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. Apparatus for studying Fermi-Fermi-Bose mixtures in optical lattices

We have completed the assembly of a new apparatus that can simultaneously cool and trap two different fermionic species, ^{6}Li and ^{40}K, as well as ^{39}K. The cold atom sources are also able to provide ^{87}Rb and ^{23}Na in the future. 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. This will allow us to create a model system for metal-insulator transitions, quantum magnets and superfluids in the presence of disorder.

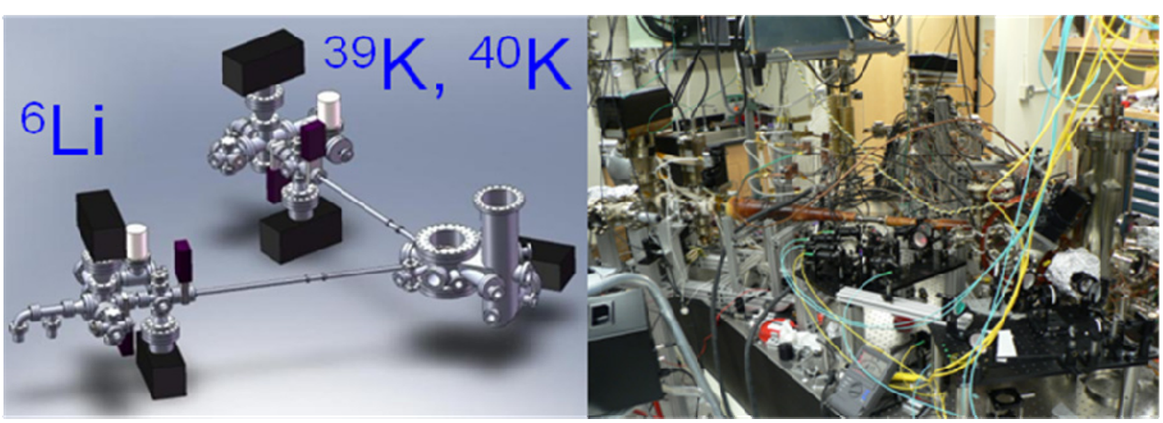

Fig. 1 Design and Reality. The new Fermi-Fermi-Bose apparatus at RLE@MIT.

Our system is able to load 4x10^{10} ^{39}K atoms in 100 ms, 1x10^{9} ^{6}Li atoms in 1 s, and 5x10^{7} ^{40}K atoms in 2 s, despite the low natural abundance of 0.01% of ^{40}K. This is an excellent starting point for the experiment. We have very recently loaded 1x10^{10} ^{39}K atoms into a magnetic trap, where it will act as the coolant for ^{6}Li and ^{40}K. By only evaporating the abundant boson, we will essentially conserve the fermion numbers and are hopeful to obtain large numbers of degenerate fermions.

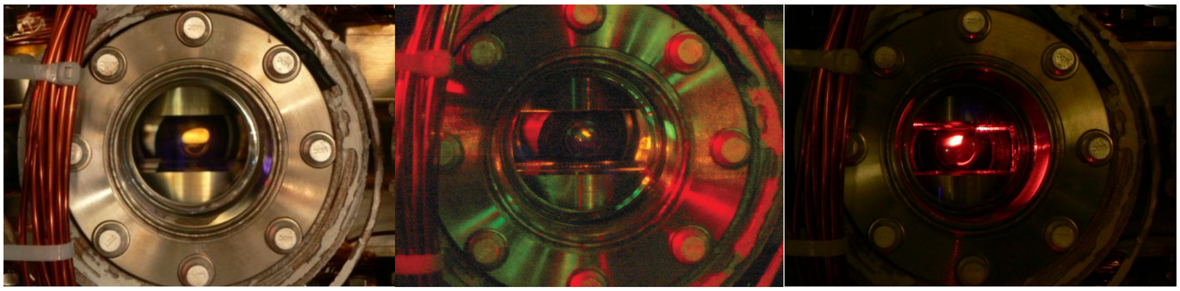

Fig. 2 Three magneto-optical traps realized in the new apparatus: ^{39}K, ^{40}K and ^{6}Li.

2. Observation of Fermi Polarons in a Tunable Fermi Liquid of Ultracold Atoms

The fate of a single particle interacting with its environment is one of the grand themes of physics. A well-known example is that of the electron moving through the crystal lattice of ions in a solid. The electron attracts positive ions, repels negative ones and thereby distorts the lattice. In other words, it polarizes its surroundings. The electron and the surrounding lattice distortions are best described as a new particle, the lattice polaron. It is a so-called quasiparticle with energy and mass that differ from that of the bare electron. Polarons are crucial for the understanding of colossal magneto resistance materials and they are responsible for conduction in fullerenes and polymers. Another famous impurity problem is the Kondo effect: Here, a localized magnetic impurity interacts with a Fermi sea of electrons, hindering their transport and leading to an increase in the metal's resistance below a certain temperature.

In the present work, we have observed Fermi polarons, dressed "spin down" impurity atoms immersed in a Fermi sea of "spin up" atoms. The interactions between the impurity and the environment can be freely tuned by means of a Feshbach resonance. This allows us to determine the polaron energy as function of interaction strength.

The work appeared as an Editor’s suggestion in Physical Review Letters [1] and was featured in “Physics” [2].

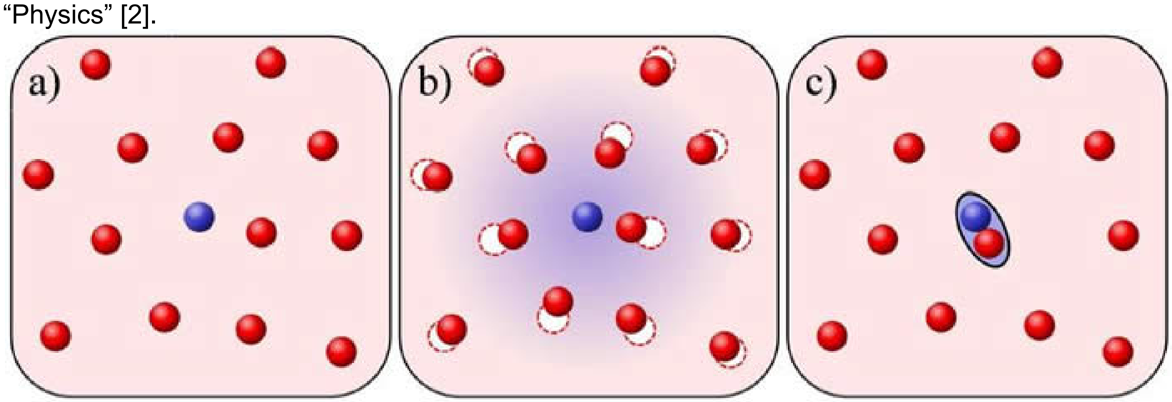

Figure 3 a) For weak interactions, the impurity (blue) can propagate freely through the environment (red), a Fermi sea of atoms. b) As the interaction is increased, the impurity starts to attract its surroundings, "dressing" itself with a cloud of environment atoms. This is the Fermi Polaron. c) For strong attraction, the spin down atom will bind exactly one spin up partner, forming a molecule. The transition from polarons to molecules occurs as soon as the binding can overcome Pauli blocking of the environment.

There exists a variational Ansatz by F. Chevy that captures the essential physics of the Fermi Polaron. The wavefunction of the single spin down particle immersed in a Fermi sea of spin ups is written as [3]:

$$\left|\Psi\right\rangle = \varphi_0 \left|\mathbf{0}_\downarrow, \mathrm{FS}_\uparrow\right\rangle + \sum_{q<k_F}^{k>k_F} \varphi_{\mathbf{qk}}\, c^\dagger_{\mathbf{k}\uparrow} c_{\mathbf{q}\uparrow} \left|\mathbf{q}-\mathbf{k}_\downarrow, \mathrm{FS}_\uparrow\right\rangle \tag{1}$$

The spin down particle is either unperturbed (amplitude φ_0), or it scatters a spin up particle out of the Fermi sea (amplitude $\varphi_{\mathbf{qk}}$) (see Fig. Fig. 4). Thus, $\left|\varphi_0\right|^2$ measures how much of the polaron still appears like a free particle. This is known as the quasiparticle weight, a central quantity in the theory of a Fermi liquid, which we here measure using RF spectroscopy as a function of the interaction strength.

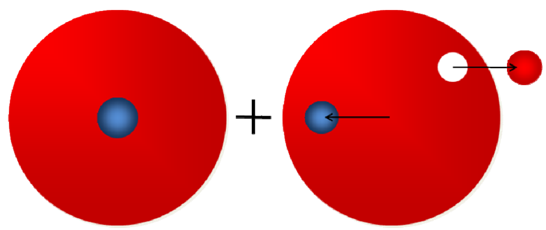

Fig. 4 Spin-polaron: A spin down atom (blue) is immersed in a Fermi sea of spin up atoms (red). Part of its wave function (amplitude) is unperturbed. With a certain probability amplitude it scatters a spin up atom out of the Fermi sea (particle-hole excitation). These contributions can be measured via RF spectroscopy.

To measure the energy and the quasiparticle weight of the Fermi polarons, we prepare a degenerate Fermi gas with high imbalance (98%/2%) in the two hyperfine states of ^{6}Li. By tuning a magnetic field close to a Feshbach resonance, we can access various regimes of interaction. RF spectroscopy is performed on both the minority and the majority component, using tomographic reconstruction to obtain homogeneous spectra, free from broadening due to the inhomogeneous densities in the trap.

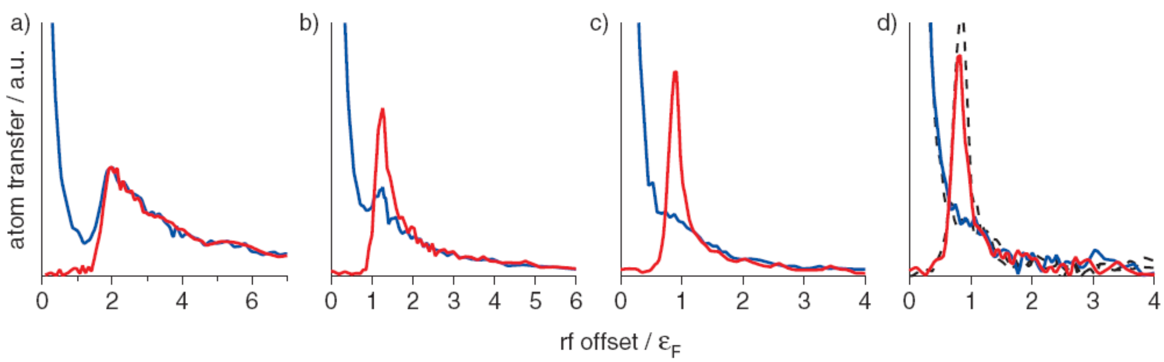

Figure 5 Rf spectroscopy on Fermi Polarons. Shown are spatially resolved, 3D reconstructed RF spectra of the environment (blue) and impurity (red) component in a highly imbalanced Fermi mixture. a) Molecular limit, b)-c) emergence of the Fermi Polaron, observed as a narrow quasiparticle peak emerging from a broad incoherent background. d) At the Feshbach resonance, the polaron peak is the dominant feature. For the spectra shown as dashed lines, the roles of impurity and environment spins are interchanged. The local impurity was 5(2)% for all spectra, the interaction strengths $1/k_F a$ were a) 0.76(2), b) 0.43(1), c) 0.20(1) and d) 0 (unitarity).

For strong attraction between the particles, far on the molecular side of the resonance, each spin down atom forms a molecule with one spin up fermion. Away from the strong "atomic" peak from unpaired majority atoms, the minority and majority spectra fully overlap. This is the regime of molecular pairing (Fig. 3c). As the attraction is reduced, a narrow feature emerges in the minority spectrum, that is not seen in the majority spectrum. This is the Fermi Polaron. The narrow peak indicates the unperturbed part of the polaronic wavefunction. By measuring the spectral weight in the peak versus that in the common background, shared between minority and majority atoms, we obtain a value for the quasi-particle residue.

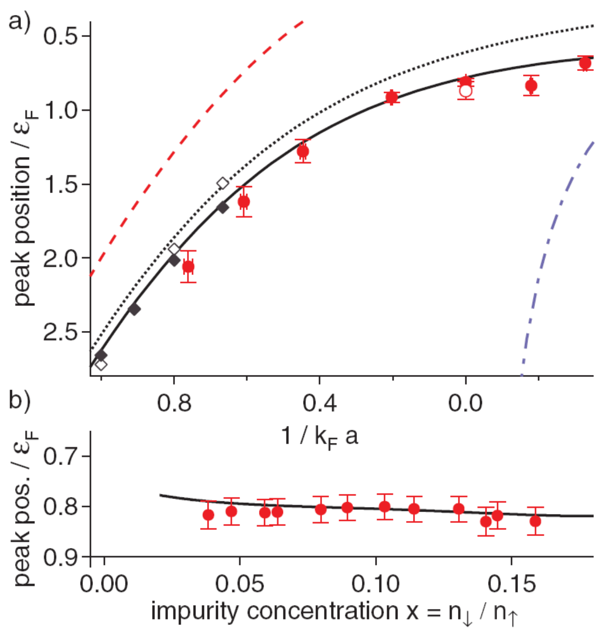

Figure 6 Peak position of the impurity spectrum as a measure of the polaron energy $E_\downarrow$. (a) peak position for various interaction strengths in the limit of low concentration x=5% (solid circles). Open circle: Reversed roles of impurity and environment. Dotted line: polaron energy from variational Ansatz Eq. (1), the solid line including weak final state interactions. Dashed line: Energy of a bare, isolated molecule in vacuum. Blue dash-dotted line: Mean field limit for the energy of an impurity atom. Solid (open) diamonds: Diagrammatic MC energy of the polaron (molecule) [4]. (b) Peak position at unitarity ($1/k_Fa = 0$) as a function of impurity concentration (solid circles). The line shows the expected peak position [1].

Our results are in good agreement with recent calculations of the Fermi Polaron energy, via the variational Ansatz [3], a full many-body analysis that obtains a series representation [5], and diagrammatic Quantum Monte-Carlo calculations [4]. In the latter work, by N. Prokof'ev and B. Svistunov, a new Quantum Monte-Carlo method is introduced that circumvents the Fermi sign problem, the computationally demanding fact that many-body wavefunctions for fermions have to be fully anti-symmetric under fermion exchange. The hope is that their method can be extended to a full N+M-body theory and compared to our experiments. If this was successful, we would have a theory for strongly interacting fermions that does not suffer from the Fermi sign problem. This would have an immense impact on condensed matter and nuclear physics.

It is remarkable that a strongly interacting Fermi gas, with interactions between bare particles that are as strong as quantum mechanics allows (the unitarity regime), redresses itself into a weakly interacting Fermi liquid of polarons. On the other hand, this is exactly what Landau predicted: Even if the ground state of a system is strongly interacting and difficult to describe, its excitations can be well-defined, weakly interacting quasi-particles.

At a certain interaction strength, at $1/k_Fa = 0.76$, the Fermi Polaron peak vanishes and we observe the transition towards two-body binding. At this point, a Fermi liquid of polarons is replaced by a Bose liquid of molecules. At low enough temperatures, this molecular cloud will form a Bose-condensate that fully phase separates from the normal state of unpaired atoms. Even further away from the Feshbach resonance, when the interactions between molecules and atoms become weaker, we might be able to observe fermionic atoms moving in a bath of bosons. This would be an example of the “classical” polaron, a fermion (electron) dressed by a boson bath (phonons).

References

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Publications

Journal Articles, Published

A. Schirotzek, C.-H. Wu, A. Sommer, and M. W. Zwierlein, Phys. Rev. Lett. **102**, 230402 (2009).

Popular Articles

M. W. Zwierlein, *Teilchen auf Partnersuche*, Physik Journal 12/2008, 31 (2008)

Meeting Papers

Fermionic Superfluidity in Ultracold Fermi Gases.
International Symposium on the Foundations of Quantum Mechanics (ISQM 2008), Advanced Research Laboratory, Hitachi, Tokyo, Japan, 8/27/2008

Swimming in the Fermi sea: Polarons in imbalanced Fermi gases.
New Laser Scientists Conference 2008, Rochester, NY, 10/24/2008

Radiofrequency Spectroscopy of Strongly Interacting Fermi Systems.
Niels Bohr International Academy, Coherent Quantum Gases - From Cold Atoms to Condensed Matter, Copenhagen, Denmark, 1/15/2009, talk by A. Schirotzek

Observation of Fermi Polarons in a Fermi liquid of Ultracold Atoms held at:
Workshop on Non-equilibrium dynamics and correlations in strongly interacting atomic, optical and solid state systems, Harvard-ITAMP, Cambridge, MA, 1/26/2009

APS March Meeting 2009, Pittsburgh, PA, 3/16/2009

Research Frontiers in Ultracold Atoms, Trieste, Italy, 5/4/2009

DAMOP 2009, Charlottesville, Virginia, 5/19/2009

CIFAR Quantum Materials workshop, Vancouver, Canada, 5/29/2009

RPMBT15, "Recent Progress in Many Body Theory", Columbus, OH, 7/27/2009

EMMI workshop "Quark-Gluon-Plasma meets Cold Atoms - Episode II", Haus Bergkranz, Riezlern, Austria, 8/5/2009