Laser cooling of strontium atoms toward quantum degeneracy

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From the viewpoint of precision measurements, collision studies, and as a new source for Bose-Einstein condensation, obtaining cold and dense atomic gases in alkaline earth species is of particular interest. The configuration of two outer electrons in alkaline earth atoms gives rise to spin-singlet ground state and triplet excited states where radiative decays to the ground state are spin-forbidden. These two spin-states favor practical applications such as scalar atom-wave interferometry free from magnetic field perturbations and optical frequency standards based on narrow intercombination lines[1]. The former advantage of having $^1S_0$ ground state, however, prevents applying elaborate cooling techniques so far developed for alkali atoms: Sisyphus cooling, evaporative cooling in magnetic traps, or Raman cooling, which utilize substructures in the ground state. Therefore, novel cooling and trapping schemes need to be developed to enjoy the future applications in alkaline earth atoms at sub-μK regime.

All-optical creation of quantum degenerate atomic gases, on the other hand, has been one of the long-standing targets in laser cooling. Until now main attention has been focused in alkali systems [2]. Here we report on a novel approach towards this direction based on a narrow-line laser cooling[3] for strontium atoms. The use of a narrow spin-forbidden transition successfully reduces the radiation trapping effects that have been shown to be one of the serious drawbacks in laser cooling at high atom density above $10^{12}/\text{cm}^3$[4], thus enabling us to attain the hitherto high phase space density.

By using two transitions with considerably different dipole moments, *i.e.*, the dipole-allowed $^1S_0 - {}^1P_1$ ($\lambda = 461\text{nm}, \gamma = 2\pi \times 32\text{MHz}$) and successively the spin-forbidden $^1S_0 - {}^3P_1$ ($\lambda = 689\text{nm}, \gamma = 2\pi \times 7.6\text{kHz}$) transition, we Doppler-cooled thermal ^{88}Sr atoms down to the photon recoil temperature of 400 nK in a magneto-optical trap (MOT) and achieved a phase space density of $\rho \sim 0.01$[5]. In order to increase the phase space density further, the cold atoms were compressed into a newly designed far off-resonant optical dipole trap (FORT)[6], in which the FORT laser wavelength was properly tuned so as to produce the same amount of light shifts in the narrow-line cooling transition of $^1S_0$ and $^3P_1$. Since the atomic resonance frequency is made spatially-unchanged in this FORT potential, Doppler-cooling can be applied simultaneously and facilitate the atom transfer into the FORT. Because of this efficient compression mechanism, we achieved $\rho \sim 0.1$ for a crossed-FORT configuration [7]. We found that the atom density was strongly limited by light-assisted inelastic collisions ($k \sim 10^{-11}\text{cm}^3/\text{s}$) occurring in this optical cooling and transferring process.

To reduce this inelastic loss, we are currently employing an evaporative cooling in a FORT with 1D-lattice configuration formed by a vertical standing wave. In contrast to the crossed-FORT configuration, this lattice configuration provides a tight axial confinement against the gravity, resulting in a three-dimensional efficient evaporation. By reducing the FORT depth in a typical time constant of 0.5 s, we observed an increase in the phase space density as well as the drop in the atom temperature. Using time of flight technique, we measured highly anisotropic temperatures, 100 nK and 270 nK for the radial and axial direction respectively, indicating the vibrational ground-state occupation in the axial direction or the formation of 2D atomic gas. The quantitative analysis for this process is underway and will be discussed.

In summary, we have developed a novel cooling scheme for strontium atoms and attained a phase space density of 10% of that required for quantum degeneracy, which is, to the authors' knowledge, the highest ever attained by purely optical means. Owing to the rapid radiative-cooling process, the total cooling time required to obtain such near degenerate atomic gas was as short as a few hundred milli-second. This short production time will open up new possibilities in applying the gas sample for precision measurements. We have shown, however, that light-assisted inelastic collisions, which occur in the optical cooling, finally set a stringent limit on the phase space density. Therefore, in order to increase the density toward the quantum degeneracy, the reduction of the inelastic collisions is crucial. The developed cooling scheme can be immediately applied to realize Fermi degeneracy in fermionic ^{87}Sr isotope, since its Fermi temperature can be higher than the recoil-limited Doppler-cooling temperature assuming atom density that is experimentally realized in ^{88}Sr so far.

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