Production of ^{87}Rb Bose–Einstein condensates in a hybrid trap*

Duan Ya-Fan(段亚凡), Jiang Bo-Nan(姜伯楠), Sun Jian-Fang(孙剑芳), Liu Kang-Kang(刘亢亢), Xu Zhen(徐 震), and Wang Yu-Zhu(王育竹)†

Key Laboratory for Quantum Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, *China*

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We report a rapid evaporative cooling method using a hybrid trap which is composed of a quadrupole magnetic trap and a one-beam optical dipole trap. It contains two kinds of evaporative coolings to reach the quantum degeneracy: initial radio-frequency (RF) enforced evaporative cooling in the quadrupole magnetic trap and further runaway evaporative cooling in the optical dipole trap. The hybrid trap does not require a very high power laser such as that in the traditional pure optical trap, but still has a deep trap depth and a large trap volume, and has better optical access than the normal magnetic trap like the quadrupole-Ioffe-configuration (QUIC) cloverleaf trap. A high trap frequency can be easily realized in the hybrid trap to enhance the elastic collision rate and shorten the evaporative cooling time. In our experiment, pure Bose–Einstein condensates (BECs) with about 1×10^5 atoms can be realized in 6 s evaporative cooling in the optical dipole trap.

Keywords: ultra-cold atoms, Bose–Einstein condensates, optical dipole trap, hybrid trap

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1. Introduction

The quantum degenerate atomic gas is a powerful tool for quantum simulation. So far, many significant pieces of research, such as disordered systems,[1,2] spin–orbit coupling,[3] and artificial non-Abelian gauge potentials in optical lattice,[4,5] have been carried out based on the ultra-cold atom experiment platform. So a simple and rapid way to generate quantum degeneracy becomes a key technology for quantum simulation. Here we report a simple method to generate ^{87}Rb Bose–Einstein condensate (BEC) in a hybrid trap[6,7] which is composed of a quadrupole magnetic trap (QMT) and a single beam optical dipole trap (ODT). Compared with the pure magnetic traps, such as the quadrupole-Ioffe-configuration (QUIC) trap,[8] the hybrid trap does not need complicated magnetic coils and current controllers, thus has a tight confinement and a high trap frequency. Compared with the crossed dipole trap,[9] the hybrid trap has a large trap volume and a high loading rate, and does not need a huge laser power.

The role of the QMT in the hybrid trap is to assist the preliminary cooling of atoms and help the atoms transfer to the ODT. Because the depth and the volume of the ODT are finite, the high energy atoms are mainly trapped by the QMT when the atoms are loaded to the hybrid trap. So we need to use the radio-frequency (RF) enforced evaporative cooling method to cool the atoms first. The RF enforced evaporative cooling is the preparation stage before loading into the ODT. With the assistance of the QMT, the ODT does not need to be very deep, and one beam can trap the atoms tightly. This can reduce the difficulty and the cost of experiment.

2. Experiment setup

In our experiment, the QMT is generated by a pair of anti-Helmholtz coils, which are also used for the three-dimensional (3D) magneto-optical trap (MOT). The axial magnetic field gradient of these coils is 12.7 Gs/cm/A, and the maximal operational current can reach 25 A. The ODT is generated by one far-off resonant Gauss laser beam with a waist of 75 μm and a Rayleigh length of 16.6 mm. We set the center of the dipole trap beam 75 μm below the zero point of the magnetic field in order to decrease the Majorana loss,[10,11] as shown in Fig. 1. The laser of the ODT is generated by a single-mode polarization-maintained fiber laser (NP Photonics RFLS-125-1062.5) amplified to maximal 50 W with a polarization-maintaining (PM) fiber laser amplifier (IPG YAR-50K-1064-LP-SF), which operates at 1062.5 nm. The laser is controlled by two electro-optic modulators (EOMs) in series, one for power stabilization and the other for switching. The extinction ratio is 100:1 for each EOM. The power stability is better than 0.03%.

In order to verify the reduction of Majorana loss in the hybrid trap, we measure the residual atom number and lifetime respectively in the QMT and the hybrid trap after the RF enforced evaporative cooling. The initial atom numbers in the two traps are the same. We ramp down the RF frequency from 30 MHz to 2 MHz and measure the lifetime in both traps. The lifetime in the hybrid trap is longer than that in the QMT, as shown in Fig. 2.

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†Corresponding author. E-mail: yzwang@mail.shcnc.ac.cn

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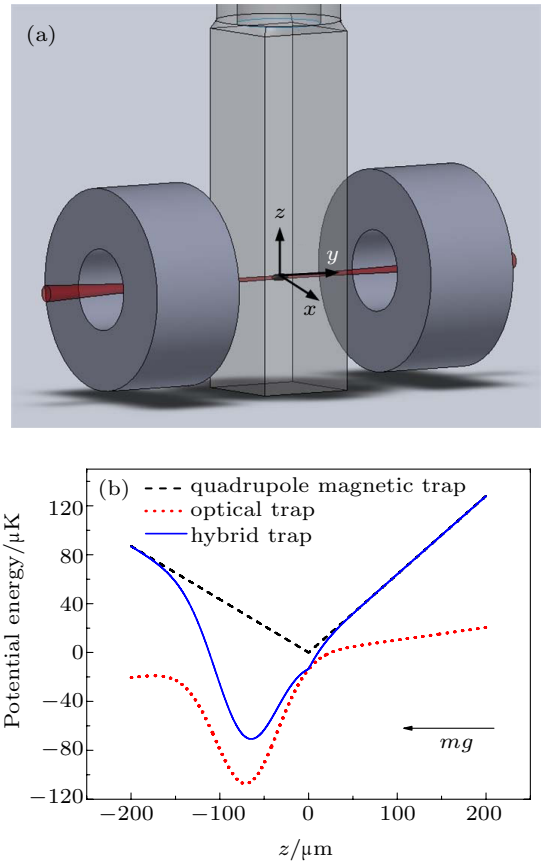


Fig. 1. (color online) (a) Illustration of the hybrid trap. The red focused Gauss light beam is the ODT beam, and the anti-Helmholtz coils form the QMT. The center of the ODT is below the zero point of the QMT which is at the zero point of the coordinate axis. (b) The depths of different traps with gravity.

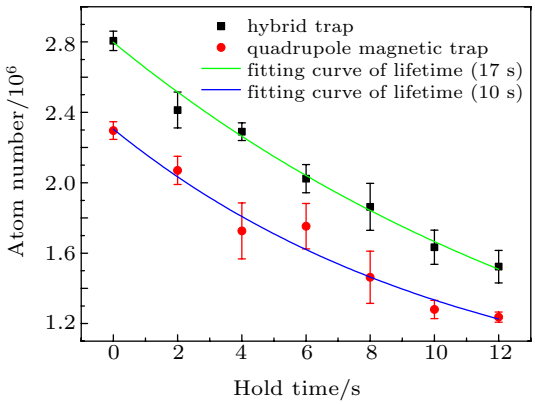


Fig. 2. (color online) Residual atom numbers in the QMT and the hybrid trap with different hold time. The lifetime in the hybrid trap is longer than that in the QMT. The atom temperature is about 11 μK.

3. Experimental results

In our experiment, we adopt the double MOT configuration[12,13] to produce 1×10^8 atoms with 45 s MOT loading in an ultra high vacuum chamber. After the MOT loading, we further cool the atoms by polarization gradient cooling, i.e., switching off the magnetic field and ramping down the laser detuning of cooling beams from −12 MHz to −100 MHz in 10 ms. The atom temperature goes down to 14 μK. Then the atoms are optically pumped to state $|F = 2, m_F = +2\rangle$ and loaded into the magnetic trap abruptly with gradient 120 Gs/cm. The magnetic trap is ramped up to 160 Gs/cm in 200 ms to increase the elastic collision rate, and the ODT depth is ramped up to 120 μK simultaneously. Then the trap frequencies are $\omega_x = 2\pi \times 2839$ Hz, $\omega_y = 2\pi \times 3210$ Hz, $\omega_z = 2\pi \times 736$ Hz (x is the horizontal direction, y is the axial direction of the ODT, and z is the gravitational direction). Finally, the atoms with temperature 130 μK are loaded into the hybrid trap, and the atom number is $(6.8 \pm 0.5) \times 10^7$.

The evaporative cooling process in the hybrid trap is composed of three stages: RF enforced evaporative cooling in the QMT, transferring the atoms to the ODT, and runaway evaporative cooling in the ODT. The whole evaporative cooling lasts 16 s. The former two stages take 10 s. In these stages, the RF power is turned on and the frequency is exponentially swept from 30 MHz to 2 MHz. The axial gradient of the QMT is kept at 160 Gs/cm in the early 9 s, and then ramps down to 26 Gs/cm in the last 1 s. The gradient force with 26 Gs/cm can confine the atoms in the axial direction of the ODT. Meanwhile the radial gradient force with 13 Gs/cm is slightly smaller than the gravity, which corresponds to gradient 15.2 Gs/cm for the $|F = 2, m_F = +2\rangle$ state. In this stage, the ODT depth is 120 μK. So the atoms are transferred to the ODT. As shown in Fig. 3, the atoms are transferred to the ODT, some high energy atoms escape from the ODT due to the gravity. The atom temperature is 11 μK and the atom number is $2.5(\pm 0.5) \times 10^6$ in the ODT.

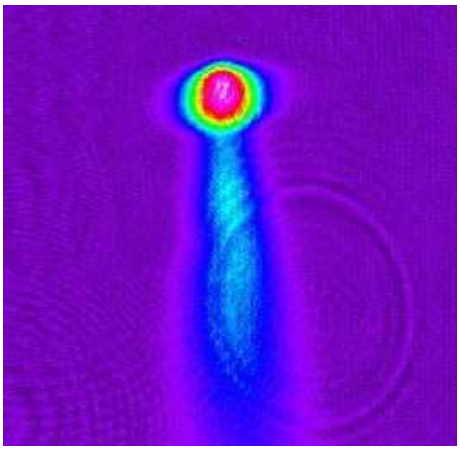


Fig. 3. (color online) Absorption image of the atoms loading into the optical dipole trap.

To enhance the phase space density, we lower the ODT depth for runaway evaporative cooling. We use the peak optical density (OD) after a long time of flight to confirm the effective evaporative cooling.[14–16] In our experiment, the runaway evaporative cooling process includes four successive linear ramps. The ODT depth is decreased from 120 μK to 4.4 μK,

and the trap frequencies also decrease to $\omega_x = 2\pi \times 516$ Hz, $\omega_y = 2\pi \times 830$ Hz, $\omega_z = 2\pi \times 323$ Hz. Figure 4 shows the dependences of the atom number and the temperature during the evaporative cooling. After 6 s of evaporative cooling, a pure Bose–Einstein condensate is obtained with the atom number of 1.0×10^5 and the temperature of 300 nK. Figure 5 shows the atom clouds of bi-model distribution and the pure condensate.

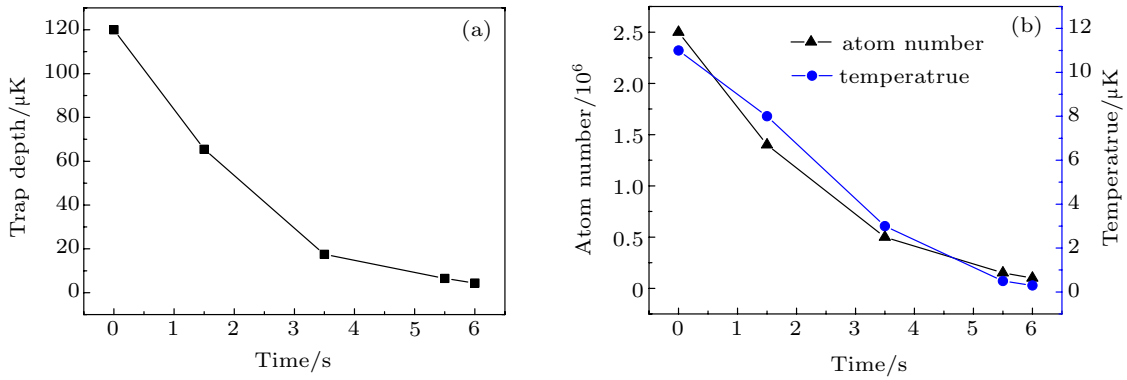


Fig. 4. (color online) Runaway evaporative cooling process in the optical dipole trap: (a) trap depth of the ODT as a function of the evaporative time, (b) atom number and temperature of the atoms as a function of the evaporative time.

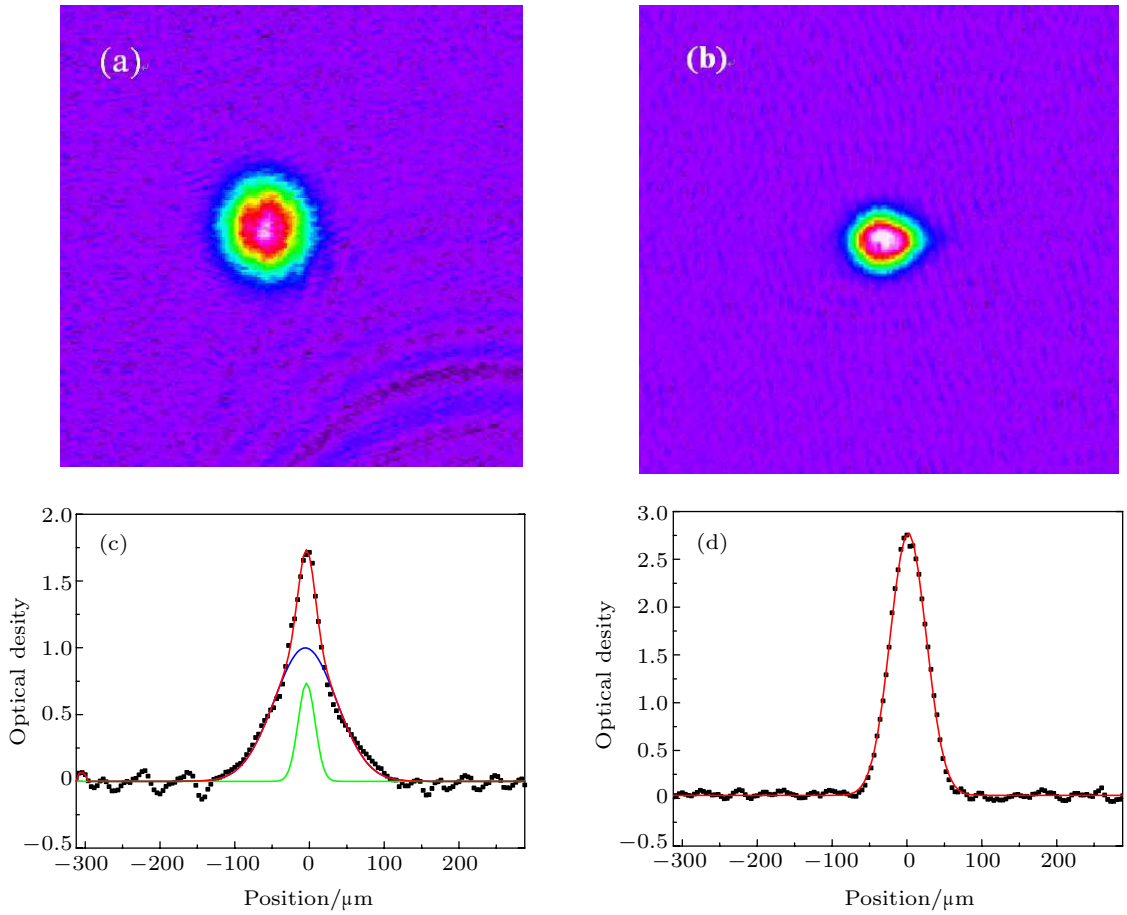


Fig. 5. (color online) The absorption images of atomic clouds and optical density profiles after 20 ms of flight. (a) Bi-model distribution, (b) pure condensate, and panels (c) and (d) show the column density profiles and the fitting curves in the horizontal direction corresponding to images in panels (a) and (b), respectively.

4. Conclusion

In conclusion, we have described a simple and rapid evaporative cooling method to produce ^{87}Rb Bose–Einstein condensates in a hybrid trap. The hybrid trap merges the advantages of QMT and ODT, which has a deep trap depth, a large trap volume, and a high trap frequency. In our experiment, we can produce a pure condensate of 1.0×10^5 atoms

through two-step evaporative cooling: the RF enforced evaporative cooling in the QMT and the runaway evaporative cooling in the ODT. The evaporative cooling process is easily controlled and quick. This provides a good experiment platform for quantum simulation.

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