Bose-Einstein Condensation

Atoms are normally considered as particles but, according to quantum mechanics, they also have wave-like properties. Indeed, an atom has an equivalent wavelength, the de Broglie wavelength, which is inversely proportional to its momentum. As atoms are cooled they slow down and their de Broglie wavelength increases. Satyendra Bose and Albert Einstein predicted 70 years ago that at a low enough temperature the wavelength exceeds the inter-particle spacing and the atoms begin to overlap. The atoms become indistinguishable, effectively entering - by a process called Bose-Einstein condensation (BEC) - a coherent state where the laws of quantum mechanics govern the behaviour of the macroscopic system. BEC has been observed in superfluid helium-4 and superconductivity, both being states of matter in which bosons (integral-spin particles) condense into macroscopic quantum states. But the bosons in these systems interact with each other, so to better understand BEC, physicists have tried for sometime to bring about condensation in an ideal gas of noninteracting atoms.

The JILA Experiment

The JILA experiment consists of three stages: A - optical loading, (pre)cooling & polarization; B - magnetic trapping & evaporative cooling in the absence of light; C - optical detection.

A - Trapping and cooling. Polarized atoms are magnetically trapped in a rapidly applied time-oscillating potential (TOP) trap, which consists of a set of coils in an anti-Helmholtz configuration with a small, uniform transverse field, rotating at 7.5 kHz, superimposed. The TOP provides an effectively harmonic potential with an axial frequency of about 120 Hz and radial frequency of about 42 Hz. In the TOP, the gas is adiabatically compressed to reach the starting conditions for evaporative cooling at about 90 μK with a number density of about 2 x 10¹⁰ cm⁻³, sufficiently large to have the elastic collision rate dominate over the loss rate in the gas. The evaporation takes 730 s and BEC is established with 2 x 10^¹⁰ atoms at an ultimately 170 nK. The evaporation is induced by a RF transition to an untrapped state of the atoms at the edge of the sample.

B - Optical detection. At the start of the detection stage the trap is expanded adiabatically to a larger size to allow a fast (destructive) absorption measurement in which the sample is imaged on a CCD camera. The appearance of a diffraction ring marks the growth of a partially resolved structure in the sample. This is consistent with BEC in an inhomogeneous sample, where the condensate is expected to appear as a very small, dense gas cloud at the centre of the potential well. To confirm this interpretation, the momentum distribution in the sample was measured and BEC is confirmed with 2 x 10¹⁰ atoms at an ultimately 170 nK. The evaporation is induced by a RF transition to an untrapped state of the atoms at the edge of the sample.

C - Optical detection. The first experimental verification came in 1985 from Teixeira, Bellissent-Funel, Chen and Dormer (TBCD) [2], who performed inelastic x-ray scattering experiments in heavy water at momentum transfer (q) values of 3.5-6.0 nm⁻¹. Their results revealed strong evidence for collective excitations propagating with a speed of sound of 3300 ms⁻¹, a value that is two times larger than the velocity of ordinary sound in water. It was speculated at the time that this fast mode may propagate via the network of hydrogen bonds. Since then, many theoretical analyses and molecular dynamics simulations have tried to clarify the origin of these excitations [3-5]. Despite these efforts, the issue could not be settled, mainly because neutron data were only available for a limited region of momentum transfer-frequency (q-ω) space. Moreover, in 1995 Bermejo et al. [6] made new neutron scattering measurements and dilute, with only a few collisions per atom per second. Since, in the absence of interactions, the compressibility of a Bose condensate is infinite, the condensate will be compressed by the trapping potential until the interatomic interactions counterbalance the potential, thus affecting the size and shape of the condensate. This effect has also been observed at JILA (see figure).

Many intriguing problems await experimental investigation, involving: a) the location of the BEC phases; b) the possibility to study normal states of matter with respect to Fermi systems. One controversial topic - the stability of condensates under an attractive mean field (negative scattering amplitude) - is already being addressed by Randall Hulet, who observed diffraction rings indicating an internal structure in ultra-cold samples of ⁸⁷Rb. Similar experiments can be done with ³⁷K. There are suggestions that the scattering amplitude of the heavy alkalis can be modified and its sign possibly even changed. Clearly, an exciting period lies ahead. It is fortunate that the results obtained by the group of Cornell and Wieman were replicated with methods available to many groups in university environments as this will allow a wide exploration of the fascinating Bose-Einstein condensates.
intermolecular distances and the \( q \)-\( \omega \) dependence of the molecular dynamics [5].

The inelastic X-ray scattering spectra were measured at \( q \)-values of 4-14 nm\(^{-1} \) using X-rays of 17794 eV with an overall energy resolution of 3.2 meV [7]. Fig. 1a gives, as a typical example, a spectrum taken at \( q = 4 \) nm\(^{-1} \) together with the corresponding fitted curve. In order to determine the energy positions and the damping of excitations at each \( q \)-value, the spectra were modelled using a function \( F(q,\omega) \) consisting of a Lorentzian for the central peak, and a damped oscillator [8] for the side peaks:

\[
F(q,\omega) = I(q) \Gamma(q) \frac{\omega_0^2}{\omega^2 + \omega_0^2} + I_0(q) \Gamma_0(q) \frac{w_0^2}{w^2 + w_0^2} + f(q) \frac{2 w_0^2}{w^2 + w_0^2} + g(q) \frac{2 w_0^2}{w^2 + w_0^2}
\]

where \( I(q) \) and \( I_0(q) \) are the width and intensity, respectively, of the central peak, \( \Gamma(q) \) and \( \Gamma_0(q) \) are the damping and intensity of the side peaks with a central frequency \( \Omega(q) \), and \( n(\omega) \) is the Bose factor. This specific function was chosen to allow a comparison with the previous neutron data [2,6], which had been analyzed using the same model. The convolution of \( F(q,\omega) \) with a Lorentzian representing the resolution function was fitted to the experimental data, after subtraction of the detector's dark counts.

The derived values of \( \Omega(q) \) are shown in Fig. 1b together with the analogous quantities obtained by TBCD from their neutron data. The \( \Omega(q) \) values follow a linear behaviour characterized by a speed of sound of 3200 ± 100 m/s up to \( q = 10 \) nm\(^{-1} \) (for higher \( q \)-values there is an indication of a decrease in the velocity). This value of the velocity of sound is identical, within the experimental error, to that of 3300 ± 250 m/s reported by TBCD for heavy water.

**Firm Conclusions**

The results shown in Fig. 1b and their comparison with those of TBCD allow for two firm conclusions: a) fast sound does indeed exist in water in the \( q \)-region between 4 and 14 nm\(^{-1} \), and b) the same value for the velocity of fast sound in \( H_2O \) and \( D_2O \) rules out the possibility that the fast-sound modes propagate in an atomic network constituted primarily by the hydrogen atoms. The data indicate instead that fast sound involves the whole molecule (the isotopic shift expected for the whole molecule is approximately 5%, well within the error bars, while it would be approximately 40% if individual hydrogen atoms were involved).

This determination of collective excitations in liquid water demonstrates the ability of inelastic X-ray scattering at meV energy resolutions to study the dynamics of disordered systems. Propagating collective excitations have been found at momentum transfers of 4-14 nm\(^{-1} \), and the existence of fast sound has been established over this entire momentum range.

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Dr. G. Martinez, Grenoble High Magnetic Field Laboratory, MPIF/CNRS, 25 avenue des Martyrs, F-38042 Grenoble Cedex 09, France.