Feshbach Resonance: The Magician in the World of Absolute Zero

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Abstract In 2003-2005, a series of ground-breaking experiments revolutionized the perspectives and the scope of ultracold atom research. By inducing magnetic *Feshbach resonances* in Bose condensates or Fermi degenerate gases, experimentalists found that atoms develop singular and, ironically, universal behaviors, which resemble other complex and correlated systems in Nature. These results lead to brand new, interdisciplinary view to address fundamental issues in many-body physics, high-Temperature superconductivity, the evolution of early universe and even new quantum computation architecture. At the *University of Chicago*, we have initiated a new research program to pursuit these goals.

Feshbach resonance Feshbach resonances are quantum mechanical scattering resonances that were first discussed in the framework of nuclear physics (see, for instance, H. Feshbach, Theoretical Nuclear Physics, Wiley, New Work, 1992). In the physics of ultracold atoms, this collision process takes place at very low scattering energies. A Feshbach resonance occurs when the state of two free colliding atoms couples to a molecular bound state, and can be induced by an external magnetic field. Interaction parameters including scattering length and the scattering cross section are drastically altered near the Feshbach resonances. See Figure 1.

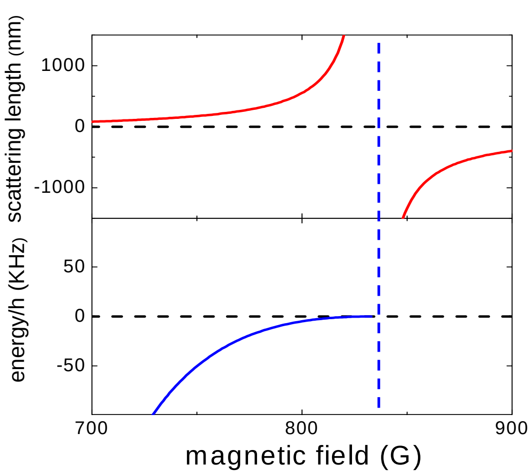

Figure 1. Scattering length of ultracold Li-6 atoms near a Feshbach resonance.

When the magnetic field is tuned close to a Feshbach resonance at 834.1(1) Gauss (earth magnetic field is 0.5 Gauss), the scattering length *a* exceeds 1000 nm. This leads to an effective atomic collision cross section of $4\pi a^2 = 13\ \mu m^2$, which is approximately 100 million times larger than the physical size of a lithium atom.

Controlled creation of molecules and ultracold chemistry

An atomic Bose-Einstein condensate (BEC) is a macroscopic quantum state in which all atoms are swinging coherently in perfect unison. When taking atoms in a BEC close to a Feshbach resonance, the fascinating prospect of creating coherent molecular matter-waves is opened. This possibility situated a wide range of exciting experiments to explore the formation of ultracold molecules and controlled molecular interactions at nano-Kelvin temperatures, see Figure 2.

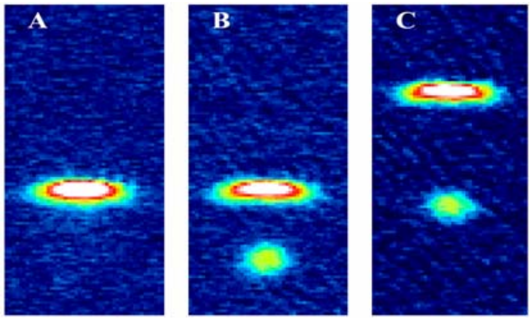

Figure 2. Creation of ultracold molecules from atomic Bose-Einstein condensates.

By ramping the magnetic field across a Feshbach resonance, the figures show that ultracold molecules (smaller clouds in B. and C.) can be created from atomic BECs (large clouds in A, B and C.) *(Courtesy of R. Grimm, Innsbruck Univ.)*

Atomic Cooper Pairs and High-Tc Superfludity Observation of pairing in ultracold fermionic atoms in 2003-04 marked a major triumph by fusing ultracold quantum gases into superconductor and helium-3 superfluid physics. Research in the following years provided a solid underpinning of BEC in the realm of superfluidity. The fermionic nature of the system attracted new and even broader interest due to its relevance to condensed matter and nuclear physics. This discovery was ranked one of the top 10 science breakthroughs in 2004 by the Science Magazine. See Figure 3.

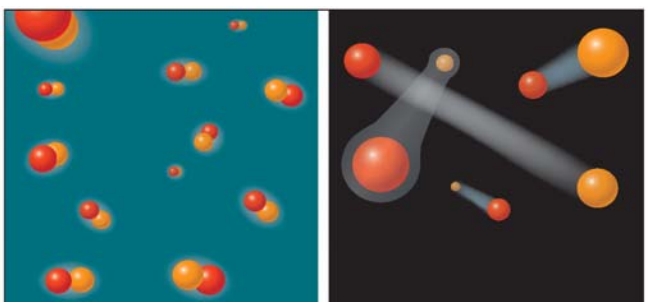

Figure 3. Crossover from molecules (Left) to atomic Cooper pairs (Right)

This process, called BEC-BCS crossover, was first observed in ultracold gases of fermionic atoms near a Feshbach resonance. *(Courtesy of Science Magazine)*

Future Experiments and Acknowledgment

At the University of Chicago, we have initiated a new research program on ultracold atoms and Feshbach resonances to explore the potential of tunable quantum gases and the precision control on ultracold atoms and molecules. Our goals are 1. Addressing fundamental issues in few- and many-body Physics to model complex quantum systems; 2. Constructing novel quantum devices to implement a precision, stereotactic control of atoms in optical lattices. Our cold atom apparatus is shown in Figure 4.

I greatly appreciate the support of the Physics Department and the James Franck institute at the University of Chicago, which provide us the opportunity to recruit first-rate students and postdocs to build modern research laboratories and to work with other excellent researchers.

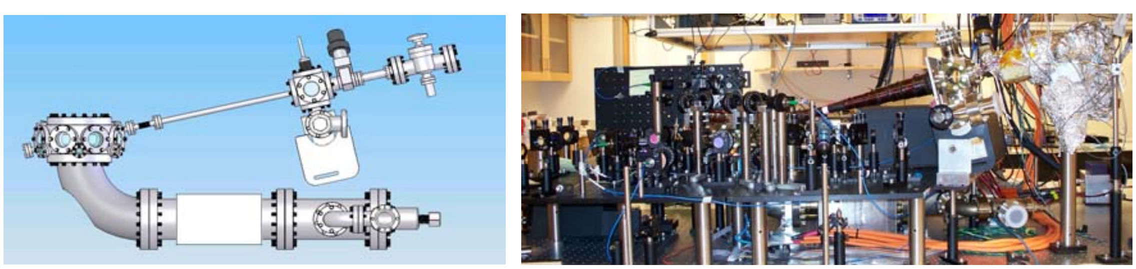

Figure 4 Experiment apparatus design (left) and the photo (right) in Cheng Chin group.