Bose-Einstein condensation into non-equilibrium states
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Chapter 1

Introduction

1.1 Background

After prediction of Bose-Einstein condensation (BEC) in 1925 [18, 35] it took seventy years to achieve its experimental realisation in pioneering experiments at JILA [4], MIT [28] and Rice [19, 20]. Experimental and theoretical studies of BEC address many-body physics. By 1995 there was an extensive literature on macroscopic quantum phenomena, such as superfluidity in liquid helium, and the closely related subject of superconductivity. BEC in dilute atomic quantum gases enabled the investigation of macroscopic quantum phenomena in the weakly interacting limit. With the availability of these systems it became possible to apply the broad range of standard tools of atomic physics to such investigations.

The first experiments on BEC revived an enormous interest in macroscopic behaviour of dilute atomic gases at low temperature, which resulted in rapid development of the research area.

Most of the theoretical groundwork on the interacting quantum gases has been developed in the 50's and the 60's in the context of superfluidity of $^4$He. However, a detailed comparison between theory and experiment is extremely difficult in the case of liquid helium because its density is rather high and can be varied only within a narrow range. In the 70's the observation of BEC in dilute atomic gases under equilibrium conditions was known to be impossible. Therefore, the efforts shifted towards investigations of metastable systems.

The first attempts to reach BEC were done in spin-polarised atomic hydrogen. Foundations for many techniques and methods were laid in the course of that work. Hydrogen quantum gas was first stabilised in a cryogenic environment by Silvera and Walraven [93] and by Cline et al. [23]. Magnetic trapping was first demonstrated in sodium [79] and in hydrogen by Hess et al. [50] and van Roijen et al. [87]. Another critically important technique, evaporative cooling, was first experimentally demonstrated in hydrogen [51] and further developed in [74, 97, 105].

Bose-Einstein condensation in alkali systems was achieved in magnetic traps through the combination of optical cooling methods with the evaporative cooling technique.
This led to a dramatic expansion of both experimental and theoretical work in the field of ultracold quantum gases. The contribution of this field to the understanding of Nature was acknowledged by the Nobel Prize in physics awarded in 2001. Although the macroscopic occupation of the ground state is the best known aspect of the phenomenon of Bose-Einstein condensation, the appearance of phase coherence is equally important.

The investigation of phase coherence phenomena provides new fundamental insights into the nature of macroscopic quantum states and is important for current and future applications. Those include, in particular, atom lasers – devices for continuous or pulsed generation of coherent matter waves, atom interferometry, improved frequency standards and systems of cold atoms for quantum computing. The first phase coherence experiments were relying on the interference of two independently prepared condensates [6] and on the measurement of single-particle correlations [15, 48, 95]. These experiments showed that trapped condensates are phase coherent, in accordance with the common understanding of BEC in three-dimensional gases. Recent theoretical [82] and experimental [31] studies revealed limitations on the phase coherence of the Bose-condensed state. It was shown that in elongated 3D traps the finite-temperature equilibrium state can be a quasicondensate: it shows the suppressed density fluctuations of a regular condensate but shows an axially fluctuating phase rather than full phase coherence.

The appearance of coherence in a condensate cannot be separated from the process of condensate formation. Theory of condensate formation was first explored by Svistunov [98] and Kagan et al. [57], and extensively studied later by Gardiner et al. [29, 38, 39, 70] and Bijlsma et al. [11]. Previous experimental investigations of formation kinetics of trapped condensates [65, 78] were decoupled from the studies of phase coherence mentioned above. Investigation of the evolution of phase coherence properties during the formation of a trapped condensate out of a non-equilibrium thermal cloud presents a great general physical interest. In particular it should allow a deeper understanding of phase coherence phenomena in macroscopic quantum states. One can expect that the evolution of phase coherence will be a primary issue for creation of CW atom lasers [22]. The rate at which the required phase coherence is formed will place an upper boundary on the feeding rate for the laser and, hence, on the generation rate of coherent matter waves.

1.2 This thesis

The main part of this Thesis is related to the studies of the condensate formation into non-equilibrium states and hydrodynamic behaviour of cold non-degenerate atomic clouds. In contrast to the experiments with equilibrium phase-fluctuating quasicondensates we investigate creation of a degenerate quantum state outside of equilibrium. This offers an
1.2 This thesis

fundamentally different path towards equilibrium as compared to the condensate formed in a quasi-static fashion.

The Thesis is organised in the following way. In Chapter 2 we compile main theoretical expressions relevant to the Bose-Einstein condensation. We begin with an introduction of the principle of magnetic trapping of spin-polarised gases and a description of the Ioffe-Pritchard quadrupole trap. It is followed by a description of trapped Bose gases below and above the phase transition temperature. Further we sketch theoretical ideas underlying phase coherence and formation of a BEC. We also introduce the bare fundamentals of evaporative cooling and derive several results specific to the experiments described further in this work. A separate section is dedicated to the scaling description of the gas clouds in harmonic traps.

In Chapter 3 various aspects of the experimental setup are described. Special attention is given to the features characteristic to the specific ideas which underlie the construction of the apparatus, e.g. creating Bose condensates with the highest density and particle number possible. An overview of the vacuum system is followed by the outline of the laser setup. A section on the magnetic trap describes the technical aspects of the generation and control of the trapping fields. Description of the experimental realisation of evaporative cooling in our experiments is presented together with details of the measurement methods. Emphasis is put on the description of imaging of cold atomic clouds. We discuss numerous sides of the problem, including the selection of the optical elements and details of the absorption detection with limitations of the method.

Chapter 4 gives a detailed description of the high-power diode laser system, the design and building of which was dictated by the needs of this experiment. In the experiments with large (rubidium) atom numbers the optical power requirements tend to go beyond the power available from the single-mode diode lasers operating at 780 nm. We introduce this setup based on a broad-area laser diode as an excellent alternative to the other solutions available commercially.

In Chapter 5 we present the experimental investigation of the hydrodynamic properties of dense atomic clouds. The understanding of the crossover to the hydrodynamic regime in thermal clouds is important from the experimental point of view. This understanding is vital for the correct interpretation of time-of-flight images of such clouds. In the collisionless regime the expansion of the gas, after release from a trap, is known to be isotropic, whereas in the hydrodynamic limit the gas expands anisotropically. We approach investigation of the hydrodynamic properties from three different sides. First, we go in detail into density and temperature analysis. Another indicator of hydrodynamic behaviour
is obtained by observation of the anisotropic character of the expansion. Finally, we measure frequency shifts and damping of shape oscillations.

In the final part of the Thesis, Chapter 6, we describe the results produced in the experiments on formation of condensates far from equilibrium. We compare our work with previous experiments on condensate formation and describe how the process of formation is triggered in our system. A brief section deals with the growth of the condensate fraction. Further, we show how the concepts of local sample temperature and the critical temperature arise in elongated clouds with high elastic collision rates. We present a simple model, which illustrates how the non-equilibrium character of the condensates leads to the quadrupole oscillations. We also discuss non-equilibrium phase fluctuations, which manifest themselves in the form of stripes in the time-of-flight absorption images. Condensate focusing is introduced as a novel method for investigation of Bose-Einstein condensates. The focusing of a condensate in free flight arises from axial contraction of the expanding cloud when the gas is released from the trap during the inward phase of a shape oscillation. Possible applications of BEC focusing are discussed, with an estimate of the coherence length given as an example. The last part of the chapter covers condensation into non-equilibrium states with high condensate fractions. The situations of large and small condensate fractions are compared.