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Optical-dipole trapping of Sr atoms at a high phase-space density

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Employing a far-off resonance optical-dipole trap (FORT), we attained a phase-space density exceeding 0.1, or an order to quantum degeneracy. Strontium atoms were magneto-optically cooled and trapped using the spin-forbidden ${}^1S_0$-${}^3P_1$ transition and then compressed into a FORT that was designed to allow simultaneous Doppler cooling. We discussed that the phase-space density was finally limited by the light-assisted collisions occurring in the optical cooling.

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The attainment of quantum degenerate atomic gases [1] has been one of the driving forces promoting laser-cooling techniques. Toward this goal, various kinds of cooling techniques have been developed, allowing us to reach down to subrecoil temperatures. Even for ultracold atoms that are laser-cooled down to the photon recoil momentum h/λ, an atom density of $n_R \sim \lambda^{-3}$ is necessary to reach a quantum degenerate regime. For atom densities such as n_R, since the average atom spacing is on the order of λ, strong atom-atom interactions via the near resonant photon, i.e., the radiation trapping [2] and the light-assisted collisions [3], manifest themselves and drastically disturb the cooling dynamics.

To overcome the difficulties inherent in optical-cooling schemes at such high atom densities, evaporative cooling in magnetic traps has been successfully employed to create Bose-Einstein condensation (BEC) in alkali-metal atomic gases [1]. Optical cooling and the trapping schemes, however, still attract strong interest because they are expected to realize rapid creation of degenerate atoms as well as their better handling. Moreover, optical schemes will give unique access to some different atom species not condensed thus far: polarized fermions, some kinds of bosons with unfavorable scattering length, or spinless particles [4], to which thermalization due to elastic collisions or magnetic trapping cannot be applied. Among them, alkaline-earth atoms [5] can be important for future applications. Using narrow-line cooling [4], fermionic isotopes such as ^{87}Sr can be Doppler-cooled down to a submicrokelvin regime, where degenerate fermion gases show its distinctive features. Spinless bosonic isotopes, on the other hand, have potential importance as an atom interferometer because of their insensitivity to magnetic fields, and as candidates for optical standards based on intercombination lines [5].

This Rapid Communication demonstrates the Doppler cooling of ^{88}Sr atoms in a far-off resonance optical-dipole trap (FORT) [6] to achieve a phase-space density higher than 0.1, which is, to our knowledge, the highest ever achieved by purely optical means. This alternative FORT design, which allows simultaneous Doppler cooling, enables high loading efficiency of magneto-optically trapped atoms. We have shown that the maximum phase-space density is finally limited by light-assisted inelastic collisions occurring in optical cooling. The developed scheme can be widely applied to alkaline earth and other species such as Yb [7], in which an intercombination transition is used for cooling.

The light-induced interactions between atoms have been the main obstacle to the creation of cold and dense atomic gas in optical cooling. The radiation-trapping effect [2], which limits the density and temperature of laser-cooled atoms, has been moderated by applying Raman (sideband) cooling [8–10], gray molasses [11], or narrow-line [4] cooling, which minimize the photon scattering or reabsorption in the course of laser cooling. Now, the last obstacle that limits the attainable atom density is light-assisted collisions [3], in which the excitations of the attractive quasimolecular potential by the red-detuned cooling photon cause inelastic two-body collisions. These light-assisted collisions with a loss rate β determine the steady-state atom density as $\sqrt{\phi/(\beta V)}$, assuming an atom flux ϕ into a trap volume V. This formula infers a simple guiding principle for high-density trapping: for the given β, the atom flux per volume ϕ/V needs to be increased.

In order to realize the idea, we have developed an optical-dipole trap that can be combined with Doppler cooling, and thus enhanced ϕ/V by efficiently transferring the atoms into a small conservative trap with the help of optical cooling. In laser cooling that employs an intercombination transition, since the cooling ground state and the excited state are mainly coupled to the respective spin states by an applied laser field, arbitrary light shift potentials for these states can be generated by tuning the laser parameters. Especially, by adjusting the light shifts of both cooling states so that they are equal, simultaneous Doppler cooling is expected.

We employed magneto-optically cooled and trapped ^{88}Sr atoms using the spin-forbidden ${}^1S_0$-${}^3P_1$ transition at $\lambda = 689$ nm. The narrow linewidth of the transition $\gamma/2\pi = 7.6$ kHz, which is less than the photon recoil shift of $\hbar k^2/m = 9.5$ kHz, cooled atoms down to the photon recoil temperature of 440 nK and enabled high-density trapping by efficiently suppressing the radiation-trapping effects, leading to a phase-space density of $\rho \sim 0.01$ [4]. To further increase the phase-space density, we applied the FORT described above. Figure 1 shows the energy levels of ^{88}Sr. The FORT laser couples the cooling ground state $5s^2\,{}^1S_0$ to the upper singlet series of $5snp\,{}^1P_1$, while the cooling upper state $5s5p\,{}^3P_1$ is coupled to the triplet series of $5sns\,{}^3S_1$,

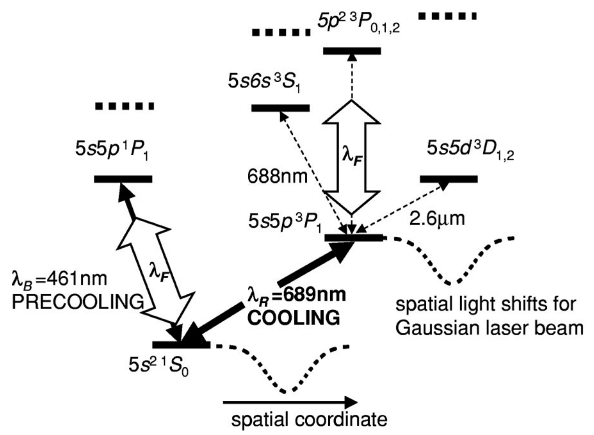

FIG. 1. The energy levels of ^{88}Sr. A FORT laser at $\lambda_F = 800$ nm couples the cooling ground state $^1S_0$ and the excited state $^3P_1$ to the upper singlet and triplet states, respectively, generating the same amount of Stark shifts. Spatial light shifts for these two states are schematically depicted by the dotted lines assuming the FORT laser with gaussian profile. Because the atomic resonance frequency is unchanged in space, the optical confinement in $^1S_0$ can be compatible with Doppler cooling on the intercombination line.

$5p^2\,{}^3P_{0,1,2}$, and $5snd\,{}^3D_{1,2}$. Our calculation and preliminary experiment [12] showed that the same negative light shifts for both states can be realized by tuning the laser wavelength to $\lambda_F = 800$ nm, at which the Stark shift coefficient for both $^1S_0$ and $^3P_1$ is $U/h = I_F \times 1.45$ mHz/(W/m^2), where I_F is the laser power density. This same amount of negative light shift guaranteed that the FORT is compatible with the Doppler cooling or the magneto-optical trapping because the atomic resonance frequency is virtually unchanged in space. In addition, as the FORT laser at λ_F is 340-nm far-off resonant from the $^1S_0$-$^1P_1$ transition, the photon-scattering rate is below 10^{-1} s for a typical laser power of $I_F = 18$ kW/cm^2; thus, recoil heating is negligible.

A crossed dipole trap formed by two horizontal beams propagating along the x and y axes was applied to provide three-dimensional tight confinement of atoms. The actual shape of the trap potential, determined by the combination of the Stark shift potentials and the gravitational potential mgz along the vertical direction, is written as

$$U(x,y,z) = -U_0\{e^{-(x^2+z^2)/a^2} + e^{-(y^2+z^2)/a^2}\} + mgz, \quad (1)$$

where a is the e^{-1} radius of the laser beam and U_0 is the depth of the Stark shift potential given by a single beam. The effective depth of the trap is set by the lowest potential barrier in either direction. $U(x,y,0)$ provides the potential depth of $u_{xy} = U_0$ on the x-y plane, and $U(0,0,z)$ gives the depth of u_z along the z axis, which varies $0 < u_z < 2U_0$ depending on the competition between gravity and the optical dipole force. For high laser intensity, where the Stark shift potential dominates the gravitational one and thus $u_{xy} = U_0 < u_z < 2U_0$ holds, energetic atoms leak along each beam axis in the horizontal plane. On the other hand, for lower intensity, since $u_z < u_{xy} = U_0$, the atoms leak along the z direction. When decreasing the laser intensity further, the local minimum of the potential disappears at $U_0 = mga\sqrt{e/2}$, below which atoms cannot be trapped.

Ultracold strontium atoms with a few photon-recoil energies were prepared by two-stage magneto-optical cooling and trapping [4]. First, strontium atoms were decelerated in a Zeeman slower and loaded into a magneto-optical trap using the $^1S_0$-$^1P_1$ transition to precool atoms. Second, we switched the laser to excite the spin-forbidden $^1S_0$-$^3P_1$ transition for further cooling and magneto-optical trapping (MOT). In order to cover the whole Doppler width (a few MHz) of the precooled atoms, the second-stage cooling laser was frequency modulated for a duration of 70 ms at the beginning, by which 30% of the precooled atoms were recaptured. The modulation of the cooling laser was then turned off, and the detuning δ_L and the total intensity I_L were set to -200 kHz and 160 μW/cm^2, respectively. Simultaneously, two laser beams, generated by the titanium-sapphire laser and passed through optical fibers, were introduced to start the loading of atoms. In order to form the FORT, these laser beams perpendicularly crossed one another at their waists almost in the center of the MOT. The laser beams had orthogonal linear polarization to avoid causing interference at the intersection. The atom transfer into the FORT continued for 35 ms in the presence of the MOT laser. After that, the MOT laser was turned off to operate the FORT alone for 10 ms, in which period the atoms not transferred into the FORT were separated.

Typically, 20% of the atoms recaptured in the MOT were transferred into the FORT, while the atom temperature remained constant. The various loading conditions were experimentally adjusted to optimize the final phase-space density. The laser detuning δ_L and the magnetic field gradient of the MOT (typically $\sim$5 G/cm) set the size of the MOT, while the intensity I_L set the atom temperature, as indicated in Ref. [4]. The optimum parameters were determined by the competition among the loading efficiency, the loss of atoms due to inelastic collisions, and the temperature of the atoms. For example, reducing the trap volume improved the loading efficiency but enhanced the collision losses. Furthermore, the FORT loading time with the MOT laser present was optimized by considering the balance between the atom loading and the collision losses. The loading atom flux ϕ decreased continuously because the available atom number in the MOT was limited, while the collision loss βn^2 increased quadratically as the FORT density n increased.

The trapped atoms were observed using an absorption imaging technique. To image the atoms in the FORT, a probe laser with an intensity of 120 μW/cm^2 tuned to 17 MHz above the $^1S_0$-$^1P_1$ resonance was sent through the atoms for 20 μs after 10 ms of FORT operation. The shadow of the atoms was imaged on a charge-coupled device (CCD) through a microscope objective lens. The magnification of the imaging system was 2.3, corresponding to the rescaled CCD-pixel size of 5.2 μm. The resolution was measured to be 6.6 μm. The image is shown in Fig. 2(a). Since the axis of the probe beam was directed to $\mathbf{e}_x + \mathbf{e}_y$ in the notation of Eq. (1), the trapped atoms were observed as a faint line and a dense ellipsoid on it, corresponding to the atoms confined

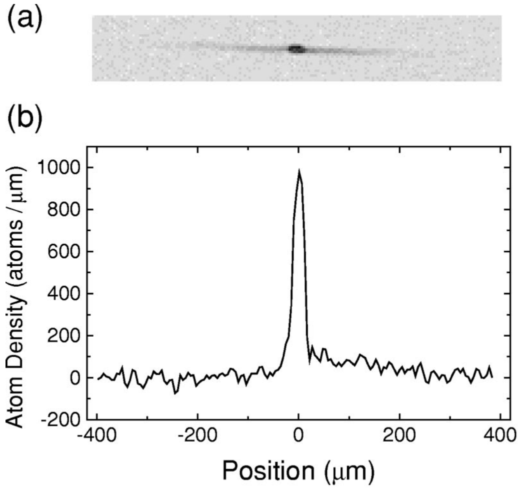

FIG. 2. (a) Absorption image of strontium atoms trapped in a crossed dipole trap. (b) Corresponding atom distribution along the horizontal direction. Over half of the atoms were trapped in the crossed region.

in each FORT laser axis and in the intersection, respectively. The typical e^{-1} radius of the ellipsoid was $\sigma_v = 6$ μm vertically and $\sigma_h = 12$ μm horizontally. The atom-number distribution corresponding to Fig. 2(a) horizontally is shown in Fig. 2(b), which indicates that over half of the atoms captured by the FORT are confined in the crossed region.

The temperature T_F and the number of atoms in the FORT were determined by time-of-flight (TOF) measurements. At 6 ms after turning off the FORT laser, i.e., 16 ms after turning off the MOT laser, the probe laser was flashed for 50 μs to image the two expanded atom clouds, corresponding to the atoms transferred into the FORT and those not transferred. These two atom clouds indicated the temperature of the atoms in the FORT and the MOT, respectively. Both temperatures are summarized in Fig. 3 as a function of the FORT laser intensity. While the temperature of atoms in the MOT was constant, T_F linearly depended on the laser intensity because the effective depth of the FORT potential u_{xy} or u_z, as shown by the dashed lines in Fig. 3, truncated the kinetic energy of trapped atoms. In the calculation of the trap depth, we assumed a beam waist of $a = 20$ μm that reasonably agreed with the measured beam radius.

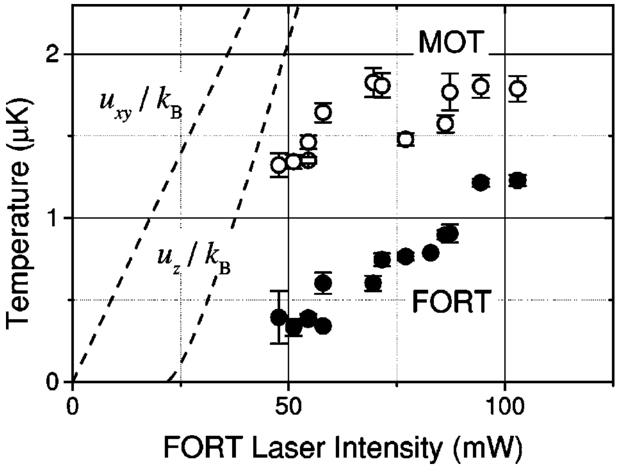

FIG. 3. Temperature of the atoms T_F in the crossed FORT (●) and the MOT (○) as a function of the single FORT laser intensity. The dashed lines u_z and u_{xy} are the calculated FORT potential along the vertical direction and in the horizontal plane, respectively. These barriers truncated the kinetic energy of atoms in the FORT, forcing the T_F to decrease proportionately to these barrier heights at the expense of trapped atoms.

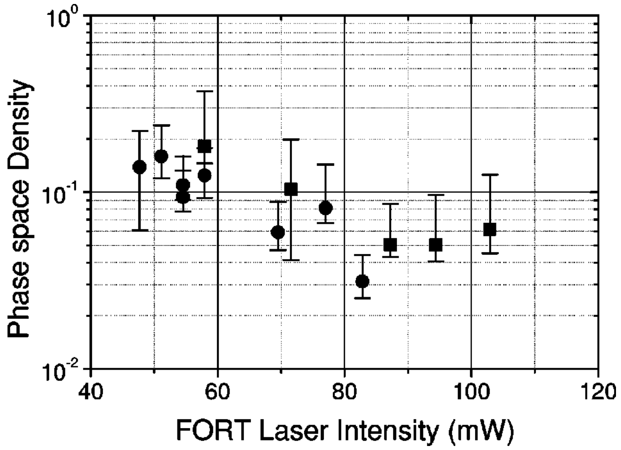

FIG. 4. Phase-space density of the atoms trapped in the crossed FORT as a function of the single FORT laser intensity. Different symbols correspond to different runs. Although the uncertainties in the estimation of the atom cloud size introduced relatively large error bars, as shown, a phase-space density exceeding 0.1 was obtained.

We carefully determined the number of atoms in the crossed FORT by combining the FORT image and the TOF image, because the high atom density ($n > 10^{12}$ cm^{-3}) in the crossed region modified the absorption rate of the probe laser due to radiation-trapping effects. We made the TOF measurement when the atoms not transferred into the FORT had been spatially separated. The total number of atoms N_t finally detected by the TOF was that of atoms trapped anywhere in the FORT laser beams, i.e., outside and inside of the beam intersection. With the help of the FORT image, we could precisely determine the number of atoms outside of the beam intersection N_{out} because of its low density. Hence the atom number inside the intersection N_{in} was inferred from both numbers, i.e., $N_{\text{in}} = N_t - N_{\text{out}}$, which ranged from 4×10^4 to 3×10^5 depending on the FORT laser intensity.

We estimated the size of the atom cloud in the crossed region by a FORT image assuming a gaussian distribution of atoms. It should be noted that these fits could overestimate the actual trap size because the radiation-trapping effects could distort the atom density profiles by reducing the probe absorption, especially in the trap center. In order to estimate the lower bound of the atom density or the phase-space density, we took the volume as $V = \pi^{3/2}\sigma_v\sigma_h^2$, where σ_v and σ_h are the vertical and horizontal e^{-1} radii obtained by the fitting. The phase-space density is thus estimated by $\rho = (N/V)\lambda_{dB}^3$ with $\lambda_{dB} = h/\sqrt{2\pi m k_B T_F}$, where m is the mass of an atom. Results are summarized in Fig. 4 as a function of FORT laser intensity. The asymmetric error bars shown in the figure are mainly due to the uncertainties in the volume measurements: The radiation-trapping effects described above may result in the reduction of volume by 60% or the increase in ρ by 150%, while the other statistical uncertainties were on the 20% level. In spite of these relatively large error bars, it is clear that the phase-space density well exceeds 0.1, with slightly increasing tendency as the FORT depth decreases [13].

The obtained phase-space density was mainly limited by the achievable atom density in the presence of light-assisted collisions occurring during atom transfer into the FORT. To examine the influence, we measured the fluorescence decay of the MOT and thus obtained the binary loss rate β with the help of atom-density measurements. The light-assisted collision loss rate was found to be $5\times10^{-12}<\beta<1.5\times10^{-11}$ $(\mathrm{cm}^3/\mathrm{s})$, rather insensitive to the MOT laser parameters that were used in the FORT loading experiment [14]. With the loading flux ϕ into the FORT volume V, the change of atom density n obeys the rate equation $dn/dt=\phi/V-\beta n^2$. We define the rising time constant as $\tau=1.5(\beta\phi/V)^{-1/2}=1.5(\beta n_f)^{-1}$, in which the density reaches 90% of the equilibrium density n_f [15]. The measured rising time $\tau=15$ ms and loss rate $\beta=10^{-11}$ cm^3/s yielded the attainable density $n_f=10^{13}$ cm^{-3}, which moderately agreed with the atom density we experimentally attained in the FORT. Since the density n_f is proportional to $\sqrt{\phi/(\beta V)}$, two orders of enhancement in $\phi/(\beta V)$ are necessary to reach quantum degeneracy.

In summary, we have demonstrated a rapid creation of nearly degenerate strontium atoms by employing an alternative FORT scheme, which is based on the successful combination of properly designed dipole force trapping and Doppler-cooling on a narrow intercombination line. We observed that the phase-space density was finally limited by the light-assisted inelastic collisions occurring in laser cooling. Therefore the reduction of these inelastic collisions is crucial to increase the density by another order. A laser suppression of light-assisted collisions or evaporative cooling [1] in an optical trap may overcome these difficulties. Even in the latter case, evaporative cooling time, which is reported typically tens of seconds for alkali-metal atoms [1], can be significantly reduced because of the high phase-space density we start with.

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[13] In decreasing the trap depth, the atom temperature decreased monotonically while the atom density remained almost constant, leading to a net increase in phase-space density. This fact may infer the manifestation of evaporative cooling in 10 ms of optical trapping.

[14] In spite of three orders of magnitude less excitation rate than that for typical alkali-metal atom experiments, the inelastic loss rate was even larger by an order of magnitude. These results may be attributed to the much longer lifetime of quasimolecules formed by two atoms in $^1S_0$ and $^3P_1$ states as well as the reduced trap depth.

[15] We assumed ϕ to be constant to simplify the discussion because the change of ϕ was estimated to be within 50% in the loading process.