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1 Introduction

A Bose-Einstein condensate can be viewed as a macroscopic quantum mechanical matter-wave. The constituent bosons (particles with integer spin) are cold enough to let their de Broglie wavelengths overlap. As a result of Bose statistics [1, 2] the system has gone through a phase transition: The particles gather in a single quantum ground state and act coherently. Bose-Einstein condensation (BEC) is related to superfluidity and to superconductivity. Superconductivity, vanishing electrical resistance in a conductor at low temperature, was discovered by Kamerlingh-Onnes [3] as a result of his development of advanced cooling techniques that led to the liquefaction of helium in 1908 [4]. It was Kapitza who first used the term superfluidity to characterize the frictionless flow observed in liquid helium below a temperature of 2.2 K (known as the λ -point), observed by him [5] and separately by Allen and Misener [6] in 1938. That same year also marked the start of vivid developments in theory when Fritz London [7] hypothesized on a relation between the behavior of liquid helium below the λ -point and BEC, and Tisza [8] connected BEC to superfluidity, for a review see [9]. Important steps towards cooling matter to even lower temperatures were made in the 1980s [10–12] with the development of magnetic trapping and evaporative cooling techniques for atomic hydrogen.

In 1995, after the introduction of laser cooling for alkali atoms [13–16], Bose-Einstein condensates of rubidium and sodium in the gas phase were realized [17, 18]. The crisp images of these macroscopic matter-waves generated huge enthusiasm amongst experimental and theoretical physicists. In the same year, also evidence for BEC in Li was reported [19] (see also [20–22]). This was especially intriguing because it showed that in a trap a BEC with *attractive* interactions can be stable, unlike the situation for a uniform gas. Experiments on Bose-Einstein condensates provide ample possibility to develop and test theory for macroscopic quantum phenomena also relevant for the description of superfluidity and superconductivity [7, 23–25].

1.1 1D Bose gas

The key ingredient for the quantum phenomena of BEC, superfluidity and superconductivity is long-range order of the phase of the macroscopic wavefunction (see [25, 26] and [27] p.31). Long-range order appears in a three-dimensional homogeneous system of bosons at finite temperature. Mermin and Wagner [28] and

Hohenberg [29] proved that in lower-dimensional systems the situation is significantly different: In two dimensions (2D) phase coherence does only exist at $T = 0$ and in one dimension (1D) phase order decays algebraically even at zero temperature. From these considerations it was established that BEC at finite temperature does not exist in 2D and 1D. The study of lower-dimensional quantum degenerate systems could promote better understanding of often complex ordering phenomena and was therefore pursued in experiments soon after the first alkali BEC's were realized. For example in 2D the locally coherent Bose gas supports vortex-antivortex pairs whose unbinding leads to the Kosterlitz-Thouless transition [30]. Experimentally, lower dimensional systems can be realized by strongly confining atoms to their motional ground state in one or two dimensions using magnetic or optical trapping, while applying a very weak harmonic potential in the residual dimension(s).

In contrast to the homogeneous case, BEC in 2D and 1D does occur in a trap [31]. Ketterle and van Druten [32] studied lower-dimensional systems of a finite number of non-interacting bosons, in the presence of external harmonic confinement and found that the transition temperature increases for lower dimensions. For experimentally realistic parameters, one-dimensionally trapped atoms exhibit interactions. These interactions in 1D can be modelled using the 3D atomic scattering length [33]. Petrov, Shlyapnikov and Walraven [34] included atomic interactions in their description and identified several, at that time experimentally unexplored, regimes of quantum degeneracy in trapped 1D gases. The 1D Bose gas is of particular interest because exact solutions for the many-body eigenstates can be obtained [35]. Furthermore, the finite-temperature equilibrium can be studied using the exact Yang-Yang thermodynamic formalism [36–38], a method also known as the thermodynamic Bethe Ansatz. The 1D regime in ultracold atomic Bose gases was first reached in experiments in the year 2001 [39–41]. Peculiarly, in 1D atoms become more *strongly* interacting for *decreasing* density. In the low density limit one has a Tonks-Girardeau gas of impenetrable bosons that was first realized using optical trapping in 2004 [42, 43].

In the experiments described in this thesis we magnetically trap atoms in a tube-like geometry. This ‘waveguide’ for atoms is created using the magnetic field from current carrying wires on a microchip. Using this ‘atom chip’ [44, 45] we realize a trapped one-dimensional Bose gas in the weakly interacting regime. Due to the finite-temperature we have a system that can be described as a degenerate 1D gas in thermal contact with a surrounding 3D thermal gas. Even for the lowest temperatures reached (~ 100 nK) finite-temperature effects reduce the phase coherence and we observe a BEC with a fluctuating phase. When we lower the atomic density, at constant temperature, the system becomes more strongly interacting and reduction of the phase-order destroys the condensate. We observe in this process, for the first time, a gas that obeys the exact Yang-Yang thermodynamics [46].

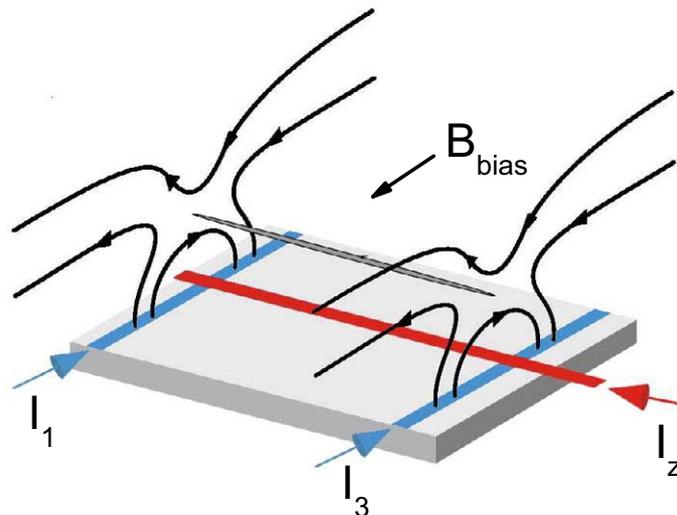


Figure 1.1: Waveguide potential for atoms. A waveguide is created when the circular magnetic field of a chip wire (I) is compensated with a perpendicular bias magnetic field B_{bias} . Three-dimensional confinement is achieved by creating end-caps with currents I_1 and I_3 .

1.2 Integrated atom optics

Rapid developments in microfabrication techniques enable spectacular advances in fundamental physics. The ‘atom-chip’ [44,45] is an example of a device that enables us to manipulate matter waves on the nanometer scale using integrated circuits. The idea of an atom chip was launched in 1995 by Weinstein and Libbrecht [47], the authors proposed to trap ultracold atoms in the magnetic field of micropatterned conductors, thus having them hover only micrometers away from the chip surface. Thermal insulation of the ultracold atoms is assured by placing the chip in an ultra high vacuum environment. Later that same year, the first BECs in atomic gases [17,18] were realized using large electromagnet-based traps. In 2001 two groups independently made a next step and created a BEC on a chip [44,45]. With the realization of an atomic matter wave on a chip the field of ‘integrated atom optics’ was born. At the time of writing more than a dozen labs worldwide do experiments with BECs on a chip, for a recent review see [48]. An introductory account of the Amsterdam work on atom chips can be found in [49].

Atoms can be magnetically trapped when their magnetic moment is anti-parallel to the local magnetic field. The trapping potential is proportional to the magnetic field strength. The simplest chip trap is a waveguide, illustrated in Fig. 1.1, that is created when the circular magnetic field of a chip wire (I) is compensated with a perpendicular bias magnetic field. End-caps are realized with currents I_1 and I_3 . With short distances between the trapped atoms and the current source, field gradients are large, hence microtraps can provide much stronger confinement than conventional electromagnet traps. Therefore the chip trap is ideally suited to study

atoms confined to one-dimension. The versatility of integrated atom traps can be extended using radio-frequency dressed potentials [50] a technique that we have recently explored in our setup [51]. Another promising recent development is the use of permanent magnetic material to trap atoms on a chip. Such traps do not suffer from ohmic heating and thus allow for the integration of large arrays of traps with a very high density [52].

1.3 This thesis

The outline of this thesis is as follows. Chapter 2 provides some theoretical background relevant to the experiments described in this thesis. The emphasis is on the description of a Bose gas confined to one dimension. In Ch. 3 the experimental setup is outlined. Details are given of the design and construction of the microtrap. Ch. 4 describes how we realize Bose-Einstein condensates in our microtrap. Subsequently, in Ch. 5, we treat a condensate as a macroscopic wave and use theory borrowed from optics to study atom coherence. In particular, we describe how we extract the temperature of an elongated quasi-condensate by measuring its width after focusing. Finally, in Ch. 6 experiments are compared to exact theory that goes beyond the macroscopic condensate description. The first observation of exact Yang-Yang thermodynamics on an atom chip is described.