

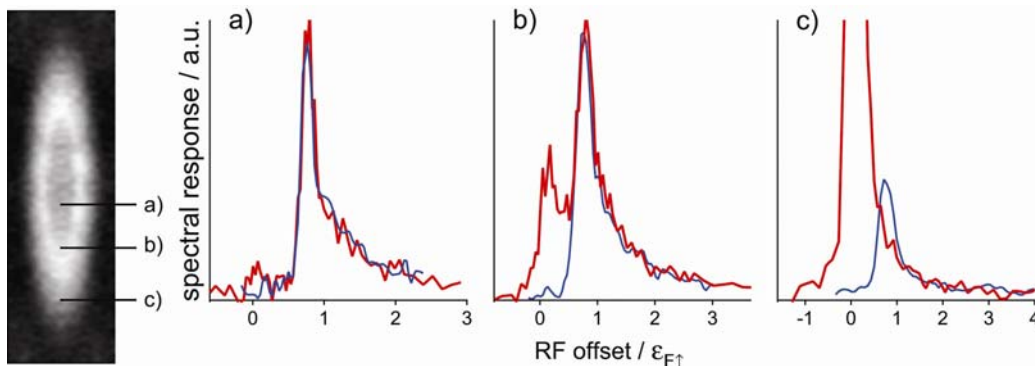
Progress in year 2008

1. Determination of the Superfluid Gap in Atomic Fermi Gases by Quasiparticle Spectroscopy

Using RF spectroscopy, we have studied pairing correlations in imbalanced Fermi gases and addressed the question what happens if we have fewer spin down than spin up fermions. Do the spin down fermions form pairs, leading to bimodal distribution of paired and unpaired majority atoms, or do minority fermions interact with the majority Fermi sea as a polarizable medium?

In a superfluid phase described by BCS theory, the excess particles can be accommodated only as thermally excited quasiparticles. A double-peaked spectrum reflects the co-existence of pairs and unpaired particles. In the BCS limit, the splitting between the two peaks is the superfluid gap parameter. Therefore, RF spectroscopy of quasiparticles is a direct way to observe the superfluid gap in close analogy with tunneling experiments in superconductors. We determined the superfluid gap Δ to be 0.44 times the (majority) Fermi energy [1].

In the normal phase, at large spin polarization, the limit of a single minority particle immersed into a Fermi sea is approached, which can be identified as a polaron. We find that these different kinds of pairing correlations are smoothly connected across the critical density imbalance, also called the Clogston- Chandrasekhar limit of superfluidity.

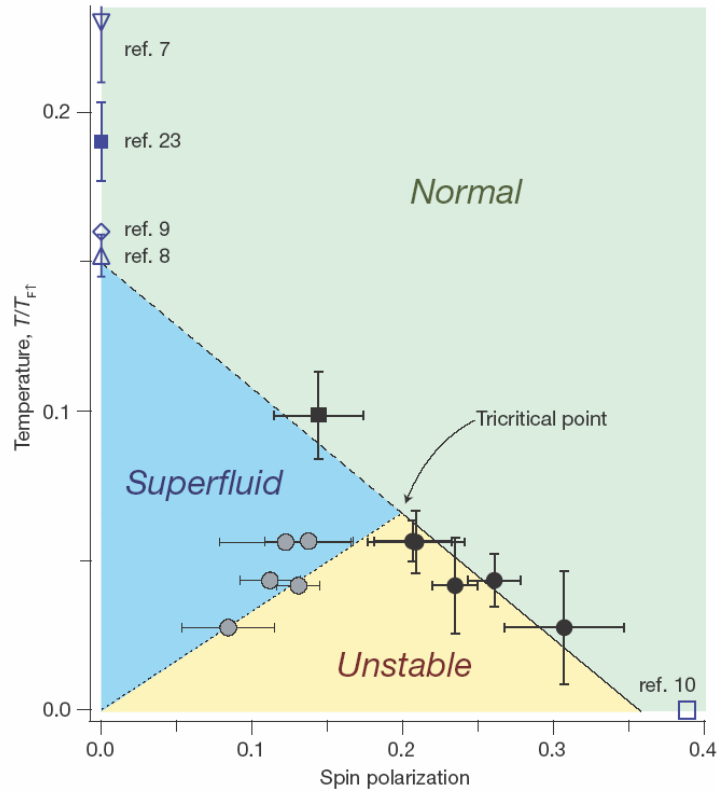


Tomographic RF spectroscopy of strongly interacting Fermi mixtures. A trapped, inhomogeneous sample has various phases in spatially different regions. The spectra of each region (red: majority, blue: minority) reveals the nature of pairing correlation of the corresponding phase. (a) Balanced superfluid. (b) Polarized superfluid. The additional peak in the majority spectrum is the contribution of the excess fermions, which can be identified as fermionic quasiparticles in a superfluid. From the separation of the two peaks, the pairing gap energy of a resonantly interacting superfluid has been determined. (c) Highly polarized normal gas. The minority peak no longer overlaps with the majority spectrum, indicating the transition to polaronic correlations.

2. Phase diagram of a two-component Fermi gas with resonant interactions

We have established the phase diagram of a spin-polarized Fermi gas of ${}^6\text{Li}$ atoms at unitarity. Using tomographic techniques, we determined the spatial structure of a trapped Fermi mixture, mapping out the superfluid phases versus temperature and density

imbalance [2]. At low temperature, the sample shows spatial discontinuities in the spin polarization. This is the signature of a first-order superfluid-to-normal phase transition, which disappears at a tricritical point where the nature of the phase transition changes from first-order to second-order. We have confirmed that at zero temperature, there is a quantum phase transition from a fully paired superfluid to a partially polarized normal gas, resolving a major controversy about the Chandrasekhar-Clogston limit of superfluidity with resonant interactions. The phase diagram provides quantitative tests of theoretical calculations on the stability of fermionic superfluidity.



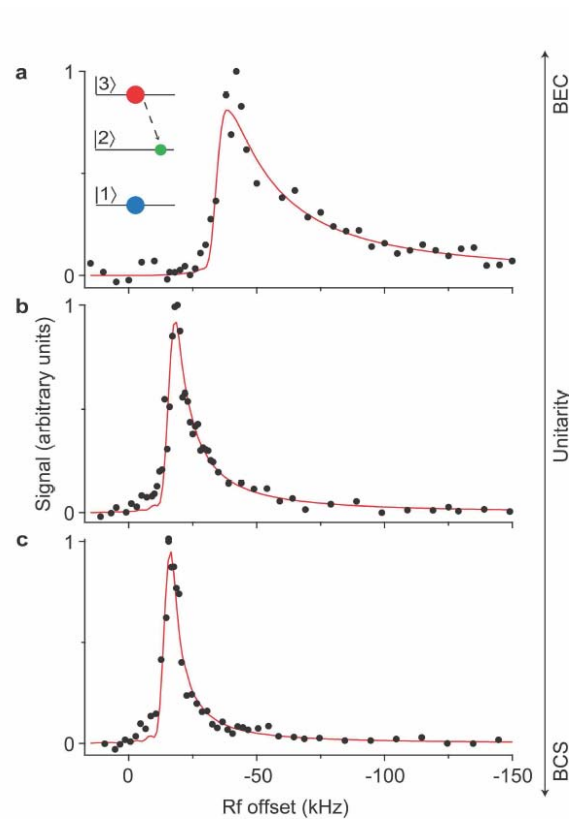
Phase diagram of a two-component Fermi gas with resonant interactions. The yellow area represents a thermodynamically unstable region, leading to phase separation between superfluid and normal. Above the tricritical point, the phase transition is continuous (second-order). The critical spin polarization at zero temperature is estimated to be $\approx 36\%$.

3. Determination of the fermion pair size in a resonantly interacting superfluid

Fermionic superfluidity requires the formation of pairs. The actual size of these fermion pairs varies by orders of magnitude from the femtometer scale in neutron stars and nuclei to the micrometer range in conventional superconductors. Many properties of the superfluid depend on the pair size relative to the interparticle spacing. For a given mass of the particles, there is a strong correlation between small pair size and high transition temperature. Even in high-temperature superconductors the reported values for the pair size are in the range of two to three interparticle spacings.

We have now been able to determine the pair size for resonantly interacting fermions, which were shown previously to have a very high transition temperature of 20 % of the Fermi temperature. The pair size was inferred from the RF dissociation spectrum of the pairs. Since an rf photon has negligible momentum, the allowed momenta for the fragments reflect the Fourier transform of the pair wavefunction, and the width of the RF spectrum is inversely proportional to the square of the pair size. In order to obtain “clean” RF spectra we had to realize resonant superfluidity in a new system, a spin mixture of lithium atoms where the final state after RF excitation has only weak interactions.

The pair size of the fermionic superfluid on resonance was determined to be 80 % of the interparticle spacing, the smallest pairs found so far for fermionic superfluids [3].



Rf dissociation spectra in the BEC-BCS crossover. Below, at, and above the Feshbach resonance, the spectrum shows the typical asymmetric lineshape of a pair dissociation spectrum and can be fitted with a line shape which has the fermion pair size as a fit parameter.

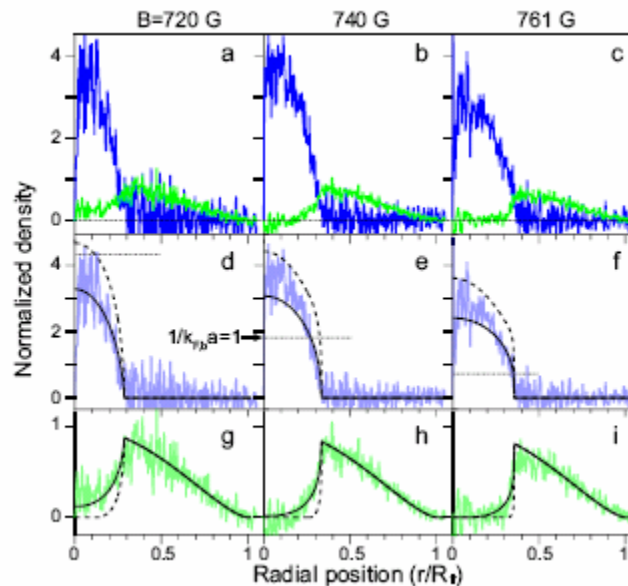
4. Realization of a strongly interacting Bose-Fermi mixture from a two-component Fermi gas

Fermions are the fundamental building blocks of matter, whereas bosons emerge as composite particles. The simplest physical system to study the emergence of bosonic

behavior is a two-component fermion mixture, where the composite boson is a dimer of the two different fermions.

By analyzing in situ density profiles of ${}^6\text{Li}$ atoms in the BEC-BCS crossover regime, we have identified a critical coupling strength, beyond which all minority atoms pair up with majority atoms, and form a Bose condensate [4]. This is the regime where the system can be effectively described as a boson-fermion mixture. We have also determined the dimer-fermion scattering length, consistent with the exact value which has been predicted over 50 years ago but has never been experimentally confirmed.

Below the critical coupling strength, the composite nature of the boson becomes essential and the degeneracy pressure from excess unpaired fermions affects the structure of the composite boson, resulting in a zero-temperature quantum phase transition to a normal state where Bose-Einstein condensation is quenched.



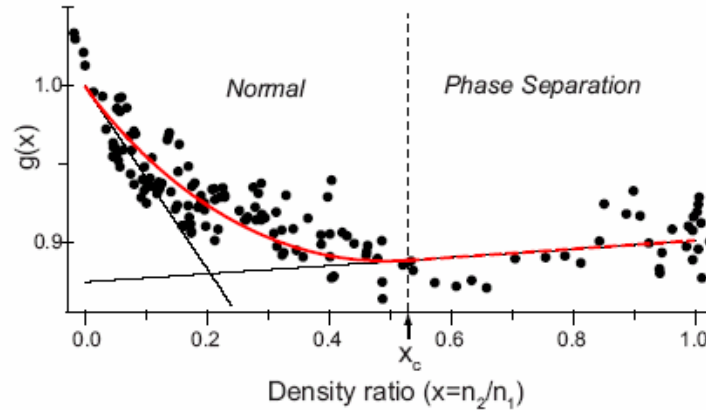
Strongly interacting Bose-Fermi mixtures. (a-c) Density profiles of bosonic dimers (blue) and unpaired excess fermions (green) for various magnetic fields, beyond the critical coupling strength. Figures (d-f) and (g-i) compare experimental results to calculated density profiles for bosons and fermions, respectively, confirming the validity of a boson-fermion description.

5. Determination of the equation of state of a polarized Fermi gas at unitarity

At unitarity, i.e. when the scattering length for the free fermions diverges, the behavior of the system becomes universal, being independent of the nature of the interactions. We have determined the universal equation of state of a two-component Fermi gas with resonant interactions by analyzing the in situ density distributions of a population-imbalanced Fermi mixture confined in a harmonic trap [5]. Since the variation of the external trapping potential across the sample scans the chemical potential, the density information of a single sample, in principle, contains the whole information on the

equation of state. We have presented a method to determine the equation of state directly from the shape of the trapped cloud.

We have found that the behavior of a partially polarized normal gas can be well described by a normal Fermi liquid picture, which includes the binding energy of a single minority atom resonantly interacting with a majority Fermi sea, the effective mass of the quasiparticles, and its correction.



Thermodynamic potential of a two-component Fermi gas with resonant interactions. The universal function $g(x)$ for the energy density $E(n_1, n_2)$ is defined as $E(n_1, n_2) = E_0(n_1) g(x)^{5/3}$, where n_1 and n_2 are the densities of component 1 and 2, respectively, E_0 is the energy density of a single-component Fermi gas, and $x = n_2/n_1$ is the density ratio. x_c is the critical density ratio for the normal-to-superfluid phase transition. The red solid line is a model fit to the normal region ($x < x_c$), using a normal Fermi liquid description.

1. A. Schirotzek, Y. Shin, C.H. Schunck, and W. Ketterle, *Determination of the Superfluid Gap in Atomic Fermi Gases by Quasiparticle Spectroscopy*, Phys. Rev. Lett. **101**, 140403 (2008).
2. Y. Shin, C.H. Schunck, A. Schirotzek, and W. Ketterle, *Phase diagram of a two-component Fermi gas with resonant interactions*, Nature **451**, 689 (2008).
3. C.H. Schunck, Y. Shin, A. Schirotzek, and W. Ketterle, *Determination of the fermion pair size in a resonantly interacting superfluid*, Nature **454**, 739 (2008).
4. Y. Shin, A. Schirotzek, C.H. Schunck, and W. Ketterle, *Realization of a strongly interacting Bose-Fermi mixture from a two-component Fermi gas*, Phys. Rev. Lett. **101**, 070404 (2008).
5. Y. Shin, *Determination of the equation of state of a polarized Fermi gas at unitarity*, Phys. Rev. A **77**, 041603(R) (2008).