Manipulation of ultracold Bose gases in a time-averaged orbiting potential

Cleary, P.W.

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
Chapter 1
Introduction

In 1925 a new state of matter was predicted by Einstein [1] following up on the work published the previous year by Bose on the quantized electromagnetic field [2]. Below a certain temperature, the critical temperature for Bose-Einstein condensation $T_c$, a macroscopic fraction of a non-interacting ensemble of massive particles (called the condensate) occupies the lowest-energy single-particle state [3]. This phenomenon only happens for bosonic particles and persists in the presence of interparticle interactions [4]. Once $T_c$ is reached the ensemble will display quantum mechanical phenomena on a macroscopic scale. The Bose-Einstein condensate (BEC) emerges as the result of a phase-transition at $T_c$. The critical temperature is density dependent and is reached in three-dimensional gases when the interparticle spacing equals the thermal wavelength. As $T_c$ is approached, the classic picture of individual particles breaks down and the ensemble has to be treated as a quantum many-body system. The presence of interactions modifies the low-energy excitation spectrum of the ensemble and is associated with the occurrence of coherence and superfluidity.

For a long time the only material known to display such characteristics was liquid Helium-4, which below its lambda point becomes a superfluid [5, 6]. Upon rotation, the fluid displays quantized vortices as demonstrated in [7] and discussed in detail in [8]. In this fluid, a macroscopic condensate fraction of up to 11% occurs. As techniques for cooling gases developed, a dilute gas of weakly interacting bosons was considered a possible candidate for a more pure condensate. Following promising results with spin-polarized atomic Hydrogen [9] and key breakthroughs in the areas of magnetic trapping [10], laser cooling [11] and evaporative cooling [12, 13], degeneracy was finally achieved with dilute gases of alkali atoms in 1995 when it was demonstrated in separate experiments at JILA [14] and MIT [15]. In these gases the critical temperature is achieved around 1 μK.

The first BEC experiment at JILA was done using a time-averaged orbiting potential (TOP) trap. The TOP trap consists of a three-dimensional magnetic quadrupole trap and a rotating modulation field which translates the zero of the quadrupole field. The result is a time-averaged effective trapping potential where the field zero orbits
the center of the effective potential [16]. As long as the sample size is much smaller than the radius of this orbit and the rotation speed is sufficiently fast, this arrangement acts as an efficient trap for spin-polarized atoms in low-field-seeking states. The atoms instantly depolarize upon crossing the field zero and are ejected from the trap. Therefore, the radius of the orbiting field zero is called the “radius of death”.

Following the success at JILA the TOP was used in a number of groups to reach BEC [17, 18, 19, 20, 21] and described in several theoretical works [22, 23, 24, 25, 27, 26]. The TOP at JILA was used to imprint the first vortices in a BEC [28] and later by introducing ellipticity to the modulation field of the TOP, vortices were induced in a rotating trap [29, 30]. Variations on the original TOP were also introduced, breaking the axial symmetry to produce a triaxial asymmetric TOP [31, 32, 33] and using alternatives to the spherical quadrupole trap such as optically plugged magnetic quadrupoles [34] and Ioffe-Pritchard traps [35, 36, 37].

1.1 This Thesis

The work presented in this thesis seeks to explore the opportunities and phenomena associated with the use of time-averaged potential fields for the investigation of Bose-Einstein condensates. In our experiments atom samples of $^87\text{Rb}$ are trapped and cooled in a static Ioffe-Pritchard trap. This trapping potential is then modified by applying a time-averaged orbiting potential. The Ioffe-Pritchard trap we use was designed to produce large dense $^{87}\text{Rb}$ condensates [38] in a cigar-shaped trapping potential and to study condensation in the hydrodynamic regime [39]. The addition of a TOP provides the opportunity to produce trapping geometries difficult to realize in a static trap. Unlike the quadrupole field, the Ioffe-Pritchard trap has a nonzero field minimum at its center. It was shown in [35], that if this trap minimum is compensated by a bias field then a double-well potential can be realized with a zero field minimum at the center of each well. Adding a rotating modulation field to the Ioffe-Pritchard trap results in a time-averaged potential allowing the achievement of BEC in the double well. Removing the bias field restores the Ioffe-Pritchard trapping potential and causes the two trapped condensates to move to the center of the trap and collide [36, 37].

The question arises as to whether it is possible to rotate the condensate and stir vortices in the Ioffe-Pritchard and TOP trap combination. Experiments involving vortex nucleation require timescales much longer than the lifetimes of the condensates produced previously on this apparatus in the $F = 2, m_F = +2$ state [38, 39]. These are typically performed in the longer lived $F = 1, m_F = -1$ state. Preparation of BEC samples in this state required considerable alteration of the apparatus. Detection of vortices also requires greater resolution and laser stability than was previously available. With these adjustments in place we proceeded to try to stir the condensate. Rotation of the TOP field is done by adjusting the amplitude of the field in one
radial direction so that an elliptical effective radial potential can be created and then sinusoidally modulating the amplitudes in the radial direction so that this elliptical shaped potential can be caused to rotate. This rotating elliptical modulation field can be added to the Ioffe-Pritchard trap in both single- and double-well potential configurations. Using the double well provides the opportunity to combine two condensates which have vorticity. Combination and splitting of condensates containing vortices has previously been shown in a quadrupole-based TOP trap [33].

In our experiments, as in several others [31, 34], condensate samples are prepared in the static trap and later transferred to the TOP. This method was chosen because the use of radio-frequency (rf) induced evaporative cooling is more efficient in a static magnetic trap than in a TOP. The consequences of the switch-on behaviour of the TOP during this transfer is not trivial and leads to a sloshing motion which is not predicted by considering only the time-averaged potential. The major results of this thesis concern the center-of-mass motion of a Bose Einstein condensate in a TOP trap. The atomic motion in the TOP consists of a fast rotating part (micromotion), and a slow oscillating part (macromotion). In the usual description of the motion, the static approximation, the micromotion is eliminated by time-averaging the instantaneous potential over a full cycle of the modulation field. This picture is inadequate to describe the motion of the TOP in realistic situations. Challis et al. [40] showed that the dynamical eigenstates of a degenerate Bose gas in a TOP are given by solutions of the usual Gross-Pitaevskii equation but taken in a circularly translating reference frame, that is, a reference frame the origin of which performs a rapid circular motion but retains a constant orientation. With this insight we model the motion of the atomic cloud in the TOP trap. The micromotion of atoms in the TOP was studied by the Pisa group who characterized this motion in a triaxial asymmetric TOP trap in measurements requiring analysis beyond the time-averaged and adiabatic approximations and demonstrating the handedness of the TOP field rotation [32, 41].

We proceed to show that manipulating the phase of the TOP, the micromotion can be used to influence the macromotion behaviour. The role of the initial phase of the TOP was studied by Ridinger and coworkers [42, 43] for the special case of a one-dimensional rapidly oscillating potential (ROP) with zero average. Ridinger et al. also showed, first for a classical particle [42] and subsequently for the quantum case [43], that the amplitude and energy associated with the slow motion can be altered by applying a suitable phase jump in the rapidly oscillating field. We succeeded in realizing these ideas in a two dimensional oscillating potential in our apparatus. We can produce a sloshing motion in the direction of our choice by choosing the initial phase appropriately. We can also quench this sloshing motion by calculating the correct timing and change in phase for a phase jump. We show this result both theoretically and experimentally for a two dimensional rotating TOP and also add an analytical model explaining the phenomenon.
1.2 Outline

This thesis is a study of the motion of Bose-Einstein condensates in a time-averaged orbiting potential (TOP) trap. In Chapter 2 the experimental apparatus used to produce the condensates is explained. The vacuum system and magnetic trap were retained in the form described in [38] but acoustically separated from each other. The two-dimensional magneto-optical trap (2D MOT) source was updated by creating the 2D quadrupole field with small bar magnets instead of race-track shaped coils. To increase flexibility the apparatus was modularized with the use of optical fibers, with an overhaul of the optics to supply light for the MOT, optical molasses, optical pumping, and detection of condensates in both $F = 1, m_F = -1$ and $F = 2, m_F = +2$ trappable states. The control system of the apparatus was also updated. The new interface enabled amplitude- and phase-controlled switching of the TOP fields, which was essential for the experiments described in Chapters 4 and 5.

Chapter 3 explores the changes made to the apparatus in the area of lasers and imaging. Lasers were stabilized on side tables disconnected from the main optical table and the power of the stabilized lasers amplified by in-house designed laser amplifiers. The implementation and characterization of the tapered amplifiers is described in detail. These amplifiers were found to be very reliable to boost the optical power, insensitive to disturbances in temperature or vibration. The apparatus was modified to allow imaging along the axis of the cloud to search for vortex lines head-on. This required overlap with the optical pathways for the MOT and for optical pumping. A detailed account is given of the improvements in resolution and signal-to-noise ratio of the imaging system.

In Chapter 4 we describe how we produce a condensate in the $F = 1, m_F = -1$ state. The properties of these condensates in our Ioffe-Pritchard trap are investigated, measuring the lifetime and inferring a value for the three-body recombination decay rate constant. Condensates are also produced in different types of time-averaged potential fields. Following an overview of methods to induce vorticity in the BEC, we introduce a rotating ellipticity to our trapping potential. We see evidence of rotation but do not find convincing visual proof of the existence of vortices in the sample.

In Chapter 5 we report on the manipulation of the center-of-mass motion ('sloshing') of a Bose Einstein condensate in a TOP trap. We start with a condensate at rest in the center of a static trapping potential. When suddenly replacing the static trap with a TOP trap centered about the same position, the condensate starts to slosh with an amplitude much larger than the TOP micromotion. We demonstrate, both theoretically and experimentally, that the direction of sloshing is related to the initial phase of the rotating magnetic field of the TOP. We show further that the sloshing can be quenched by applying a carefully timed and sized jump in the phase of the rotating field.