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Exploring Quantum Degenerate Bose-Fermi Mixtures Toward Cooper Pairing of Fermionic Atoms

Abstract

We have been exploring interaction dynamics in an ultracold, trapped gas of bosonic and fermionic atoms. Investigation of this new class of quantum degenerate gases concentrates on interaction dominated phenomena such as sympathetic cooling, phase separation, excitations, Feshbach resonances, and the effects of quantum degeneracy. In addition to exploring these new phenomena, we seek to understand and ultimately control the interactions in the gas. In particular, effective interactions between the fermionic atoms will be explored in the context of the longer term goal of realizing Cooper pairing of atoms.

Introduction

In this report, we present results achieved during the three-year funding period. We achieved a quantum degenerate Bose-Fermi mixture using evaporative cooling of the bosonic ^{87}Rb atoms and sympathetic cooling of the fermionic ^{40}K atoms. We characterized the interactions between bosons and fermions in this mixture by measuring the magnitude of the interspecies s-wave scattering length.^{1,2} We then implemented a far off resonance optical dipole trap to confine the ultracold gas mixture with atoms in spin states that cannot be magnetically confined. This allowed us to observe four distinct interspecies Feshbach in the ultracold $^{87}\text{Rb}/^{40}\text{K}$ mixture.³ These resonances open up exciting new possibilities for controlled exploration of interaction effects in ultracold Bose-Fermi gas mixtures. In recent work (unpublished) we have been further investigating the Feshbach resonances, with an emphasis on looking for evidence of heteronuclear molecule creation.

Our results are discussed in more detail below.

Results and Conclusions

Evaporative cooling in the optical trap

With direct evaporation of the bosonic ^{87}Rb atoms and sympathetic cooling of the ^{40}K atoms we reached quantum degeneracy with the Bose-Fermi mixture in the magnetic trap. However, our first observation of Feshbach resonances used a relatively hot ($T=14\text{ }\mu\text{K}$) gas in the optical trap. For future experiments using an interspecies Feshbach resonance we clearly would require a gas cooled to a temperature below or near quantum degeneracy. For example, it has been shown that Feshbach molecule creation depends on the quantum degeneracy of the atom gas.⁴

Before attempting evaporative cooling in the optical trap we first improved our trap stability to reduce heating effects. We improved the pointing stability of the optical

trap beam by implementing more stable mounting of the relevant optics. We also improved the intensity stability of the optical trap beam using active feedback. Evaporation was then implemented by ramping down the beam intensity to lower the trap depth. This simultaneous evaporation of the ^{87}Rb and ^{40}K atom gases works well and with about 10 seconds of evaporation we can achieve quantum degeneracy of the mixture.

A p-wave Feshbach resonance

Loss of trapped atoms near a Feshbach resonance, due to inelastic collisions, provides a very convenient method of detecting a Feshbach resonance. However, high temperatures can mask features of the resonance, such as in the case of a p-wave resonance. In Fig. 1 we see that at $T \sim 300$ nK we can resolve the predicted double peak structure of a p-wave resonance between ^{40}K atoms and ^{87}Rb atoms.⁵ These features correspond to different projections of the pair angular momentum onto the magnetic-field direction.

Fig. 1. Loss of K atoms near a p-wave Feshbach resonance. The two features correspond to different projections of the pair angular momentum, $m_L = \pm 1$ and $m_L = 0$. The fact that the mixture is ultracold ($T \sim 300$ nK) allows us to resolve the two features, which are separated by only 0.15 G.

Creating heteronuclear Feshbach molecules

Since the observation of heteronuclear Feshbach resonances^{3, 6} a number of experimental groups have been trying to create heteronuclear Feshbach molecules. Very recently this has been achieved for ^{87}Rb and ^{40}K atoms in an optical lattice⁷, as well as for a mixture of two Rb isotopes in an optical trap⁸. In this section, we discuss our preliminary results in creating ^{87}Rb - ^{40}K Feshbach molecules in an optical trap.

For this work we added the capability to perform fast magnetic-field sweeps, using an auxiliary pair of coils whose current is provided by the controlled discharge of a

large capacitor. When initially charged to a high voltage the capacitor can drive a fast current change in the coils and thus provide a fast change in the magnetic-field.

We tried making molecules using the relatively wide s-wave Feshbach resonance at about 545 G and sweeping the magnetic field from 5 G above the resonance to 5 G below the resonance. Since the Feshbach molecule state appears for magnetic field strengths below the resonance, this sweep should produce molecules. Moreover, one expects an exponential dependence for the number of molecules created as a function of sweep rate. Our results are shown in Fig. 2. We chose to work with a near degenerate gas, with $T \sim 1.3 \cdot T_c$ where T_c is the ^{87}Rb BEC transition temperature, to avoid possible losses due to the high density of a BEC. When we sweep through the resonance we observe a loss of atoms; this is consistent with molecule production since molecules are not detected by our resonant absorption imaging. We find that the loss is exponentially dependent on the sweep rate, as expected for molecule creation. Also consistent with molecule creation is the fact that we see much less loss, for similar sweep speeds, when sweeping the magnetic field in the opposite directions (low to high).

Fig.2. Measured number of ^{40}K atoms as a function of the inverse sweep speed of a ramp across an s-wave Feshbach resonance. The data are consistent with the creation of about 40,000 heteronuclear Feshbach molecules. The error bars correspond to statistical fluctuations in repeated measurements. For this data $T = 500$ nK and the number of ^{87}Rb atoms was 5 times the initial number of ^{40}K atoms.

We find that the observed atom loss, which we associate with molecule creation, depends critically on whether or not we actually cross the Feshbach resonance, as one would expect. This provides a precise measure of the resonance location, which we find to be $B_0 = 546.44 \pm 0.12$ G.

Finally we have attempted to reverse the process and convert the molecules back to free atoms with an additional sweep back above the resonance. Preliminary results with such a double sweep experiment showed that we could recover about half the “lost” atoms. The conversion from atoms to Feshbach molecules should in principle be

completely reversible and we are currently investigating why we are not able to recover more of the atoms. We can measure the lifetime of the molecules by inserting a variable hold time at some magnetic field before the sweep back across the resonance. One such measurement gave a relatively short molecule lifetime, $\tau = 25 \pm 9 \mu\text{s}$, however we need to explore the dependence on the ultracold gas density, the ratio of the numbers of ^{87}Rb and ^{40}K atoms, and the value of magnetic field relative to the Feshbach resonance.

DOE-supported Publications

1. "Measurement of the interaction strength in a Bose-Fermi mixture with ^{87}Rb and ^{40}K ," J. Goldwin, S. Inouye, M. L. Olsen, B. Newman, B. D. DePaola and D. S. Jin, *Phys. Rev. A* **70**, 021601(R) (2004).
2. Observation of heteronuclear Feshbach resonances in a mixture of bosons and fermions, S Inouye, J. Goldwin, M. L. Olsen, C. Ticknor, J. L. Bohn and D. S. Jin, *Phys. Rev. Lett.* **93**, 183201 (2004).
3. "Cross-dimensional relaxation in Bose-Fermi mixtures", J. Goldwin, S. Inouye, M. L. Olsen, and D. S. Jin, *Phys. Rev. A* **71**, 043408 (2005).

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2. "Cross-dimensional relaxation in Bose-Fermi mixtures", J. Goldwin, S. Inouye, M. L. Olsen and D. S. Jin, *Phys. Rev. A* **71**, 043408 (2005).
3. "Observation of heteronuclear Feshbach resonances in a mixture of bosons and fermions", S. Inouye, J. Goldwin, M. L. Olsen, C. Ticknor, J. L. Bohn and D. S. Jin, *Phys. Rev. Lett.* **93**, 183201 (2004).
4. "Production efficiency of ultra-cold Feshbach molecules in bosonic and fermionic systems", E. Hodby, *et al.*, *Phys. Rev. Lett.* **94**, 120402 (2005).
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8. "Observation of heteronuclear Feshbach molecules from a ^{85}Rb - ^{87}Rb gas", S. B. Papp and C. E. Wieman, *cond-mat/0607667* (2006).