Observing Condensations in Atomic Fermi Gases

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Abstract

Observing condensation in a gas of fermions has been another interesting topic after the realization of the Bose-Einstein Condensation in atomic gases. The condensation of fermions may happen either in the BEC or the BCS manner, depending on how the fermions are paired to each other. This paper gives a brief review on the recent breakthroughs in this area.

1 Introduction

For boson particles, the well-predicted phenomenon of Bose-Einstein Condensation (BEC) has been first realized experimentally in the system of trapped alkali atoms in 1995. After that, people have been naturally thinking about its equivalent phenomenon in fermions.

The Pauli principle wouldn't allow the fermions to condensate into a single quantum state like bosons do, therefore the only way for fermions to form a condensate is to pair-up. One simple way for them to pair-up is just forming diatomic molecules, which are always bosonic and can certainly make the BEC if the temperature is low enough. Another way, which is more complicated, is that the fermions may form weakly-bounded pairs like Cooper-pairs of electrons in a Type I superconductor, which has been well-explained by the BCS theory; in this way the system will also condensate in low temperatures, and people has already used this to explain the superfluidity of ^{3}He.

Whether the fermions will pair-up in the first way or the other, depends on whether the effective interactions between the particles are repulsive or attractive[1]. A repulsive interaction corresponds to the molecular BEC and an attractive interaction would produce Cooper pairs. In comparison, a boson gas can only condensate when their interactions are repulsive, otherwise the whole system would collapse and end with an explosion. Thus it is the Pauli principle that gives the fermions the unique way of forming Cooper-pairs.

Realizing such kind of condensate in atomic Fermi gases is of significant importance for physics theorists. Ultracold dilute atomic gases are ideal systems to probe and control quantum emergent phenomena. They offer a unique way to study the universal behavior of strongly-interacting many-body systems, such as high-T_c superconductors.

An ultimate goal for experimentalists has been the realization of "superfluidity" in atomic Fermi gases. However, realizing and probing such a condensation is much more challenging than the simple BEC for bosons. The required temperature for a BCS-typed condensation is only a small fraction of the Fermi temperature T_F (about $10^{-2}T_F$ in a high-T_c superconductor), still lower than the currently available lowest temperatures in cooled atomic gases. Also, in ultra-low temperatures identical fermions tend to avoid head-on collision which is essential for the evaporate-cooling process and therefore the system is hard to be cooled down further. Another serious problem is how to probe the Cooper pairs when they have been formed in an atomic gas.

Fortunately, people have solved the first two problems. In 1999, DeMarco and Jin solved the cooling problem[2]. In 2001 theorists pointed out that a superfluid phase transition may occur at a high critical temperature ($\sim 0.5 T_F$ for ^{40}K atomic gas) when a Feshbach resonance paring occurs in a dilute Fermi gas[3]. After these breakthroughs people have made significant progresses towards the fermionic condensation and, in last year (2003), three experimental groups has reported their realization of the molecular BEC in atomic Fermi gases[4-6].

After realizing the molecular BEC, people have in principle been able to create the BCS-typed condensation since they can already tune the effective interactions between the trapped atoms from repulsive to attractive by taking advantage of the Feshbach resonance. But the problem is how to prove the existence of the condensate on the BCS side? A paper in Jan. 2004[7] reported a recent experiment which might be the first time for people to produce and prove the existence of such a degenerate quantum system.

The rest part of this report will mainly focus on this recent experiment. We will first give a brief description of the experiment and its results; then some basic concepts, like the *s-wave scattering* and the *Feshbach resonance*, will be reviewed in detail to have a better understanding of the physical processes involved in this experiment. After that we will discuss the remaining interesting problems arose from the experiment.

2 The Experiment

2.1 Description of the Experiment

In Jan. 2004 the team of JILA, NIST and University of Colorado at Boulder declared that they observed condensation of fermionic atom pairs in the BCS-BEC crossover regime[7].

In this experiment, a dilute gas of fermionic ^{40}K atoms were trapped and cooled in a magnetic trap and then loaded in to a far-off resonance optic dipole trap. The ^{40}K atom has a total atomic spin $f = 9/2$ in its ground state. In the initial stage, an incoherent mixture of the $\left|9/2,-7/2\right\rangle$ and $\left|9/2,-9/2\right\rangle$ was prepared in order to realize s-wave collisions in the ultracold Fermi gas (we will explain this in more detail later); in this way the gas was evaporated and cooled to temperature far below the Fermi temperature($T_F \approx 0.6\mu\text{K}$). Then a magnetic field B_{hold} was applied to the system with its magnitude near to the Feshbach resonance ($B_0 = 202.10 \pm 0.7\text{G}$). Note that the interactions between the atoms are effectively repulsive when $B_{\text{hold}} < B_0$, which corresponds to the Bose-Einstein Condensation of diatomic molecules; and effectively attractive when $B_{\text{hold}} > B_0$, which corresponds to the BCS-type condensation of Cooper pairs.

In order to probe the condensation after the magnetic field is applied, the JILA team used an idea of "projection": they sweep the magnetic field rapidly down by $\sim 10\text{G}$, which put the gas far on the BEC side of the resonance, where it is weakly interacting. The inverse speed of this sweep is $\sim 50\mu s/\text{G}$, which, they believed, was fast enough to prevent forming of a molecular condensate but also sufficiently slow to convert the original Cooper pairs into bounded molecules. Along with this sweep, the gas was simultaneously released from the trap and allowed for free expansion; then after 17ms of expansion the molecules are selectively detected using radio-frequency photodissociation immediately followed by spin-selective absorption imaging; -- these techniques were basically employed to determine the fraction of molecules having zero-momentum, which should correspond to the fraction of initial condensation.

Figure 1 and 2 shows the main result of the JILA team's experiment. Figure 1 presents the measured condensate fraction N_0 / N as a function of the magnetic-field detuning from the resonance, $\Delta B = B_{\text{hold}} - B_0$. The data were taken with two different hold times t_{hold}, which means the time in which the system stayed with the magnetic field B_{hold} before the rapid sweep. Figure 2 shows the time-of flight images for the fermionic condensate with three different B_{hold} values. These results clearly, and for the first time, demonstrated that a condensate did form at the BCS side nearby the Feshbach resonance, where the BEC of diatomic molecules is impossible. The researchers called it a fermionic condensate.

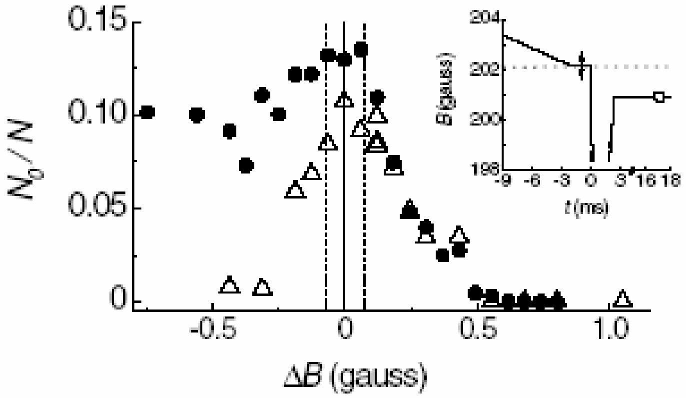

Figure 1. Measured condensate fraction as a function of detuning from the Feshbach resonance $\Delta B = B_{\text{hold}} - B_0$. The region between the dashed lines is the region of the Feshbach resonance. Circles correspond to $t_{\text{hold}} = 2\text{ms}$ and triangles correspond to $t_{\text{hold}} = 30\text{ms}$

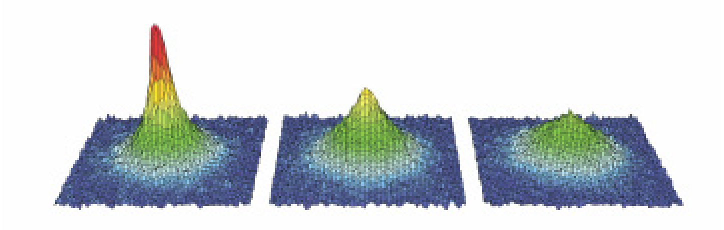

Figure 2. Time of flight images taken after the projection of the fermionic system onto a molecular gas. $\Delta B = 0.12$, 0.25 and 0.55 G(left to right) on the BCS side of the resonance.

Two months after this report, another team in MIT reported a similar observation which was performed with a different type of atom: ^{6}Li[8]. In contrast to the previous experiment, where the condensate fraction was at most 15%, the MIT team reported a high fraction of condensate, which was up to 80%.

2.2 Some Basic Concepts In The Experiment

To understand this new experiment in more detail, we need to get into some more basic ideas/concepts.

2.2.1 The *s*-wave scattering

The *s*-wave scattering length is a basic quantity in describing the interactions in dilute ultra-cold atomic gases (either bosonic or fermionic). Firstly, a basic assumption in these problems is that, in a dilute atomic gas, particles interact essentially as binary atom systems. Specifically, the atom-atom interactions can be described as in binary collisions, partly because the collision complex is so short lived that its interaction with other particles may be neglected.

The collision between two atoms can be treated as a standard quantum scattering problem. Here we can make another important simplification. For ultra-cold atoms, whose thermal-energy are very small, the 2-body scattering with angular momentum $l \neq 0$ can be neglected, since for $l \neq 0$ the probability of finding two atoms at a distance r_0 from each other falls off as $(kr_0)^{2l}$, where k is the relative wavevector. Thus we may restrict our discussions to the $l = 0$ (*s*-wave) scattering.

The so-called *s*-wave scattering length, a_s, is defined as follows,

$$\psi_s(r) \propto \frac{\sin\left[k(r - a_s)\right]}{r},$$

where $\psi_s(r)$ is the wavefunction of the scattered *s*-wave; and we can see that the *s*-wave phase shift $\delta_s = -ka_s$. The value of a_s is in general a function not only of the chemical and isotopic species involved but of the hyperfine indices of the two atoms, and even the external magnetic field. A positive a_s corresponds to a effectively repulsive interaction between the two atoms; and a negative a_s means attractive. The value of a_s also reflects the strength of the interactions. Further, it's not hard to show that for fermions, when $a_s > 0$ they tend to form diatomic molecules and when $a_s < 0$ they prefers to pair-up like Cooper-pairs in a superconductor. A brief derivation on this could be found in Ref.[1] by A. Leggett in 1980.

Interestingly, although the *s*-wave scattering always works in bosonic systems, it's not always the case for fermions! Actually, the spatial wavefunction of two identical fermions with no other degrees of freedom will never take the form of an *s*-wave due to the Pauli principle, which means identical fermions can only interact through a *p*-wave scattering which is much weaker than the *s*-wave process; and this has already made a big problem for experimentalists to cool down atomic Fermi gases. Because the fermionic atoms do not make head-on collisions, one cannot perform the evaporate-cooling which has been essential in cooling down the bosonic atoms to achieve the BEC. Fortunately, people have found ways to overcome this difficulty.

DeMarco and Jin from the JILA team circumvented this roadblock in 1999[2]. The trick they invented is using a mixture of two spin states of the same atom, between which the s-wave collisions are allowed. This method has proved to be quite effective and that's why we saw they include both the $|9/2,-7/2\rangle$ and $|9/2,-9/2\rangle$ states in this latest experiment (see the previous section).

2.2.2 The Feshbach Resonance

The success of the current experiments in this area are all directly based on the ability to tune the value of the *s*-wave scattering length, i.e., the effective interaction strength (and also sign) between the atoms. Such ability is achieved by taking advantage of the physical phenomenon called the Feshbach resonance. A comprehensive discussion of Feshbach resonance in atomic condensate systems can be found in Ref.[9], here let's just have a brief review of the basic ideas.

Consider a system with two degrees of freedom, one of which is associated to the fragmentation of the system. If at a resonance the system would turn into a bound state if the coupling between these two degrees of freedom is set to zero, then such a resonance is a *Feshbach resonance*. For a simple example, we can consider a rare gas atom with a vibrationally excited diatomic molecule. When the rare gas atom is far from the molecule, it sees a weakly attractive potential. During the collision it may excite the molecule into an excited vibrational state, meanwhile it lose some energy and fall into the well of the attractive potential. It would stay trapped in this bound state if the coupling between the movement of the rare gas atom and the vibration of the molecule were zero; while in reality this non-zero coupling turns this bound state into a Feshbach resonance and is responsible for its finite lifetime.

Here in our case of two-body scattering of alkali atoms, the two degrees of freedom involved in the Feshbach resonance are the distance between the atoms and the total spin of the system. More specifically, in the presence of an external magnetic field, an atom should stay in an eigenstate $\left| f, m_f \right\rangle$, where $\mathbf{f} = \mathbf{s} + \mathbf{i}$ is the total atomic spin, with **s** and **i** referring to the total electronic and nuclear spin respectively. A two-atom scattering process would be trivial if the total spin of the system $\mathbf{F} = \mathbf{f}_1 + \mathbf{f}_2$ were conserved. However, the hyperfine interaction term in the Hamiltonian has the form of

$$H_{hf} = \text{const.} \times \left(s_1 \cdot i_1 + s_2 \cdot i_2 \right),$$

which does not commute with the total spin **F**. Therefore during the scattering, this term will give some probability for the system to undergo a spin-flip and thus turn into another channel of molecular dissociation. The Feshbach resonance occurs if the interaction potential of another “spin-flipped” binary atom channel, accessible from the incident channel by virtue of the hyperfine interaction, supports a bound state with energy E_m near the continuum level of the incident channel. Figure 3 (taken from Ref.[9]) gives a schematic representation of such energy levels. The dashed curve corresponds to the potential curve of the incident channel and the solid curve corresponds to another channel with a different total spin. The middle horizontal line gives the Feshbach resonant energy, at which a bound state exists in the upper potential curve.

Since the energy difference between these different spin channels depends on the external magnetic field, people are able to tune the two-atom scattering process to be in the upper or lower neighborhood of the resonance by tuning the magnetic field. Ref.[9] gives the dependence of the effective scattering length on the external magnetic field as:

$$a_{eff} = a - \frac{\gamma}{(B - B_R) \times \frac{\partial \Delta}{\partial B}}$$

where a is the scattering length calculated with the incident channel potential only, B_R is the magnetic field value exactly at resonance, Δ is the energy gap between the two channels when $r \to \infty$ (as shown in Fig.3), and γ is a quantity depending on the matrix elements of the hyperfine interaction. From this formula it's clear that when B is tuned to approach the value of B_R, a_{eff} goes to infinity and can take either positive or negative sign.

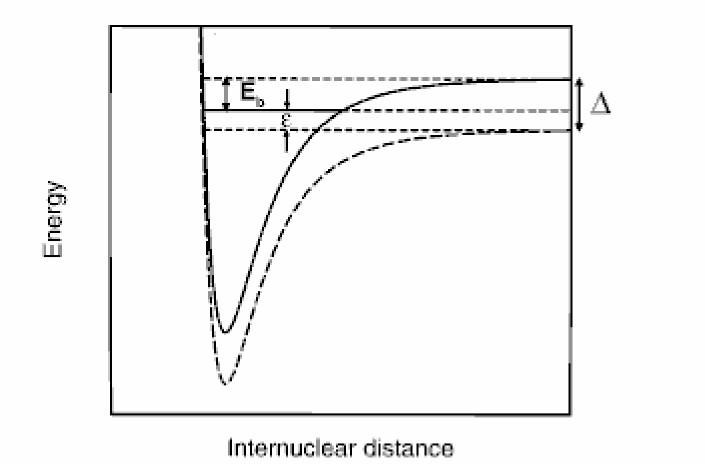

Figure 3. Schematic representation of the molecular potentials of the incident and intermediate state channels in a Feshbach resonance (from Ref.[9]).

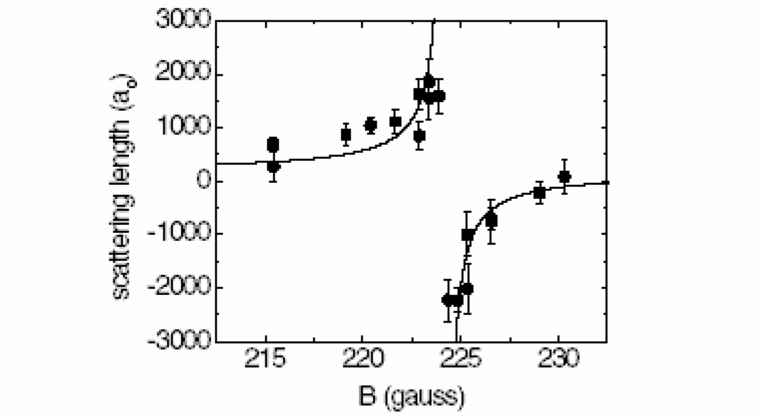

Figure 4. Scattering length versus magnetic field near the Feshbach resonance (from Ref.[10])

Such a dependence of a_{eff} on B has been verified in experiments. Figure 4 shows the measured *s*-wave scattering length between the $m_f = -9/2$ and $m_f = -5/2$ states of ^{40}K atoms near the Feshbach resonance[10]. The divergence of a_{eff} at resonance is clearly shown.

3 Discussion

Although the JILA team's observation was performed successfully and has been widely recognized as an important step forward, their results has also arisen a lot of arguments. The most important question is that, did they really measure the Cooper pairs on the BCS side of the condensation? After their rapid sweep of the magnetic field, do those molecules they observed directly correspond to the initial weakly-bounded Cooper pairs? According to a brief report on this experiment in Physics Today by B. Levi[11], theorist Tin-Lun Ho has made some doubts on this issue. Ho argued that the size of the pairs formed on the BCS side of the resonance should be much larger than the size of the molecules formed at the BEC side, and such difference would not allow any overlap to form molecules after the sweep of the field. Furthermore, he said the collision rate in the strongly interacting regime should allow enough collisions during the magnetic field sweep that the momentum distribution of the molecular condensate can not represent that of the original BCS system.

In the later paper by the MIT group[8], who performed a similar experiment with ^{6}Li and observed the similar phenomena, the authors also explained their results in a different way from the JILA team's arguments. They said that, at the Feshbach resonance, a molecular state has a finite lifetime; and while in the presence of a Fermi sea, its lifetime will be increased due to Pauli blocking from all the other particles. The molecular level will be populated until its energy becomes larger than twice the Fermi energy corresponding to the total number of atoms. The BEC-BCS crossover should occur at this point instead of the location of the two-atom Feshbach resonance. Therefore, instead of declaring having observed atomic Cooper pairs, the MIT scientists tentatively interpreted their result as "a BEC of pairs of atoms which are molecular in character and stabilized by the existence of the Fermi sea"; and they remained that the exact nature of these atom pairs were yet to be elucidated. Then, one week after the publication of the MIT group's paper, two theorists from Netherlands reported that they believe the data reported by the JILA group in Ref.[7] can be understood in terms of a BEC of molecules[12].

In conclusion, despite the remaining mysteries, people have for the first time made a successful attempt to observe an unexplored territory of the BCS-typed condensation of the strongly-interacting fermionic atoms. This has been an important step towards forming an “artificial” fermionic superfluid in atomic gas; and also opened the way towards studying the ideal system of strongly-interacting fermions which might be helpful to the understanding of the high-T_c superconductors. This area is definitely expected to have much more exciting results coming out in the near future.

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