Realisation and Characterisation of the BEC for ^{87}Rb Atoms

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Abstract

The Bose-Einstein condensate (BEC) created in a magnetic trap in the Quadrupole-Ioffe configuration (QUIC). This kind of trap combines an anti-Helmholtz quadrupole field with an offset field produced by a single coil perpendicular to the quadrupole field axis to suppress Majorana transitions. In the quadrupole trap, evaporative cooling is performed by using radio frequency, reaching the phase transition to a BEC in the QUIC trap. By using Time of Flight (TOF) technique, the expansion velocity is measured with $\upsilon_x = (5.98 \pm 0.08) mm/s$ and $\upsilon_y = (5.78 \pm 0.07) mm/s$ which lead to temperature of $T_x = (374 \pm 7) nK$ and $T_y = (350 \pm 5) nK$. It is roughly around the recoil temperature.

Key words: Laser cooling, Bose-Einstein Condensate, Magneto-Optical Trap

1. Introduction

The first experimental realisation of the BEC in dilute gases was in 1995 for ^{87}Rb atoms [1]. Then, this work was followed by many experimental demonstrations [2, 3]. In quantum mechanics, atoms are known to be either half integer spin fermions, which cannot occupy the same quantum state according to the Pauli exclusion principle, or integer spin bosons without restriction on the number of atoms occupying the same quantum state. If a vapour of bosonic atoms is cooled down a very low temperature, and then the particles' separation is close to the thermal de Broglie wavelength, the wave packets of the atoms overlap. Therefore, it is not possible to distinguish different atoms. Thus, the system approaches the quantum degeneracy and follows the Bose-Einstein statistics. The phase-space density (PSD) denoted by ρ, defined as the particles number in a cubic volume of the thermal de-Broglie wavelength, is used as a quantity to measure the degree of the quantum degeneracy of a system [4, 5]:

$$\rho = n\lambda_{dB}^3 \quad \ldots\ldots\ldots(1)$$

where n is the atom number density $n = N/V$, and λ_{dB} is given by:

$$\lambda_{dB} = \frac{h}{\sqrt{2\pi m k_B T}} \quad \ldots\ldots\ldots(2)$$

where h is Planck's constant, m is the atomic mass, k_B is Boltzmann's constant and T is the temperature in Kelvin. When a bosonic gas is confined in three

dimensions, the atoms can accumulate in the lowest energy quantum state when the phase space density ρ approaches 2.6 [6].
Laser cooled atoms are neither cold nor dense enough to generate a sufficient phase space density for the BEC transition. The breakthrough in Bose-Einstein condensation happened with the implementation of magnetic traps and evaporative cooling, which enabled far lower temperatures and higher densities than previously reached.

2. Methodology

Cooling and trapping of neutral atoms requires a stable source of laser light, with narrow linewidth and precise tunability [7]. In addition, a high power laser is also crucial to achieve a large number of trapped atoms for BEC experiments in which an initial high particle number is indispensable. Many parameters contribute to the amount of trapped atoms, such as the optical alignment, the frequency detuning, the polarisation and the magnetic field gradients. In addition, it is well known that larger cooling beams ($\approx 2.5\ cm$ in this experiment) increase the capture cross section and therefore the atom number in the trap. Furthermore, an ultra-vacuum system is important here therefore the experiment is achieved in a double MOT chamber [8].

Since the power provided by the diode laser is insufficient for a BEC experiment, a Master Oscillator Power Amplifier (MOPA) system is used as a laser source. It is based on a master diode laser which is fed through a 2W GaAs tapered amplifier, achieving up to 500mW of single mode usable cooling light at 780 nm. This configuration amplifies the power from a few milliwatts to up to 2W [8]. Without injection, the tapered amplifier gain profile has a width of $\approx 11\ nm$. When it is injected by a seed laser, the output gain is narrowed down to the same wavelength of the seed laser (780 nm). The action of the amplifier relies on the chip design which consists of two gain sections: ridge and taper sections. The ridge stage works as a waveguide for the input seed laser from the rear facet. This narrow section selects only the laser mode TEM_{00} and suppresses the undesired laser modes. The taper section is an amplification region with an output gain guide for the broad pumped area with output facet dimensions$(256 \times 1.1)\mu m^2$. On the contrary to laser diodes with small facets that can be damaged with high intensity, the tapered amplifier, with its wide output facet, does not suffer from this problem.

Temperature stabilisation is required since the gain and therefore the output power depend strongly on the temperature of the amplifier chip. The stabilisation also prevents thermal breakdown of the chip which produces a considerable amount of heat during operation. For optimistic performance, the MOPA in which the amplifier chip and the lens mounts are fixed on a temperature stabilised copper base. Therefore, the resulting temperature and therefore power are stable. The temperature is stabilised by two Peltier elements connected in parallel and placed between the copper base and the aluminium block with thermal paste to increase the thermal conductivity between the surfaces. A temperature sensor is attached to the copper block close to the chip. A temperature controller is used to control and monitor the temperature of the amplifier chip. Two aspheric lenses are utilised to collimate the input and output of the tapered amplifier: the input lens from Thorlabs has a numerical aperture of 0.5 while the output lens from Melles Griot has a higher numerical aperture of 0.62. Owing to the tapered gain region from the output facet, a higher numerical aperture lens is required. Both input and output lenses have 8mm focal length. This arrangement offers fine adjustment, good injection of the input beam and appropriate collimation of the output light. Since the emitted beam from the tapered amplifier is quite astigmatic and divergent, the vertical direction of the beam is collimated by the output lens inside the amplifier housing. A 100mm cylindrical lens is utilised in order to collimate the stronger divergence in the horizontal plane. The beam shape is roughly circular, which enables coupling into a single mode optical fibre with 60% coupling efficiency. The injection is first achieved at low driving current of the amplifier [8].

A quadrupole magnetic field (QUAD) is produced by arranging two coils in the so-called anti-Helmholtz configuration. At some point where the zero magnetic fields, the magnetic potential has a minimum. Atoms from the magneto-optical trap can be loaded efficiently into the QUAD trap owing to the common centres of the magnetic fields. However, cold atoms can be ejected from the trap due to Majorana spin-flip [9]. In a BEC experiment, it is required to cool the atoms to very low temperatures, but this moves the atoms closer to the trap centre (B=0) and then Majorana spin-flips may take place and then reduces the atomic density, which is essential for achieving the evaporative cooling. Atom losses can be prevented by using the so-called Quadrupole-Ioffe trap [10]. This is the method used in the current work.

The QUIC trap configuration consists of three coils: two quadrupole coils and one Ioffe coil. The low field seeker atom experiences a linear optical potential, in which the quadrupole trap field increases linearly with the distance from the zero magnetic field. The atoms are then transferred into the potential of the QUIC trap, produced by turning on the Ioffe coil current. This turns the trap potential from linear into parabolic with a minimum magnetic field above zero in order to suppress Majorana spin-flip losses.

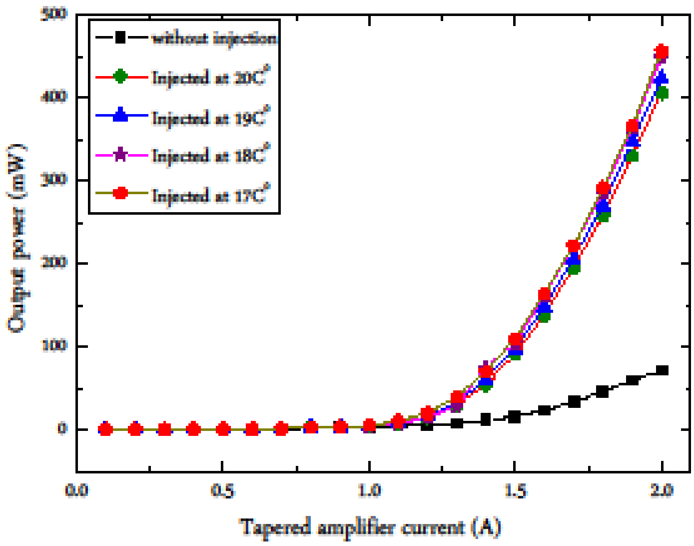

Figure 1. MOPA output power as a function of the current of the tapered amplifier for different temperatures.

3. Experimental results

At first, the behaviour of the amplifier is studied when driving it with different currents, The output power is recorded as a function of the driving current. These measurements were taken with and without seeding the chip and for different chip temperatures. Fig. 1 shows the dependence of the power output of the tapered amplifier on its current. Without injection, the maximum output power of the MOPA is about 50mW. A threshold behaviour over the range (0-1.5)A can be observed similar to a diode laser. Thus, the emission starts from 1.25A and 1.5A with and

without injection respectively. When the MOPA is injected, it can be operated with up to 4 A, which supplies about 2W of laser power.
Then, the magnetic field of the quadrupole coils is characterised as shown in Fig. 2. The magnetic field is measured as a function of the displacement from the position of the trap zero. The measurements in blue data were taken with zero Ioffe current, and show a linear behaviour. The parabolic curve (black

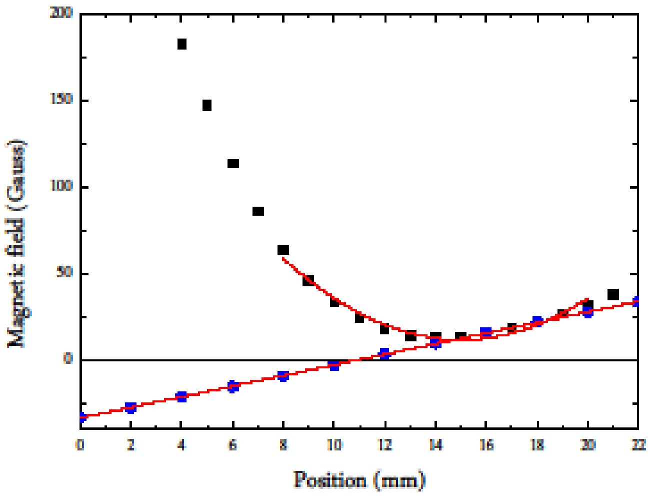

Figure 2. The QUIC trap coils characterisation. The blue data represent the magnetic field in Gauss as a function of the displacement from the trap centre.

data) is obtained when switching the Ioffe current on with 2 A, thus removing the magnetic field zero. The magnetic field is measured using a magnetometer, which was calibrated so to subtract the magnetic field of the earth.

One of the crucial steps in this experiment is transferring the atoms from the Magneto-Optical Trap (MOT) into the magnetic quadrupole trap efficiently. It is important to optimise each phase before the magnetic trap to obtain the highest atom number possible, sufficient phase space density and a maximised collision rate in the trap to ensure good evaporative cooling performance.

The experimental sequence starts with loading the magnetic quadrupole trap and determining its lifetime. First a dense and cold atomic cloud is prepared in the magneto-optical trap with a laser detuning of $\Delta = -1.6\,\Gamma$ (Γ is the scattering rate of the excited state of the ^{87}Rb).

In spite of the high atom number trapped in the MOT ($\approx 2 \times 10^8$) in 3 s, the density of the atoms is not sufficient for the next phase towards the BEC (i.e.

magnetic trap and evaporative cooling). A phase of compression of the MOT is therefore introduced. The Laser beams are switched off and the trapped atoms are compressed for (50 ms) [11]. This is done by doubling the magnetic field

gradient applied on the MOT from (10 G/cm to 20 G/cm) to compress the trap, and increasing the laser detuning to ($\Delta = -3\Gamma$). Since this phase heats the trapped atoms, an optical molasses phase is necessary to reduce the trap temperature. Therefore, the magnetic field is switched off to start a phase of optical molasses, which lasts for (10 ms) at a detuning of ($\Delta = -5\Gamma$). After the molasses phase, the atoms are distributed over all Zeeman sublevels.

For [87]Rb atom, there are five magnetic substates $(m_J = 0, \pm 1, \pm 2)$ of the higher hyperfine ground state of which just two are trappable by a magnetic quadrupole trap. To increase the number of trappable atoms and thus the loading efficiency of the magnetic trap, the atoms are optically pumped into the low-field seeking $|F = 2, m_F = 2\rangle$ spin state. This is done by switching off the cooling laser beams while the imaging beam is briefly flashed on for $50\mu s$ on resonance with the cycling transition. This mechanism is done with assistance of a small magnetic bias field (500mG) parallel to the beam and some re-pumping light. The magnetic field is applied by increasing the current through the compensation coil pair on axis with the imaging beam. This process of optical pumping transfers the ground state population of the [87]Rb ensemble into the highest magnetic sublevel. $(50\mu s)$ is sufficient for optical pumping since the life time of the [87]Rb $5^2P_{3/2}$ excited state is 26 ns [12] so that multiple optical pumping events can occur.

The magnetic life time is measured and the result is shown in Fig. 3. The left graph of Fig. 4 shows the atom number in the MOT for different loading times. This graph was taken to optimise the loading of the atoms from the MOT into the magnetic trap. Longer loading times increase the atom number in the MOT but produce large fluctuations which appear in the graph as large error bars. Accordingly, the life time measurement of the magnetic trap is done with only a (3 s) loading time as illustrated in the right graph of Fig. 3. This prevents the fluctuations in the initial atom number.

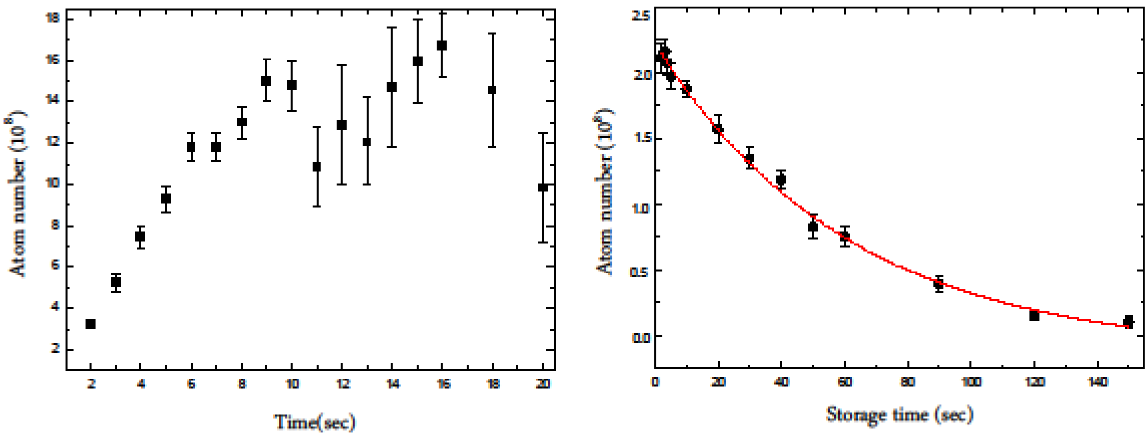

Figure 3. Optimisation the MOT loading into magnetic trap. Left: The atom number in the MOT is observed with different loading times. Right: The atoms are held for different storage times in the magnetic trap.

The number of atoms in the magnetic trap decreases exponentially with the hold time. A fit of the atom number over this time revealed a lifetime of the magnetic trap of (60.8 ± 4.6)s which is sufficient for evaporative cooling and Bose-Einstein condensation. The exponential fit is expected for real atomic systems due to the trap losses mechanism. This can be attributed to the inelastic collisions. Therefore, it is related to the residual background gas in the vacuum system. The evaporative cooling is the final cooling stage to reach the quantum phase transition in all experiments of Bose-Einstein condensate accomplished so far.

When this cooling process is successively repeated, the hotter atoms are enforced to leave the trap reducing its temperature dramatically via the so-called forced evaporative cooling. In this mechanism, the RF radiation functions as an evaporative RF-knife lowering the depth of the confining potential [13]. The evaporative cooling is implemented in our setup by applying radio frequency (RF) radiation to the confined ^{87}Rb atoms in a magnetic trap. The radio frequency ejects atoms from the trap by inducing spin- flips and thus driving transitions from the trapped state $|F=2, m_F=2\rangle$ into untrapped states $|F=2, m_F=0,-1,-2\rangle$. This turns the attractive trapping force into a repulsive force. The radio frequency ω_{RF} is progressively reduced so that atoms with corresponding energy undergo a spin- flip transition and are expelled from the trap. While, atoms with lower energy remains trapped.

Experimentally, the RF radiation is generated by four turns radio frequency antenna on axis with the quadrupole coils. The coil is positioned 1.5 cm away from the atomic sample and is directly attached to the glass cell. It is necessary to investigate the best frequency ramp which allows us to control the threshold energy and then maintain the runaway evaporation regime. This was achieved via a function generator. The start and final evaporative frequencies are determined by observing the atom number as a function of different frequencies. This suggested that the RF starts at a frequency of 30MHz to start removing the hotter atoms. The final radio frequency is set to be 0.45MHz when the BEC is observed. The generated RF is swept logarithmically down in two stages [10]. First, the RF frequency is ramped down with the atoms in the quadrupole trap from the initial value of 30MHz to 10MHz in 5 s. Then the atoms are transferred into the Quadrupole-Ioffe coil (QUIC) trap by ramping up the QUIC current to its final value in 350 ms. The second evaporation stage happens with the atoms in the QUIC trap and lasts 13 s during which the RF is ramped logarithmically from 10.5MHz to the final value around 0.45 MHz. It starts at a slightly higher frequency than the end frequency of the QUAD trap evaporation to accommodate for the lifted trap bottom in the QUIC trap and provide a seamless evaporation sweep. The RF frequency is optimised in term of the phase space density and the atom number so to reach the runaway evaporation regime.

3.1. Temperature measurements

The reduction of the temperature of the atomic cloud is essential during the evaporative cooling sequence. To measure the temperature of the atomic sample the standard time of flight method is used [14]. After the cooling stages of the

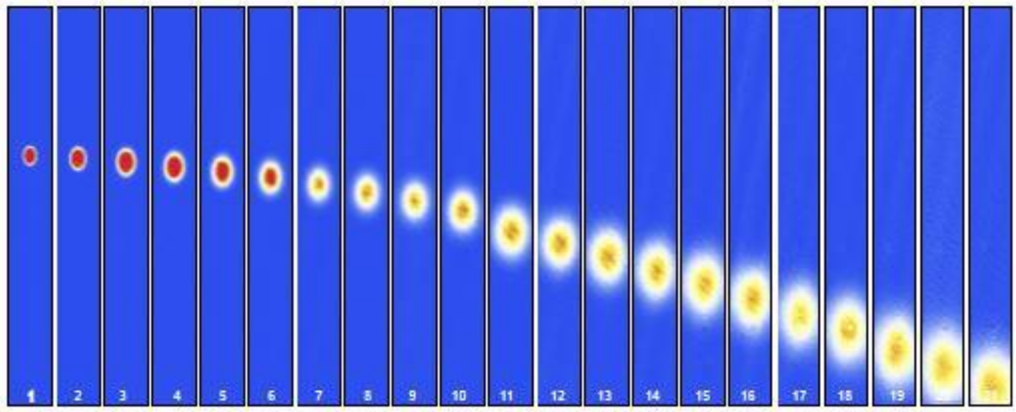

Figure (4) Absorption images for different times of flight of the atomic sample. The time indicated in each image in ms. Clearly visible is the parabolic drop according to the acceleration under gravity as well as the expansion of the ensemble due to its Gaussian velocity distribution.

trapped ^{87}Rb, the magnetic field and all the laser beams are switched off so that the cloud can expand freely according to its velocity distribution and fall down under gravity. As an example of a temperature measurement, Fig. 4 shows absorption images for different times of flight between (1 - 21) ms (plus an additional delay of (2 ms) to account for switching delays). For each image the
cloud is fitted with a 2D Gaussian to extract its width and position. The width is then plotted as a function of the expansion time. The data were fitted by a linear function to obtain the velocity of the cloud in both directions.
For the particular example shown in Fig. 4, the expansion velocity was determined as $\upsilon_x = (5.98 \pm 0.08) mm/s$ and $\upsilon_y = (5.78 \pm 0.07) mm/s$. So, the temperature can be calculated with $T = \frac{m\upsilon^2}{k_B}$ to $T_x = (374 \pm 7) nK$ and $T_y = (350 \pm 5) nK$ which is a temperature roughly around the recoil temperature for ^{87}Rb (Tr = 362 nK). The atomic velocity distribution of this thermal ensemble is still Gaussian and its phase space density slightly above the BEC transition.

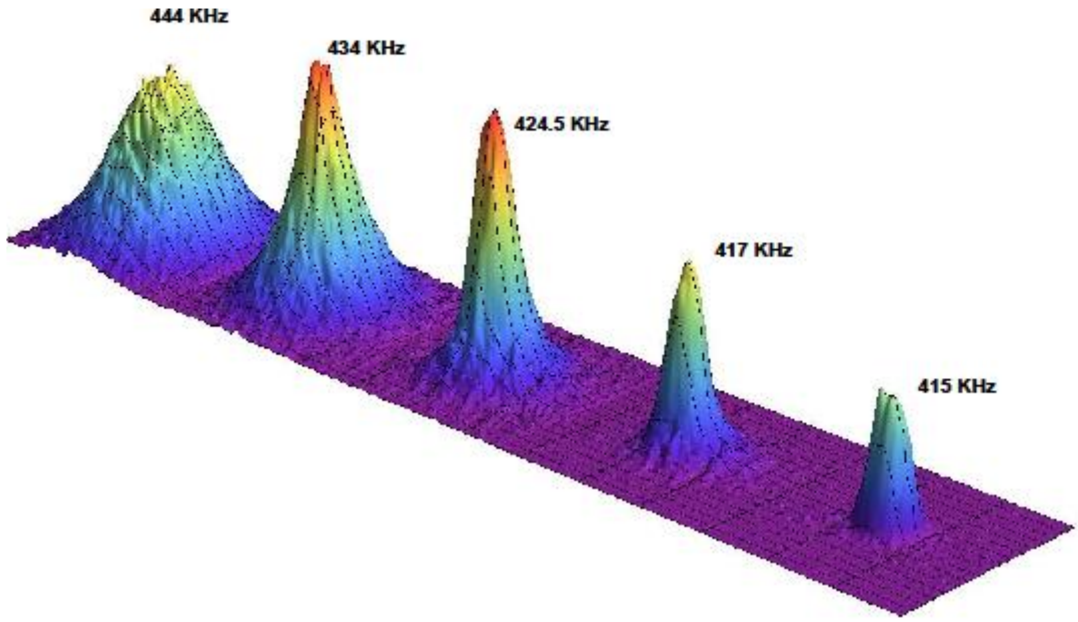

Figure 5. A 3D plots of the optical density after 22 ms time of flight for different final evaporation frequencies.

3.2. Observation of Bose-Einstein Condensate

The phase transition to a Bose-Einstein condensation occurs when the phase space density of the ensemble, which is the product of particle density and their thermal de Broglie wavelength cubed, becomes larger than 2.612. The key factors here are temperature and atom number in our magnetic trap after the evaporation sequence. The phase space density can be increased by reducing the final radio frequency of the sweep. The atomic condensate is observed by switching the magnetic field off to let the cloud expand ballistically over 22ms. Then absorption images of the cloud can be used to observe the phase transition when the final evaporation frequency is reduced. Fig. 5 shows a combined 3D plot of five successive absorption images. The same data set can be seen in Fig. 6 in a further analysis involving the profile of the cloud and its fit with the sum of a Gaussian and a parabolic function. While the first image of the set shows a thermally distributed cloud (with its Gaussian shape as an indicator of that), reducing the final radio frequency produces a fraction of the atoms in the ground state of the trap. This is the onset of Bose-Einstein condensation and the velocity distribution becomes bimodal which is a combination of a thermal and a condensate distribution. Most atoms are still thermal with a Gaussian velocity distribution, but in the centre of the distribution another part with a parabolic distribution due to the magnetic trap profile is formed. Evaporating further reduces the amount of atoms in the thermal portion and increases the BEC part until in the last image, at a frequency of 415 kHz, the distribution becomes purely parabolic and we are left with a nearly pure Bose-Einstein condensate.

4. Conclusion

This work illustrated the realisation of a Bose-Einstein condensate with ^{87}Rb by RF evaporation in QUIC trap. A MOPA system was used as a laser source to cool and trap (2×10^8) atom in 3s loading time. The trap life time in the magnetic trap was optimised and measured to be about 60 s. Then, atoms in the trap were cooled by ramping the radio frequency down. Bose-Einstein Condensation was observed.

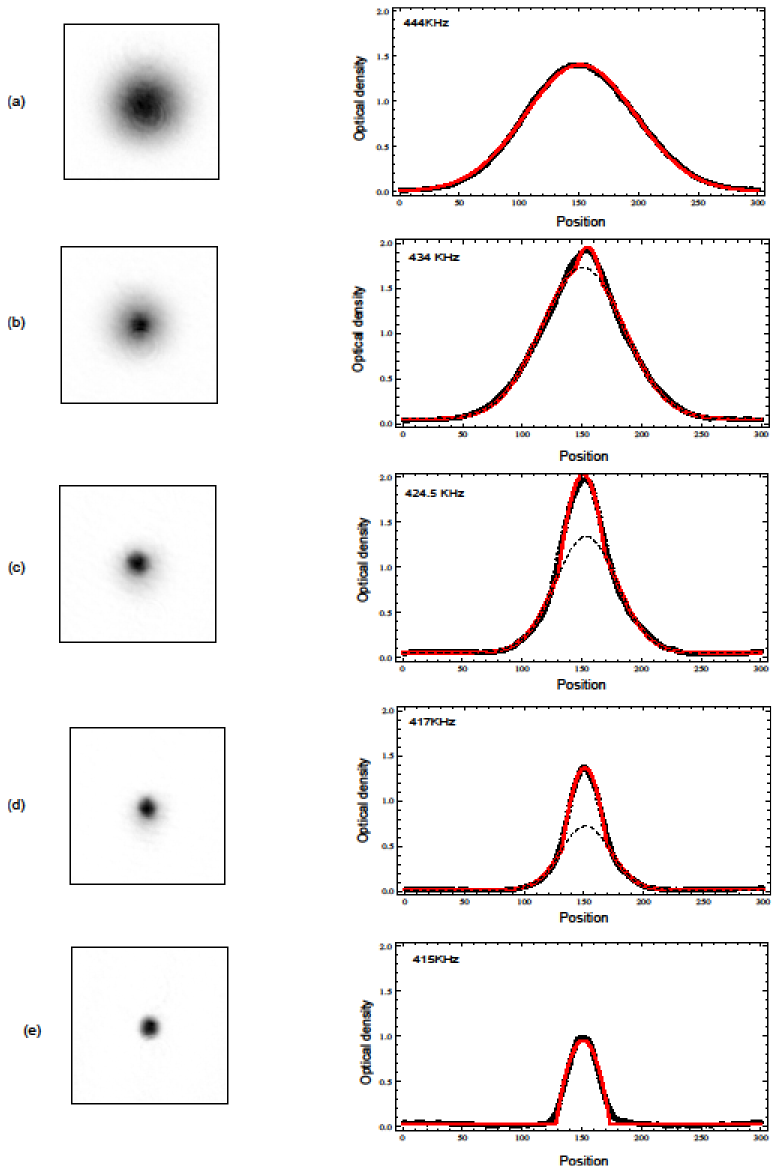

Figure 6. Absorption images and the corresponding density distribution of the trapped ^{87}Rb atom cloud when lowering the evaporative RF and then observing Bose-Einstein condensation. Left column: the absorption images of the atomic cloud after 20 ms expansion time. Right column: The density distribution of the trapped ^{87}Rb. (a) The cold thermal ^{87}Rb cloud fitted by a Gaussian function (the red curve). (b) The distribution is narrower than previous image. (c-d) Bi-modal distribution, which consists of two components: thermal and condensate distribution, fitted by a function which is a combination of a Gaussian function for the thermal cloud and a parabola function for the condensate. (e) Pure condensate of ^{87}Rb.

CONFLICT OF INTERESTS.

There are non-conflicts of interest.

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الخلاصة

تكاثف بوز− انشتاين هي حالة من حالات المادة يتم خلقها عن طريق تبريد ذرات غاز لدرجة حرارية فائقة الأنخفاض وبكثافة منخفضة جداً. تم توليد تكاثف بوز− انشتاين الى ذرات ^{87}Rb عن طريق المصيدة المغناطيسية بترتيب يطلق عليه Quadrupole –Ioffe Configuration الذي يتكون من مجال مغناطيسي رباعي يتولد عن رتيب زوج من الملفات بترتيب يسمى Anti−Helmholtz coils . كما يستخدم سلك منفرد اضافي يولد مجال عمودي على المجال السابق يطلق عليه Offset coil والغرض منه هو كبح انتقالات ماجورانا Majorana flip−flop . اول خطوات العمل هو تبريد وقنص الذرات باستخدام الليزر في المصيدة المغناطيسية الضوئية Magneto−Optical Trap وصولاً الى عدد ذرات بحدود 2×10^8 ذرة بزمن 3 ثواني. بعد ذلك يتم تبريد الذرات في ميكانيكية Optical Molasses للوصول الى درجة حرارة أقل وتحقيقاً لكثافة ذرية عالية. الخطوة التالية هوتحميل الذرات الى المصيدة المغناطيسية بزمن عمر قدره $(60.8 \pm 4.6)s$ وهو كافي لتبريد الذرات لدرجة حرارية اقل لعملية التبخير Evaporative cooling ومن ثم انتاج ال BEC . يتم التبريد بالتبخير باستخدام ترددات راديوية للوصول الى انتقال الطور الى BEC . تم قياس درجة حرارة الذرات باستخدام تقنية زمن الطيران Time Of Flight وان سرعة تمدد الغيمة الذرية قيست بمقدار $v_x = (5.98 \pm 0.08)mm/s$ $v_y = (5.78 \pm 0.07)mm/s$ والتي تودي الى قياس درجة الحرارة بمقدار $T_x = (374 \pm 7)nK$. and $T_y = (350 \pm 5)nK$ وهي مقاربة الى درجة حرارة الارتداد Recoil temperature للربيديوم.