Bose-Einstein condensation with high atom number in a deep magnetic trap

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Citation for published version (APA):
Dieckmann, K. (2001). Bose-Einstein condensation with high atom number in a deep magnetic trap
Chapter 1

Introduction

1.1 Research area

Bose-Einstein condensation was predicted in 1925 [Bose, 1924, Einstein, 1925], at the time when quantum mechanics was being developed. Seven decades later in 1995 Bose-Einstein condensation (BEC) in dilute atomic gases was first observed. Within a few months BEC was observed with the alkali atoms rubidium [Anderson et al., 1995] and sodium [Davis et al., 1995]. Lithium [Bradley et al., 1995, 1997] followed rapidly. This exciting achievement attracted a lot of attention in the scientific community and the mass media alike, in which Bose-Einstein condensation was referred to as a 'new state of matter'.

Dilute gases of neutral atoms can be studied at ultra-low temperature by confining them in a magnetic trap. Bose-Einstein condensation occurs when at high density and low temperature the thermal wavelength of the atoms becomes of the order of the interparticle separation between the atoms, and the atomic waves overlap. As the condensate forms, a macroscopic amount of atoms populate the ground state of the trap and share coherently the same wavefunction. The BEC transition temperature of dilute gases is typically slightly below 1 μK. Under normal conditions alkalis are in the solid state at room temperature and below. Therefore, the BEC in dilute gases is achieved in a metastable state, where the density of the gas is sufficiently low to prevent inelastic decay, and a long life time of the gas is achieved. For alkali gases at the highest attainable densities the dominant decay is three-body recombination by which diatomic molecules are formed and a third atom enables conservation of energy and momentum. Elastic collisions are essential for achieving a kinetic equilibrium after cooling of the gas and during the formation of the Bose-Einstein condensate. At microkelvin temperatures elastic collision happen in the s-wave scattering channel. At typical densities, the interparticle separation is big compared to the s-wave scattering length. In many experiments the mean interaction energy exceeds the kinetic energy of the Bose-condensed atoms. In this so called Thomas-Fermi case, the properties of the cloud are strongly influenced by the interactions between the atoms. For example, the shape of the Bose-condensed cloud
deviates strongly from the shape according to the ground state of the trapping potential.

Much of the early theory of interacting quantum gases was developed in the period 1940 – 1965 and provided a microscopic basis for macroscopic quantum phenomena like suprafluidity of $^4$He and superconductivity. However, the behaviour of the quantum fluid liquid helium is dominated by the strong interaction between the constituting particles. In order to focus the research on the Bose-Einstein phase transition itself, it was necessary to investigate dilute atomic gases.

The first attempts to achieve BEC in dilute gases were done with atomic hydrogen. Atomic hydrogen was supposed to be a good candidate for a nearly ideal Bose gas, as spin-polarized hydrogen does not form a many-body bound state, even at $T = 0$ [Etters et al., 1975]. The experimental techniques developed for trapping and cooling hydrogen strongly differ from the ones used in laser cooling and trapping of alkali atoms. The hydrogen atoms were first stabilized [Silvera and Walraven, 1980, Cline et al., 1980] in a cryogenic environment at subkelvin temperature. Magnetic trapping of hydrogen was realized by [Hess et al., 1987, van Rijen et al., 1988]. For the analysis of the gas samples spectroscopic methods as Lyman-α and two-photon spectroscopy have been developed requiring a demanding laser system. Evaporative cooling of the trapped gas, the crucial method that allowed to reach the phase transition, was first experimentally demonstrated [Hess, 1986] and developed [Luiten et al., 1996, Walraven, 1996] in the hydrogen work. BEC of atomic hydrogen led to the so far largest condensates and was achieved in 1998.

BEC was first achieved with alkali gases. This was a consequence of the development of laser based cooling and trapping methods for neutral atoms. Alkali atoms have been favored for this purpose, as for these species continuous wave lasers are available for the manipulation of the motion of the atoms. For example in case of rubidium easy to handle diode lasers can be used. A variety of methods for cooling and trapping, such as the magneto-optical trap, the optical dipole trap, sub-Doppler cooling, velocity selective coherent population trapping, and Raman-cooling have been developed [Phillips, 1998, Adams and Riis, 1997]. For the discovery and explanation of sub-Doppler laser cooling the Nobel prize was given in 1997 [Chu, 1998, Cohen-Tannoudji, 1998, Phillips, 1998]. So far, optical cooling methods did not lead directly to Bose-Einstein condensation, but are used in current experiments to produce precooled, trapped atomic samples in a non-cryogenic environment. As a final cooling process towards BEC evaporative cooling is used, during which typically 7 orders of magnitude in the phase-space density is gained.

The first achievements of BEC led to an enormous boost of activity and were followed to the present date by at least 24 successful BEC experiments world wide. The experimental progress is accompanied by extended theoretical work, which is leading to a deep understanding of the behaviour of Bose-condensed matter. A collection of articles and reviews can be found at [Edwards]. A theoretical review is given in [Dalfovo et al., 1999]. A number of experimental techniques, which are of importance for achieving BEC are summarized in [Ketterle et al., 1999, Cornell et al., 1999]. To the striking properties of Bose-condensed matter belongs the long range phase coherence which was experimentally demonstrated by [Andrews et al., 1997b, Stenger et al., 1999b]. Matter wave amplification due to Bosonic stimulation was demonstrated by [Inouye et al., 1999b,a]. In other experiments collisional properties were studied, such as the s-wave scattering length [Roberts et al., 1998, Boesten et al., 1997], the existence of two-species conden-
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sates [Myatt et al., 1997], the three-body combination rate [Burt et al., 1997, Söding et al., 1999], and the existence and energy of Feshbach resonances [Tiesinga et al., 1992, Inouye et al., 1998, Roberts et al., 2000]. Important research related to condensed matter properties of the gas are the investigation of excitations of the condensate, such as the frequency spectrum and damping of elementary excitations [Jin et al., 1996, Mewes et al., 1996b, Jin et al., 1997], the propagation of sound waves [Andrews et al., 1997a] and solitons [Burger et al., 1999], and the creation of vortices [Matthews et al., 1999, Madison et al., 2000].

1.2 This thesis

This thesis deals with the quantum gas phase of atomic rubidium. The work involves the development of the experimental apparatus to reach the quantum degenerate regime and a first series of experiments with the rubidium quantum gas, including the attainment of Bose-Einstein condensation.

Emphasis is put on experiments with a large number of atoms. The availability of large numbers of cold atoms enables experiments with high density samples. From a practical point of view this allows fast thermalization and thus fast experimental procedures. From a theoretical point of view it allows the investigation of the cross-over from the collisionless into the hydrodynamic behaviour in the rubidium quantum gas.

This thesis is divided into the following chapters: In Chapter 2 some theoretical principles and results are briefly summarized to an extend as is needed for the description of the experiments. The atomic properties of rubidium, which are relevant for laser cooling and magnetic trapping are discussed. The principle of magnetic trapping is introduced, and the magnetic trapping configuration used in this thesis, which is of the Ioffe-Pritchard type [Pritchard, 1983], is explained. Bose-Einstein condensation of the trapped ideal gas is described followed by the main theoretical results for the case of repulsive interactions between the particles and large atom numbers. As of great importance for the achievement of Bose-Einstein condensation the principle evaporative cooling is briefly introduced.

Chapter 3 describes the main components of the experimental apparatus. First, it gives an overview over the laser system consisting of 5 diode lasers and the purpose of the produced laser beams for the experiment. In order to load a large atom number into a magneto-optical trap (MOT) an amount of laser power is required which exceeds the power of commonly used and commercially available diode lasers. In order to provide sufficient laser power a broad-area diode laser system, delivering 130 mW of usable laser power, was build and characterized for this experiment by [Shvarchuck et al., 2000]. For the work in this thesis the broad-area laser was integrated in the laser system and was for the first time applied in an experiment on laser cooling and trapping. Second, the vacuum system is described including a rubidium vapor cell for the realization of the atomic beam source and a UHV chamber where trapping and cooling of the gas cloud takes place. Next, a detailed portrait of the magnetic trap is given. In this work the design of the trap assembly was optimized to obtain high stability, flexibility in adjusting the trapping parameters, and a strong confinement of the gas. This enables fast and efficient evaporative cooling yielding high atom numbers and densities at the BEC phase
transition. Furthermore, the components for the rf-signal source used for evaporative cooling are specified. The chapter is ending with a description of the imaging system by which the properties of the cold gas clouds are measured.

Chapter 4 is based on the publication [Dieckmann et al., 1998] dealing with the intense atomic beam source developed in this experiment. The high atomic flux of the source is the basis of obtaining high atom numbers in a short time. The operation principle is based on the two-dimensional vapor cell magneto-optical (2D-MOT) trap. It is investigated how the atomic flux of a vapor cell based source can be optimized and an experimental comparison between different variations of the 2D-MOT geometry used as atomic beam sources has been performed. The highest achieved flux exceeds the atomic flux of existing vapor cell based atomic beam sources by almost two-orders of magnitude, for the same low laser (50 mW) power in use.

As described in Chapter 5 the atomic beam source is applied to load a magneto-optical trap with large atom number. This is done with the goal to take benefit of the high beam flux and to achieve a high atom number after a short loading time. The measured atomic beam flux is compared to the measurements of the trap loading. For the first time it was demonstrated that the effective loading flux can be improved by avoiding loss from the atomic beam due to a repulsive light force originating from fluorescence light from the magneto-optically trapped cloud. This is realized by optically pumping the atoms into a dark hyperfine state. After loading polarization gradient cooling is used to cool the cloud to a temperature below the Doppler limit, which is 144 $\mu$K for rubidium. Further, it is described how the temperature of the atomic cloud after sub-doppler cooling was minimized for the case of a large atom number.

Chapter 6 explains how the atoms are loaded from the magneto-optical trap into the magnetic trap. Further, the steps for adiabatic compression of the sample in the trap are individually characterized in detail. The characterization of magnetic trapping is completed by the measurement of the life time of the atomic sample and the measurement of the harmonic frequencies of the trap. Measurement of the life time of the sample in the compressed magnetic trap gives information on whether efficient evaporative cooling is possible and BEC can be achieved. Measurement of the harmonic trap frequencies is essential for subsequent quantitative analysis of the trapped Bose-gas.

In the first part of Chapter 7 evaporative cooling in the runaway regime is described. The efficiency of the evaporation process with respect to the particle loss is evaluated. Thereafter, the observation of Bose-Einstein condensation is presented including a description of the analysis methods used to obtain the cloud parameters from the absorption images. As highest atom numbers are achieved, gas samples can be produced which are in the transition region between the collisionless and the hydrodynamic regimes. As the last part of this chapter a demonstration of the so called ‘atom laser’ is added.

Chapter 8 deals with the so called Oort cloud. This is a cloud of rubidium atoms which populates the magnetic trap to energies of several mK. This is possible due to the large depth of the magnetic trap. It is demonstrated how for the first time clear evidence of an Oort cloud was obtained. A method for measuring the Oort cloud atom number is presented, and information on the energy distribution of the Oort cloud population is obtained. It is investigated, how the effects of the Oort cloud on the cold cloud can be suppressed by means of rf-shielding. With the origin of the Oort cloud identified, a
method for the reduction of the Oort cloud atom number is demonstrated. This enables to compare the effect of the Oort cloud on the cold cloud for large and reduced Oort cloud. Finally, the consequences of the observations on the non condensed samples for the possibilities of entering the hydrodynamic regime with a Bose-Einstein condensate are discussed.