Bose-Einstein condensation into non-equilibrium states
Shvarchuck, I.

Citation for published version (APA):

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Summary

In this Thesis we describe experimental studies of the condensate formation into non-equilibrium states and investigation of the hydrodynamic behaviour of cold non-degenerate atomic clouds. Non-equilibrium nature of the condensates offers an essentially different path towards equilibrium as compared to the condensate formed in a quasi-static fashion. Investigation of the crossover between collisionless and hydrodynamic regimes is interesting from both experimental and theoretical points of view.

Bose-Einstein condensation (BEC) was predicted in 1925 [18, 35] and was achieved experimentally seventy years later in pioneering experiments at JILA [4], MIT [28] and Rice [19, 20]. This led to a dramatic expansion of both experimental and theoretical work in the field of ultracold quantum gases. Although the macroscopic occupation of the ground state is the best known aspect of the phenomenon of BEC, 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 appearance of coherence in a condensate cannot be separated from the process of condensate formation. Previous experimental investigations of formation kinetics of trapped condensates [65, 78] were decoupled from the studies of phase coherence [31, 82] 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 Thesis is organised in the following way. In Chapter 2 we compiled main theoretical expressions relevant to the Bose-Einstein condensation, including the principle of magnetic trapping and the description of trapped Bose gases below and above the phase transition point. Further we sketched theoretical ideas underlying phase coherence and formation of a BEC. We also introduced the bare fundamentals of evaporative cooling and derived several results important for the experiments described in later chapters. A separate section was dedicated to the scaling description of the gas clouds in harmonic traps.
In Chapter 3 various aspects of the experimental setup were described. Special attention was given to the features characteristic to the specific ideas, which motivated the construction of the apparatus, e.g. creating Bose condensates with the highest density and particle number possible. An insight into evaporative cooling in our experiments was presented together with some details of the measurement methods. A great deal of emphasis was put on the description of imaging of cold atomic clouds.

Chapter 4 was fully dedicated to 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 Chapter 5 we presented 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 approached 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. All three methods proved to be consistent with each other and the completeness of our description was verified.

In the final part of the Thesis, Chapter 6, we discussed the results produced in the experiments on formation of condensates far from equilibrium. We compared our work with the previous experiments on condensate formation. In a brief section some attention was given to the growth of the condensate fraction. Further, we showed how the concepts of local sample temperature and the critical temperature arise in elongated clouds with high elastic collision rates. We presented a simple model, which illustrates how the non-equilibrium character of the condensates leads to the quadrupole oscillations. This model was found to be in good agreement with the experiment. We also presented evidence of non-equilibrium phase fluctuations, which manifested themselves in the form of stripes in the time-of-flight absorption images. Condensate focusing was 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 were discussed. We applied BEC focusing to calculation of the coherence length of non-equilibrium condensate. The last part of the chapter covered condensation into non-equilibrium states with high condensate fractions. We discussed a method of achieving high condensate fractions, while keeping the system far from equilibrium. The phase fluctuations
and the excitation modes had the same qualitative character as in the experiments with small BEC fractions. However, in some aspects, such the damping rates of the quadrupole oscillations, we could observe significant differences.