Ultracold Quantum Gases

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

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Overview

Our group studies 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 high-temperature superconductors, colossal magnetoresistive materials and heavy fermions.

1. Creation of Fermi-Fermi-Bose mixtures

In our newly built apparatus we have been able to create mixtures of the two fermionic atoms ^{6}Li, ^{40}K, together with the boson ^{41}K. A first breakthrough has been the direct Bose-Einstein condensation of ^{41}K.

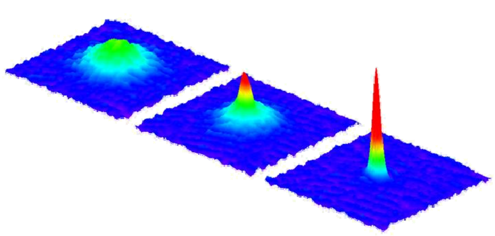

Figure 1 Emergence of a Bose-Einstein condensate of ^{41}K. The time-of-flight pictures of the atom cloud show in the center the characteristic bimodal velocity distribution of thermal and condensed atoms.

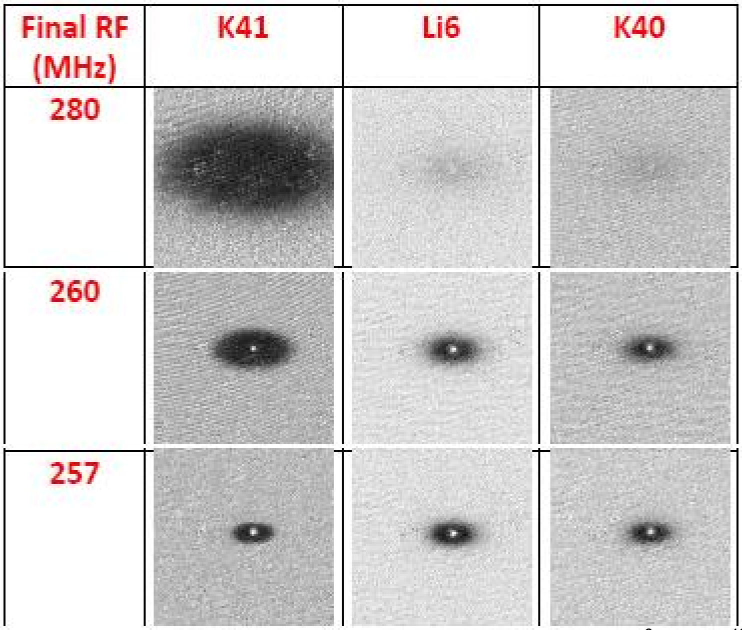

Figure 2 Cooling of three different atomic species. The two fermionic atoms ^{6}Li and ^{40}K are sympathetically cooled by the boson ^{41}K in a magnetic trap, “plugged” in the center by a repulsive laser beam.

We have since been able to sympathetically cool the different species together in the same trap. This now sets the stage for experiments on strongly interacting quantum gas mixtures. We have recently observed new Feshbach resonances between ^{6}Li and ^{41}K, as well as ^{40}K and ^{41}K that will allow the control of the interaction strength between atoms and the creation of heteronuclear molecules.

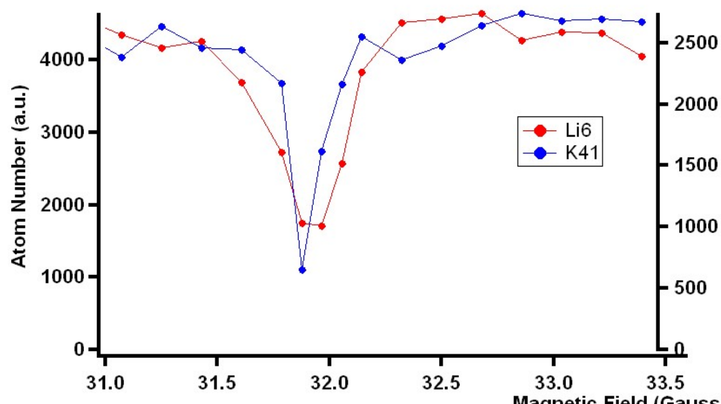

Figure 3 Feshbach resonance between ^{6}Li and ^{41}K, observed in atom loss through molecule formation.

In their ground state, these molecules carry a strong electric dipole moment. Confined in optical lattices, they 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. This will allow us to create a model system for metal-insulator transitions, quantum magnets and superfluids in the presence of disorder.

2. Equation of State of a Strongly Interacting Fermi Gas

The equation of state of a gas, i.e. the relation between density, temperature and pressure governs all of its thermodynamic properties. Its behavior can reveal whether the system consists of bosonic or fermionic degrees of freedom, or the location of phase transitions. The equation of state of strongly interacting Fermi gases is important for the modeling of neutron stars. Cold atomic gases allow direct access to such strongly interacting matter, as the interaction strength can be freely tuned near a Feshbach resonance. Right on resonance, interactions are as strong as allowed by quantum mechanics – a limit known as the unitarity limit. At this point the only length scales relevant for the gas are the interparticle spacing and the de Broglie wavelength, the only energy scales are the Fermi energy and the temperature. On dimensional grounds, the density *n* then must obey a universal equation of state:

$$n\lambda^3 = f(e^{\beta\mu})$$

Where λ is the de Broglie wavelength, $\beta=1/k_BT$ is given by the inverse temperature, and μ is the chemical potential of the gas. Away from resonance another length scale comes into play, the scattering length *a*, which diverges on resonance, and the equation of state then also depends on the dimensionless quantity λ/a.

From in-situ density profiles we have obtained the equation of state of strongly interacting Fermi gases to highest accuracy to date. It provides a benchmark for many-body theories of such systems. The most advanced such theory, which is believed to provide exact results, is the diagrammatic Monte-Carlo method by B. Svistunov and N. Prokof'ev [1]. However, so far the calculation only works at high temperatures. Our experiment fully agrees with the theoretical limit, but goes far beyond into the degenerate regime where eventually the gas becomes a superfluid of fermion pairs. The hope is that with such high accuracy we can conclude whether there is a so-called "pseudo-gap" regime of preformed pairs right above the critical temperature for superfluidity, or whether the gas is better described as a Fermi liquid all the way down to that critical temperature. This would solve a long-standing debate in the field. Previous studies [2-3] suffered from systematic errors that did not allow reliably concluding on this question.

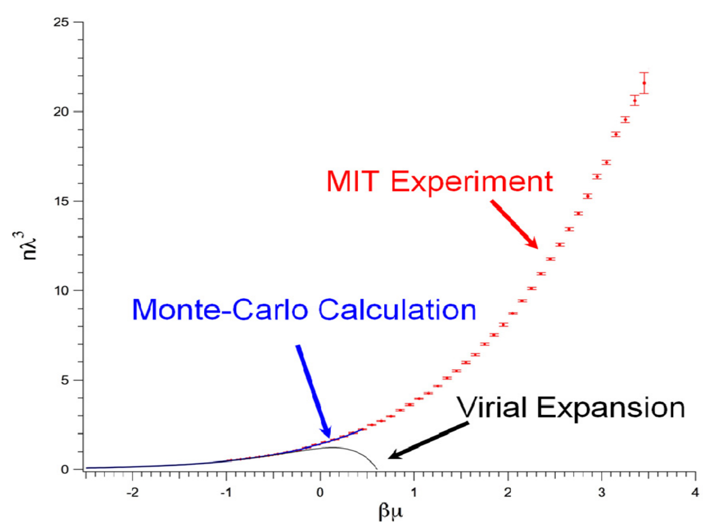

Figure 4 Equation of state for strongly interacting Fermi gases. The Virial expansion becomes exact for high temperatures.

References
[1] N. Prokof'ev, and B. Svistunov, Phys. Rev. B **77**, 020408 (2008).
[2] S. Nascimbène et al., Nature **463**, 1057 (2010)
[3] M. Horikoshi et al., Science **327**, 442 (2010)

3. Universal Spin Transport in Strongly Interacting Fermi Gases

We have observed universal spin transport in strongly interacting Fermi gases. In such a gas, the mean free path between collisions for an atom is as short as at all possible, one interparticle spacing. That means that particles scatter as soon as they meet, a situation that is believed to lead to ‘perfect fluidity’.

In a first experiment, we completely separated the two interacting components of our gas (‘spin up’ and ‘spin down’), and then let them collide with each other. Although a million times thinner than air, the two gas clouds were observed to almost perfectly repel each other. This is a dramatic manifestation of the strong interactions in resonant Fermi gases.

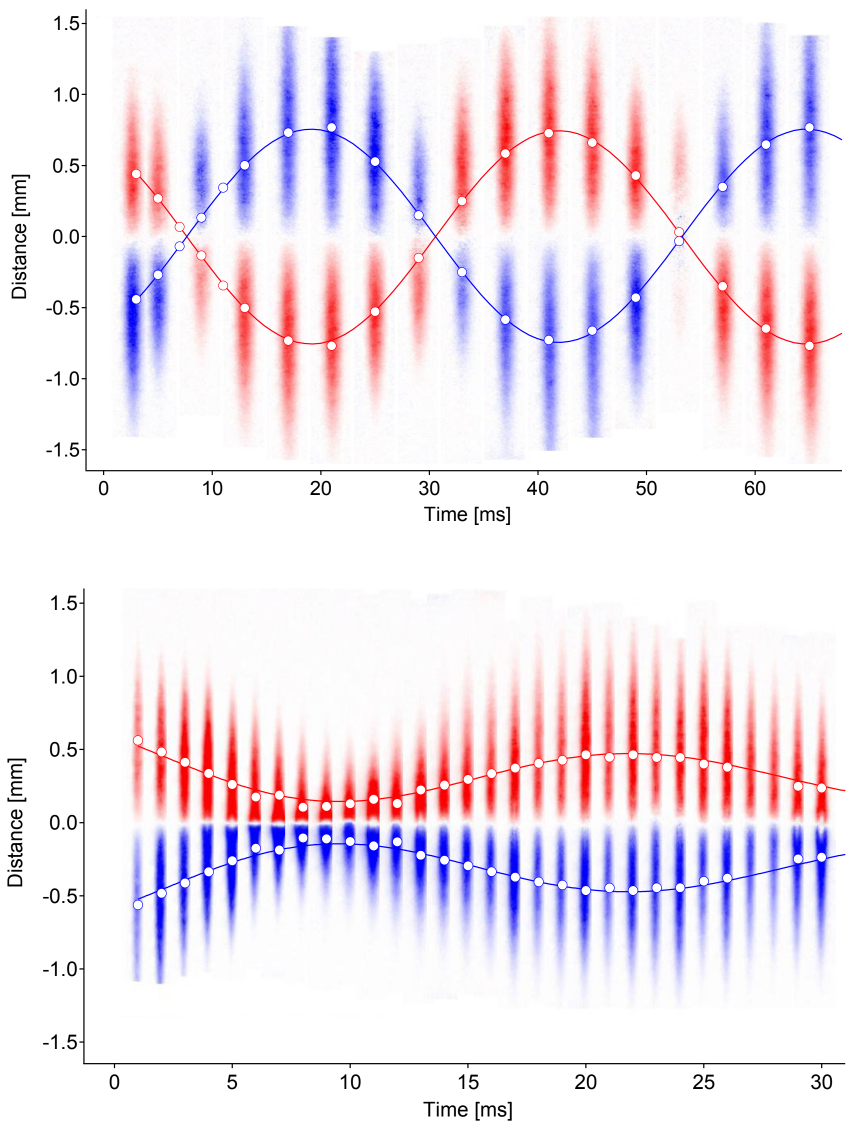

Figure 5 Evolution of Spin current in non-interacting (top) and strongly interacting (bottom) Fermi gases. Non-interacting spin up (red) and spin down (blue) gases simply penetrate through each other without undergoing collisions. For resonant interactions, repulsion is so strong that the clouds bounce off each other.

After several ‘reflections’ and collisions, the clouds very slowly begin to penetrate through each other. We found the diffusion constant D to be given by constants of Nature, Planck’s quantum h divided by the mass of the particles, m. This is the slowest diffusion possible in three-dimensional free space.

Our study of spin transport is relevant for the use of the electron spin as a carrier of information in ‘spintronics’; and to the transport in other strongly interacting systems, most notably the Quark-Gluon Plasma. String theorists are currently working on a unified view of such strongly interacting systems, and our experiment will provide a valuable benchmark for these novel theories.

4. Competition between pairing and ferromagnetic instabilities in ultracold Fermi gases near Feshbach resonances

This theoretical study investigated the fate of a repulsive Fermi gas whose interactions are suddenly switched on. Two effects compete: As unlike spins repel each other, beyond a certain strength of repulsion, the gas would have the tendency to phase separate into spin up and spin down domains (Stoner ferromagnetism). However, there is also an attractive, inelastic channel – atoms can form molecules. In the ground state, the system would be a Bose-Einstein condensate of molecules. Here we studied the timescale of these two competing effects – phase separation and pairing, and found that pairing is in fact faster. This suggest that fast quench experiments cannot access the metastable repulsive branch long enough for domain formation to occur.

Publications

Journal Articles, Published

Martin Zwierlein, *News&Views: Neutral Atoms put in Charge,* Nature **462**, 584 (2009)

Journal Articles, Submitted for Publication

D. Pekker, M. Babadi, R. Sensarma, N. Zinner, L. Pollet, M. W. Zwierlein, E. Demler *Competition between pairing and ferromagnetic instabilities in ultracold Fermi gases near Feshbach resonances*, preprint arXiv:1005.2366 (2010)

Chapters in Books

Martin Zwierlein, *Fermionic Superfluidity and the BEC-BCS Crossover in Ultracold Atomic Fermi Gases,* in Foundations of Quantum Mechanics in the Light of New Technology, ISQM-Tokyo '08, 25-28 August 2008, eds. Sachio Ishioka and Kazuo Fujikawa, (World Scientific, 2009)

Meeting Papers, Presented

1. *Observation of Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms.* RPMBT15, "Recent Progress in Many Body Theory", Columbus, OH, 7/27/2009¶
2. *Observation of Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms.* EMMI workshop "Quark-Gluon-Plasma meets Cold Atoms - Episode II", Haus Bergkranz, Riezlern, Austria, 8/5/2009
3. *Observation of Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms.* BEC 2009, San Feliu, Spain, 9/5/2009
4. *Fermi Polarons - Building up a Fermi Liquid from the Bottom Up.* International Symposium on "Novel states in correlated condensed matter -- from model systems to real materials", Berlin, Germany, 3/2/2010
5. *Fermi Polarons - Building up a Fermi Liquid from the Bottom Up.* 3rd Boston Area Quantum Matter meeting, Boston, MA, 4/3/2010

6. *Radiofrequency Spectroscopy of Strongly Interacting Fermi Systems.* International Workshop on Ultracold Fermi Gases: Superfluidity and Strong Correlations, Tokyo, Japan, 5/14/2010 (Talk by A. Schirotzek)
7. *Universal Spin Transport in Strongly Interacting Fermi Gases.* Nordita program "Quantum solids, liquids, and gases", Stockholm, Sweden, 8/11/201

Meeting Papers, Published

1. *M. Ku, A. Schirotzek, A. Sommer, M. Zwierlein Equation of state of a strongly interacting Fermi gas.* APS March Meeting 2010, Portland, OR, 3/14/2010
2. *A. Sommer, A. Schirotzek, M. Zwierlein Universal Spin Transport in a Strongly Interacting Fermi Gas.* APS March Meeting 2010, Portland, OR, 3/15/2010
3. *A. Sommer, A. Schirotzek, M. Ku, M. Zwierlein Spin Transport in a Strongly Interacting Fermi Gas.* DAMOP 2010, Houston, TX, 5/27/2010
4. *F. Werner, K. van Houcke, E. Kozik, N. Prokof'ev, B. Svistunov, A. Schirotzek, A. Sommer, M. Ku, M. Zwierlein Equation of State of the Unitary Gas: Theory and Experiment.* DAMOP 2010, Houston, TX, 5/27/2010
5. *C.-H. Wu, I. Santiago, J.-W. Park, P. Ahmadi, M. W. Zwierlein Towards strongly interacting Fermi-Fermi mixtures of ultracold atoms.* DAMOP 2010, Houston, TX, 5/28/2010
6. *M. Ku, A. Schirotzek, A. Sommer, M. Zwierlein Equation of state of a strongly interacting Fermi gas.* DAMOP 2010, Houston, TX, 5/29/2010

Reports

7. *Strongly Interacting Gases of Ultracold Fermions.* AFOSR-MURI meeting, Cambridge, MA, 10/30/2009
8. *Strongly Interacting Gases of Ultracold Fermions.* DARPA OLE Phase II kick-off meeting, Miami, FL, 12/2/2009
9. *Universal Spin Transport in Strongly Interacting Fermi Gases.* CUA Advisory Committee Meeting, Harvard University, Cambridge, MA, 5/13/2010
10. *Universal Spin Transport in Strongly Interacting Fermi Gases.* DARPA OLE Review meeting, Houston, TX, 5/25/2010

Theses

André Schirotzek, *Radiofrequency Spectroscopy of Ultracold Atomic Fermi Gases*, PhD-Thesis, 2010
Sara Campbell, *Building an Apparatus for Ultracold Lithium-Potassium Fermi-Fermi Mixtures*, BA thesis, 2010