Bose-Einstein-Condensation (BEC): Short introduction

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1 Introduction

The idea of Bose-Einstein condensation (BEC) dates back to 1925 when A. Einstein, based on a work of S.N. Bose devoted to the statistical description of the quanta of light, predicted the ocurrence of a phase transition in gas of noninteracting atoms. This phase transition is connected with the condensation of bosonic atoms that occupy the lowest energy state. This occurs due to the quantum statistical effects.

2 Experimental verification

It took about 70 years to verify Einstein´s prediction. This was independently done by E.Cornell and C. Wieman at the University of Colorado and W. Ketterle at MIT in 1995. They used a gas of Rubidium atoms cooled down to 170 nK. For this work they received the Nobel prize in 2001.

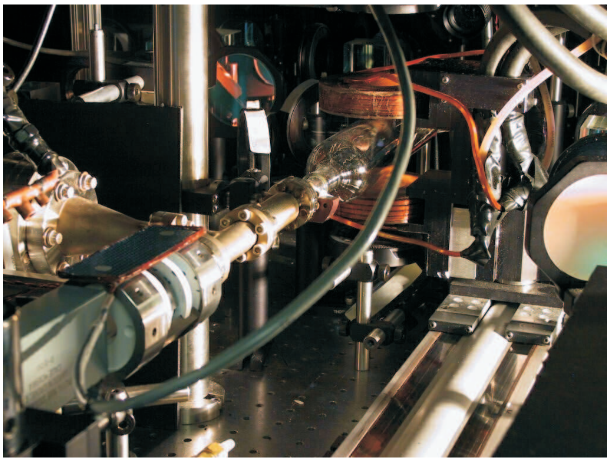

Figure 1: "Easy" BEC machine. From [http://jilawww.colorado.edu/bec/]

3 How to make atoms cold?

The experimental search for BEC started in the early 1970´s, making use of techniques based on magnetic and optical trapping, and advance cooling mechanisms. The first studies were focused on the spin polarized hydrogen. It was one of the most naturally candidates for BEC because of its light mass. Experiments on hydrogen atoms, based on the techniques named above, were close to BEC, but this approach is still limited by the recombination of the individual atoms to molecules (Silvera [5] and Walraven [6], 1980 and 1986). Later, in the 1980´s, making use of laser-based techniques, such as laser cooling and magneto-optical trapping, it was possible to cool alkali atoms to very low temperatures because of their favorable internal energy-level structure. Once the gas is trapped, the temperature can be lowered further by evaporative cooling (Ketterle and van Drute [7] 1996). One notices that during this, the equilibrium configuration of the system could be a solid phase. In order to observe BEC, one has to maintain the system in a metastable gas phase for sufficient time. This is made possible in a dilute gas because one can neglect the three-body collisions, which would cause a solid phase in the ground state of the gas.

The technique used by Cornell and Wieman at Boulder and Ketterle at MIT is based on the experimental studies of dilute atomic gases. They combined different cooling techniques and succeeded in reaching the temperatures and the densities required to observed BEC.

4 BEC in other areas of physics

From the beginning the experimental and the theoretical research on this unique phenomenon predicted by quantum statistics has involved different areas of physics. F. London, directly after the discovery of superfluidity in liquid Helium (^{4}He), postulated that it could be a manifestation of Bose-Einstein condensation. Landau developed the first self-consistent theory of superfluids in terms of the spectrum of elementary excitations of the fluid. Evidence for BEC in helium emerged later from the analysis of the momentum distribution of the atoms measured in neutron-scattering experiments. In recent years, BEC has been investigated in the gas of paraexcitons in semiconductors, but up to now there is no evidence for it. Another famous manifestation of BEC is superconductivity as explained by Bardeen, Cooper and Schieffer, electrons in conventional superconductors form pairs over a range of hundreds of nanometers, three orders of magnitude larger than the lattice spacing. Called Cooper pairs, these coupled electrons can be characterized as bosons and condense into the ground state. The condensation of Cooper pairs is the foundation of the BCS theory of superconductivity.

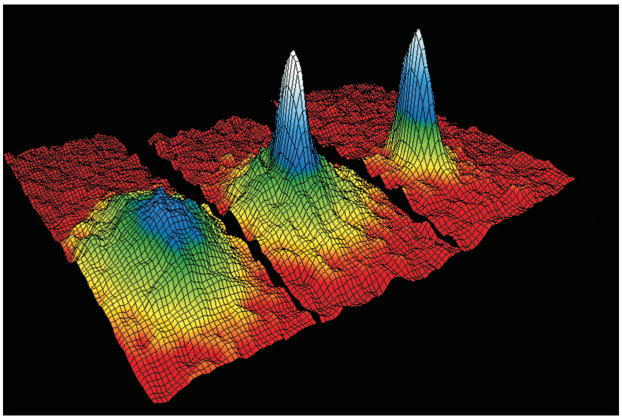

Figure 2: Images of the velocity distribution of Rubidium atoms. The left image corresponds to the gas at a temperature above the critical temperature where the atoms can occupy the energy levels according to Bose-Einstein statistics. The centre frame shows the appearing condensate (condensation state), i.e. the occupation of the lowest state of energy by the atoms. And the right frame shows the condensate after further evaporation when the majority of atoms are in a condensed state. From Cornell (1996)

5 Why are BEC interesting?

One of the most important features of the trapped bose gases is that they are inhomogeneous and finite systems, i.e. the number of particles is ranging from few thousands to millions. The fact that these trapped gases are inhomogeneous has the important consequence that the compression of the gas takes not only place in the momentum space, but in the coordinate space as well (see Fig. 2). This double possibility of investigating the effects of condensation is interesting from both experimental and theoretical point of view. It allows to study of new physical quantities which were not accessible with previous experiments: for example, the temperature dependence of the condensate, energy and density distribution, interference phenomena, etc.

The recent experimental achievements of BEC in alkali vapors have resurrected interest in the theoretical studies of Bose gases. Lots of efforts in theoretical research have been made with the aim of interpreting and explaining the observations and predicting the new phenomena. This opens the way for the interdisciplinary work as well. Most recent reviews and books on this subject are [1], [3], [4].

6 Can fermions be cooled as well?

In a system consisting of fermions at a very low temperature the Pauli exclusion principle plays an important role. It forbids that two fermions occupy the same quantum state. To exhibit Bose-Einstein condensation, the fermions must form pairs, i.e. compound particles (e.g. molecules or Cooper pairs) which are bosons. The first molecular Bose-Einstein condensates were created in November 2003 by the groups of Rudolf Grimm at the University of Innsbruck, Deborah S. Jin at the University of Colorado at Boulder and Wolfgang Ketterle at MIT.

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