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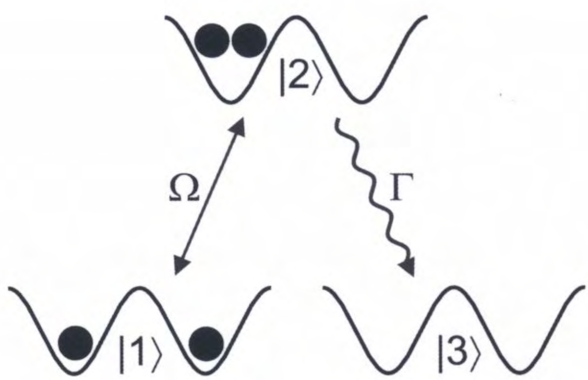
PUSHING THE FRONTIERS OF ATOMIC PHYSICS



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TUNABLE INTERACTIONS IN A BOSE-EINSTEIN CONDENSATE OF LITHIUM: PHOTOASSOCIATION AND DISORDER-INDUCED LOCALIZATION

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Lithium-7 exhibits a broad Feshbach resonance that we exploit to tune the interactions in a Bose-Einstein condensate (BEC). We find that the rate of photoassociation can be enhanced by several orders of magnitude by tuning close to the resonance, and use this effect to observe saturation in the rate of association of a BEC for the first time. We have also used a lithium BEC to explore the effects of disorder on the transport and coherence properties of the condensate. We also show that the scattering length goes through a shallow zero-crossing far from the resonance, where it may be made positive or negative with a magnitude of less than 0.1 a_o, and have made preliminary transport measurements in the regime of weak repulsive and attractive interactions.

Keywords: BEC; photoassociation; association; disorder; soliton; Feshbach resonance.

1. Introduction

Our original BEC experiment with ^{7}Li used the $|F = 2, m_F = 2\rangle$ state,[1] for which the number of condensate atoms was limited by the negative scattering length a of the state. The $|1, 1\rangle$ state, on the other hand, has a broad Feshbach resonance located near 737 G (see Fig. 1), which enables large condensates to be formed when the interactions are repulsive. Moreover, the strength of the interactions may be adjusted from strongly interacting to essentially non-interacting. Three experiments are described in the following sections: (1) photoassociation in the strong coupling regime; (2) the effects of disorder on a BEC with tunable interactions; and (3) the measurement of a vs. magnetic field, and in particular, the achievement of $a < 0.1a_o$, where a_o is the Bohr radius.

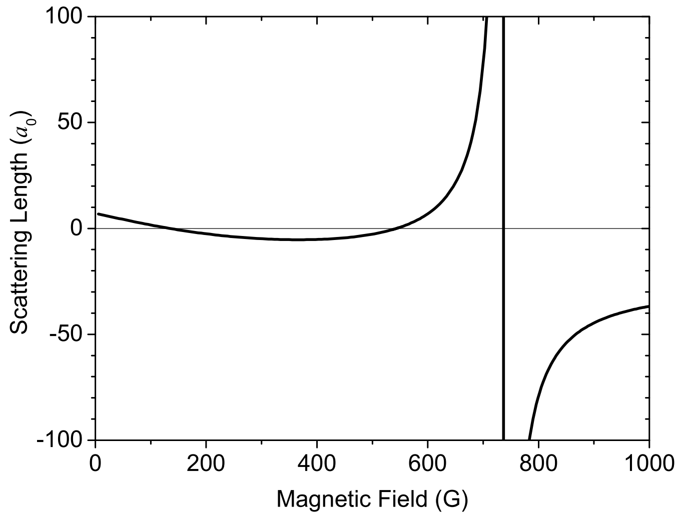

Fig. 1. Coupled-channels calculation of the scattering length for the $|1,1\rangle$ Feshbach resonance in ^{7}Li.

2. Photoassociation

A productive path for creating ultracold molecules is to associate ultracold atoms. Two methods have been employed for this purpose: magnetic field sweeps through Feshbach resonances, and photoassociation. Photoassociation is, in many ways, a more promising method because the strength of the atom-molecule coupling is adjustable, and the number of suitable systems is vastly greater than with Feshbach sweeps. A question of both fundamental and practical interest, for both methods, is what are the limitations on the rate of association?

Quantum mechanical unitarity limits the scattering amplitude for two-body scattering to the de Broglie wavelength. This mechanism usually sets the maximum rate of association for non-condensed atoms, as verified in several experiments, including our past work with ^{7}Li in the $|2,2\rangle$ state cooled to the transition temperature T_c for BEC.[2] In the case of a condensate, the unitarity limit is extremely high and has been considered unreachable. Javanainen and his collaborators have suggested a process they term "rogue photodissociation" that should result in a more stringent rate limit than unitarity. In this process, atom pairs are stimulated back to the energetic continuum and are thereby lost from the condensate.[3] The maximum rate of association achieved in a previous condensate experiment was close to the rogue limit, but no saturation was observed.[4]

Motivated by this background, we designed an experiment in which the strength of the coupling between free atoms and an excited molecular state would be extremely large. The rates we achieved are unprecedented and sufficiently large to directly test the rogue model.[5] This was accomplished by varying the free-bound coupling via a Feshbach resonance. By tuning near the Feshbach resonance, the scattering wavefunction is enhanced at short internuclear distances where photoassociation occurs. The $v = 83$ vibrational level of the electronically excited $1^3\Sigma_g^+$ state was chosen as compromise between a large free-bound coupling strength, and a large detuning (60 GHz) from the $2\mathrm{P}_{1/2}$ atomic resonance. Excited molecules created by the photoassociation laser pulse decay into pairs of energetic atoms that escape the trap and are detected as atom loss. The on-resonance rate coefficient K_p is defined by the time evolution of the density distribution: $\dot{n}(t, \mathbf{r}) = -K_p n^2(t, \mathbf{r})$

2.1. *Results*

Figure 2 shows K_p for a thermal gas ($T > T_c$). The rate coefficient varies by more than 4 decades for fields near the Feshbach resonance. The enhancement of K_p at the resonance (737 G) is due to the large enhancement of the scattering wavefunction. The minimum at 710 G, on the other hand, is a result of a node in the scattering wave function that occurs when a is tuned to the Condon radius of the transition.[5]

The data of Fig. 2 demonstrate that K_p can be extraordinarily large near the Feshbach resonance, making it an ideal system for exploring saturation. Figure 3 shows K_p vs. the intensity I of the PA laser beam. The data in this plot correspond to a condensate with no visible thermal fraction. By achieving extremely large Feshbach-enhanced loss rates, saturation is observed in a condensate for the first time. The maximum K_p of 1.4×10^{-7} cm^3/s is nearly a factor of 10 larger than that of any previous photoassociation experiment.[2]

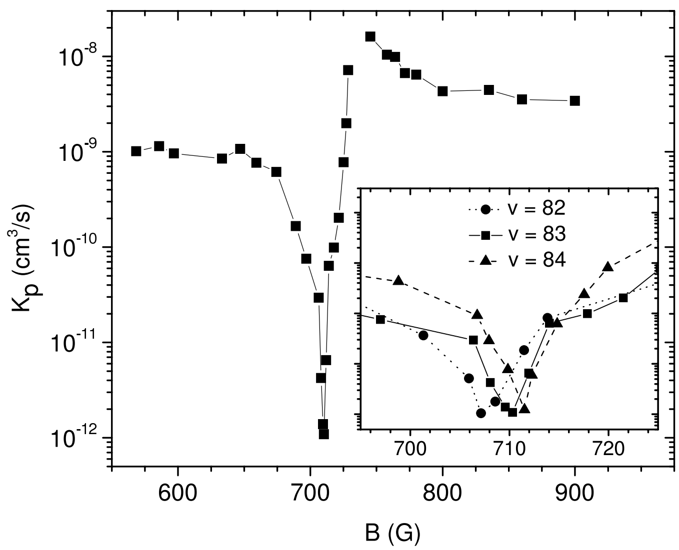

Fig. 2. K_p for a thermal gas ($\sim$10 μK). The inset shows K_p for three different excited state vibrational levels, using the same scale as the main figure. Reprinted from Ref. 5.

2.2. *Analysis*

A comparison of the data with theory is facilitated by defining K_p in terms of a characteristic length L, as $K_p = (\hbar/m)L$. The rogue photodissociation limit K_{pd} is obtained by taking L to be the average interatomic separation, ${n_o}^{-1/3}$, evaluated at the peak density n_o.[3] For the data of Fig. 3, $n_o = 1.6 \times 10^{12}$ cm^{-3}, giving $K_{pd} \sim 8 \times 10^{-9}$ cm^3/s. Surprisingly, the measured maximum K_p is nearly 20 times greater than K_{pd}. More recent calculations[6,7] show that while dissociation does impose a rate limit on condensate loss, it is not as stringent as K_{pd}. Our measured maximum K_p is, nonetheless, nearly 7 times greater then predicted from the equations given in Ref. 7.

An alternative explanation is provided by quantum mechanical unitarity. If we take $L \sim 2R_{TF}$, where $R_{TF} \simeq 10$ μm is the radial Thomas-Fermi radius, then $K_p \sim 1.8 \times 10^{-7}$ cm^3/s, in good agreement with the measured value of 1.4×10^{-7} cm^3/s. The observed saturation could also be explained by a higher than expected rogue limit, perhaps due to cross coupling between the photoassociation and Feshbach resonances, as discussed in Ref. 8.

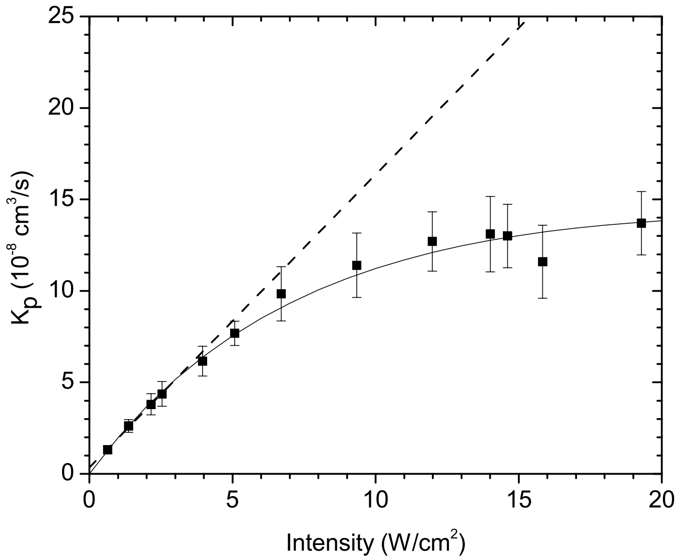

Fig. 3. K_p vs. I for a BEC at 732 G ($a \simeq 1000\,a_o$). Reprinted from Ref. 5.

3. Disorder

Materials, no matter how pure they may be or how carefully they are prepared, inevitably have some random disorder. This disorder can be caused by crystal defects, impurities, or anything that changes the landscape of how electrons move about in the material. Disorder can play an important role in the transport properties of real materials. Superconductors, for example, can have zero resistance in the presence of material defects, but with increasing disorder the electrons will localize, resulting in an insulating state. This effect has been explored in many systems experimentally, including superfluid helium in porous media, and thin-film and granular superconductors. Many fundamental questions, such as the nature of the insulating state and the characterization of phase coherence, remain to be resolved.

Gases of ultracold atoms have proven to be extremely useful stand-ins for actual materials because of the ability to control many of the parameters, including the characteristics of the disorder itself, as well as the particle interactions via a Feshbach resonance. Following the pioneering work at Florence,[9] Orsay,[10] and Hannover,[11] we use optical speckle to create a highly-controllable disordered potential in a ^{7}Li $|1,1\rangle$ BEC.[12] The speckle in our experiment is created by passing a 1030 nm laser beam through a microlens array. The resulting intensity autocorrelation function is Gaussian with a characteristic length $\sigma_d = 15\ \mu$m. The strength of the disordered optical potential V_d is proportional to the intensity and is continuously controllable up to the chemical potential of the condensate ($\sim$1 kHz).

3.1. *Results*

We have performed two transport experiments and have also studied coherence as revealed by interference in time-of-flight (TOF) expansion imaging.[12] These experiments were performed near 720 G, where $a \simeq 200\, a_o$. Pinning of the condensate by disorder was studied by slowly dragging it through the disorder. This was accomplished by using a magnetic gradient to change the trap center. The data show that the condensate is pinned when $V_d \simeq \mu$,[12] where μ is the chemical potential of the condensate. In a related experiment, the trap center is suddenly displaced causing the condensate to undergo damped, dipole oscillations. The results, displayed in Fig. 4, show that even small disorder produces significant damping, and that the motion is overdamped for $V_d \gtrsim 0.4\mu$. The damping coefficient β is found to related to V_d by a power law, $\beta \propto (V_d/\mu)^{5/2}$. We do not have an explanation for the value of the exponent.

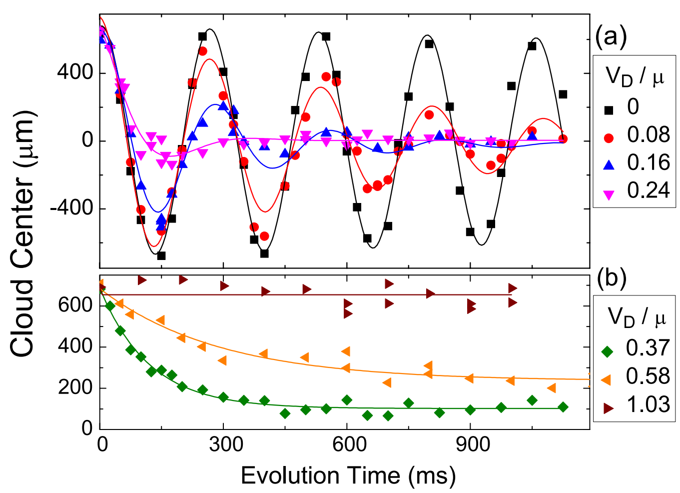

Fig. 4. Damping of dipole oscillations for various V_d. Reprinted from Ref. 12.

Figure 5 shows both *in situ* and the corresponding TOF images for various values of V_d. The *in situ* images reveal how the density distribution is affected by the disorder, while the TOF images provide complementary information on condensate coherence. We find that the condensate density becomes increasingly modulated with increasing V_d. When $V_d \simeq \mu$, the condensate appears to fragment into disconnected pieces. Interference fringes are observed in the corresponding TOF images, but in the case of TOF, the maximum contrast occurs for intermediate disorder strength, $V_d \simeq 0.5\,\mu$.

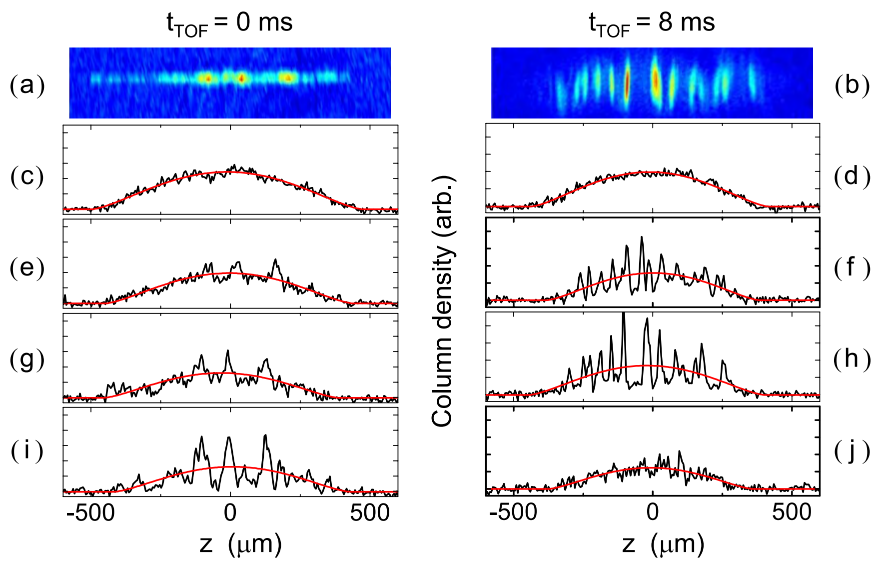

Fig. 5. *In situ* (left) and TOF images (right) for various V_d. (c, d) $V_d = 0$; (e, f) $V_d \approx 0.3\ \mu$; (a, b, g, h) $V_d \approx 0.5\ \mu$; (i, j) $V_d \approx 1.0\ \mu$. Reprinted from Ref. 12.

3.2. *Analysis*

The transport measurements indicate that global superfluidity is absent when $V_d \gtrsim 0.5\mu$, which is also where the condensate begins to fragment, as shown by the *in situ* density measurements. A key to interpreting the interference observed in the TOF images is that the interference patterns are completely *repeatable*. This observation rules out phase fluctuations in the initial condensate as the cause of the TOF interference. At intermediate V_d, sufficient local coherence remains in the initial condensate to produce these reproducible and high-contrast TOF interference patterns. We conclude that the condensate must remain connected under these conditions. For higher V_d ($\sim\mu$), the TOF contrast diminishes as the condensate fragments into multiple sites. Similar observations and conclusions were made by the authors of Ref. 13, although at lower V_d/μ.

4. Direct Measurement of the Scattering Length

The Feshbach resonance in ^{7}Li is unusually broad, and moreover, it has a very shallow zero-crossing near 544 G (see Fig. 1). These features make the Feshbach resonance particularly useful for experiments where fine control of a is desired. The zero-crossing was previously exploited to create bright matter-wave solitons,[14,15] and may also prove useful for achieving a non-interacting, or at least a very weakly interacting gas for disorder studies.

4.1. *Results*

We determine a by measuring the axial size and atom number for a BEC as a function of magnetic field, and compare with solutions of the Gross-Pitaevski equation. Figure 6 shows the extracted a for fields between the zero-crossing at 544 G and the resonance at 737 G, where 6 decades of dynamic range are resolved. The solid line in Fig. 6 is a fit to the standard Feshbach resonance form:

$$a(B) = a_{bg}\left(1 + \frac{\Delta B}{B - B_o}\right),$$

where $a_{bg} = -24.5\,a_o$, $\Delta B = 192$ G, and $B_o = 737$ G are the best fits to the data. The fit is remarkably good despite the large dynamic range.

The inset in Fig. 6 shows the extracted values of a near the zero-crossing in more detail. The two sets of points correspond to whether the magnetic dipolar interaction is accounted for in the Gross-Pitaevski equation, or is neglected. The dipolar interaction is generally quite small in lithium because its magnetic moment is only one Bohr magneton, yet its effect is significant when the a is smaller than $\sim$0.1 a_o. Since the slope of $a(B)$ near the zero-crossing is 0.1 a_o/G, only moderate field stability is needed to be in the regime where the dipolar interaction dominates. Similarly small scattering lengths have been measured in Cs (Ref. 16) and ^{39}K (Ref. 17), but since the slope of the zero-crossing in ^{7}Li is 6 times smaller than in ^{39}K and 600 smaller than for Cs, the ultimate resolution is significantly better for lithium.

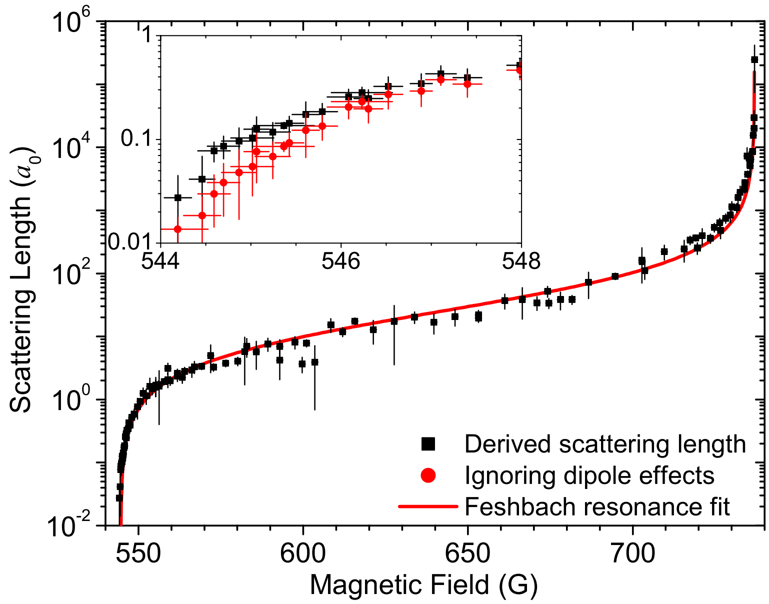

Fig. 6. Scattering length a vs. B. The inset shows the zero-crossing in detail. The squares are the extracted values of a when the magnetic dipole interaction is accounted for, while the circles correspond to its neglect.

We have repeated the dipole oscillation experiment described in Section 3.1 with very small interaction strength. For small positive a the oscillations damp as before. Negative a can also be obtained by tuning B below the zero-crossing, where solitons are formed. Preliminary measurements indicate that damping is qualitatively different for solitons: the amplitude of the oscillation appears undamped while the number of atoms continuously decreases.

5. Conclusions

We have used a Feshbach resonance to tune the interactions in Bose condensates of ^{7}Li. The strong enhancement of the free-bound wavefunction overlap enables enormous photoassociation rates and the observation of saturation in a BEC for the first time. Rates far above the predicted "rogue photodissociation" limit are achieved. The transport and coherence properties of a BEC in a disordered potential have been explored with optical speckle. We have used the Feshbach resonance to make a as small as 0.1 a_o, and observe the damping of dipole oscillations in the presence of disorder for both weakly repulsive and attractive interactions. These preliminary experiments indicate that damping of dipole oscillations of solitons is manifested by the loss of atoms rather than damping of oscillation amplitude.

Acknowledgments

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