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

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. 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 development became possible after magneto-optical trapping and laser cooling of alkali atoms to ultra-low temperatures were realized. For the discovery and explanation of sub-Doppler laser cooling the Nobel prize was given in 1997 [Chu, 1998, Cohen-Tannoudji, 1998, Phillips, 1998]. In the above mentioned experiments Bose-Einstein condensation was achieved after transfer of the optically precooled gas sample into a magnetic trap and application of evaporative cooling. 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'. 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.

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 $\mu$K.

In this work 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 to the hydrodynamic behaviour in the rubidium quantum gas.

This thesis is divided into the following chapters: Following an introduction, Chapter 2 summarizes some theoretical principles and results are briefly 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 of 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 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. With a magnetic field gradient of 353 G/cm and a curvature of 286 G/cm² the steepest magnetic trap of this type was realized. 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, almost $10^{10}$ atoms/s at an average velocity of 10 m/s, 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 power (50 mW) in use.

As described in Chapter 5 the atomic beam source is applied to load a magneto-optical trap with large atom number of $10^{10}$. 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 resulting
in a transfer efficiency of 70\%. 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 of 40\(\mu\)K. This temperature lies below the Doppler limit, which is 144\(\mu\)K for rubidium. The chapter ends with a description of 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. After the compression the cloud is populated with \(4 \times 10^9\) atoms at a temperature of 760\(\mu\)K and a density of \(7 \times 10^{11}\) atoms/cm\(^3\). 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. Evaporative cooling is usually completed within 10\(s\), but can also lead to Bose-Einstein condensation within 2\(s\) with a 60\% reduction of the atom number. Second, 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. The phase transition is reached with \(1.5 \times 10^7\) atomen at a temperature of 1.5\(\mu\)K and a density of \(7 \times 10^{14}\) atoms/cm\(^3\). 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, by which the phase coherence of the Bose-condensed atoms is shown.

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 (12 mK) 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. This method is based on the release of the atoms from the magnetic trap and recapture into a magneto-optical trap. In this experiment an Oort cloud population above an energy of 250\(\mu\)K of up to \(2.4 \times 10^6\) atoms with an averaged energy of 3 mK was found. It is investigated how atoms from the Oort cloud can lead to heating and losses from the cold cloud. To investigate these Oort cloud related phenomena cold clouds under conditions just above the BEC phase transition were used. Such clouds allow to study the essential phenomena and to trace the origin of the Oort cloud without the added complexity of the presence of a condensate. Further, it is investigated, how the effects of the Oort cloud on the cold cloud can be suppressed by means of rf-shielding. As the origin of the Oort cloud incomplete evaporation during evaporative cooling at high energies is identified. Therefore, it is possible to reduce
the Oort cloud population by a factor of 6 by applying a modified scheme of adiabatic compression and evaporative cooling. This enables to compare the effect of the Oort cloud on the cold cloud for large and reduced Oort cloud. A remarkable result is the observation of an increase of the cold cloud atom number accompanied by a decrease of the Oort cloud atom number which occurs only for the highest densities of the cold cloud. This is interpreted as capture of atoms from the Oort cloud into the cold cloud by a collisional cascade. 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.