Creation of *p*-wave Feshbach molecules in two dimensions

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1. Introduction

1.1 Background

In recent years great progress has been made in the field of ultracold atomic physics with *s*-wave interactions ($l = 0$). However the *p*-wave ($l = 1$, projections of the angular momentum are $|m_l| = 1$ and $m_l = 0$) superfluidity with trapped Fermi gases has not been realized and it remains as one of the greatest challenges. It is because of the experimental difficulties such as the instability of the *p*-wave molecules and low phase space density. The *p*-wave interaction is anisotropic, where multiple phase of superfluidities and the phase transitions are expected in ultracold atomic systems. This *p*-wave superfluidity can also be found in the liquid ^{3}He and Strontium Ruthenate superconductor. The ultracold atomic system provides the ability to achieve difficult measurements and higher degree of freedom which are not available in other systems. Thus it plays an important role for researches in condensed matter physics, many-body physics and quantum phase transitions.

Similar to other systems like liquid ^{3}He and Strontium Ruthenate superconductor, the formation of pairs is essential to *p*-wave superfluidity in an ultracold atomic system. These pairs of molecules have the possibility of forming a molecular Bose-Einstein condensate. Thus the formation of *p*-wave Feshbach molecules is considered to be the precursor of *p*-wave superfluidity in an ultracold atomic system. Recent experiments and theoretical investigations have been carried out on creating *p*-wave molecules [1-4]. An adiabatic magnetic field ramp method is used in the above experiments, molecule creation rates of 15% [3] and 3% [1] are demonstrated. The experiment of *p*-wave Fermi gases in optical lattices [5] focused on Feshbach resonances and possible superfluidity in low dimensions.

1.2 *p*-wave Feshbach resonance

One of the essential tools in ultracold atomic system is Feshbach resonance. It enables the control of atomic interactions by applying an external magnetic field. Each scattering channel depends on the spin configuration of the colliding particles, thus the two channels have different magnetic moments. The two channels are separated into the so called open channel, and the bound state called closed channel as shown in Figure 1. Feshbach resonance occurs when the total energy of the two free atoms in the open channel is coupled to the bound state in the closed channel.

One of the properties of *p*-wave Feshbach resonance is the narrow resonance. It is caused by the

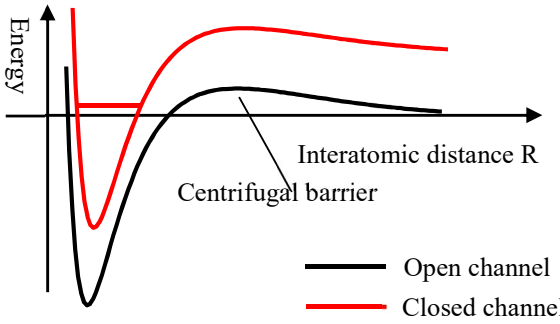

Figure 1: For p-wave Feshbach resonance with the centrifugal barrier, the resonance is narrower.

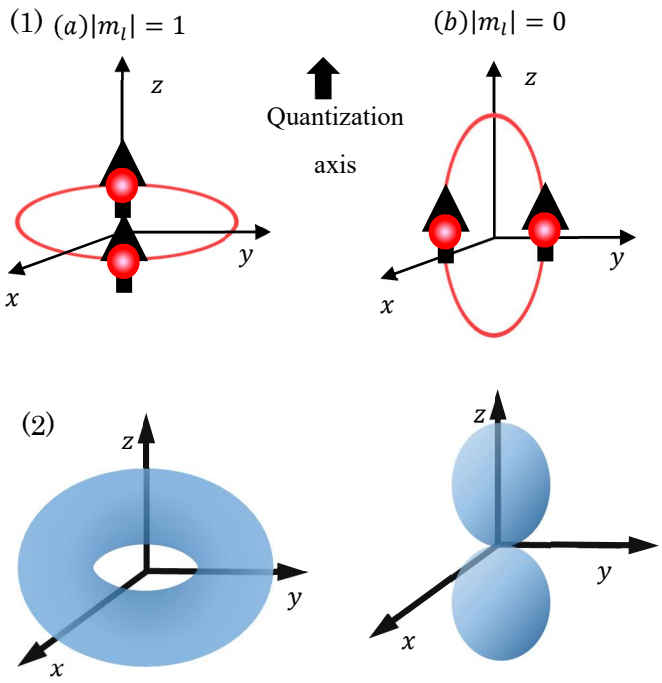

Figure 2: (1) Classical picture and (2) wavefunctions of the $|m_l| = 1$ and $m_l = 0$ (quantization axis along z).

colliding atoms having to tunnel through the centrifugal barrier before interacting with the other atom as shown in Figure 1.

Another interesting property is the splitting of the resonance caused by the magnetic dipole-dipole interaction. We consider a classical picture shown in the Figure 2. In Figure 2(1)(a) the rotations of the two spins are always stay side-by-side, so the energies of the two atoms remain constant as they rotate. While in Figure 2(1)(b) they alternatively change from an attractive head-to-tail to a repulsive side-by-side configuration. Thus the $m_l = 0$ scattering state has a lower energy because the attractive interaction and its resonance occurs at lower magnetic fields.

For ^{40}K, the splitting of the resonance is about 500 mG, which is also observed experimentally. Previous experiment [2] with ^{40}K, $|m_l| = 1$ and $m_l = 0$ p-wave molecules are created ($|m_l| = 1$ molecules are "donut shaped", see wavefunction in Figure 2(2)). However, for ^{6}Li, this splitting is only about 10 mG, much narrower than ^{40}K. In the current setup, the stabilization of the magnetic field is about 10 mG. Thus the two resonance probably overlap each other, making the splitting not able to be resolved. This narrow splitting is complex and extremely interesting. Not only multiple superfluid phases are possible, furthermore the phase transitions between superfluid phases is possible. In order to study this narrow p-wave resonance of ^{6}Li, it is necessary to study the accurate splitting to better understand the p-wave superfluid.

By using optical lattices, the dimensions of atomic quantum gases can be reduced by suppressing scattering in specific directions. By the confinement of optical lattice, a low dimensional system is obtainable. Thus it is possible to select specific m_l states. In our experiment, we follow this idea and investigate on creating p-wave molecules in a 2D system by using a 1D optical lattice. First we focus

on the $|m_l| = 1$ state, by investigating the creation of *p*-wave molecules of $|m_l| = 1$ projection. Our initial goal is to explore the possibility of creating a *p*-wave pairing superfluid.

1.3 Creation of *p*-wave Feshbach molecules

By using Feshbach resonance, molecules can be created. An adiabatic magnetic field ramp across the resonance can convert atoms to bound molecules as shown in Figure 3.

The energies of the two atoms in the open channel and the molecules in the closed channel near the Feshbach resonance have the magnetic field dependences. The black and the red lines indicate the atoms in the open channel and bound state in the closed channel respectively. One would expect that by sweeping the magnetic field across the Feshbach resonance adiabatically, the unbound atoms in the open channel can be converted to the molecule state.

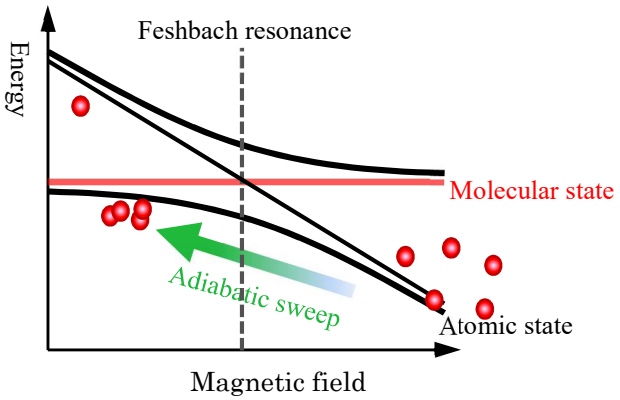

Figure 3: Creation of *p*-wave molecules via adiabatic magnetic field ramps.

2. Preparation of a 2D system—Band mapping method

We start from a degenerate fermi gas of the state $|1\rangle$ atoms with atom number $\sim 10^5$ in a 3D system. Then we use a 1D optical lattice along *z*-direction with variable lattice depths. The optical lattice is ramped down adiabatically to zero in 2.5 ms. Figure 4(a), (b) and (c) show absorption images with 5 ms of Time of flight (TOF) of the atomic cloud with variable lattice depths. Here lattice is along z-direction.

Figure 4(d′) shows the integration along the lattice direction (z), which gives the information of the non-lattice direction. We can see that without the confinement of the lattice, atomic motion is Gaussian like.

Figure 4(a'), (b') and (c') are the integration from the non-lattice direction (y) with different lattice depths, and the atomic momentum distributions are changing as shown. Indicating that with increasing depth of optical lattice, the system is turning from 3D to 2D. In Figure 4(c') with lattice depth $V_0 = 8.7\ E_{rec}$, a near-square shaped image is observed. Indicating along the lattice direction, the

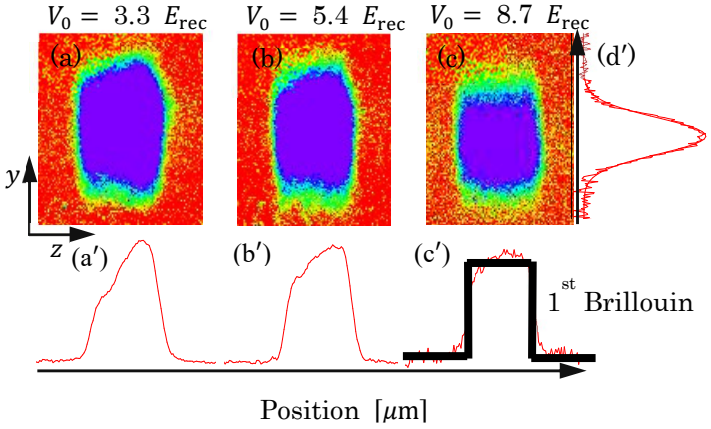

Figure 4: (a) (b) and (c) are the absorption images with variable optical lattice depths. (a′) (b′) (c′) and (d′) are the integration of the experimental data.

atomic cloud is restricted to the ground state — within the 1st Brillouin zone. From Figure 4(c) we can know the energy $k_B T \sim 2.5\,\mu$K, which is smaller than the interband transition energy $\hbar\omega_z$ (estimated to be around 8.4 μK). Thus we confirm that the system is kinematically 2D.

3. Creation of *p*-wave molecules in a 2D system

In our first experiment (shown in black lines in Figure 5), we create molecules by ramping down the magnetic field near the $|1\rangle|1\rangle$ resonance at $B_0 = 158.5$ G. Then we use an atomic resonant light (blast light) to remove the unpaired atoms (the molecules cannot sense the blast light because of the different optical transitions). After shinning the blast light, we quickly increase the magnetic field to dissociate the molecules. Lastly we take an absorption image of the dissociated atoms shown in Figure 5(1).

In our next experiment, we keep the magnetic field away from the resonance (shown in red lines), then blast the atoms, and lastly take absorption image. No atoms are detected as shown in Figure 5(2). It proves that without ramping the magnetic field near the resonance, no molecules are created. Also indicating the blast light had almost removed all the unpaired atoms. Thus atoms shown in Figure 5(1) are only from the dissociated molecules.

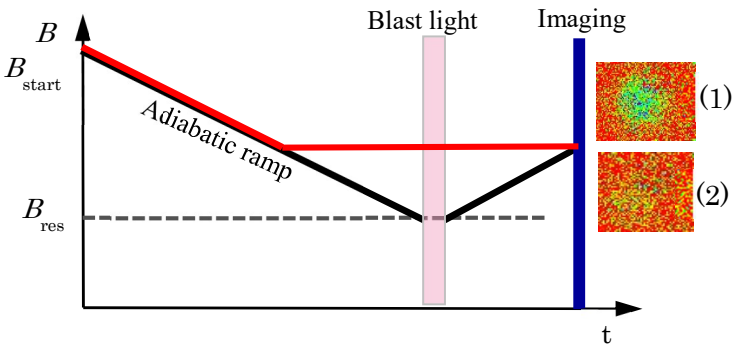

Figure 5: Absorption image with ramping the magnetic field (1) across the resonance and (2) away from the resonance.

4. Experimental results

4.1 *p*-wave Feshbach molecule association

In order to create molecule efficiently, one important parameter is the speed of the magnetic field ramp across the resonance. If the magnetic field ramp speed is too fast, molecules cannot be created. If the magnetic field ramp is too slow, the collisions between the molecules and the atoms will cause the loss of the molecules. This indicates that the magnetic field ramp speed should be slow enough to be adiabatic.

We used a fixed starting magnetic field, and changed the magnetic field ramp down time

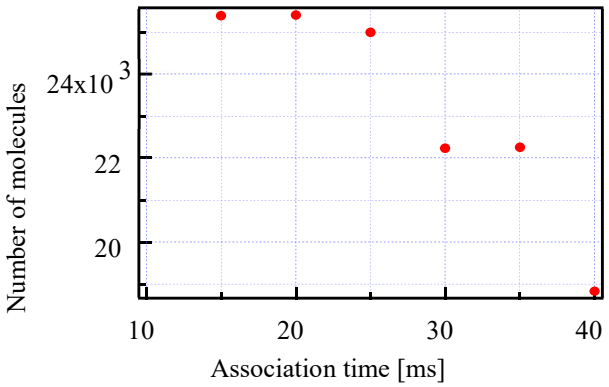

Figure 6: Number of molecules vs association time with a fixed starting magnetic field B_{start}.

(molecule association time). We plotted the number of molecules with variable association time. We found out that at this situation we have more molecules at association time of 20 ms as shown in Figure 6, corresponding to a magnetic field ramp speed of $dB/dt = 0.12\mathrm{G/ms}$.

4.2 Blast light magnetic field

We further investigated the blast light magnetic field at where molecules can be created efficiently. We change the initial and final ramping down magnetic field, but keep the association rate to be $dB/dt = 0.12$ G/ms as we measured in the last experiment. The red line shows the blast light is shined at the resonance magnetic field. The yellow and blue lines show the blast light magnetic field are 20 mG above and below the resonance, respectively shown in Figure 7. Figure 8 shows the number of molecules vs the blast light magnetic field detuning B-B_{res}. We found out at around 22.23 mG below the $|1\rangle|1\rangle$ resonance we have more molecule creation.

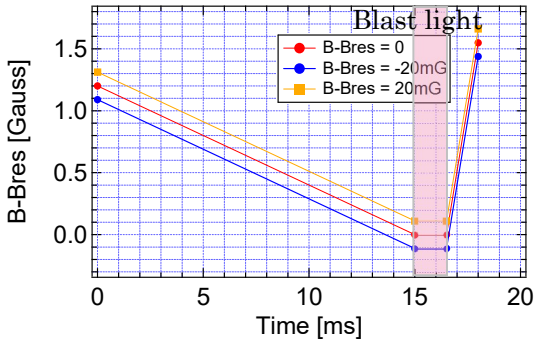

Figure 7: Time sequence of experiment for shining blast light.

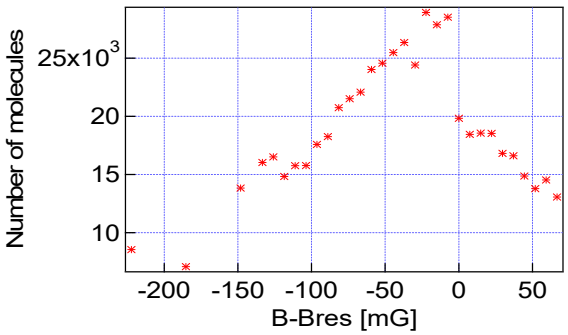

Figure 8: Number of molecules vs blast light magnetic field detuning B-B_{res}.

4.3 Molecule dissociation

Previous experiment [3] demonstrated the cloud width expanding more widely with higher dissociation magnetic field. However in our experiment, the cloud size do not change too much with higher magnetic field. Neither the donut shape of the $|m_l| = 1$ p-wave molecules is observed. In order to observe this donut shape, the dissociation energy has to be larger than the kinetic energy. Thus if one can apply fast magnetic field ramps, it will lead to higher dissociation energy, thus more widely the cloud could expand. With a fast enough magnetic field ramps, molecules will have enough dissociation energy to fly away. In order to observe the donut shape, the magnetic field can be ramped up very quickly. Though our current main coil has good magnetic field stabilization, it cannot provide fast enough magnetic field ramps for the observation of the donut shape. Thus we use a new coil at the bottom of the glass cell, above the MOT coil, to generate the magnetic field to the atoms.

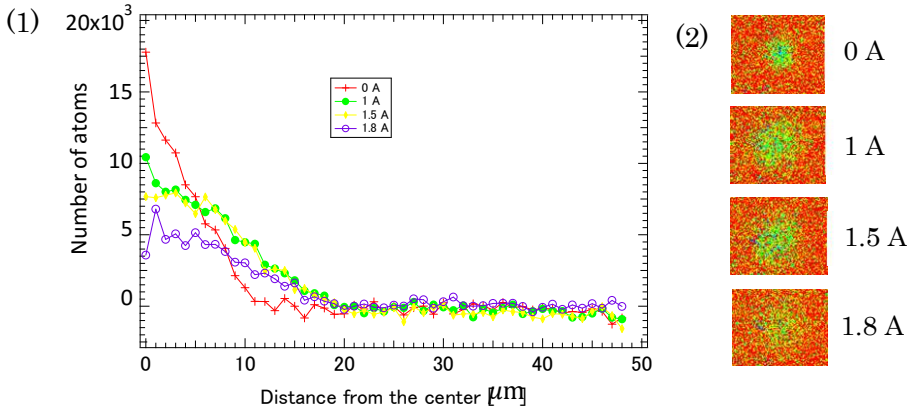

Figure 9: (1) Absorption images with variable current running through the second coil.
(2) Radial profile of the average atom number vs the distance from the center.

We plotted the radial average atom number with the distance from the center point of the atom cloud with variable current running through the new coil as shown in Figure 9(1). With higher current, the center part turns from sharp edge to a near-flat top. This is very likely to be the signal of the donut shape of the dissociated molecules. Figure 9(2) shows the absorption images with different current in the new coil. With increasing current, the average width is expanded, also indicating higher dissociation energy is achieved by this new coil. We will work on applying higher current to provide more dissociation energy to investigate this donut shape.

5. Conclusion

By using a 1D optical lattice, we are able to achieve a 2D Fermi gas. We confirmed this 2D system by using a band mapping method. By adiabatically ramping the magnetic field across the resonance, we created $|m_l| = 1$ p-wave molecules using a ^{6}Li gas in a 2D system. We studied the molecule creation and detected the p-wave molecules. In the future, we will further investigate on optimizing the molecule association and investigate on the donut shape.

6. Reference

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