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Bose–Einstein condensation on an atom chip*

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This paper reports an experiment of creating Bose-Einstein condensate (BEC) on an atom chip. The chip-based Z-wire current with a homogeneous bias magnetic field creates a tight magnetic trap, which allows for a fast production of BEC. After a 4.17-s forced radio frequency evaporative cooling, a condensate with about 3000 atoms appears. The transition temperature is about 300 nK. This compact system is quite robust, allowing for versatile extensions and further studying of BEC.

Keywords: Bose–Einstein condensate, atom chip
PACC: 3280P, 4250

1. Introduction

The realization of Bose–Einstein condensation is a great achievement in cold atom physics.[1,2] Although many groups in the world have realized Bose–Einstein condensate (BEC), making BEC is still a challenge to a new group.[3] Now, BEC has been realized in several types of systems, such as the magnetic trap,[4] the dipole trap,[5] the mini trap,[6,7] the atom chip,[8,9] and so on. Among them, the atom chip is specially intriguing. It provides a much tighter trap in comparison with the traditional magnetic trap. A tighter trap means a higher elastic collision rate, which leads to a less strict vacuum requirement and a fast production of BEC. Also, the wires on the atom chip can be designed flexibly to meet different goals, like the Ioffe-Pritchard trap which uses a z-shaped wire,[10] magnetic lattice which uses a gridding structure,[11] double traps which use both direct current and radio frequency current.[12] In addition, optical components can be easily integrated on an atom chip, for example micro-cavity[13] and optical fiber[14] are integrated on an atom chip to study the strong coupling between light and cold atoms or BEC. Atom chip is a useful platform to study BEC extensively. In this paper, we report our experiment of making BEC on an atom chip.

2. Experimental setup

Our experimental system is a single-chamber system, as shown in Fig.1. A quartz cell of 40 mm× 40 mm×120 mm is used as the main working chamber, a chip is placed upside down in the cell. The atom source is provided by a ^{87}Rb dispenser which can be controlled by electric current conveniently. A background pressure below 1×10^{-8} Pa is maintained by an ion pump and a sublimation pump.

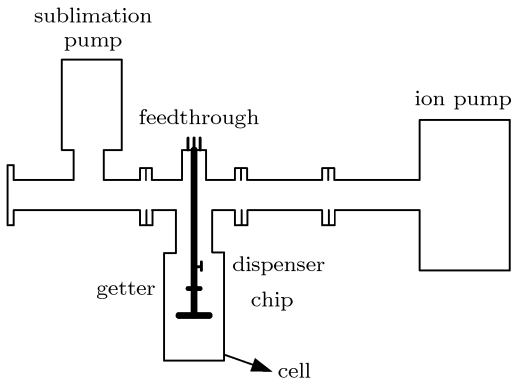


Fig.1. The schematic setup of our vacuum system. It is a single-champer system with a quartz cell. An ion pump, a passive getter and a sublimation pump are used to keep the vacuum. The atom source is a dispenser.

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For the optical system, the D_2 transition of Rb is used. We use three diode lasers to form our four kinds of laser beams: the trapping light, the repumping light, the pumping light and the probe light. All lasers are locked by the saturated absorption spectrums, which have frequency widths of several hundreds hertz, then are modulated by acousto-optical modulators (AOM) to the desirable frequencies and intensities. Finally they are coupled into four single mode fibers and injected to the cell. The trapping light and the repumping light are used in the magneto-optical trap (MOT) which couple $F = 2$ to $F' = 3$ and $F = 1$ to $F' = 2$ respectively, the pumping light is a $\sigma+$ light and couples $F = 2$ to $F' = 2$. It pumps atoms to $m_F = 2$ state which increases the efficiency of loading atoms to the chip-based Z-trap. The probe light is resonant with $F = 2$ to $F = 3$.

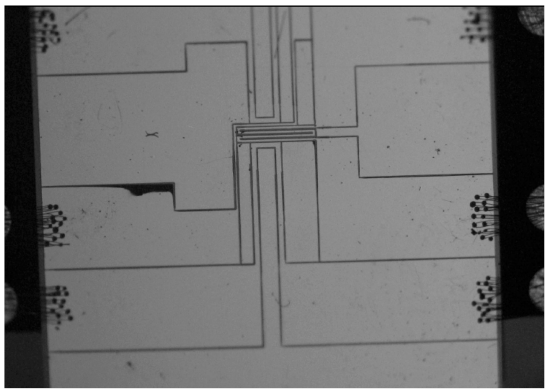


Fig.2. The picture of our chip. The gold layer is 5-μm thickness. The wires are isolated from the rest of the gold layer by 10 μm gaps. The width of two U-wires is 200 μm and 100 μm for the Z-wire. Each chip wire is connected to the electrode by spot welding of 20 thin gold wires as shown in the picture.

Our chip is shown in Fig.2. A gold layer with a thickness of 5 μm is deposited on a Si wafer with a 500-nm SiO_2 film. The wires are defined by photolithography which produces gaps to insulate the wires from the rest gold layer. The width of the gap is about 10 μm. The surface of the gold layer is excellently smooth with a 90% reflection at 780-nm wavelength. Since we use the gold layer as a mirror to reflect the laser beams to form a mirror-MOT,[8] good reflection is demanded to increase atom number collected by the mirror-MOT. There are three kinds of wires on the chip: two U-shaped wires with width of 200 μm, a Z-shaped wire with width of 100 μm and a W-shaped wire on the chip. More details of the chip fabrication refer to Refs.[15] and [16]. The Z-wire combining with a bias field creates an Ioffe-Pritchard-like trap which is used in evaporative cooling since the "Majorana flops" can be avoided.[17] The W-wire is used as the radio frequency (RF) terminal for RF-evaporative cooling. Because it is near the Z-wire, the shielding effect of the gold layer can be avoided, and a strong RF field can be provided. Many researches show that the gold layer absorbs Rb atoms, which leads to a reduction of the light reflectivity and pollutes the vacuum.[18] In order to overcome this disadvantage, a thin 10-nm quartz film is deposited on the chip surface. This thin film does not effect the reflectivity since the thickness is much smaller than the laser wavelength, but it can isolate the strong attractive interaction between Au and Rb atoms. In our experiment, it works well.

3. Vacuum and lifetime

The precondition of creating BEC is extremely strict. One of the most important demands is ultra-high vacuum (UHV) requirement. Even for an atom chip system, where the vacuum limitation is a bit loosened, a pressure of 10^{-8} Pa is still required. So special attention should be paid to the vacuum. In our experiment, all components placed in the vacuum are UHV compatible and pretreated in strictly cleaning processes. After being installed, the whole system is baked at 120 °C for 72 hours continuously. Finally the vacuum of our system reaches about 1×10^{-8} Pa. It is maintained by a $40L/s$ ion pump and a sublimation pump which works once a week. A passive getter is also placed in the cell to improve the pump rate. It works even at room temperature.

The atom source is an Rb dispenser which releases Rb atoms when heated by an electric current. Such a device provides a convenient way for time-dependent control of Rb pressure. It is a way to solve the contradiction between loading enough atoms and high vacuum requirement.[19,20] The critical current for our dispenser starting to release atoms is about 3.5 A. In the experiment of making BEC, we use a pulsed method: heating the dispenser with a 5.7-A current pulse for 30 s, waiting for 60 s to recover the vacuum, then starting MOT to collect cold atoms. In this way, adequate atoms are collected in MOT while a relatively good vacuum pressure is obtained. Typically 2×10^7 atoms are collected in MOT, and 3.5×10^6 atoms are loaded into the Z-trap, the temperature of atoms in the Z-trap is about 100 μK, the lifetime is 11 s. It is the beginning of the forced evaporative cooling.

4. Forced radio frequency evaporative cooling and Bose–Einstein condensate

Up to now, the evaporative cooling is the only way to achieve BEC.[21] In order to evaporate continuously to BEC, a runaway evaporative cooling regime should be reached. The good-to-bad collision ratio which is the production of the elastic collision rate $\gamma_{\rm el}$ and the lifetime of atoms in the Z-trap $\tau_{\rm loss}$ should satisfy[21]

$$\gamma_{\rm el}\tau_{\rm loss} > 150. \quad (1)$$

In order to increase the elastic collision rate, the Z-trap is adiabatically compressed to $I = 3.6$ A, $B_x = 4$ Gs (1 Gs=10^{-4} T), $B_y = 72$ Gs, with trap frequency (26, 3900, 3900) Hz. It is about 90 μm away from the chip surface. The measured good-to-bad collision ratio is $\gamma_{\rm el}\tau_{\rm loss} > 1000$, runaway evaporation regime is reached. After an optimized 3.5-s RF-evaporative cooling from 74 MHz to 4.3 MHz, 1.3×10^5 atoms are left, the temperature is about 10 μK. In order to reduce the heating rate and three-body collisions, the trap is then decompressed to $I = 2$ A, $B_x = 2.8$ Gs, $B_y = 33.6$ Gs, of trap frequency (21, 1900, 1900) Hz. It is about 110 μm away from the chip surface. This decompressed process lasts 160 ms, and at the same time an RF sweep from 4.3 MHz to 2.7 MHz is present. The atom cloud is further cooled to 3.4 μK, 1.1×10^5 atoms are left. Finally, we apply an RF sweep from 2.7 MHz to 2.315 MHz, lasting 510 ms, and BEC appears. We use the time of flight method to determine the result of phase transition. In order to get a good signal-to-noise ratio, the Z-trap is decompressed to $I = 3.6$ A, $B_x = 0$, $B_y = 24$ Gs, the trap frequency is (38, 700, 700) Hz. The adiabatic decompression does not change the phase space density but reduces the temperature and moves atoms away from the chip surface, a better signal to noise ratio is obtained. As shown in Fig.3, the nonisotropic expansion of the atom cloud in free space is observed which is strong evidence of achieving BEC. The flight time is 2, 6, 10, 14 and 20 ms respectively. The transition temperature is about 300 nK, and there are about 3000 atoms in the pure BEC.

The aspect ratio after atoms are released from the Z-trap is measured. For a thermal cloud, it expands isotropically, the aspect ratio approaches one as the flight time becomes longer. For a BEC released from a cigar-shaped trap, the radius along the tightly trapped direction expands rapidly. This is a fundamental difference between BEC and thermal gases.[23,24] We observe this phenomenon when we detect the time of flight signal as shown in Fig.4, the aspect ratio becomes much bigger than one when the flight time is longer than 10 ms. The change of aspect ratio during free expansion is also an important criterion of achieving BEC.

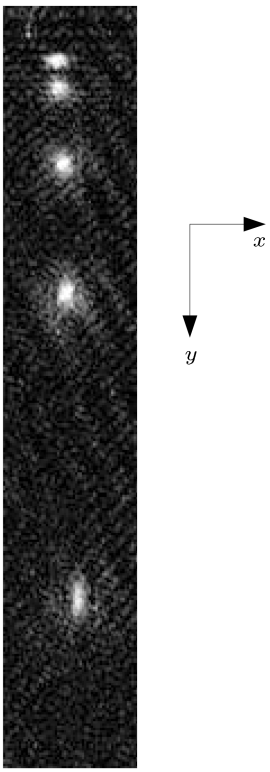


Fig.3. Time of flight images of the atom cloud after released from the trap. The free flight time is 2, 6, 10, 14 and 20 ms respectively from top to bottom. The nonisotropic expansion is a strong evidence of BEC.

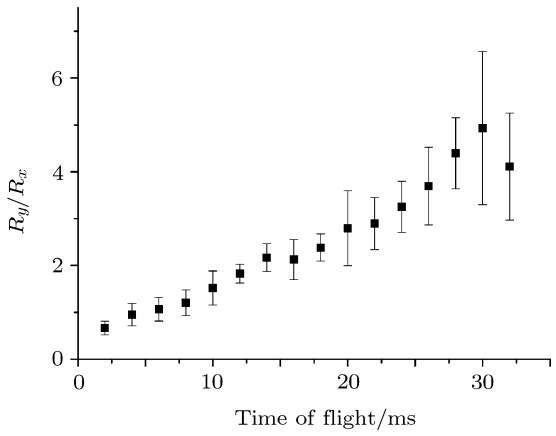


Fig.4. The measurement of aspect ratio of free expansion between the cloud radius in y direction and x direction as shown in Fig.3. The radius in the tight trapped direction expands rapidly, and the aspect ratio is much bigger than one when time of flight is longer than 10 ms. It is an important criterion of achieving BEC.

In order to measure the critical transition point of our BEC, the RF sweep is stopped at a different frequency. As shown in Fig.5, the pictures are taken after 12 ms of flight. When the end frequency is 2.36 MHz or 2.34 MHz, it is still a thermal gas since the optical depth profile is Gaussian distribution. But when we sweep to 2.33 MHz, a bimodal distribution appears, the optical depth increases suddenly and the cloud size reduces suddenly. At this time, a partial condensate appears. When we sweep further to 2.32 MHz, It is clearly shown that a sharp peak lies on a low thermal gas background. At this time, the BEC is quite pure. There are some stripes shown in the picture when BEC appears, it is due to the diffraction of the imaging system.[25]

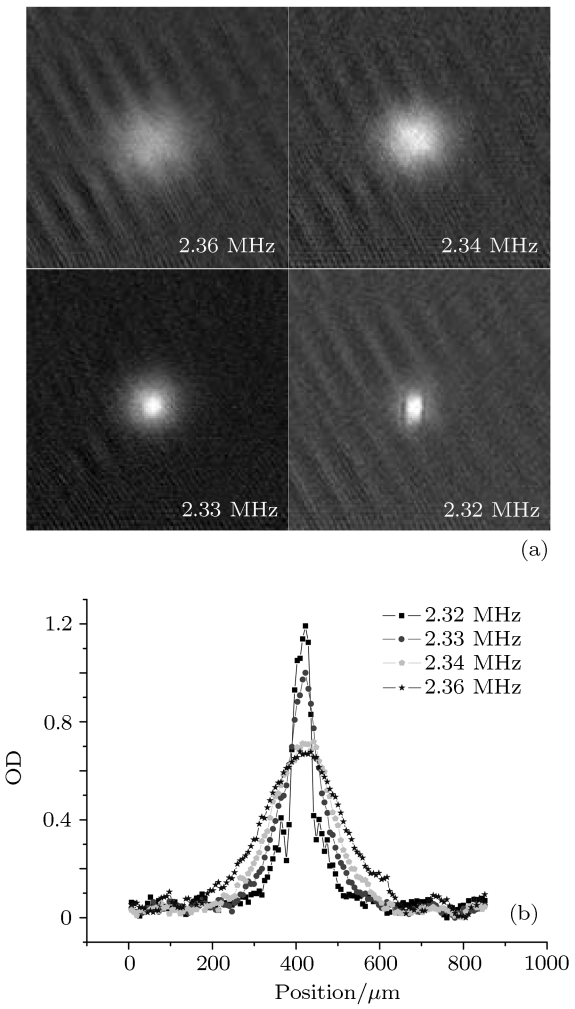


Fig.5. Determining the critical frequency where BEC appears. (a) When the end frequency is 2.34 MHz, it is still a thermal cloud, and the profile is a Gaussian distribution. When end at 2.33 MHz, partial condensate appears. And when end at 2.32 MHz, a more pure BEC is created and a sharper peak of the profile appears; figure 5(b) is the section profile of the cloud. A sudden increase of optical depth and a bimodal distribution appear when sweep to 2.33 MHz which is the critical frequency when BEC appears.

We also measure the lifetime of BEC in the Z-trap. The dominating limitation of the lifetime is the heating when atoms are held in the trap. We measure the temperature when atoms are held in the Z-trap for a different time, the heating rate is 3.4 μK/s. The thermal radiation of the chip, the stray light scattering and the current noise are all possible heating sources.[10] The measured lifetime of BEC is about 90 ms. In order to increase the lifetime, an RF field with a bit higher frequency than the end frequency is presented when atoms are held. Heated atoms are evaporated away by the RF radiation before interacting with other atoms. So it does not destroy BEC and the lifetime is prolonged to 500 ms.

5. Conclusion

In conclusion, we have achieved BEC on our atom chip system. As we know, it is the first chip BEC in China. The nonisotropic expansion, bimodal distribution profile and aspect ratio measurement after releasing provide the strong evidence of BEC creation. Such a fast production of BEC (evaporative cooling time is less than 5 seconds and the circle time is about 2 minutes) provides a robust and convenient platform to study the properties of this special matter. Further experiments are being carried out and we hope to go deeper into the research of BEC.

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