Chapter 1

Introduction

The creation of the field of ultracold atomic physics has opened up many new possibilities for studying the effects of quantum mechanics in theoretically accessible systems. Ultracold temperatures reduce the complexity of the system by reducing the possible states a system can occupy, thus allowing a more complete understanding of the system. An extreme case of a sample of ultracold atoms is a Bose-Einstein condensate (BEC), in which all of the atoms occupy a single quantum state.

The theory of Bose-Einstein condensation was first suggested by Bose [1] and expanded upon by Einstein [2] more than 75 years ago. However it was not until 1995 that a BEC was first produced in a dilute vapor. The time lag in the experimental realization of the predicted phase transition is not so incredible, once one realizes the extraordinary conditions that must occur in order to Bose condense a gas.

In everyday life, quantum statistics does not play a major role in our experiences because the thermal wavelength of particles is small compared to the interparticle spacing. However if a particle's wavelength is made comparable to the interparticle spacing, quantum statistics will become important. The relevant parameter that determines whether particles obey classical or quantum statistics is the phase-space density, which is the number density times the thermal de Broglie wavelength cubed. As this parameter approaches one, quantum statistics becomes relevant. For Rubidium gas at room temperature and typical vacuum density of 10^{-9} torr, the phase space density of the sample is $\sim 10^{-20}$, which is twenty orders of magnitude away from the Bose-Einstein condensation transition. It was predicted that one would have to cool Rubidium vapor below 1 millionth of a degree above absolute zero to observe a BEC. Remarkably, with the advent of laser and evaporative cooling, this goal turned out to be obtainable. Now over 35 groups in the world have condensed eight different atomic species. This accomplishment was recently recognized by the awarding of the 2001 Nobel prize in physics "for the achievement of Bose-Einstein condensation in dilute gases of alkali atoms, and for early fundamental studies of the properties of the condensates" [3].

It is somewhat ironic that, after finally achieving the goal of producing a condensate, the studies in our group concentrated on the most basic system in quantum mechanics: the two-level system. We wanted to study the macroscopic quantum phase of a condensate, and how this phase is affected by both internal and external couplings. One cannot measure the absolute phase of a particle, but rather only the relative phase with respect to another particle. Therefore if we want to study the phase of a condensate, we must have another condensate as a phase reference. We meet this requirement by producing a condensate in two distinct spin states, which we can manipulate and measure by standard atomic-physics techniques. The ultimate goal was to study how a normal cloud interacting with a condensate affects the phase of the condensate. Before we began our condensate coherence studies, we felt we should understand fully normal cloud coherences and correlations. This initial study led to many significant results including the unexpected observation of spin waves and precision measurements of interatomic collisions and correlations. These studies are directly relevant to the field of atomic clocks, where interatomic collisions currently limit the accuracy. After an extensive study of normal clouds in two spin states, we began studies of pure-condensate coherence and the effects of the normal cloud on condensate coherence. The studies of condensate coherence are still ongoing with the hope that we may be able to understand the coupling between the normal cloud and the condensate. It is a pleasure to note that a two-level system can still yield surprises, 75 years after the advent of quantum mechanics.

1.1 Overview

We originally set out with two goals in mind. First, we wanted to design and build a new type of BEC apparatus, which would be simpler and more robust than was currently in use in dozens of labs around the world. Second, we wanted to use our stable apparatus to study phase coherence of condensates.

In the seven years since their first observation, dilute vapor condensates have been studied extensively. In most cases the condensate properties themselves are the focus of the investigations. Relatively little work has been done using a condensate as a tool to explore questions in other fields. We feel that physicists in other fields such as condensed matter have a different and unique perspective on possible experiments that could make use of condensates. Therefore, developing a system that could be used for these purposes is worthwhile. The current experimental systems [4, 5, 6] were designed by people with a tremendous amount of knowledge and experience in experimental atomic physics, and until now producing a BEC without expertise in ultracold atom trapping has been a daunting task. We felt, however, that with some modifications to the current experimental design, any experimental physicist, regardless of discipline, could produce a BEC in their lab.

1.2 Organization of this thesis

This thesis is organized as follows. The first part of this thesis (Chapter 2) will describe most of the basic steps in detail on how to build a BEC apparatus. Many of the techniques described have been developed by others [7, 8, 9] over the last 20 years but are included so that this thesis may serve as a ‘recipe’ for creating a BEC. Besides the traditional methods we also describe several new features of our design, which include a new method of atom transfer and a hybrid magnetic trap.

The second part of the thesis (Chapters 3-6) is devoted to the scientific studies of two spin-state ultracold and condensed atom samples. We started our study of two-component samples by spectroscopically measuring cold-collision properties, which include mean-field and Zeeman energy shifts, as well as correlations between the spin states. The basic theory behind the spectroscopy is described in Chapter 3, and the results of these studies are described in Chapter 4. During our spectroscopic measurements, we observed by accident an effect we initially called anomalous spin-state segregation. We observed the spin states separating spatially in the trap in an unexpected way. Eventually, with the help of several theorists, we understood the spin dynamics to be spin waves. Chapter 5 discusses the origin of and our extensive measurements of spin waves produced in our two-component cloud. Armed with the knowledge of coherences and correlations gained from our experiments of cold collisions and spin waves, we studied how loss of coherence affected two-component condensates. Chapter 6 describes our results on coherence effects on finite temperature condensates.