Conversion of a Degenerate Fermi Gas of ^{6}Li Atoms to a Molecular BEC

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Abstract. Atomic Feshbach resonances have recently been used to produce a strongly interacting Fermi gas, where the BCS/BEC crossover can be explored. We have used both narrow and broad Feshbach resonances to convert a quantum degenerate Fermi gas of ^{6}Li atoms into an ultracold gas of Li_2 molecules. For the narrow resonances, the molecules are formed by coherent adiabatic passage through the resonance. We find that 50% of the atoms are converted to molecules. Furthermore, the lifetime of these molecules was measured to be surprisingly long, 1 s. We will discuss these measurements in the context of the present theoretical understanding. Molecules can also be formed using static fields near the broad Feshbach resonance. The lifetime of these molecules is again long, and sufficient to enable their evaporation to a Bose-Einstein condensate. Phase contrast images of the molecular condensate are presented. The BCS/BEC crossover may be explored by starting with a pure molecular condensate on the low-field side of the Feshbach resonance, and adiabatically changing the field to any final value around resonance. We combine this ability with optical spectroscopy on a bound-bound molecular transition to probe the nature of the many-body wavefunction in the crossover regime.

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INTRODUCTION

Magnetically tuned Feshbach resonances are a remarkable tool for controlling the interaction energy of ultracold atomic gases. These resonances arise when a two-body atomic collision is tuned into resonance with a bound state of the diatomic molecule by an external magnetic field. The collisional resonance not only leads to a tunable scattering length, but also to a method for converting atoms into diatomic molecules [1, 2, 3, 4, 5, 6]. Several groups have exploited this connection between Feshbach resonances and molecular bound states to convert atomic Fermi gases into bosonic molecules [7, 8, 9, 10]. Soon after, the first molecular Bose-Einstein condensates (BEC) were reported [11, 12, 13, 14]. These molecular condensates are remarkable because of their close connection with Cooper pairs, the entities responsible for superconductivity and for superfluidity in ^{3}He. Feshbach resonances may also enable investigation of the crossover between BEC physics and the BCS regime of weakly interacting correlated pairs. Evidence for atomic pairs on the high-field side of Feshbach resonances in ^{40}K [15] and ^{6}Li [16], and for superfluidity itself [17, 18] have recently been presented.

^{6}Li is well-suited for investigations of Fermi superfluidity [19] because of its large and negative s-wave scattering length of -2260 a_o [20]. The large negative scattering

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length imparts a large hyperfine induced singlet/triplet coupling that gives rise to a strong Feshbach resonance [21, 22]. The resonance between pairs of atoms in the two lowest going Zeeman sublevels ($F = 1/2, m_F = \pm 1/2$) and the $v = 38$ vibrational level of the molecular ground state $^1\Sigma_g^+(\mathrm{X})$, actually gives rise to two resonances [23, 24], as shown in Fig. 1. The one located near 837 G is the broadest of any known atomic Feshbach resonance, while the same states also produce a resonance at 543 G that is nearly 1000 times narrower in field width. While both resonances correspond to the molecular singlet level $v = 38$, the broad resonance has a total spin $F = 0$, while the narrow resonance has $F = 2$ [22].

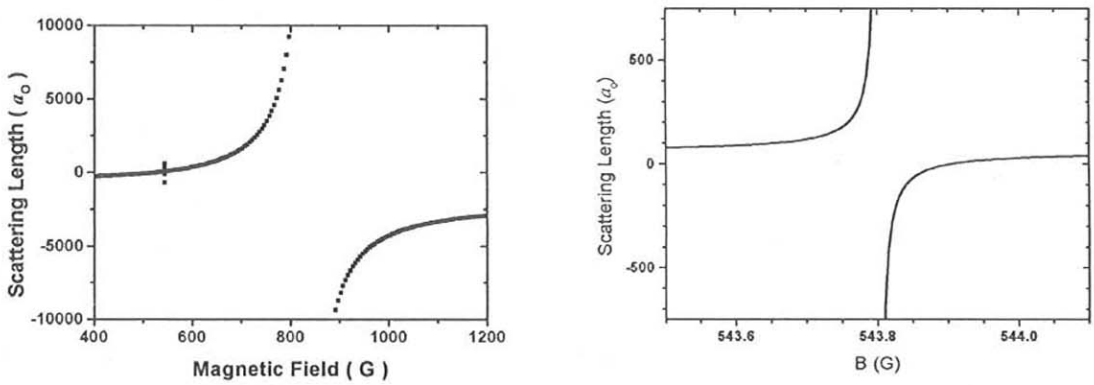

FIGURE 1. Coupled channels calculations of the ^{6}Li Feshbach resonances involving the energetically two lowest Zeeman sublevels. Left: The broad resonance is located near 837 G, while the narrow one is near 543 G. Right: Blow-up of the narrow resonance. The narrow resonance is experimentally measured to be at 543.25 G [8].

There is considerable interest in the character of Fermi superfluidity for narrow resonances compared to broad ones [25, 26, 27, 28, 29, 22, 30]. Much discussion revolves around the issue of whether the physics of resonances that are broad in comparison to the Fermi energy is universal, in the sense that macroscopic properties are independent of the microscopic physics. Such "single-channel" models were originally developed by the condensed matter community, especially in the context of high temperature superconductors [31, 32]. While the applicability of single-channel models to broad atomic Feshbach resonances is still debatable, there is no doubt that narrow resonances will be strongly effected by the presence of bare molecules and the microscopic details of the interaction. Since ^{6}Li exhibits both a narrow and a broad resonance, it affords the opportunity to explore these differences.

This chapter is organized as follows: The first section presents an experiment in which an atomic Fermi gas of ^{6}Li atoms is coherently converted into a molecular Bose gas using the narrow resonance. In the second section, the achievement of a molecular Bose-Einstein condensate utilizing the broad resonance is described. Finally, the last section discusses optical molecular spectroscopy as a means of probing the many-body wavefunction in the BCS/BEC crossover and initial results for the broad ^{6}Li resonance are discussed.

For fields above the lithium Feshbach resonances the molecular energy is greater than the free atom energy, while below the resonance the molecular energy is lower. Therefore, by slowly sweeping the magnetic field from above resonance to below, an atomic gas can adiabatically follow the lower energy path and emerge as bound diatomic molecules [1, 2, 3, 4, 5, 6]. Such a scheme was first demonstrated by the Jin group for ^{40}K. [7]. Figure 2 shows our measurement of the loss of atoms as a function of ramp speed through the ^{6}Li narrow resonance [8]. Efficient formation of molecules requires that the ramp be sufficiently slow to be adiabatic with respect to the atom/molecule coupling. A Landau-Zener analysis can be used if the process is coherent [3, 6], and in this case, the conversion efficiency should depend exponentially on the inverse ramp speed. Indeed, the efficiency has the predicted exponential dependence, as can be seen in Fig. 2. However, the data show that the maximum transfer efficiency is only 50%, to sufficiently high accuracy that it is unlikely to be accidental. The original ^{40}K experiment at JILA also measured a 50% efficiency [7], although their subsequent experiment obtained somewhat higher conversion [33]. The ^{6}Li experiments utilizing the broad resonance [9, 10, 13] are different, in that significantly greater than 50% of the atoms were converted. A notable distinction between our experiment and other fermion experiments is that it is the only one that has been performed using a resonance whose width is narrow in comparison to the Fermi energy. We believe this accounts for the difference in conversion efficiency, as well as differences in the molecular lifetime discussed below. The conversion is likely coherent in the case of the narrow resonance, while for experiments performed with the broad resonances the high collision rate should cause rapid decoherence. There have been several attempts to explain the 50% efficiency [34, 35, 36, 37], although none have yet been proven experimentally. The authors of ref. [37], for example, assume a mean-field like regime where only one collision can occur during the sweep. In this case, there is a 50% probability that this single collision will involve an atom colliding with another atom in the "right" (i.e. opposite) spin state which will lead to the creation of a molecule.

The molecules created during the downward field ramp can be dissociated by sweeping back up to the starting field. By introducing a variable delay between the downward and return ramps, the lifetime of the molecules can be measured. Contrary to all expectations, the data (Fig. 3) indicate that the lifetime of the molecules is extraordinarily long, almost 1 s. Previous experiments had observed molecular lifetimes of 1 ms [38, 7], limited, presumably, by collisions that cause vibrational relaxation to lower lying vibrational levels. Other fermion experiments have subsequently observed similarly long, or longer, molecular lifetimes as ours [9, 10, 33]. A recently published explanation suggests that the stability against vibrational quenching is due to a combination of Fermi statistics, in which 3-body collisions are suppressed due to the presence of only two distinguishable spin states, and weak molecular binding, which gives a spatially extended molecular vibrational level with poor wavefunction overlap with the more deeply bound vibrational levels [39]. Although this theory does seem to fit observations made by other groups that the molecular lifetime decreases rapidly away from the Feshbach resonance [9, 10, 33], in our case the resonance is so narrow that all of our sweeps terminate far below the resonance, where the molecules are purely singlet in character and are deeply

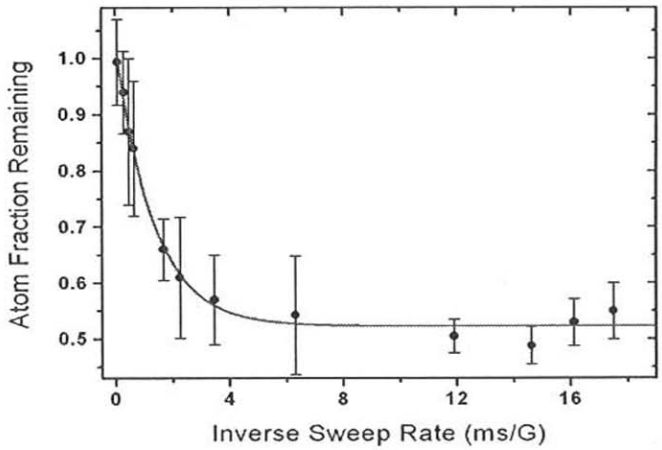

FIGURE 2. Atom loss as a function of the inverse rate at which the magnetic field is swept through the narrow resonance [8] .

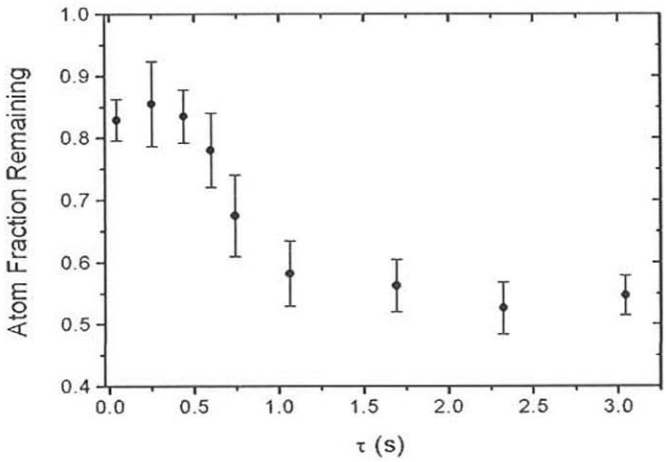

FIGURE 3. Atom fraction remaining after a two-way ramp, as a function of the delay between ramps [8].

bound. While the long lifetime observed in our experiment must certainly be related to Fermi suppression of inelastic collisions, a theory has yet to be developed that gives a quantitative explanation.

BOSE-EINSTEIN CONDENSATION OF MOLECULES

Subsequent to producing long-lived molecules from atomic Fermi gases, several groups demonstrated that the molecules could be Bose condensed [12, 11, 13, 14]. We have duplicated the other ^{6}Li experiments by simply fixing the magnetic field on the low-field

side of the broad resonance and allowing molecules to form via thermalizing collisions. At 760 G, the scattering length is 4000 a_o and the collision rate is enormous. Evaporative cooling of the molecules is accomplished by reducing the trapping laser intensity to reduce the trap depth from 35 μK to 2 μK in 300 ms. Although the condensate has likely formed at this stage, the repulsive interaction energy between molecules is so large [39, 40] that it is not possible to differentiate the condensate from the Fermi gas in absorption images of the gas. Therefore, we reduce the field to 700 G, where the scattering length is a more modest 1600 a_o before imaging. Figure 4 shows the emergence of the condensate from a background of thermal molecules.

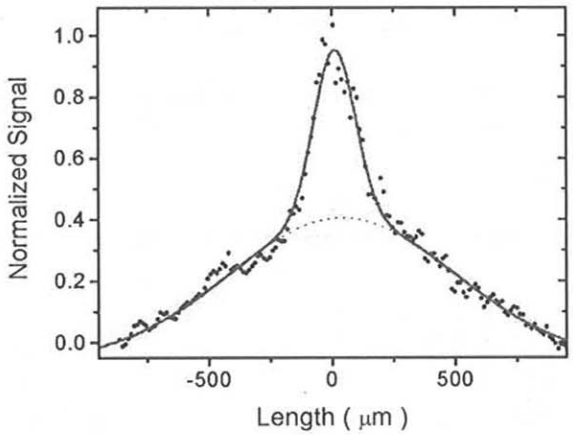

FIGURE 4. Phase contrast image of a molecular Bose-Einstein condensate. The condensate sits on a pedestal of thermal molecules. The solid line is a fit to two Gaussians, and is meant to guide the eye.

MOLECULAR PROBE OF THE BCS/BEC CROSSOVER

The molecular BEC can be considered a paired Fermi gas in the extreme strong coupling limit. It is the ideal starting point for investigations of Fermi superfluidity and the BEC/BCS crossover regime where the gas is not strictly a BEC of molecules, nor a Cooper paired gas like a traditional superconductor. Rather, inside the resonance the atoms are strongly interacting. This regime cannot be understood by mean-field theory, which has been enormously successful in describing quantum gases in the past. Nevertheless, the two-body physics is straightforward, as the coupled-channels calculations can be performed. In the ^{6}Li case, the open collision channel is an electronic spin triplet, while the closed channel is associated with the spin singlet potential. In a single-channel model, the closed channel is ignored, and the binding energy of the weakly bound molecules formed on the low-field (i.e. positive scattering length a) side of the resonance have binding energy of $\hbar^2/ma^2$. The extremely large triplet scattering length of -2260 a_o for ^{6}Li [20] conspires to create an open-channel dominated resonance [21, 22] which is over 100 G wide. The closed channel molecular state is explicitly included in two-channel models. In this case, the weakly-bound molecules are "dressed" by the closed channel molecules, that is, they are hybridized combinations of free atoms

in the open channel with bare molecules in the closed channel [27]. Recent observations of correlated pairs within the crossover regime [15, 16] have generated considerable discussion [27, 29]. The issue is the role of the bare molecules, if any, which in turn relates to the spatial size of the pairs. Although the two-body physics indicates that bare molecules are relatively unimportant in the broad resonances used in the ^{40}K [15] and ^{6}Li [16] experiments, this question remains unresolved in the presence of many-body effects.

In an effort to better understand the nature of the paired wavefunction, we have developed a new molecular spectroscopic technique, which is shown schematically in Fig. 5. In this scheme, a laser is tuned between pairs, or dressed molecules in the ground state and an excited singlet molecular level. Since the excited state is a spin singlet, the laser excitation will project out only the singlet molecular character of the paired state. We have recently observed this transition, which occurs at a wavelength several nm greater than the corresponding atomic transition, in a molecular BEC at fields in the crossover region. In a preliminary experiment, the trap was completely depleted of all atoms and molecules in a 1 ms pulse with an intensity of only 100 mW/cm^2. We are currently performing quantitative measurements of the bare molecule fraction of the dressed molecule superposition.

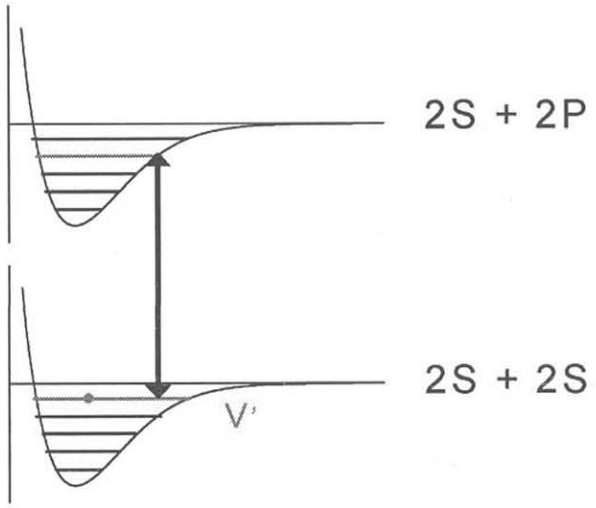

FIGURE 5. Schematic of the molecular probe scheme. The laser is tuned between the pairs or dressed molecules in the ground state and a vibrational level of the electronically excited singlet potential A $^1\Sigma_g^+$.

In summary, we have presented results of investigations of fermionic ^{6}Li atoms near narrow and broad Feshbach resonances. The narrow resonance has been used to coherently convert an atomic Fermi gas to a molecular Bose gas. The bare molecules produced in this experiment are found to have a surprisingly long lifetime. Molecules were also produced using the broad resonance, and evaporatively cooled to form a Bose-Einstein condensate. Finally, we have discussed the nature of the dressed molecule pairs near a broad Feshbach resonance, and have described an optical spectroscopic scheme to probe the nature of the many-body wavefunction of these pairs in the BCS/BEC crossover.

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