mg, so that the number of trapped atoms decreased quite rapidly.

Finally we examined the density dependence of the atom temperature, which was found to be $dT/dn \sim 0.4\ \mu\mathrm{K}/(10^{12}\ \mathrm{cm^{-3}})$ in the range $n = (1-5) \times 10^{11}\ \mathrm{cm^{-3}}$. This slow heating rate may be attributed to the radiation trapping as discussed in Ref. [6]. Our value is an order of magnitude smaller than the best value reported for gray molasses [6], which implies the efficient suppression of the radiation trapping due to the narrow linewidth γ_2. Because of this slow heating rate, a further increase in the trap density while keeping the temperature relatively low can be expected by increasing the atom flux in the initial loading procedure.

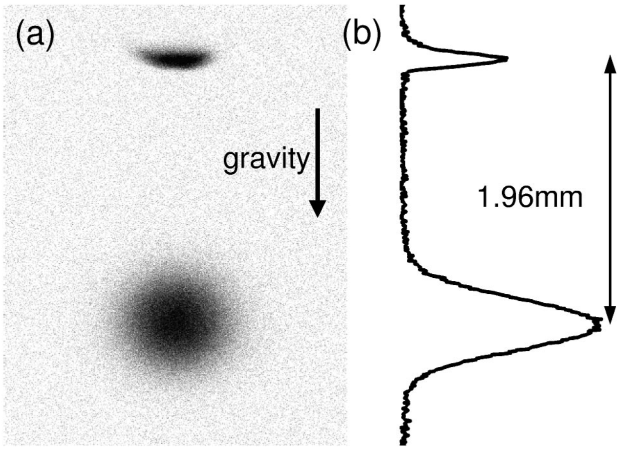

FIG. 2. (a) CCD image of a red-MOT (upper disk) and an expanded atomic cloud in 20 ms free flight (a sphere below the MOT). The gravity directs toward the bottom. (b) A cross section of the image (a) along the vertical axis. The expanded atom cloud was well fit by the Gaussian profile with $T = 830$ nK.

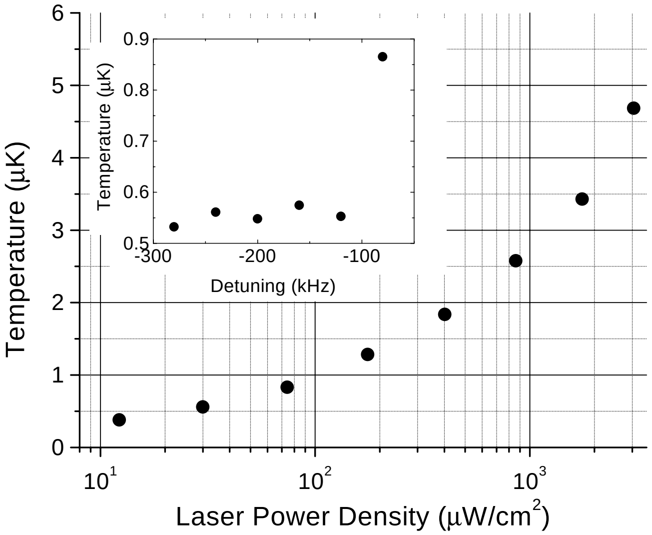

FIG. 3. The change of the atomic temperatures as a function of total laser intensity I_s with laser frequency detuned 120 kHz below ${}^1S_0$-${}^3P_1$ resonance. The inset shows the frequency dependence of the temperature with $I_s = 30\ \mu\mathrm{W/cm^3}$.

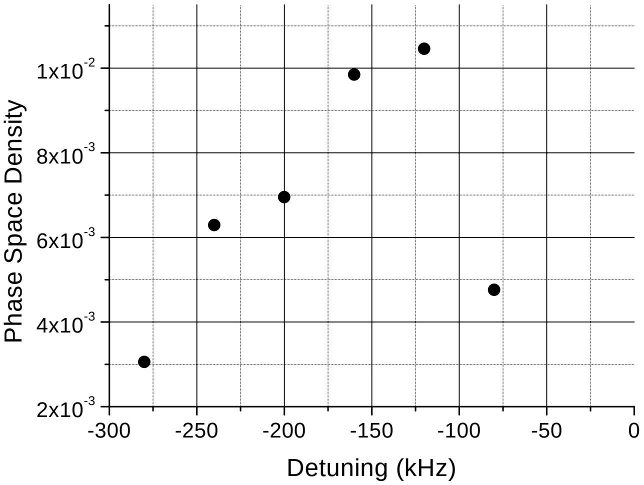

FIG. 4. The change of the phase space density as a function of laser detuning from ${}^1S_0$-${}^3P_1$ with $I_s = 30\ \mu\mathrm{W/cm}^2$.

The phase space density just before TOF measurement is readily determined by $\rho = (N/V)\lambda_{\mathrm{dB}}^3$ with $\lambda_{\mathrm{dB}} = h/(2\pi m k_B T)^{1/2}$, as there is no degeneracy in the ground state. The atomic number N was estimated by the total fluorescence intensity of the expanded atom cloud and the volume $V = \pi^{3/2}\sigma_v\sigma_h^2$ by the red-MOT size; assuming an ellipsoid with the vertical and horizontal e^{-1} radius of σ_v and σ_h, both were measured from the image shown in Fig. 2(a). The results are summarized in Fig. 4 as a function of laser frequency. The maximum phase space density observed was $\rho = 10^{-2}$ with $T = 550$ nK and $N/V = 6.5 \times 10^{11}\ \mathrm{cm}^{-3}$.

In summary we have demonstrated the magneto-optical cooling and trapping of strontium atoms down to the photon recoil temperature using a spin-forbidden transition. The use of narrow transition $\gamma_2 \sim E_R/\hbar$ has made it possible to increase the phase space density more than 3 orders of magnitude over the conventional MOT using broad transitions $\gamma \gg E_R/\hbar$, because of the efficient suppression of the radiation trapping as well as the reduced Doppler cooling limit. These cooled atoms could be easily loaded into a far off resonant dipole trap [4,5], where the atoms could be evaporatively cooled [1,2] or confined by an adiabatically deformed potential [21] to achieve higher phase space density. Another interesting experimental possibility is applying sideband cooling between $5s^2\,{}^1S_0$ and $5s5p\,{}^3P_1$ states. Coupling these two states to upper $5s5p\,{}^1P_1$ and $5s6s\,{}^3S_0$ states, respectively, by an infrared laser may realize optical potentials with the same vibrational energy separation $\hbar\omega_m$ for both states simultaneously. Since ω_m can be larger than the linewidth γ_2 or $E_R/\hbar$, the well established scheme in a single ion cooling [22] can be applied to the ensemble of neutral atoms. In this case, the final state of the sideband cooling impressively depends on the quantum statistics of the isotopes, ^{88}Sr or ^{87}Sr, corresponding to BEC or degenerate Fermi gas, respectively.

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