Some Remarkable Developments in Bose-Einstein condensation of Molecules

A. ``Bose-Einstein Condensation of Molecules"

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B. ``A Molecular Bose-Einstein Condensate Emerges From a Fermi Sea"

Authors: Markus Greiner, Cindy A. Regal, and Deborah S. Jin

C. ``Observation of Bose-Einstein Condensation of Molecules

Authors: M.W. Zwierlein, C.A. Stan. S.H. Schunck, S.M.F. Raupach, S. Gupta, Z. Hadzibabic, and W. Ketterle,

Recommended by Tin-Lun (Jason) Ho, Ohio State University and Chandra Varma, Bell labs and University of California, Riverside and a Commentary by Tin-Lun (Jason) Ho

These three papers report the observation of Bose-Einstein condensation (BEC) in a quantum gas of molecules. The discovery of molecular Bose condensate is a milestone in the research of quantum gases and a major progress in the current race to achieve BCS superfluid in dilute Fermi gases. It is also the cumulative success of a sequence of remarkable experimental progress last year which show the rich and intriguing physics of Feshbach resonance. To put this discovery in the right context for readers with different background, we shall first give a brief summary of the rapid experimental development in the last twelve months.

1: Progress of using Feshbach resonance to reach the superfluid phase: It is known for sometime that fermions are more difficult to cool than Bosons. This is because at low temperatures, Fermi statistics severely limits the phase space for scattering. As a result it is hard to get a dilute Fermi gas to equilibrate. This has led to the use Feshbach resonance which increases the interaction between fermions. Larger interaction will not only help the fermions to equilibrate, but will also increase Tc for superfluidity. That Tc will be of order of Fermi energy E_{F} near Feshbach resonance was suggested by Holland et.al. , PRL 87,120406 (2001).

Feshbach resonance is facilitated by an external magnetic field, which controls the energy difference between a pair of atoms in scattering state and that in a bound state. When the magnetic field B is below certain value, (say B_o), the bound states become more stable and molecules begin to emerge. As the magnetic field approaches the resonance (B_{o}) from above or below, the s-wave scattering length approaches negative or positive infinity. (See fig.1). Since the s-wave scattering length gives the coupling constant in an low energy effective field theory, the system near resonance is generally referred to as strongly interacting. The region of magnetic field where scattering length is positive or negative is generally referred to as the ``repulsive" or ``attractive" side of the resonance.

2. Universality near resonance: In early 2003, the interesting many-body physics of Feshbach resonance began to emerge. A number of experiments have shown that many properties of Fermi gases near resonance become universal. These include the interaction energy (found by John Thomas's group at Duke and by Chris Salmon's group at Ecole Normale Superiore), and energy shift of quasi-particle as reflected in RF spectroscopy experiments, (Wolfgang Ketterle's group at MIT and Debbie Jin's group at JILA). See also Search and Discovery in Physics Today, November 2003.

3. Production of long lived molecules using Feshbach resonance: In May 2003, Debbie Jin's group at JILA reported successful conversion of over 50 percent of the atoms (of a Fermi gas of K-40) into molecules by tuning the system from the attractive side to the repulsive side of the resonance. Remarkably, such conversion is reversible. All molecules are converted back atoms when the magnetic field is tuned back to the attractive side. A few months later, other groups (Randy Hulet's group at Rice and Chris Salomon's group at ENS) have also reported similar conversion of the atoms in Li-6 into molecules. The molecules in all these experiments are found to very long lived, setting the stage to Bose condensation.

4. Discovery of molecular BEC: Within a period of about a month around November 2003, Rudi Grimm's group at Innsbruck, Debbie Jin's group at JILA, and Wolfgang Ketterle's group at MIT have reported the discovery of molecular BEC. These reports have immediately generated world wide attention. Not only is the discovery an important step towards the realization of BCS superfluid, it also brings forth a new condensate where the constituent Bosons have a tunable internal structure, as external magnetic field can change the size of the molecules. The followings are brief descriptions of the findings in these experiments.

A. The Innsbruck experiment: Molecular BEC (of Li-6) is achieved by using a cleverly designed trap which enables one to spill out the atoms but not the molecules. Evidence of BEC comes from estimates of the number of ferimions in the trap, since a lot more fermions can be accommodated when fermion pairs turn into condensed Bose molecules. The strongest evidence, however, comes from the observation of a collective mode characterized of Bose-Einstein condensate.

B. The JILA experiment: Molecular condensate (of K-40) is formed by adiabatically tuning a highly degenerate Fermi gas from the attractive to the repulsive side of the resonance. No evaporative cooling is needed in this progress . The formation of molecular BEC is observed by direct imaging. In this experiment, both atoms and molecules coexist on the repulsive side of the resonance. It is found that the system is in thermal equilibrium but not chemical equilibrium. Moreover, the maximum amount of atoms can be converted to molecules is found to be 88%, and that there is always a heating of about 27K when the system is brought from the attractive side to repulsive side of the resonance and back, independent of initial condition. All these findings are yet to be understood.

C. The MIT experiment: The setup of this experiment is similar to that of Innsbruck's. The molecular condensate (of Li-6) is found by direct imaging. The MIT group have measured the chemical potential from expansion of the condensate and observed a molecule-molecule interaction an order of magnetic smaller than that predicted theoretically (D.S. Petrov, C. Salomon, and G. Shlyapnikov, cond-mat/0309010).

The study of molecular condensate is just starting. The phase diagram has yet to be mapped out and many properties have to be studied. So far, the molecular condensates are produced sufficiently far from resonance so that the size of molecules are smaller than the inter-particle spacing. As a result, the properties of these condensate are similar to that of atomic condensates. The situation will surely be changed as experiments begin to explore the regions close to resonance where the size of molecules become so big that they begin to overlap. Currently, many experimental groups are trying to obtain a BCS superfluid by bringing the molecular condensate back to the attractive side of the resonance. (See fig.2). It is expected great progress will be made in the coming months.

Figure: Typical behavior of S-wave scattering length near Feshbach Resonance

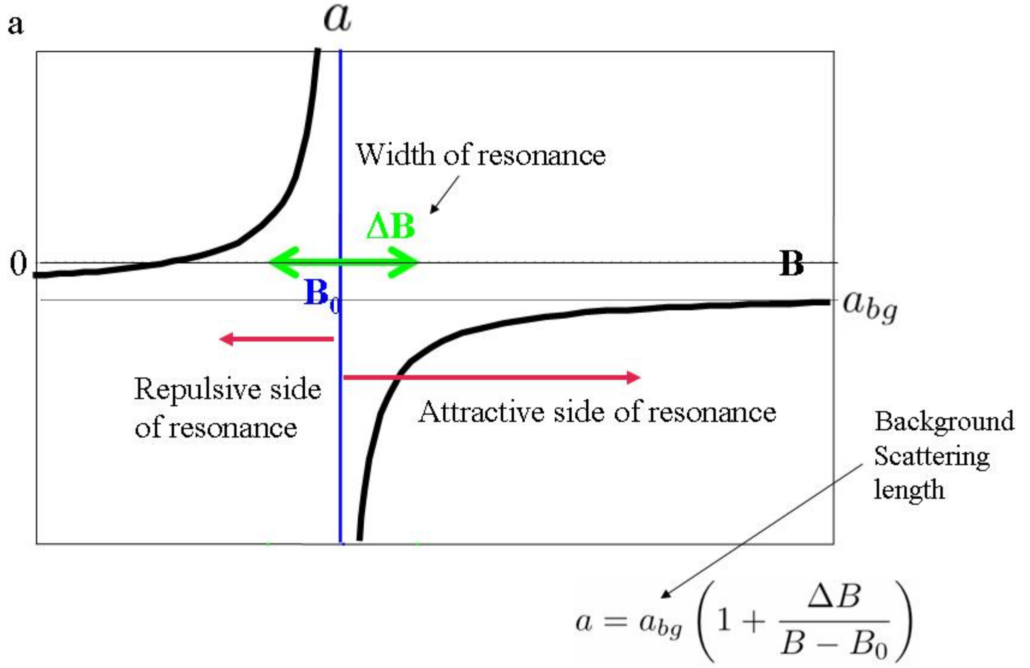
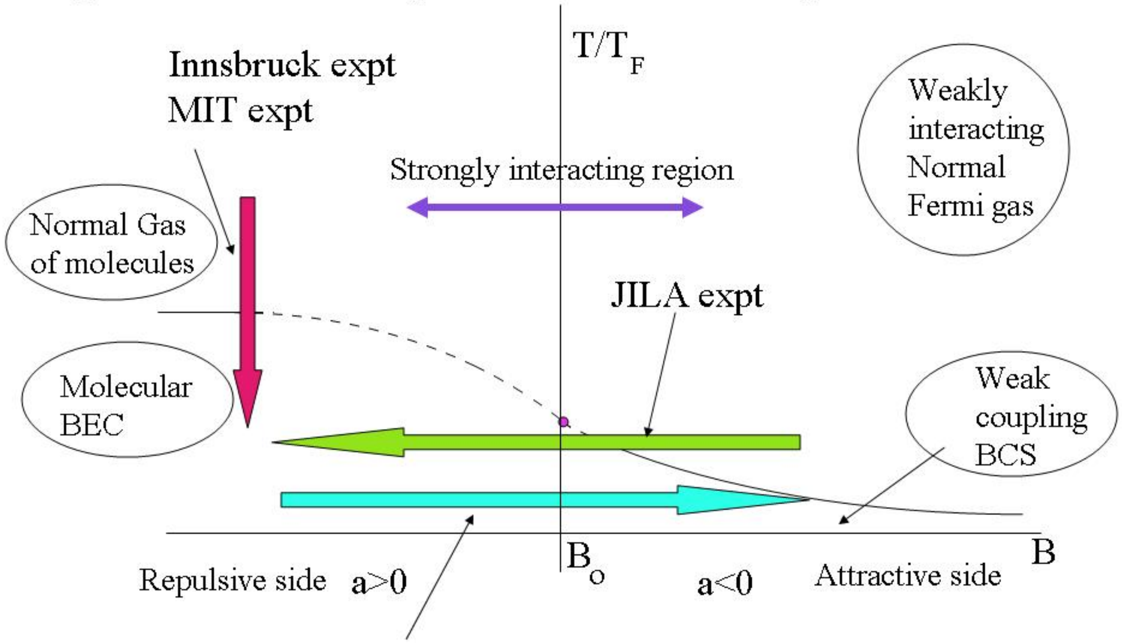


Figure 2 : Schematic Representation of current experiments



Current attempt of generating BCS superfluid from a molecular BEC