Realization of Bose-Einstein Condensation in dilute gases

Guang Bian

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Abstract:

This essay describes theoretical aspects of Bose-Einstein Condensation and the first experimental realization of BEC in dilute alkali gases. In addition, some recent experimental progress related to BEC are reported.

1 Introduction

A Bose–Einstein condensate is a state of matter of bosons confined in an external potential and cooled to temperatures very near to absolute zero. Under such supercooled conditions, a large fraction of the atoms collapse into the lowest quantum state of the external potential, at which point quantum effects become apparent on a macroscopic scale. When a bosonic system is cooled below the critical temperature of Bose-Einstein condensation, the behavior of the system will change dramatically, because the condensed particles behaving like a single quantum entity. In this section, I will review the early history of Bose-Einstein Condensation.

In 1924, the Indian physicist Satyendra Nath Bose proposed a new derivation of the Planck radiation law. In his derivation, he found that the indistinguishability of particle was the key point to reach the radiation law and he for the first time took the position that the Maxwell-Boltzmann distribution would not be true for microscopic particles where fluctuations due to Heisenberg's uncertainty principle will be significant. In the following year Einstein generalized Bose's method to ideal gases and he showed that the quantum gas would undergo a phase transition at a sufficiently low temperature when a large fraction of the atoms would condense into the lowest energy state. At that time Einstein doubted the strange nature of his prediction and he wrote to Ehrenfest the following sentences, 'From a certain temperature on, the molecules "condense" without

attractive forces, that is, they accumulate at zero velocity. The theory is pretty, but is there also some truth to it? '

From then on, many phenomena were found related to the idea of Bose-Einstein Condensation, such as superfluidity, superconductivity and laser. However, Einstein's original idea of BEC in weakly interacting gases were not realized due to technical difficulty in reaching the low temperature necessary for BEC. In the 1980s the development of laser cooling and trapping made it possible to realize BEC in laboratory. Finally, in 1995, several group observed the expected phenomena of BEC in dilute alkali gases.

2 Theory

Detailed calculation using Bose-Einstein statistics tells us that BEC occurs when the dimensionless phase-space density $n\lambda_{dB}^3$ exceeds 2.612, where the thermal wavelength is defined as

$$\lambda_{dB} = \frac{h}{(2\pi m k_B T)^{1/2}}$$

For an alkali atomic gas of densty $10^{13} \sim 10^{14} cm^{-3}$, the critical temperature is several hundred nano-kelven. So creating a BEC is simple in principle: cool a gas until the thermal de Broglie wavelength is roughly the distance between atoms.

The dynamic property of the condensate is different from that of normal state. The state of the BEC can be described by the wave function of the condensate $\psi(\vec{r})$. For a system of this nature, $|\psi(\vec{r})|^2$ is interpreted as the particle density, so the total number of atoms is

$$N = \int d\vec{r} |\psi(\vec{r})|^2$$

Provided all atoms are in the condensate, and treating the bosons using Mean field theory, the energy (E) associated with the state $\psi(\vec{r})$ is:

$$E = \int d\vec{r} \left[\frac{\hbar^2}{2m} |\nabla \psi(\vec{r})|^2 + V(\vec{r}) |\psi(\vec{r})|^2 + \frac{1}{2} U_0 |\psi(\vec{r})|^4 \right]$$

Minimizing this energy with respect to infinitesimal variations in $\psi(\vec{r})$, and holding the number of atoms constant, yields the Gross-Pitaevski equation :

$$i\hbar \frac{\partial \psi(\vec{r})}{\partial t} = \left(-\frac{\hbar^2 \nabla^2}{2m} + V(\vec{r}) + U_0 |\psi(\vec{r})|^2 \right) \psi(\vec{r})$$

Where m is the mass of the bosons, $V(\vec{r})$ is the external potential, U_0 is representative of the inter-particle interactions.

The Gross-Pitaevski equation provides a good description the strange behavior of the BEC such as vortices, and is the approach often applied to their theoretical analysis.

3 Experimental realization

Bose-Einstein condensation was observed experimentally for the first time in 1995 by a group in Boulder, Colorado. This section is devoted to a description of this famous experiment.

The General strategy to realize BEC in the 1995 experiment: first precool the gas by laser cooling techniques , then confine the gas in a magnetic trap, finally further cool the trapped gas by forced evaporative cooling to reach the critical temperature. The experimental apparatus is shown below:
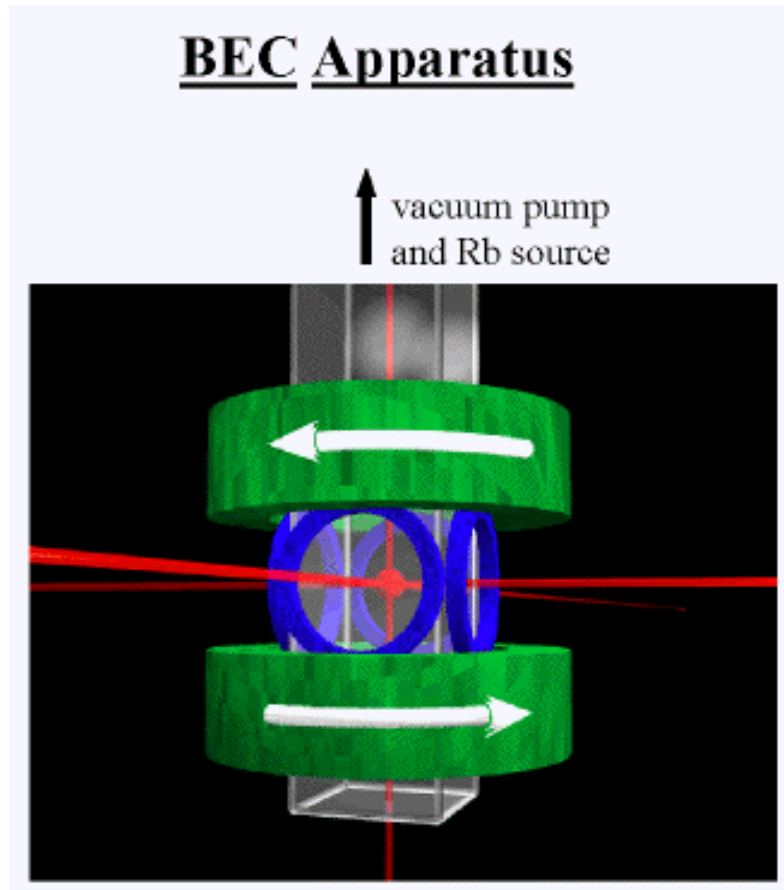
In this experiment, six laser beams intersect in a glass cell, creating a magneto-optical trap (MOT). Rb-87 atomic gases is contained in the cell which is 2.5 cm square by 12 cm long, and the beams are 1.5 cm in diameter. The coils generating the fixed quadrupole magnetic field and rotating transverse components of the TOP trap magnetic fields are shown in green and blue, respectively.

After laser-cooling techniques achieved temperatures in the range of a few µK, evaporative cooling was carried out to further cool the atom gases. However, at that time there was a severe problem in the magnetic trap. The magnetic trap is shown in the figure below, (a) is the magnetic configuration and (b) is the cylindrically symmetric potential of the quadrupole trap.
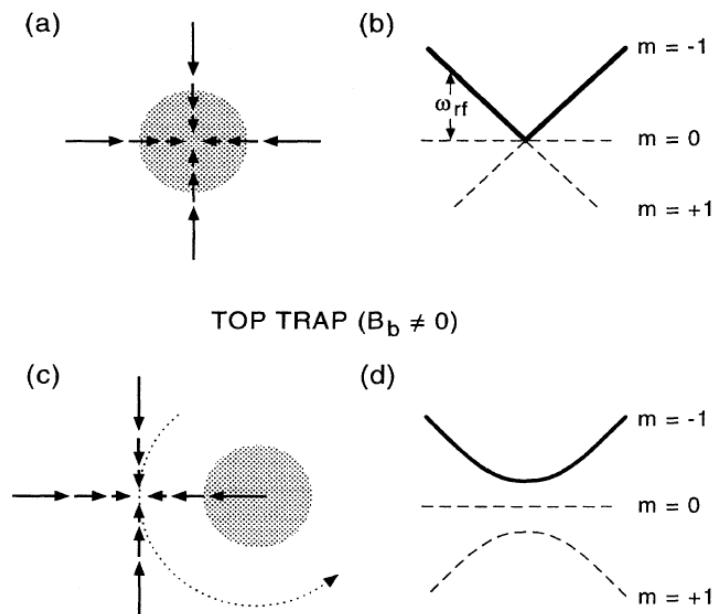
The magnetic trap had a field zero at the centre where atoms could undergo Majorana transitions and thus escaped from the trap. As the cloud got colder, atoms spent more time near the hole and were quickly lost from trap. Eric Cornell proposed a solution to the leaky trap problem: the time-orbiting potential (TOP) as shown in (c) and (d). The idea of TOP is like this: when you add a transverse magnetic field to the quadrupole trap, the hole will be moved away from the trap centre to a place in the direction of the transverse magnetic field. If you move the

location of the hole faster than the average time taken for atoms to find it, the atoms will be constantly chasing the hole and will never find it. A smooth way to achieve this is to add a rotating field that moves the hole around in a circle. The time averaged pseudo-potential is then a smooth potential well with a non-zero minimum. To be concrete, the magnetic field in the quadrupole trap is

$$\vec{B} = B'(x, y, -2z)$$
$$B = B'(x^2 + y^2 + 4z^2)$$

After adding a rotating, spatially-uniform magnetic field , the field becomes

$$\vec{B} = (B'x + B_0 \cos \omega t, B'y + B_0 \sin \omega t, -2B'z)$$

$$B(t) = [(B_0 \cos \omega t + B'x)^2 + (B_0 \sin \omega t + B'y)^2 + 4B'^2 z^2]^{1/2}$$

$$\approx B_0 + B'(x \cos \omega t + y \sin \omega t) + \frac{B'^2}{2B_0}[x^2 + y^2 + 4z^2 - (x \cos \omega t + y \sin \omega t)^2]$$

$$<B>_t = B_0 + \frac{B'^2}{4B_0}(x^2 + y^2 + 8z^2)$$

Plugging the leaky trap was the final hurdle in achieving BEC. In July 1995, Cornell and Wieman announced that they had observed BEC in a gas of Rb-87 atoms. The transition temperature was 170 nK. The researchers had imaged the cloud by first allowing it to expand and then illuminating with a pulse of resonant light. The light absorbed by the cloud cast a shadow on a CCD camera. The velocity distribution of the atom cloud is shown below.
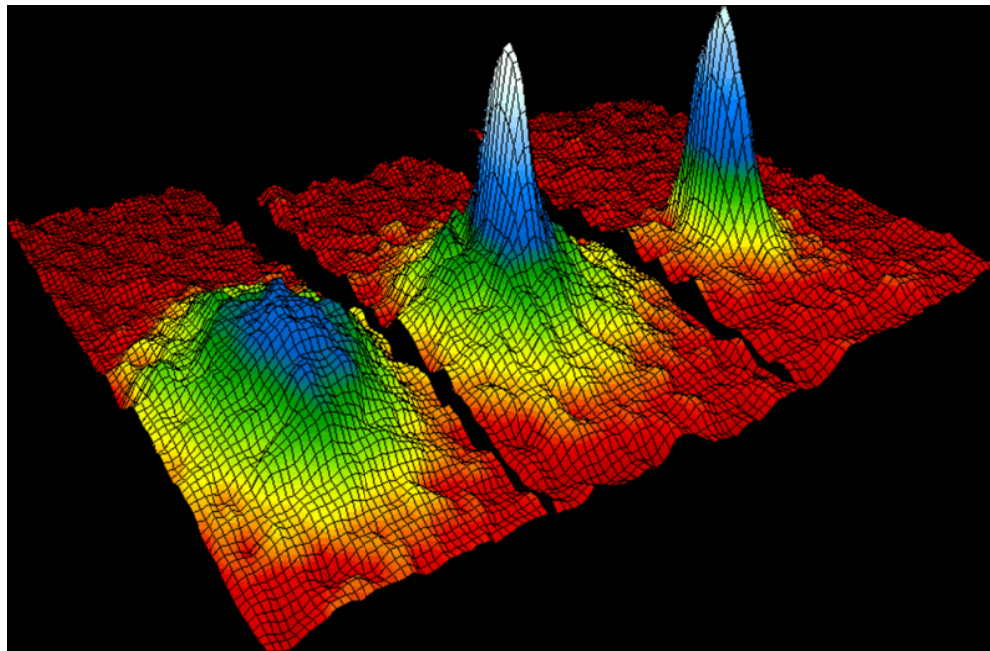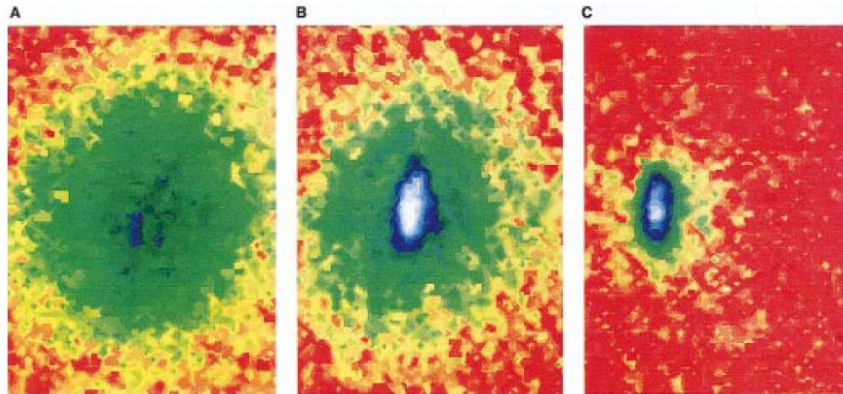
The temperature of the three plots are 400 nK, 200 nK and 50 nK (from left to right), respectively. The field of view of each image is 200 microns by 270 microns. Obeservation was made with laser pulse resonant with the 5S_1/2, F=2 to 5P_3/2, F=3 transition.

The striking feature of this work was that there were three clear and distinct signatures of BEC which made any skeptic immediately convinced:

(1) The appearance of the condensate was marked by a narrow, intense peak of atoms near the centre (zero-velocity region), corresponding to the ground state of the trap.

(2) As the temperature was lowered below the transition temperature, the density of atoms in the peak increased abruptly, indicating a phase transition.

(3) The atoms in the peak had a nonthermal velocity distribution as predicted by quantum mechanics for the ground state of the trap, thus indicating that all these atoms were in the same quantum state.

4 Recent progress

Compared to more commonly-encountered states of matter, Bose–Einstein condensates are extremely fragile. It is likely to be some time before any practical application are developed. However, BEC have been proved to be very useful in exploring a wide range of questions in fundamental physics:

- Demonstrating interference between condensates due to wave-particle duality.
- Realization of atom laser which is a propagative atomic wave obtained by extraction from a previously realized BEC.
- Studying superfluidity and vortices in BEC.
- Realizing BEC in a wide range of isotopes and molecular gases.
- Studying BEC in optical lattice and exploring the transition between a superfluidity and a Mott insolator.

- Creating the first fermionic condensate composed of Cooper pairs.
- Studying Bose–Einstein condensation in fewer than three dimensions, for example the Tonks-Girardeau gas.

Another interesting application of BEC is slowing light pulses to very low speeds using electromagnetically induced transparency. In 1999, a team of scientists led by Lene Hau were able to slow the speed of a light pulse to about 17 metres per second; in 2001, they were able to momentarily stop a beam.

5 Conclusion

It is seventy years after Einstein conjectured the existence of atom condensate that people for the first time succeeded observing BEC in laboratory. The experimental result is of striking beauty which catches every physicist's attention. The subsequent experiments using BEC have been truly elegant illustrations of quantum physics. I think, maybe after several decades, we can encounter various application of BEC in our everyday life. I will end my essay with a sentence by Wolfgang Ketterle,

"Beauty is created by nature, sometimes we succeed in making it visible."

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