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Experiment studies of Bose Einstein Condensation

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1. Introduction

The recent observation of Bose-Einstein condensation (BEC) in alkali vapors [1-3] was the realization of many long-standing goal(1) To cool neutral atoms into the ground state of the system, thus exerting ultimate control over the motion and position of atoms limited only by Heisenberg's uncertainty relation. (2) To generate a coherent sample of atoms all occupying the same quantum state (this was used to realize a rudimentary atom laser, a device which generates coherent matter waves). (3) To produce degenerate quantum gases with properties quite different from the quantum liquids He-3 and He-4. This provides a testing ground for many-body theories of the dilate Bose gas which were developed many decades ago but never tested experimentally. (4) BEC of dilute atomic gases or of excitations is a macroscopic quantum phenomena with similarities to super fluidity, superconductivity and the laser phenomenon. (5) Bose-Einstein condensation is based on the wave nature of particles, which is at the heart of quantum mechanics, In a simplified pictures atoms in a gas may be regarded as quantum-mechanical wave packets which have an extent on the order of a thermal de Broglie Wavelength (the position uncertainty associated with the thermal momentum distribution). The lower the temperature, the longer is the de-Broglie Wavelength is comparable to the interatomic separation, then the atomic Wave packets "overlap" and the in distinguishability of particles becomes important (Fig. 1).

Bosons undergo a phase transition and form a Bose-Einstein condensate, a dense and coherent cloud of atoms all occupying the same quantum mechanical state. (6) The relation between the transition temperature and the peak atomic density and can be simple expressed as $n\lambda^{3}_{dm}$=2.612, Where the thermal deproglie wavelength is defined as $\lambda_{dB}(2\lambda h^2/mC_BT)^{\frac{1}{2}}$and M is the mass of the atom.

High temperature T: Thermal Velocity V density d^{-3}

"Billiard balls"

d

Low temperature T: De Broglie Wavelength

$\lambda_{dB=}$ h/mv<$T^{-v}{}_2$

"Wave Packets"

T= Tcrit :

Bose-Einstein condensation
$\lambda_{dB} \approx d$
"Matter Wave Overlap"
T=0 :

Pure Bose condensate "Giant Matterwave"

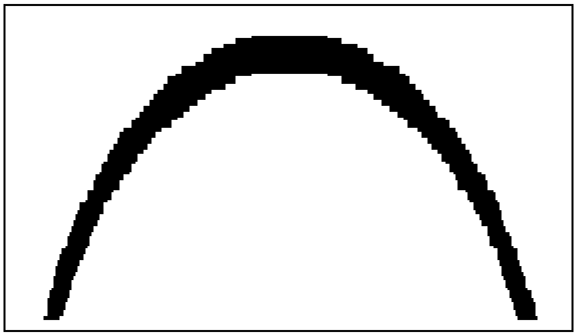
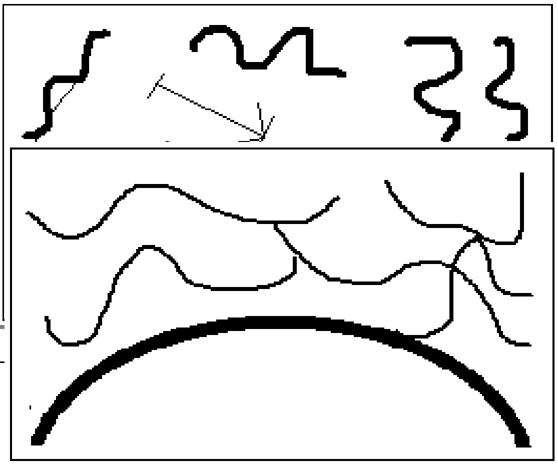


Fig:1:- Criterion for Bose-Einstein condensation. At high temperatures, a Weakly Mteracting gas can be treated as a system of "billiard balls". In a simplified quantum description, the atoms can be regarded as Wave packets with an extension Δx, approximately given by Heisenberg's uncertainty ration Δx=h/DP Where DP Denotes the width of the thermal momentum distribution. Δx is approximately equal to the thermal de-Broglie Wavelength λ_{dB}. The matter wavelength for an atom moving with the thermal velocity. When the gas is cooled down the de-Broglie wavelength increases. At the BEC transition temperature, λ_{dB}becomes Comparable to the distance between atoms, and the Bose condensates forms which is characterized by a macroscopic population of the ground state of the system. As the temperature approaches absolute Zero the thermal cloud disappears leaving a pure Bose condensate. The realization of Bose-Einstein



condensation requires techniques to cool gases to sub-microkelvin temperatures and atom traps to confine then at high density and keep than away from the hat walls of the vacuum chamber. Over the last is years, such techniques have been developed in the atomic physics and low-temperaturecommunities[5]. The MIT experiment uses a multistage process to cool het sodium vapor down to temperatures Where the atoms form a condensate [2,7]. A beam of sodium atoms is emitted from an atomic beam oven at a density of about 10^{14} atoms per cm^3, similar to the eventual density of the condensate. The gas is Cooled by nine orders of magnitude from book to 1 uk by first slowing the atomic beam, then by optical trapping and evaporative cooling [10].

The first experimental demonstrations of BEC [1-3,11] were followed by several experimental studies and numerous theoretical papers (see Refs. [10,12,-18] for reviews).

We refer to our previous review[10].

For the historical context, for an account of the developments which led to BEC, and for an overview of the techniques used to realize BEC. In this paper We summarize some experimental studies of Bose-Einstein condensation and illustrate them with animations of experimented results, These illustrations display another important aspect of Bose-Einstein condensation. Since a Bose condensate is characterized by a macroscopic population of a single quantum state, the imaging of condensates and their dynamical behavior constitutes a dramatic visualization of quantum-mechanical Wave functions and give Wave functions a new leaves of reality. The animations and many figures in this paper have not been published before, whereas all experimental results have been previously reported in more technical papers.

2. Identifying the Bose-Einstein Condensate

Bose-Einstein condensation was achieveal by evaporatively cooling a gas of magnetically trapped atoms to the transition temperature. In the first observations [1,2] four features were used to identify the formation of a Bose-Einstein condensate.

(1) The sudden increase in the density of the could

(2) The sudden appearance of a bimodal cloud consisting of a diffuse normal components and a dense core (the condensate)

(3) The velocity distribution of the condensate was anisotropic in contrast to the pso tropic expansion of the normal (Non-condensed) component.

(4) The good agreement between the predicted and measured transition temperatures.

The first three points are illustrated in fig 2. It shows time of hight pictures of expanding clouds released from the magnetic trap by suddenly switching off the trap. These images, taken during our secma data run which produced Bose-Einstein condensation were recorded by illuminating the cloud with resonant laser light and imaging the shadow of the cloud on to a CCD camera [2].

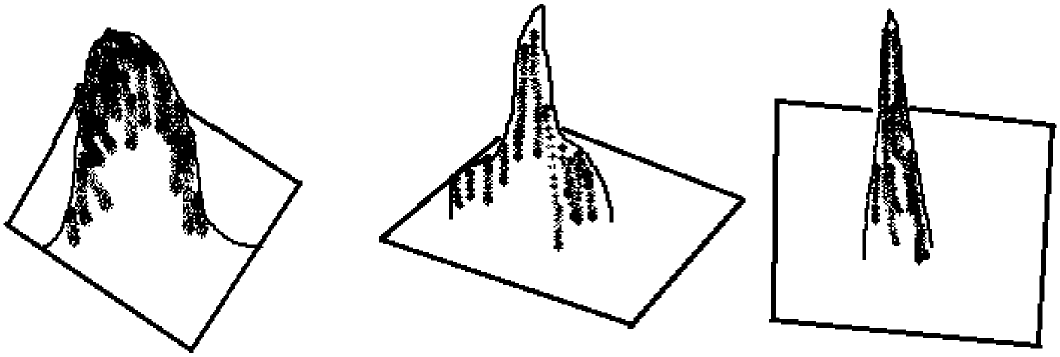


Fig.2 Observation of Bose-Einstein condensation by absorption imaging. Shown is absorption vs two spatial dimensions. The Bose-Einstein condensate is characterized by its slow expansion observed after 6 m sec time of flight. The left picture shows an expanding cloud cooled to just above the transition point; middle: Just after the condensate appeared; right: after further evaporative cooling has left an almost pure condensate. The width of the images is 1.0mm. The total number of atoms at the phase transition is about $7x10^5$ the temperature at the transition point is 2uk.

The animations in Fig. 3. Shows the suddenness of the formation of the condensate each frame required a new loading and cooling cycle. Frames were taka for various final frequencies of the rf sweet which controlled the evaporative cooling process. To a very good approximation, the temperature of the cloud is linearly related to the final rf frequency discrete frames were interpolated in such a way that the rf frequency decreases at a constant rate during the length of the animation since close to the phases transition the radiofrequency was swept linearly in time, fig.3. represent the temporal dynamics of the cooling process drawing the last fraction of a second (the Whole evaporation process took only seven seconds).

Fig.3. Formation of a Bose-Einstein condensate. Two dimensional probe absorption images, after 6 m sec time of flight, show the sharpness of the phase transition. This sequence includes the three images on fig.2 The evaporative cooling was induced by on externally applied rf field As the final rf frequency (labeled on the plots) was lowered lower temperatures and higher phase space densities were reached. The cloud at the start of the animation had a temperature of about 5 uk. Above the phase transition (frequency >700khz) the clouds expanded spherically, as expected for a normal thermal distribution. As the frequency was reduced, the spherical cloud shrank in size, due to the lower temperatures reached. Below the transition point (frequency <700KHZ,2uk) an elliptical core appeared, which is the signature of the condensate. As the frequency was lowered the spherical part became invisible, corresponding to a pure condensate. Finally, When the threshold for evaporation reached the bottom of the trap (around 300 KHZ), the condensate itself was last by evaporation. Note that the color scale here has been chosen to represent optical density (OD) instead of absorption (a), as used in the other images The two are related by OD=-in(1-A). The rf frequency displayed in the animation changes when a new original frame is displayed and stays constant when interpolated frames are shown the size of the frame is 1.1 by 1.6 mm.

3. Collective Excitations of a Bose Condensate

Collective excitation of liquid helium played a key role in determining its superfluid properties [24]. It is now well understood that the phonon nature of the low-lying excitations imply superfluidity up to a critical velocity which is given by the speed of sound. The low-lying excitations of a trapped Bose condensate show discrete modes due to the small finite size of the trapped, sample. They correspond to standing sound waves. The few lowest-lying excitations were studied in Boulder [25] and at MIT [26]

Fig. 6 Shows our first observation of collective excitations. The cloud is contracting along the axial direction while expanding radially and vice versa and therefore corresponds to a quadruple mode of a spherical cloud.

The oscillations were excited with a time-dependent modulation of the trapping potential. A variable time delay was introduced between the excitation and the release of the cloud. In this way, the free time evolution of the system after the excitation was probed. The cloud was observed by absorption imaging after a sudden switch-off of the magnetic trap and 40 m sec of ballistic expansion. The measured frequency of oscillation were in excellent agreement with predictions based on the non-linear Schrodingerequation[27,28]

In order to understand the observed damping time of 250 m sec studies have recently ben extended to finite temperatures [28,29].

Our studies were done using direct observation of the spatial oscillation by dispersive imaging. Since the method is much less destructive than absorption imaging, "real-time movies" with ug to 30 pictures of the same oscillation condensate cloud be taken. Fig.7 Shows the observation of the axial dipole motion (center of mass motion) Which was excited by periodically moving the center of the magnetic trap. The dipole motion is undamped in a harmonic trapping potential although the dipole mode by itself doesn't reveal anything about the nature of the Bose Condensate, an accurate measurement of its frequency is important since it is needed to normalize the other collective excitation frequencies in order to compare them with theory. Images like these in Fig.7. allow a single-frequencies with 0.2% precision.

When the cloud was excited by modulation the axial confinement the quadruple-type oscillation cloud be observed in the spatial domain Fig.8. In Fin9. Thirteen pictures like Fig.8. bat With various delays were combined into an animation it shows the dynamics of the condensate over a period of one second. One can clearly see the damping of the oscillations of the shape of the condensate where as the Centre-of-mass motion is undamped. Several theoretical schemes have recently been developed to describe the damping of collective excitations as a function of temperature. (see reference in [28])

4. Realization of an Atom laser

An atom laser is a device which generates an intense coherent beam of atoms through a stimulated process. It does for atoms what an optical laser does for light;

Where as the optical laser emits coherent electro magnetic Waves, the atom laser emits coherent matter Waves. The condition of high intensity requires many particles per mode or quantum state. A thermal atomic beam has a population per mode of MVT 10^{-12} compared to values much greater than for an atom laser. The realization of an atom laser there for required methods to largely enhance the mode occupation. This was done by Cooling to sub-micro kelvin temperatures to the onset of Bose-Einstein condensation.

Laser light is created by stimulated emission of photons, a light amplification process. Similarly, an atom laser beam is created by stimulated amplification of matter Waves. The conservation of the number of atoms is not in conflict With matter Wave amplification: The atom laser takes atoms out of a reservoir and transforms them into a coherent matter wave similar to the manner in which an optical laser converts energy into coherent electromagnetic radiation. An atom laser is possible only for botanic atoms because the accumulation of atoms in a single quantum state is a result of Bose-Einstein statistics. In a normal gas, atoms scatter among a myriad of possible quantum states but When the critical temperature for Bose-Einstein condensation is reached, they scatter predominantly into the lowest energy state of the system. This abrupt process is closely analogous to the threshold for operation of an optical laser. The presence of a Bose-Einstein condensate causes stimulated scattering into the ground state. More precisely, the presence of a condensate with no atoms enhances the probability that an atom will be scattered into the condensate by a factor of notes, in close analogy to the optical laser.

There is some ongoing discussion what defines a laser, even in the case of the optical laser [30,31]; eg. It has been suggested that stimulated emission is not necessary to obtain laser radiation[30]. In our discussion we don't attempt to distinguish between defining features and desirable features of a leaser

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