Ultracold Quantum Gases

RLE Groups
Atomic, Molecular and Optical Physics Group; MIT-Harvard Center for Ultracold Atoms

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Overview

Our newly founded research group has taken quarters on the second floor of MIT's building 26, in the Center for Ultracold Atoms. Here we study the properties of ultracold gases of atoms and molecules. Our focus lies on strongly interacting mixtures of fermionic atoms, atoms with half-integer spin. In these novel systems we can realize superfluids of fermion pairs and other paradigms of many-body physics. The goal is to improve our understanding of strongly correlated systems, such as nuclear matter, high-temperature superconductors or quantum magnets.

1. Laser cooling and trapping of potassium-40 using a natural abundance sample

In a recently renovated laboratory we have begun the construction of a new apparatus that can simultaneously cool and trap two different fermionic species, lithium-6 and potassium-40. One major interest lies in the creation of heteronuclear, stable ground-state molecules that carry a strong electric dipole moment. Confined in optical lattices, these molecules could be addressable qubits of a quantum computer. Another major thrust area will be the study of many-body physics with mass-imbalanced Fermi mixtures: The creation of fermionic superfluids with mass imbalance and rudimentary analogues for quark matter, employing Fermi mixtures with three different "colors".

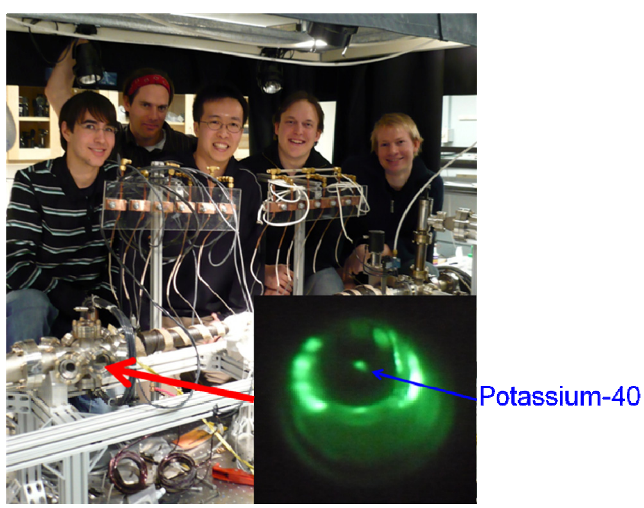

Fig.1: The new lab and its crew, with a picture showing fluorescence of trapped potassium-40 atoms.

One potential difficulty had been the low natural abundance of potassium-40 of only 0.012%. In previous setups, experiments had to resort to expensive sources of enriched potassium-40. We have overcome this problem via direct loading of non-enriched potassium-40 from a Zeeman slowed atomic beam, and demonstrated laser cooling and trapping of 50 million potassium-40 atoms at a loading rate of more than 107 atoms/s, competitive with experiments using enriched sources. This provides us with a very good starting point for our experiments on mass-imbalanced Fermi-Fermi mixtures.

2. Stability of a three-state mixture of ultracold fermions

We have initiated the study of Fermi mixtures with atoms in three different spin states. This realizes the three-fold “color” symmetry of quarks. Thanks to the phenomenon of Feshbach resonances, interactions between the three different spin states change as a function of the applied magnetic field. We found that the stability of the mixture varies dramatically, by over four orders of magnitude, with the interaction strength. We identified a region of weak interactions where the mixture survives for over 20 s, and a resonant loss for strong interactions between at least two of the three states, with lifetimes of less than a millisecond. Intriguingly, there exists a peculiar loss resonance for the three colors around a particular value of the magnetic field where all two-particle interactions are attractive. This might be related to an Efimov resonance. Here, three particles with attractive interactions can form a bound state, a trimer, even though two particles alone would not be paired. We are currently investigating ways to prove or disprove the relevance of Efimov physics for the observed resonance.

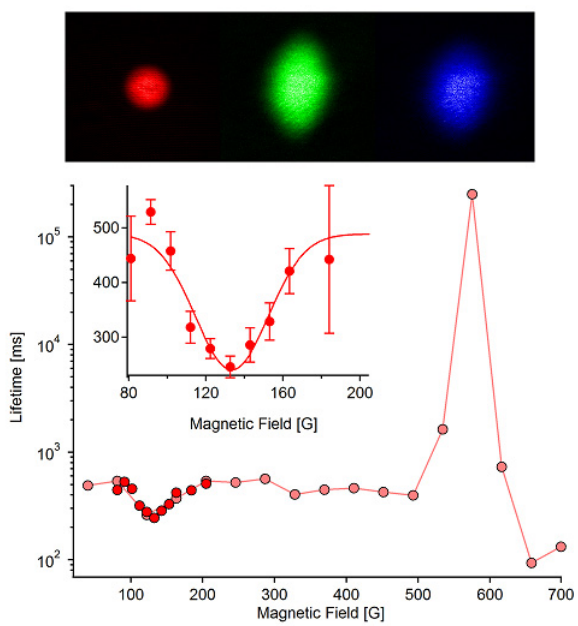

Fig. 2: Top: Stable, “color” mixture of three different spin states of fermionic ^{6}Li atoms at 570 G. Bottom: Lifetime of the three-state mixture as a function of magnetic field. The mixture is stable around 570 G, where all interactions are weak. A three-body loss resonance is identified at 135 G. Beyond 600 G, the mixture becomes unstable towards two-body losses near Feshbach resonances.

3. Coherence and clock shifts in ultracold Fermi gases with resonant interactions

Mixtures of lithium-6 atoms with tunable interactions provide a remarkable new system to study fermionic superfluidity, the BEC-BCS crossover and spin-imbalanced superfluids. Here, one major result has been on the theoretical front:

Interatomic interactions limit the accuracy of today’s atomic clocks, causing density-dependent clock shifts in radiofrequency (RF) transitions. Similarly, such shifts play an important role in probing correlations in atomic gases, where, e.g., RF spectroscopy has been used to detect the presence of molecules and provide evidence for pairing gaps. Surprisingly, experimentally observed clock shifts become small when interactions are resonantly enhanced, a result which we were now able to explain [1]. We derived a general theory for the average clock shift in interacting gases, and showed that in the strongly interacting regime the shifts depend inversely on interatomic scattering lengths. Our results also highlight the crucial role played by final state effects in RF transitions.

References

[1] Gordon Baym, C. J. Pethick, Zhenhua Yu, and Martin W. Zwierlein. Phys. Rev. Lett. **99**, 190407 (2007).

Publications

Journal Articles, Published

Gordon Baym, C. J. Pethick, Zhenhua Yu, and Martin W. Zwierlein, “Coherence and clock shifts in ultracold Fermi gases with resonant interactions”, Phys. Rev. Lett. **99**, 190407 (2007).

Chapters in Books

W. Ketterle and M. W. Zwierlein, “Making, probing and understanding ultracold Fermi gases,” in *Ultracold Fermi Gases, Proceedings of the International School of Physics “Enrico Fermi”, Course CLXIV, Varenna, 20 - 30 June 2006*, eds. M. Inguscio, W. Ketterle, and C. Salomon (Amsterdam: IOS Press, 2008); e-print: arXiv: 0801.2500.

Meeting Papers

“High-Temperature Superfluidity in an Ultracold Fermi Gas”, M.W. Zwierlein, J. Abo-Shaeer, A. Schirotzek, C.H. Schunck, and W. Ketterle, DAMOP 2007 – Thesis Prize Session, Calgary, Canada, 6/7/2007

“Fermionic Superfluidity with Imbalanced Spin Populations”, M.W. Zwierlein, A. Schirotzek, C.H. Schunck, Y. Shin, and W. Ketterle, IQEC / CLEO Europe 2007, Munich, Germany, 6/21/2007

“The Ground State of Imbalanced Fermi Mixtures”, C.H. Schunck, A. Schirotzek, Y. Shin, M.W. Zwierlein and W. Ketterle, A.I. Larkin Memorial Conference, Landau Institute, Chernogolovka, Russia, 6/24/2007

“Pairing and Superfluidity in Ultracold Fermi Mixtures”, M.W. Zwierlein, Correlated Quantum Gases Workshop, Marburg, Germany, 7/3/2007

“The Ground State of Imbalanced Fermi Mixtures”, C.H. Schunck, A. Schirotzek, Y. Shin, M.W. Zwierlein and W. Ketterle, Control of Quantum Correlations in Tailored Matter, Schloss Reisensburg, Reisensburg, Germany, 10/6/2007

“RF Spectroscopy of Strongly Interacting Fermi Gases”, G. Baym, C.J. Pethick, Z. Yu, and M.W. Zwierlein, Ultracold Atoms and Quark-Gluon Plasmas, Niels Bohr International Academy and NORDITA, Copenhagen, Denmark, 6/23/2008