

Chapter 1

Introduction

1.1 Breakdown of the thesis

This thesis describes experiments with a novel state of matter that only exists at very low temperature, known as a Bose-Einstein condensate or BEC. The different atoms in a BEC are so cold and slow-moving that they cannot be distinguished from one another. Using Heisenberg’s uncertainty principle, one finds that in a BEC, the uncertainty in the position of each atom is comparable to the average spacing between the atoms. Thus, it is almost meaningless to talk about individual atoms anymore — the BEC is a kind of “super-atom”. The task of creating a condensate is very difficult and depends on a number of fairly exotic experimental techniques that were developed quite recently (in the past 10 to 15 years). To make a BEC, one usually starts with a room temperature sample of alkali atoms, such as lithium, sodium, rubidium, or cesium. These atoms are confined in a vacuum chamber and then cooled to a few $100\ \mu\text{K}$ using laser-cooling and trapping techniques. Although the laser cooling can dramatically reduce the temperature of the atoms, this type of cooling is not sufficient for creating a condensate. To achieve the conditions for BEC, the atoms must be further cooled (to 50-100 nK) using evaporative cooling — a method for selectively removing only the hottest atoms from the sample.

After forming a BEC, one may study a wealth of different quantum-mechanical phenomena. One of the most interesting properties of an alkali atom BEC is the presence

of inter-atomic interactions in the condensate, which are mediated by elastic collisions between the atoms. Due to a fortuitous internal atomic structure, the collisions of ^{85}Rb atoms can be strongly affected by applying an external magnetic field. This magnetic field dependence is known as a Feshbach resonance. The existence of the Feshbach resonance allows one to change the BEC interaction in a highly controlled fashion. We took full advantage of the tunable interaction to study a number of interesting behaviors of ^{85}Rb BEC. These experiments are discussed at length in the present thesis.

Before conducting the experiments described in this thesis, I worked with Jake Roberts on the first experiments with ^{85}Rb Bose-Einstein condensates [1]. Initially, we developed techniques to cool and magnetically trap the rubidium atoms. We used cold samples of atoms to locate the Feshbach resonance by studying the effects of a variable magnetic field on the elastic scattering of the trapped atoms. The discovery of the ^{85}Rb Feshbach resonance allowed us to improve the efficiency of evaporative cooling so that we were eventually able to create condensates. This achievement marked the first time that the ^{85}Rb isotope was cooled to quantum degeneracy. After forming condensates in 1999, we utilized the Feshbach resonance to control the atomic interactions in the BEC. This control allowed us to study a number of fascinating effects, including an adjustable size and shape for the quantum-mechanical wavefunction of the BEC. By changing the sign of the interaction from repulsive to attractive, we induced an implosion or “collapse” of the condensate.

The collapse experiments mark the point in time when Jake’s thesis ends and my thesis begins. The present thesis begins with a detailed description of the dynamics of collapse in a BEC with attractive interactions. We also describe a series of new experiments involving time-varying magnetic fields applied to the BEC near the Feshbach resonance. By improving our magnetic field control apparatus, we were able to probe the response of the condensate to B-field changes on time scales as short as 10 microseconds. Surprisingly, the rapid magnetic field changes caused significant number loss from

the BEC, which implied the presence of microscopic dynamics occurring between the BEC atoms. We later showed that the mysterious BEC loss resulted from non-adiabatic transitions to another state — a diatomic molecular state that was nearly degenerate with the initial BEC state due to the Feshbach resonance. We observed evidence for atom-molecule coherence in the BEC and we used this coherence to precisely determine many detailed properties of the Feshbach resonance and interatomic interactions.

In the rest of the Chapter, we outline each of the subsequent parts of the thesis.

1.1.1 The 155 G ^{85}Rb Feshbach resonance (Chapter 2)

This Chapter provides a brief description of the Feshbach resonance that was so important for our experiments. We motivate the importance of the Feshbach resonance by showing how it affects the interactions in a BEC. Some discussion of the two-body scattering physics is given, and we show how the elastic scattering length varies as a function of magnetic field near the resonance. We also explain the most important properties of the weakly bound molecular state that causes the Feshbach resonance. The magnetic field dependence of the both the energy and spatial size of the molecular state can be adjusted via the applied B-field.

1.1.2 The ^{85}Rb experimental apparatus: new tools and upgrades (Chapter 3)

Here we explain new techniques and additions to the experiment that allowed us to collect the data described in Chapters 4-7. The first part of the Chapter describes a high-power laser upgrade to the experiment. We used the new laser to improve the process of collecting rubidium atoms from a room temperature vapor. We also devised a greatly improved method to measure the magnetic field on short time scales using short pulses of rf radiation. The new B-field measurement technique was essential for characterizing the magnetic field produced by another addition to the experiment — an

auxiliary magnetic field coil. We built the auxiliary coil to apply rapid B-field changes to the BEC. By varying the current through the auxiliary coil, we could precisely control the magnetic field on short time scales. The final part of the Chapter discusses our improved methods for measuring the most important properties of the condensed atoms — their number and temperature. We used the variable interaction strength afforded by the Feshbach resonance to change the BEC size and shape, which enhanced our ability to determine the BEC characteristics.

1.1.3 Dynamics of collapsing and exploding ^{85}Rb Bose-Einstein condensates (Chapter 4)

In this Chapter, we describe the startling response of a BEC to a change in the condensate self-interaction from repulsive to attractive. The sudden change caused a variety of unusual effects in the condensate. After a short delay that followed the change in the interaction, the BEC abruptly began to lose atoms. The atoms disappeared from the condensate over a time scale of a few milliseconds. During the same time period, an explosion of hot atoms was emitted from the collapsing condensate. We also observed strange features in the BEC density distribution. After the completion of the number loss, part of the initial condensate remained visible in a highly excited state of motion. We discuss the detailed behavior of the BEC collapse dynamics and summarize these results. At the end of the Chapter, the prominent features of the data are compared to theory.

1.1.4 Microscopic dynamics in a strongly-interacting Bose-Einstein condensate (Chapter 5)

Here we discuss condensate number dynamics resulting from rapid changes to the magnetic field. Using the auxiliary coil, we applied a short B-field pulse toward the Feshbach resonance to the condensate. The condensate responded to the pulse

by losing a large fraction of its initial number. Some of the atoms that left the BEC were visible in an explosion that was quite similar to the explosion seen in the collapse experiments of Chapter 4. We studied the dependences of both the BEC loss and the explosion characteristics on the exact shape and size of the magnetic field pulse. The time dependence of the loss suggested the presence of non-adiabatic transitions of the condensate atoms to the molecular state associated with the Feshbach resonance. We give some justification for this claim using a simple avoided crossing model for the Feshbach resonance.

1.1.5 Atom–molecule coherence in a Bose-Einstein condensate (Chapter 6)

This Chapter is an extension of the work in Chapter 5. Rather than using a single pulse, here we applied two magnetic field pulses to the condensate. The pulses approached the Feshbach resonance and were separated in time by a variable delay. As a function of the delay time between pulses, we observed oscillations in the number of BEC atoms. The oscillation frequency matched the binding energy for the molecular state of the Feshbach resonance. We also observed oscillations in the population of atoms in the explosion that resulted from the B-field pulses. These atom-molecule coherence data inspired a flurry of theoretical activity. We present a comparison of the data and theory at the end of the Chapter.

1.1.6 Very high precision bound state spectroscopy near a ^{85}Rb Feshbach resonance (Chapter 7)

The atom-molecule oscillations observed in Chapter 6 allowed us to dramatically improve our knowledge of the Feshbach resonance. We made very precise measurements of the oscillation frequency corresponding to the molecular binding energy. The frequency measurements were combined with precise measurements of the magnetic field

using a new experimental technique from Chapter 3. We fit the frequency and magnetic field data to a theoretical model of the scattering physics. The best fit to the data allowed us to extract greatly improved values for the Feshbach resonance properties, including its position and width in magnetic field. We improved the precision of the position and width determinations by more than a factor of 20. In addition, we used our data to obtain new values for several important parameters of the interatomic potentials for ^{85}Rb . Our results for the potential parameters had comparable precision to those of other recent high-precision experiments in rubidium. The agreement between our results and the results of the other analysis was very good.

1.1.7 Prior publication of our work

Most of the experiments described in this thesis were previously published in scientific journals. The experiments of Chapter 4 appeared in Ref. [2], while Chapter 5 was published in Ref. [3]. The work in Chapter 6 appeared in Ref. [4]. The observations of Chapter 7 were submitted but not yet published at the time of writing the thesis.