Evaporative cooling of ^{87}Rb atoms into Bose-Einstein condensate in an optical dipole trap

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We create a Bose-Einstein condensate (BEC) of ^{87}Rb atoms by runaway evaporative cooling in an optical trap. Two crossed infrared laser beams with a wavelength of 1064 nm are used to form an optical dipole trap. After precooling the atom samples in a quadrupole-Ioffe configuration (QUIC) trap under 1.5 μK by radio-frequency (RF) evaporative cooling, the samples are transferred into the center of the glass cell, then loaded into the optical dipole trap with 800 ms. The pure condensate with up to 1.5×10^5 atoms is obtained over 1.17 s by lowering the power of the trap beams.

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The optical dipole force trap has been used extensively in cold atom experiments. It can transport atoms over distances of up to 44 cm[1], and can also be used to study strong coupling in single-photon photoassociation of cesium dimers[2]. Moreover, due to the versatility of the trapping potential, it can be used to produce periodic lattice[3,4], which is employed in many fields, such as in the transition from superfluid to the Mott insulator phase[5−9]. One of the most important applications is the direct production of Bose-Einstein condensation (BEC) in an optical dipole force trap[10]. BECs in the optical trap have been achieved by many researchers for alkaline atoms[10−13] and in ytterbium[14] or alkaline-earth atoms[15,16]. The all-optical method of creating a BEC is advantageous in many respects. It can quickly produce the BEC within only a few seconds. It also allows atoms to be trapped in their lowest internal state[17], avoiding two-body losses. Moreover, because the all-optical evaporation procedure may not rely on an external magnetic field, it can directly produce spinor condensates[18]. For some atoms without ground-state magnetic moments, all-optical trapping and cooling is the only clear option[14].

In this letter, a forced evaporative cooling in a crossed optical dipole trap is demonstrated to create a ^{87}Rb BEC in the hyperfine state $|F = 2, m_F = 2>$. In our experiment, atoms were first precooled to 1.5 μK by radio-frequency (RF) evaporative cooling in a quadrupole-Ioffe configuration (QUIC) trap[19,20]. Subsequently, the atom sample was transferred back to the center of the glass cell[21] in favor of the optical access. This was then loaded into a crossed optical dipole trap to perform runaway evaporative cooling and achieve the ^{87}Rb BEC with a critical transition temperature of 0.44 μK. In the optical dipole trap, the depth of the potential trap in the z direction was reduced successively because of the gravity potential (Fig. 1(a)); thus, a levitating magnetic field gradient of 10 G/cm was applied to counteract the gravity in our experiment.

Our optical dipole trap is composed of two horizontal crossed beams at 90° and overlapped at the focus (Fig. 1(b)). Both beams were extracted from a 15-W laser (MOPA 15 NE, InnoLight Technology, Ltd.) operating at the wavelength of 1064 nm. Two beams passed through two acousto-optic modulators (3110-197, Crystal Technology, Inc.); one beam was frequency shifted by −100 MHz, and the other by −110 MHz. Thus, the beams were frequency shifted by 10 MHz relative to each other to avoid any spatial interference patterns between the two beams[22]. Then, the two beams were coupled into two high power single-mode fibers that maintained polarization (NEW PMJ-3AC, 3AC-1064-6/125-3AS-4-1, OZ OPTICS Ltd.) to increase stability in terms of beam pointing as well as to enhance beam-profile quality. After this, one beam was focused to a waist size of 38 μm by an achromatic lens with a focus length of 300 mm, and the other beam was focused to 49 μm by a 400-mm lens.

When two beams run at their full powers of 370 (38 μm) and 650 mW (49 μm), respectively, we calculate the depth of our crossed optical trap potential[23] according to

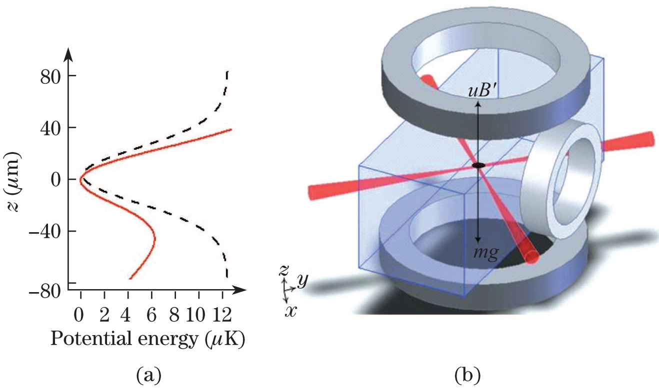

Fig. 1. Illustration of the crossed optical dipole trap in the glass cell. (a) Trap cuts of the vertical potential energy show the trap depth with gravity (solid line) and without gravity (dashed line). They are plotted with a 38-(49-) μm waist and 99-(126-) mW power. (b) Two focused 1064-nm laser beams in a horizontal plane are overlapped and crossed at 90°.

$$U(x,y,z) = -U_1 e^{-2(x^2+z^2)/w_1^2} - U_2 e^{-2(y^2+z^2)/w_2^2}, \quad (1)$$

with the individual trap depths[17,23]:

$$U_{1(2)} = -\frac{3\pi c^2}{2\omega_{\rm eff}^3}\frac{2P_{1(2)}}{\pi w_{1(2)}^2}\left(\frac{\Gamma_{\rm eff}}{\omega_{\rm eff}-\omega}+\frac{\Gamma_{\rm eff}}{\omega_{\rm eff}+\omega}\right), \quad (2)$$

where $P_{1(2)}$ and $w_{1(2)}$ are the powers and waists of the two beams, respectively. $\omega_{\rm eff} = \frac{1}{3}\omega_{D1} + \frac{2}{3}\omega_{D2}$ and $\Gamma_{\rm eff} = \frac{1}{3}\Gamma_{D1} + \frac{2}{3}\Gamma_{D2}$ are the effective transition and the effective line width defined by the weighted average of both the $D1$ and $D2$ lines of ^{87}Rb atoms. The resulting trap depths are 26.0, 26.9, and 52.9 μK in the x, y, and z directions, respectively. Thus, the effective trap depth is 26.0 μK. Near the bottom of the potential well, the crossed optical trap potential is given as

$$U(x,y,z) = -(U_1+U_2)+2\frac{U_1}{w_1^2}x^2+2\frac{U_2}{w_2^2}y^2+2\left(\frac{U_1}{w_1^2}+\frac{U_2}{w_2^2}\right)z^2, \quad (3)$$

and the trap oscillation frequencies are $\omega_x = 2\pi\times422$ Hz, $\omega_y = 2\pi\times330$ Hz, and $\omega_z = 2\pi\times536$ Hz.

The experimental sequence began with a standard magneto-optical trap (MOT). The details were described in our previous work[20,24,25]. The trapping beams consisted of six counterpropagating beams in the $\sigma^+ - \sigma^-$ configuration, and were red-detuned 19 MHz from the transition $5S_{1/2}$, F=2 $\rightarrow$ $5P_{3/2}$, $F'=3$ of the D$_2$ line of ^{87}Rb. The repump beams tuned 10 MHz below the $5S_{1/2}$, F=1$\rightarrow$$5P_{3/2}$, F'=2 transition were used to repump rubidium atoms into the cooling cycle. Then, the temperature of the atoms was brought close to the recoil limit in an optical molasses phase. Afterwards, atoms were pumped to their spin state $|F$=2, m_F=2>. The cold rubidium atoms were moved toward the Ioffe coil about 12 mm from the quadrupole potential center and trapped in the QUIC trap. At this point, runaway evaporation[20] in the QUIC trap was initiated. Subsequently, atoms were transferred back to the center of the glass cell[21] for over 3 s by reducing the current in the quadrupole coils from 32 to 10.2 A and keeping the present Ioffe current at 32 A. In Refs. [26–28], BECs created in a magnetic trap have been transferred directly into optical traps for further study. In this letter, we did not directly cool atoms below the phase transition point of BEC, but above it. This is because the atoms had to be transferred about 12 mm to the center of the cell, and the condensates, typically T < 500 nK, exhibited quick loss and heating during the transfer because of high density. In our experiment, evaporation was controlled at the stage when the number of atoms was $\sim3.5\times10^6$ and the temperature was $\sim$1.5 μK.

Once the atoms were transferred to the center of the cell, two 1064-nm lasers were switched on and adiabatically ramped up to their full powers of 370 and 650 mW for over 800 ms. Then, the magnetic trap potential was adiabatically reduced over 600 ms. Finally, we generated a levitating magnetic field gradient of 10 G/cm in the z direction and a shallow magnetic trap with approximate frequencies ω_x, ω_y < $2\pi\times1$ Hz near the atoms in the horizontal plane. For ^{87}Rb atoms in ground-state hyperfine state $|F$=2, m$_F$=2>, the levitating field gradient completely counteracting the gravity should be B' = mg/μ = 15.2 G/cm, where mg is the gravitational force; μ = 1.00116 μ_B is the magnetic moment of the atoms in $|F$ = 2, m$_F$ = 2> state; and μ_B is the Bohr magneton. At this time, the temperature of the atoms is $\sim$3 μK and the number of the atoms in the optical trap is about 2.5×10^6. Figure 2 shows the absorption image of atoms loaded into the crossed dipole trap with 100-ms waiting time and 2.5-ms expansion time.

The procedure for forced evaporative cooling was immediately performed after the loading of the dipole trap. Forced evaporative cooling was performed by lowering the powers of the two beams. To achieve BEC, we optimized our evaporative cooling processing, as shown in Fig. 3(a). Figures 3(b) and (c) show the dependence of the number of atoms and the temperature on evaporation time. The number of atoms and the temperature clearly decrease with the evaporation time. Figure 4 shows the absorption images of atoms and the density distribution along the horizontal direction, indicating the formation of BEC. After the evaporation time of 1170 ms, the pure condensate shown in Fig. 4(c) was obtained with the number 1.5×10^5 at the powers of 99 (38 μm) and 126 mW (49 μm) of the two beams. Here, the calculated final trap depth is 5.2 μK and the trap oscillation frequencies are ω_x

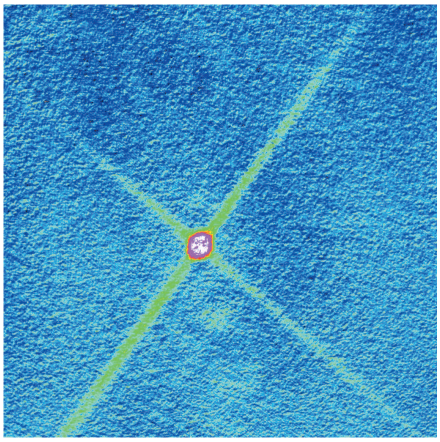

Fig. 2. Absorption image of atoms loaded into the optical trap with a 2.5-ms expansion time after a 100-ms waiting time in an optical trap at full power.

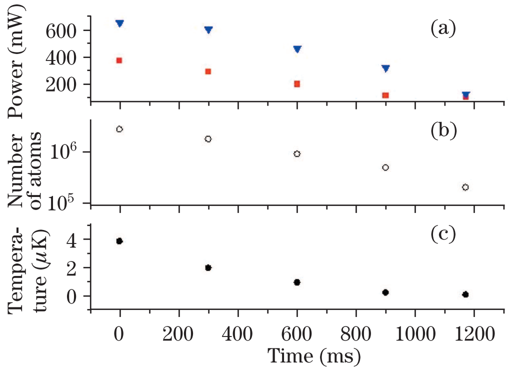

Fig. 3. Evaporation process in a crossed optical dipole trap. (a) Optical powers of two trap beams as functions of evaporation time. The squares (trigonals) correspond to the powers of the beams with the 38 (49) μm waist. (b) Number and (c) temperature of atoms as functions of evaporation time.

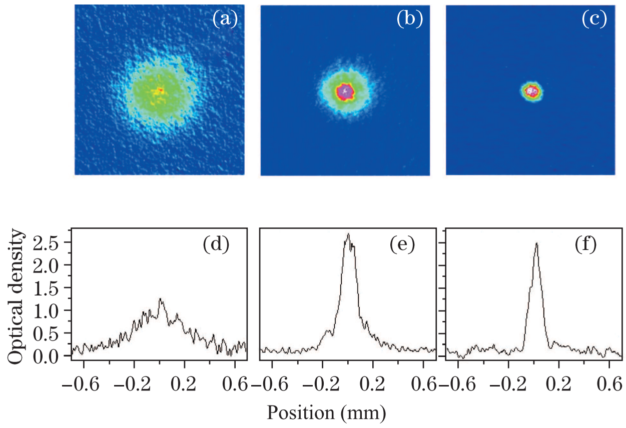

Fig. 4. Absorption images of atomic cloud and density profiles showing the appearance of BEC with 30-ms free expansion time. (a) Thermal atomic cloud of T= 0.44 μK, which is the BEC transition point, (b) mixture of condensate and thermal cloud with T=0.12 μK, (c) nearly pure condensate with the number 1.5$\times$10^5, and (d), (e), and (f) are the linear density profiles along the horizontal direction corresponding to (a), (b), and (c), respectively.

$= 2\pi \times 218$ Hz, $\omega_y = 2\pi \times 145$ Hz, and $\omega_z = 2\pi\times262$ Hz. Figure 4(a) shows the thermal cloud at the critical transition point of T=0.44 μK, and Fig. 4(b) shows an obviously bimodal nature of the momentum distributions below the BEC transition temperature.

In conclusion, we demonstrate the creation of ^{87}Rb BEC in an optical trap with an initial efficiency trap potential of 26.0 μK. The dipole trap consists of two 1064-nm laser beams crossed at their foci. After the atoms are precooled in the QUIC trap with a temperature of 1.5 μK by RF evaporative cooling, they are transferred into the center of the glass cell and loaded into the optical dipole trap. Afterwards, the atoms are evaporated by lowering the power of the trap beams. The pure condensate obtained in an optical trap is up to 1.5$\times$10^5. This result is useful in studying the property of atoms[29] and Feshbach resonance. We are currently preparing for the synchronous loading of ^{87}Rb and ^{40}K, and investigating the mixture of these atoms into an optical trap.

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References

1. T. L. Gustavson, A. P. Chikkatur, A. E. Leanhardt, A. Görlitz, S. Gupta, D. E. Pritchard, and W. Ketterle, Phys. Rev. Lett. **88,** 020401 (2002).
2. S. D. Kraft, M. Mudrich, M. U. Staudt, J. Lange, O. Dulieu, R. Wester, and M. Weidemüller, Phys. Rev. A **71,** 013417 (2005).
3. Z. Xu, P. Li, and F. He, Acta Opt. Sin. (in Chinese) **29,** 523 (2009).
4. J. Lu, H. Lu, Q. Zhou, and J. Yin, Acta Opt. Sin. (in Chinese) **28,** 1816 (2009).
5. M. Greiner, O. Mandel, T. Esslinger, T. W. Hänsch, and I. Bloch, Nature **415,** 39 (2002).
6. S. Ospelkaus, C. Ospelkaus, O. Wille, M. Succo, P. Ernst, K. Sengstock, and K. Bongs, Phys. Rev. Lett. **96,** 180403 (2006).
7. T. Rom, T. Best, O. Mandel, A. Widera, M. Greiner, T. W. Hänsch, and I. Bloch, Phys. Rev. Lett. **93,** 073002 (2004).
8. I. B. Spielman, W. D. Phillips, and J. V. Porto, Phys. Rev. Lett. **98,** 080404 (2007).
9. K. Xu, Y. Liu, J. R. Abo-Shaeer, T. Mukaiyama, J. K. Chin, D. E. Miller, W. Ketterle, K. M. Jones, and E. Tiesinga, Phys. Rev. A **72,** 043604 (2005).
10. M. D. Barrett, J. A. Sauer, and M. S. Chapman, Phys. Rev. Lett. **87,** 010404 (2001).
11. T. Weber, J. Herbig, M. Mark, H.-C. Nägerl, and R. Grimm, Science **299,** 232 (2003).
12. G. Cennini, G. Ritt, C. Geckeler, and M. Weitz, Appl. Phys. B **77,** 773 (2003).
13. D. Rychtarik, B. Engeser, H.-C. Nagerl, and R. Grimm, Phys. Rev. Lett. **92,** 173003 (2004).
14. Y. Takasu, K. Maki, K. Komori, T. Takano, K. Honda, M. Kumakura, T. Yabuzaki, and Y. Takahashi, Phys. Rev. Lett. **91,** 040404 (2003).
15. S. Kraft, F. Vogt, O. Appel, F. Riehle, and U. Sterr, Phys. Rev. Lett. **103,** 130401 (2009).
16. Y. N. M. de Escobar, P. G. Mickelson, M. Yan, B. J. DeSalvo, S. B. Nagel, and T. C. Killian, Phys. Rev. Lett. **103,** 200402 (2009).
17. R. Grimm, M. Weidemüller, and Yu. B. Ovchinnikov, Adv. At. Mol. Opt. Phys. **42,** 95 (2000).
18. J. F. Clément, J.-P. Brantut, M. Robert-de-Saint-Vincent, R. A. Nyman, A. Aspect, T. Bourdel, and P. Bouyer, Phys. Rev. A **79,** 061406 (2009).
19. T. Esslinger, I. Bloch, and T. W. Hänsch, Phys. Rev. A **58,** R2664 (1998).
20. D.-Z. Xiong, H.-X. Chen, P.-J. Wang, X.-D. Yu, F. Gao, and J. Zhang, Chin. Phys. Lett. **25,** 843 (2008).
21. D. Xiong, P. Wang, Z. Fu, and J. Zhang, Opt. Express **18,** 1649 (2010).
22. M. T. DePue, C. McCormick, S. L. Winoto, S. Oliver, and D. S. Weiss, Phys. Rev. Lett. **82,** 2262 (1999).
23. T. Weber, "Bose-Einstein condensation of optically trapped cesium", PhD Thesis (Universität Innsbruck, Innsbruck, 2003).
24. D. Wei, D.-Z. Xiong, H.-X. Chen, P.-J. Wang, L. Guo, and J. Zhang, Chin. Phys. Lett. **24,** 1541 (2007).
25. D. Xiong, P. Wang, H. Chen, and J. Zhang, Chin. Opt. Lett. **8,** 351 (2010).
26. D. M. Stamper-Kurn, M. R. Andrews, A. P. Chikkatur, S. Inouye, H.-J. Miesner, J. Stenger, and W. Ketterle, Phys. Rev. Lett. **80,** 2027 (1998).
27. H.-J. Miesner, D. M. Stamper-Kurn, J. Stenger, S. Inouye, A. P. Chikkatur, and W. Ketterle, Phys. Rev. Lett. **82,** 2228 (1999).
28. B. P. Anderson and M. A. Kasevich, Science **282,** 1686 (1998).
29. J. Lu, X. Ji, and J. Yin, Chin. Opt. Lett. **4,** 683 (2006).