

## Chapter 1

### Introduction

That the impossible should be asked of me,  
good, what else could be asked of me? But  
the absurd! Of me whom they have reduced  
to reason.

- Samuel Beckett, *The Unnamable*

This thesis describes some of the first experiments probing and manipulating the cross-species interactions in an ultracold dilute gas mixture of Bosons and Fermions. To date most systems of this type have been used as practical tools, bypassing the Pauli exclusion principle in order to cool gases of fermionic atoms to only a fraction of the Fermi temperature. Bose-Fermi mixtures, however, additionally allow us to study a variety of many-body quantum mechanical systems of interest to condensed matter physics, with the degree of control and relative theoretical simplicity of atomic gases. In our systems interactions between atoms are typically short-range and two-body in nature, impurities are absent, and smooth, regular, time-dependent trapping potentials are easily generated in the lab. Furthermore, through the use of Feshbach resonances, the interactions may be controlled in real time in the experiments.

In this thesis I describe the design, construction, and operation of an experimental apparatus we have built for trapping and cooling to quantum degeneracy a dilute-gas mixture composed of  $^{87}\text{Rb}$  (boson) and  $^{40}\text{K}$  (fermion) atoms. It is shown that such a mixture can be cooled using relatively standard techniques until a nearly pure Bose-Einstein condensate coexists with a quantum degenerate gas of fermions at around 20% of the Fermi temperature. I will describe measurements we have made of the  $s$ -wave elastic collision cross-section between  $^{87}\text{Rb}$  and  $^{40}\text{K}$  atoms in the ultracold, but non-degenerate regime. These measurements give us important information on the interactions between species in quantum degenerate mixtures. Finally, I will present our most recent work where we have identified a number of inter-species Feshbach resonances in the  $^{87}\text{Rb}$ - $^{40}\text{K}$  system. These resonances represent, in principle, a means for exerting complete real-time control over the interactions between species. This kind of control may allow us to study a significant number of exciting new phenomena in the future.

A more detailed overview of this thesis is given in Section 1.3. Before proceeding, however, I would like to give some motivation for our interest in quantum degenerate atomic Fermi gases and Bose-Fermi mixtures.

## 1.1 I See Fermions

It is a peculiar fact of the quantum mechanical world that all of the constituents of the ordinary matter and light around us fall into one of two categories — they are either bosons or fermions. Bosons and fermions are distinguished on the one hand by their quantum mechanical spin, which takes on integer values for bosons and half-integer values for fermions. On the other hand the differences between bosons and fermions can become manifest even in the absence of spin-dependent forces. The bulk properties of ensembles of identical particles can be strikingly different depending on which family the particles belong to. The

behavior of groups of identical fermions underlies the rich variety of elements in the periodic table, and the concerted efforts of identical bosons have brought us the laser.

The experiments described in this thesis aim to study and exploit the behavior of ensembles of  $^{87}\text{Rb}$  atoms (which are composite bosons) and  $^{40}\text{K}$  atoms (composite fermions). In Fig. 1.1 I show schematically some of the fields of research that can benefit from the type of work we are doing. Particular applications of Bose-Fermi mixtures are discussed in the next section, but these mixtures were originally conceived as a tool for producing degenerate Fermi gases, and this is how they have been most commonly used to date. Atomic Fermi gases may be used to understand such wildly different fermionic systems as normal metals, neutron and white dwarf stars, heavy nuclei, superfluid  $^3\text{He}$ , and metallic hydrogen. There is much to be learned about high- $T_c$  superconductivity, for example, from the study of ultracold gases. And if we make a quantum computer in the process, then who's going to complain?

In qualified defense of our friend the fermion, I would like to argue against the notion that fermions are less “sociable” than bosons [1]. The renowned Pauli exclusion principle only describes a fermion's reluctance to share a quantum state with an *identical* fermion. A fermion will happily make room for a *distinguishable* fermion, or even a boson. In this sense I would argue that fermions are more open and sociable than the narcissistic bosons — the bosons, who would all crowd into their ground state with others just like themselves, and never ask what lies above.

For better or worse, Pauli taught us that identical fermions will not share a quantum state. It is this very behavior that leads to the well known statistical distribution of fermions at zero temperature, with a single fermion in each available quantum state, starting at lowest energy and moving up one state at a time until we run out of particles. The very last fermion occupies a special place in this

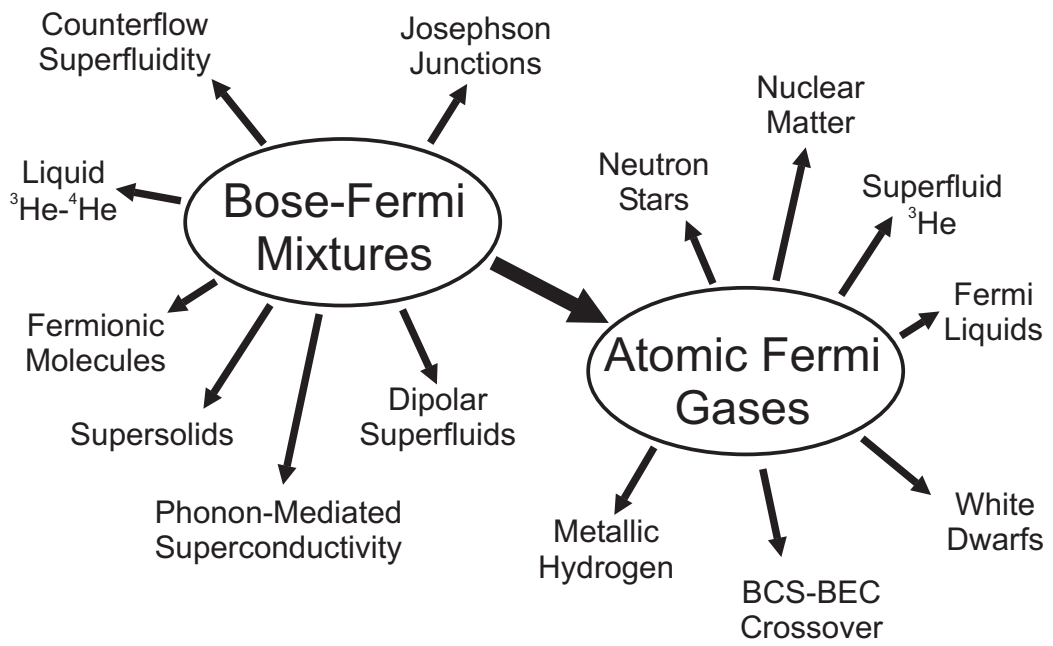


Figure 1.1: Applications of work with atomic Fermi gases and Bose-Fermi mixtures.

distribution, which defines the Fermi energy  $E_F$  of the system. Only particles in states near the Fermi energy can partake in the joys of perturbative excitation [2]. States far above  $E_F$  are not occupied, and particles below  $E_F$  are pinned by the presence of the fermions around them, with no unoccupied state to scatter into. The Fermi temperature, defined by  $T_F = E_F/k_B$  with  $k_B$  Boltzmann's constant, defines the characteristic temperature that the system must approach before quantum statistical effects may begin to appear.

The Fermi temperature is directly related to the density of a system, in the sense that high densities lead to high  $T_F$ , and low to low. One reason that dilute atomic gases are so useful to study is our ability to understand their behavior with relatively simple theories. This in turn is due to the fact that our systems are dominated by short-range interactions, and have such low densities that we rarely have to go to more than a two-body picture to get some understanding of what is happening. As seen in Fig. 1.2, where I outline some typical values of  $T_F$  for various quantum degenerate fermion systems, this means we must get our atoms extremely cold in order to access their quantum statistical properties. This incredible technical achievement has only been possible in the last decade, and is at the heart of the work I'll describe here.

## 1.2 Fermions And Bosons Unite!

When we began designing the experiment described in this thesis there was still only one successful Fermi gas experiment [3], using simultaneous evaporative cooling of two spin states of  $^{40}\text{K}$ . The presence of a second spin state helps bypass the reluctance of fermions to collide during the cooling. The common wisdom at the time was that a simpler approach might be to sympathetically cool a gas of fermions in the presence of bosons. Although we can debate the premise that this is "simpler," I know of ten quantum degenerate Fermi gas experiments in the

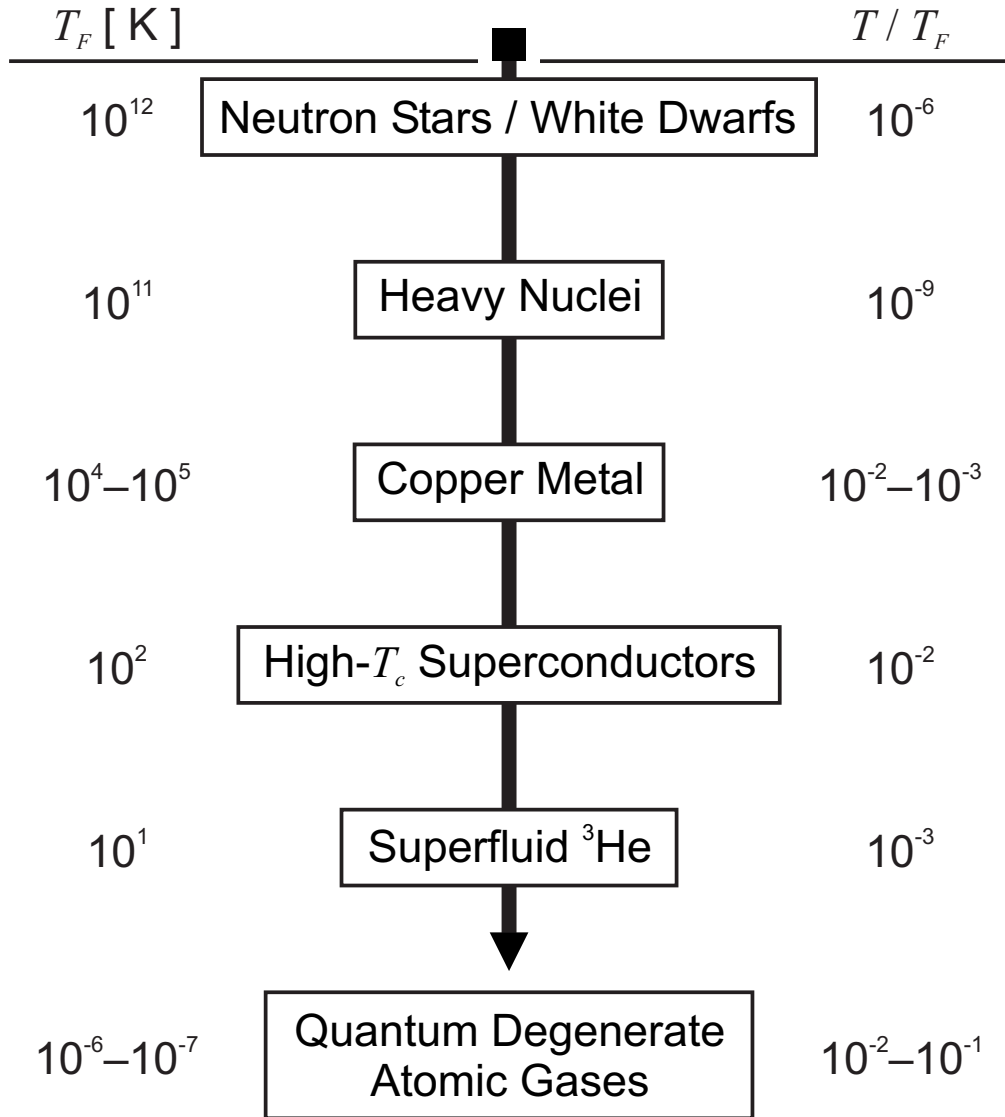


Figure 1.2: Characteristic Fermi temperatures and operating temperatures of some quantum degenerate fermion systems.

world, and only two of them use different spin states of a single isotopic species. The rest are produced by sympathetic cooling. There are at least seven more sympathetic cooling experiments being built.

It is my belief that the quantum degenerate Bose-Fermi mixture will ultimately be seen as more than just a way to produce degenerate Fermi gases. For example, although fermions in optical lattice potentials already provide a great system for simulating Fermi gases in metals [4], the optical lattice cannot play all the roles of the condensed matter lattice it pretends to be. Specifically, optical lattices do not exhibit excitations such as phonons, which are crucial to our understanding of superconductivity in the BCS regime. I think the most exciting prospect for Bose-Fermi mixtures is the prediction of a boson-mediated pairing of the fermions [5, 6, 7], where phonons in the condensate give rise to the effective attractive interactions between fermions needed for Cooper pairing and Fermi superfluidity. Other applications of Bose-Fermi mixtures include the formation of ultracold fermionic molecules [8], which can only be produced from a combination of bosons and fermions, and the creation of a supersolid phase [9] or a host of other exotic phases [10] in optical lattices.

### **1.3 Overview of this Thesis**

As stated at the beginning of this chapter, this thesis describes some of the first experiments probing and manipulating the cross-species interactions in Bose-Fermi mixtures. Although many of the theoretical descriptions and experimental techniques presented here are extensions of work already established in the field, the Bose-Fermi mixture is more than the sum of its parts and deserves to be considered a unique and rich system on its own. In this thesis I hope to lay out a very specific and detailed account of the tools needed to produce such a system, as well as a more general treatment of the kind of physics one may encounter by

studying it. In this final introductory section, I would like to lay out the basic structure of this thesis, in order to guide the interested reader.

In chapter 2 I give a very detailed technical description of the apparatus we have built for producing a quantum degenerate  $^{87}\text{Rb}$ - $^{40}\text{K}$  mixture. This chapter is intended mainly for the benefit of people in our lab, and for others working with or developing new ultracold gas experiments. I describe the design and assembly of the vacuum system, the various elements of computer control, the magnetic trapping coils and their control circuits, and the many lasers and optics used in the experiment.

Chapter 3 describes the cooling and trapping techniques needed to achieve simultaneous quantum degeneracy of bosons and fermions. The process begins with the capture and cooling of atoms in a two-species magneto-optical trap; the atoms are subsequently transferred in a three-step process to a Ioffe-Pritchard type magnetic trap for the final stages of evaporative and sympathetic cooling. The experimental procedure is described, and the characterization of quantum degeneracy is outlined in some detail for bosons and fermions. Some possible limits to the temperature we can achieve with sympathetic cooling are discussed, along with implications for future experiments. This “incredible journey” the atoms take from room temperature to a few tens of billionths of a degree above absolute zero is outlined schematically in Fig. 1.3.

Chapter 4 details the main experimental results we have achieved with the machine. I first discuss some ways to probe the collisional interactions between species. The discussion focuses on our extension of cross-dimensional rethermalization techniques to the (non-degenerate) Bose-Fermi mixture. I will describe why the knowledge gleaned from these measurements, namely the magnitude of the cross-species scattering length, is so important in understanding a variety of properties of the mixture. I will then present some measurements of collective ex-

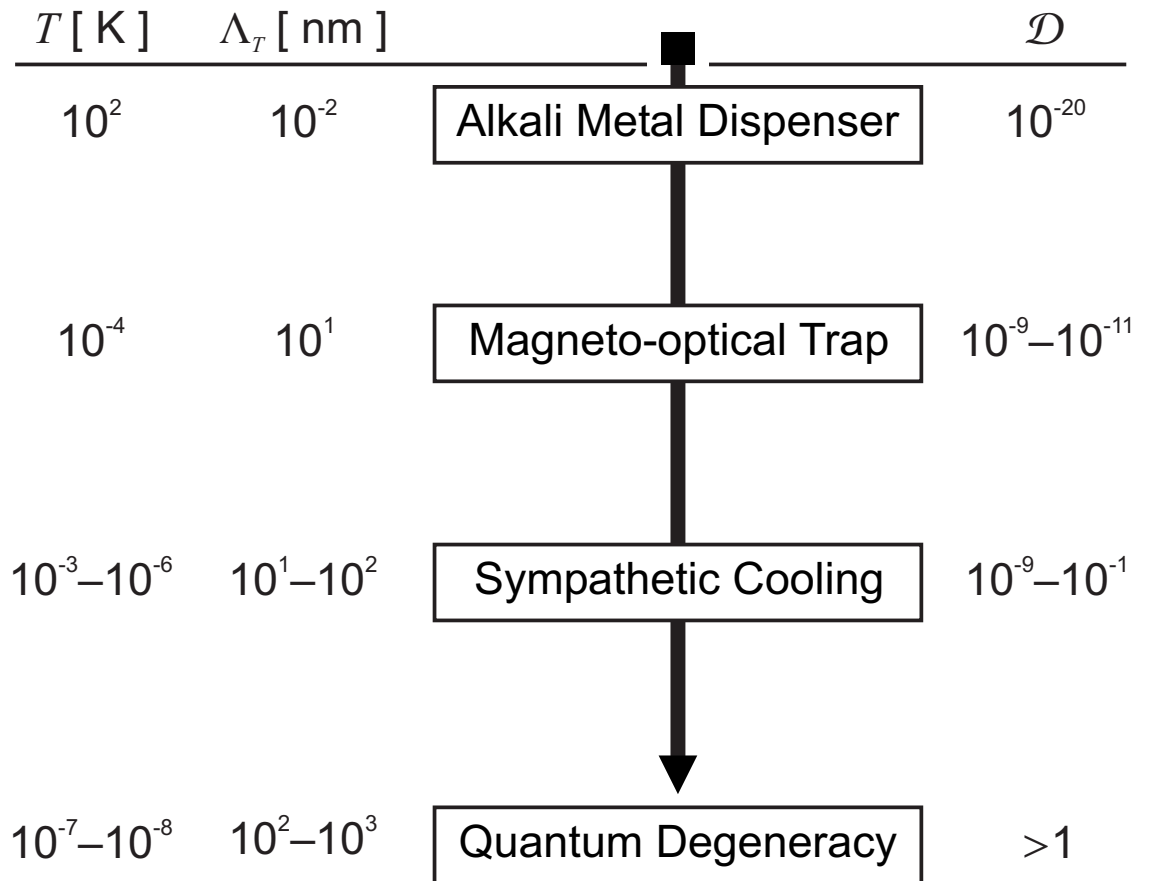


Figure 1.3: The incredible journey from room temperature to quantum degeneracy. The quantities  $\Lambda_T$  and  $\mathcal{D}$  are the thermal de Broglie wavelength and peak phase-space density, respectively. Both are discussed in detail in Sect. 3.4.

citations of the mixture, and describe a variety of related measurement techniques, with an eye towards future experiments.

Also in chapter 4 I describe our search for, and discovery of, several heteronuclear Feshbach resonances in the  $^{87}\text{Rb}$  -  $^{40}\text{K}$  system. These resonances represent, in my view, the crowning achievement of the work described here, due to the large number of significant and exciting experiments that resonant control of the interactions renders accessible to us. I describe our use of a far off-resonant optical trap and discuss the preparation and detection of resonant states of the mixture. Implications for the theoretical understanding of the  $^{87}\text{Rb}$  -  $^{40}\text{K}$  system are laid out, based on detailed coupled-channel calculations of the collision processes performed by Chris Ticknor and John Bohn. The comparison between theory and experiment allows us to refine the parameters characterizing the collisions between  $^{87}\text{Rb}$  and  $^{40}\text{K}$  atoms.

Finally in Chapter 5 I conclude with a summary of the work presented in this thesis, and describe what I think are the natural next steps for the experiment. I will additionally describe some proposals for some of the more exciting future experiments that could be performed with our system, including the coveted boson-mediated mechanism for the high- $T_c$  pairing of fermions.