Fermion Superfluidity

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Exchange Symmetry

Symmetry with respect to particle exchange

Bosons (integer spin)	**Fermions** (½-integer spin)
$\psi_{12}(r_1, r_2) \rightarrow +\psi_{12}(r_2, r_1)$	$\psi_{12}(r_1, r_2) \rightarrow -\psi_{12}(r_2, r_1)$
Multiple state occupation	Obey Pauli exclusion principle
S. Bose, 1924 A. Einstein, 1924-5	E. Fermi, Feb. 1926 P.A.M. Dirac, Aug. 1926

E_F
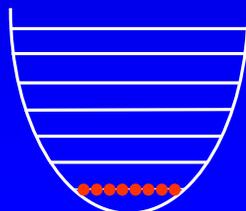
At T=0
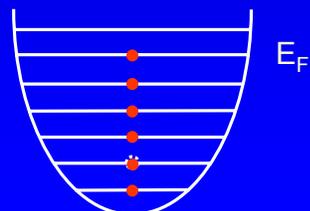
Fermions and bosons differ in respect to particle exchange. This difference leads to a completely different hierarchy of quantum state occupation at low temperatures.

Ultracold Fermi Gases – The Next Frontier?

- Building blocks of matter
- Connections to condensed matter
  - Superconductivity (high-T_c?)
  - Pseudo-gap
  - Lattices
  - Luttinger liquid, spin-charge separation, …

Fermions are the building blocks of matter. Consequently, many of the important paradigms of condensed matter physics can be realized with cold atomic gas that obey Fermi statistics. However, because the densities in cold atom experiments are many orders of magnitudes less than those in condensed matter, these systems are much simpler theoretically.
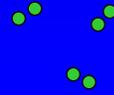
BCS/Pairing Transition

- Cooper pairing
  - Superconductivity
  - Superfluidity ^{3}He
  - Dilute gas?

- For *s*-wave pairing, $T_c \cong T_F \exp(-1/k_F|a|)$ (BCS)

- For ^{6}Li, a = -1100 Å $\Rightarrow$ T_c = 30 nK @ 10^{12} cm^{-3}
  - Stoof *et al.*, PRL **76**, 10 (1996)

- Interactions variable for quantum gases
  - current theories break down for strong coupling:

$$k_F|a| > 1 \quad \text{or} \quad n|a|^3 > 1$$

Weak coupling - BCS

Strong coupling - BEC of molecules?

Cooper pairing is the mechanism underlying both superconductivity in certain solids, as well as superfluidity in liquid helium-3. BCS theory predicts that the transition temperature to the superfluid state depends exponentially on the scattering length *a*. Henk Stoof and I proposed that lithium-6 would be a good candidate for creating a Fermi superfluid in ultracold gases. However, the current theories of superconductivity and superfluidity break down for strong interactions, necessitating the development of new theory. This is currently underway at a number of institutions. In this regime, the Cooper pairs resemble loosely bound diatomic molecules.
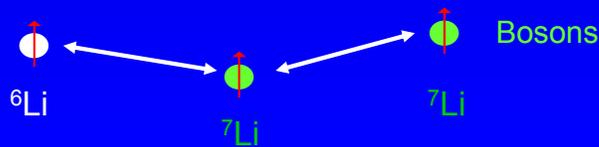
Sympathetic Cooling of Fermions

• Pauli principle forbids *s*-wave interactions between identical fermions

$\Psi(1,2)$ = $\psi_{spatial}\,\chi_{spin}$ must be antisymmetric

Symmetry = $(-1)^\ell \times +1$ $\Rightarrow$ ℓ = 1, 3, …   but too cold for *p*-wave

Fermions

^{6}Li ^{6}Li

Use both ^{6}Li and ^{7}Li

Bosons

^{6}Li ^{7}Li

^{7}Li

Spin-polarized fermions are forbidden to interact via *s*-wave interactions by their exchange symmetry requirement. Since other partial waves are "frozen out" by the low temperatures, a spin-polarized Fermi gas is essentially ideal. This prevents evaporative cooling by the usual direct method employed successfully to cool bosons. We use a "sympathetic" technique, where actively evaporated lithium-7 atoms (bosons) cool the lithium-6, the fermions, by thermal contact.

Quantum Degenerate Fermions

- JILA: ^{40}K, two spin states

- Rice, Paris: ^{6}Li, symp. with ^{7}Li

- Duke: ^{6}Li, two spin states in optical trap

- Florence: ^{40}K, symp. with ^{87}Rb
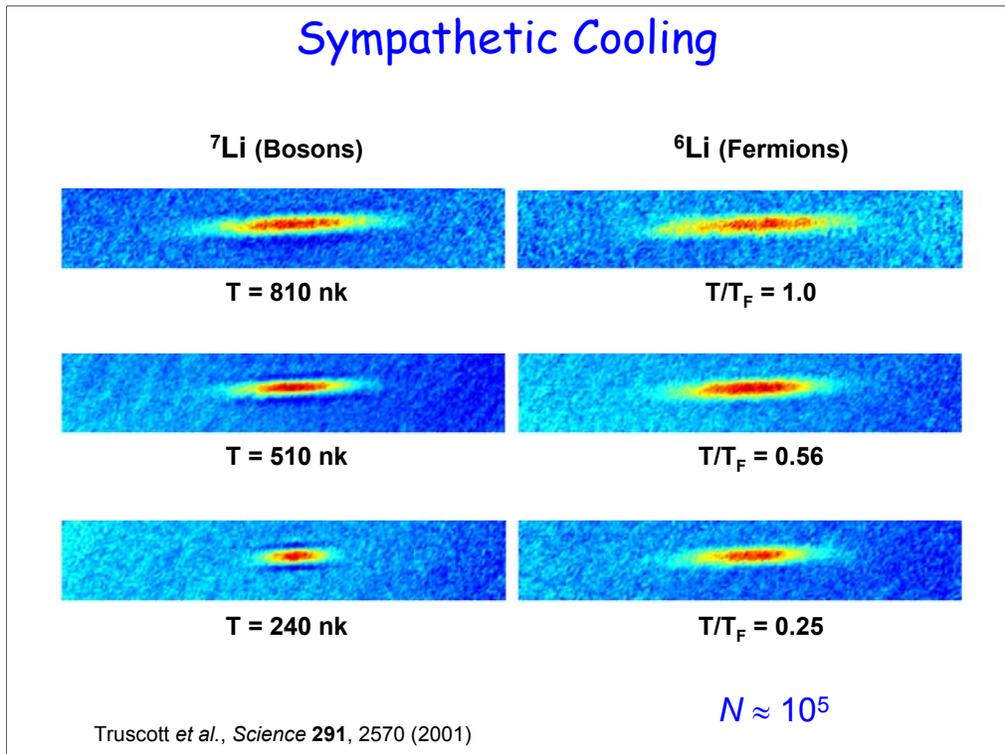
- MIT: ^{6}Li, symp. with ^{23}Na

A number of groups have undertaken ultracold fermion research and have adopted several different strategies for cooling the atoms.

Dual Source Apparatus

Cloverleaf Trap

Zeeman Slower

Oven

$^7Li/\ ^6Li$

Require vacuum pressure ~ 10^{-11} Torr
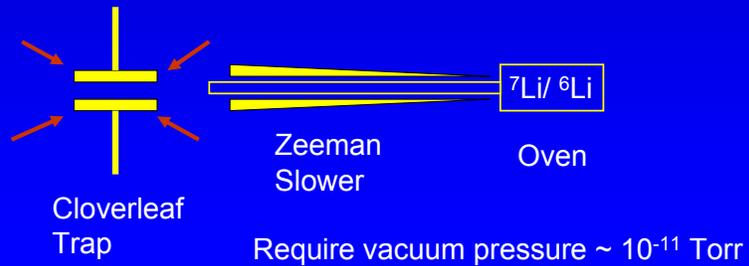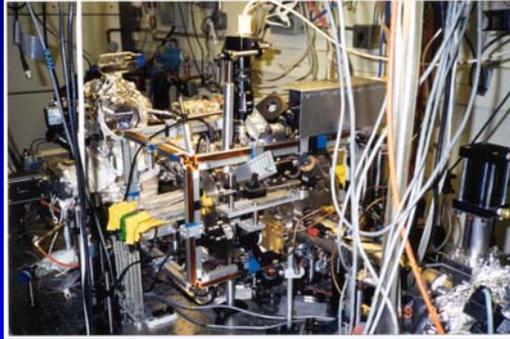
The apparatus consists of an atomic beam source, a Zeeman slower and a cloverleaf-type magnetic trap.

Sympathetic Cooling

^{7}Li (Bosons) ^{6}Li (Fermions)

T = 810 nk $T/T_F = 1.0$

T = 510 nk $T/T_F = 0.56$

T = 240 nk $T/T_F = 0.25$

$N \approx 10^5$

Truscott *et al.*, *Science* **291**, 2570 (2001)

We succeeded a couple of years ago to cool the Bose/Fermi mixture of lithium isotopes to quantum degeneracy. The size and shape of the Bose cloud changes significantly with temperature as can be seen in the images on the left side. However, the fermions obey the Pauli principle which causes them to have a residual energy and pressure at zero temperature. This Fermi pressure is the same physical mechanism responsible for stabilizing white dwarf and neutron stars.
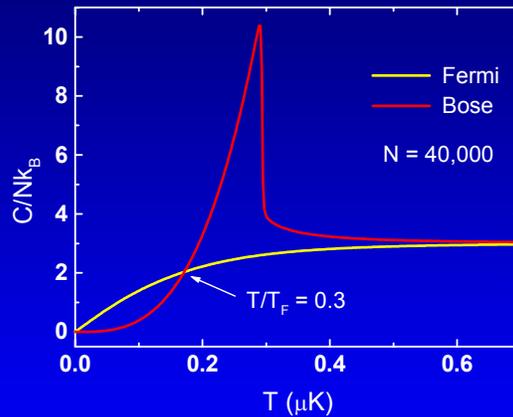
Fermi Pressure in Trapped Atoms
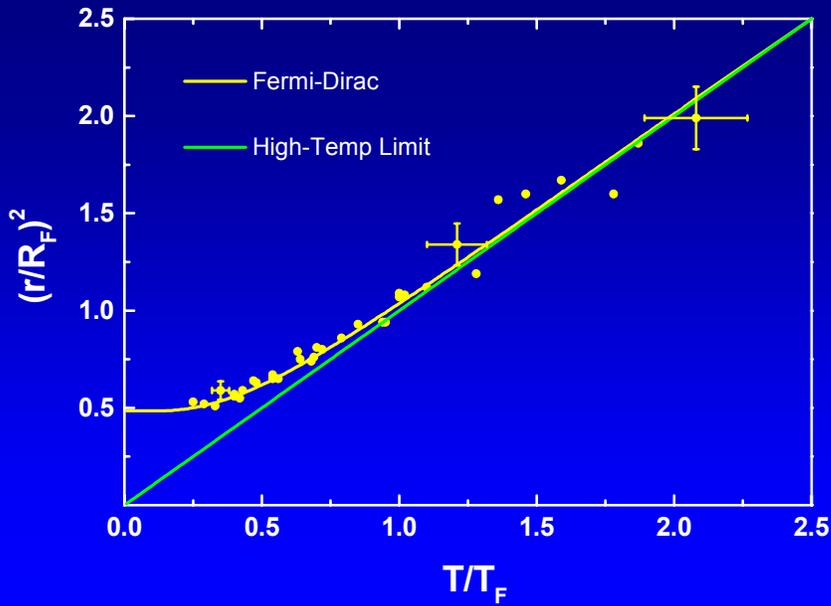
Truscott *et al.*, *Science* **291**, 2570 (2001)

This figure shows the axial size of the fermion cloud as a function of temperature. The effect of Fermi pressure is observed at the lowest temperatures.

Limit of Sympathetic Cooling With Bosons

- Want $C_B > C_F$

- But $C_B = 11\ N_c k_B$
  and
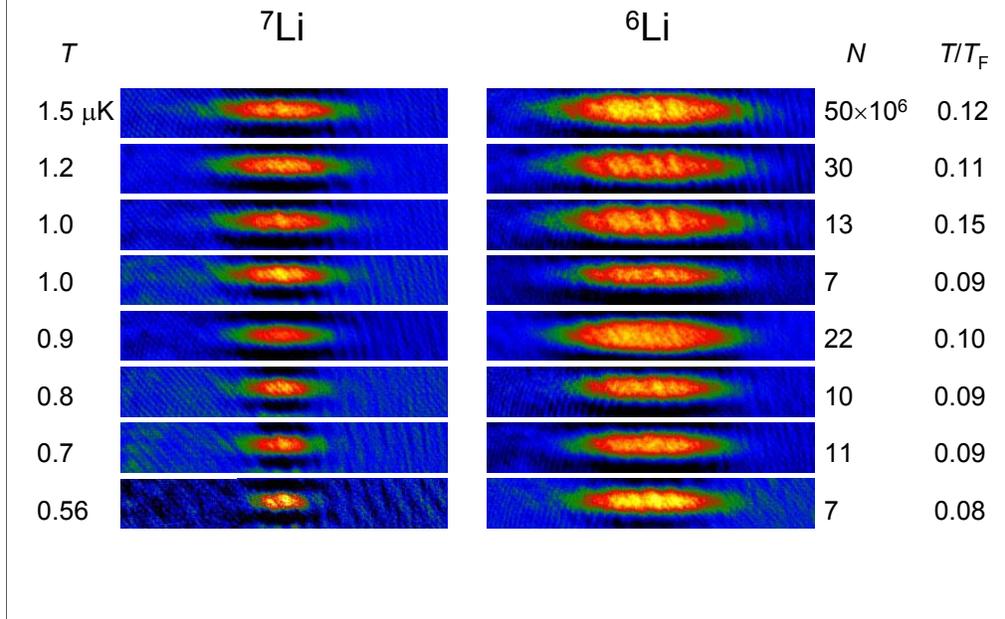 $C_F = \pi^2 N_F k_B (T/T_F)$

- $\Rightarrow\ T/T_F > 0.3$

Figure:

C/Nk$_B$ vs T (μK)

Legend: Fermi, Bose

N = 40,000

$T/T_F = 0.3$

- Deeper cooling obtained by evaporation of fermions *and* bosons

Dual Evaporation

Sympathetic cooling is no longer effective when the heat capacity of the refrigerant, the bosons, falls below that of the fermions. This happens when the temperature T goes below 0.3 T_F. This limit is consistent with our minimum observed temperature of 0.25 T_F. Further cooling can be accomplished by evaporating both the fermions and bosons, a process of dual evaporation.

Dual Evaporation Results

T	^{7}Li	^{6}Li	N	T/T_F
1.5 μK			50×10^6	0.12
1.2			30	0.11
1.0			13	0.15
1.0			7	0.09
0.9			22	0.10
0.8			10	0.09
0.7			11	0.09
0.56			7	0.08

These images demonstrate the large improvement made possible by dual evaporation. We have increased the number of fermions by a factor of 100 while simultaneously lowering the minimum temperature by a factor of 3.
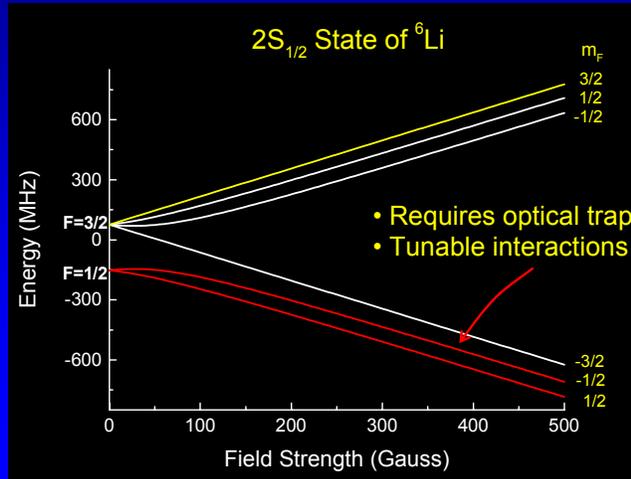
Fit to the Data

$T = 0.9 \, \mu K$, $T/T_F = 0.08$

■ ^{6}Li

● ^{7}Li

Normalized Absorption vs. Axial Profile (μm)
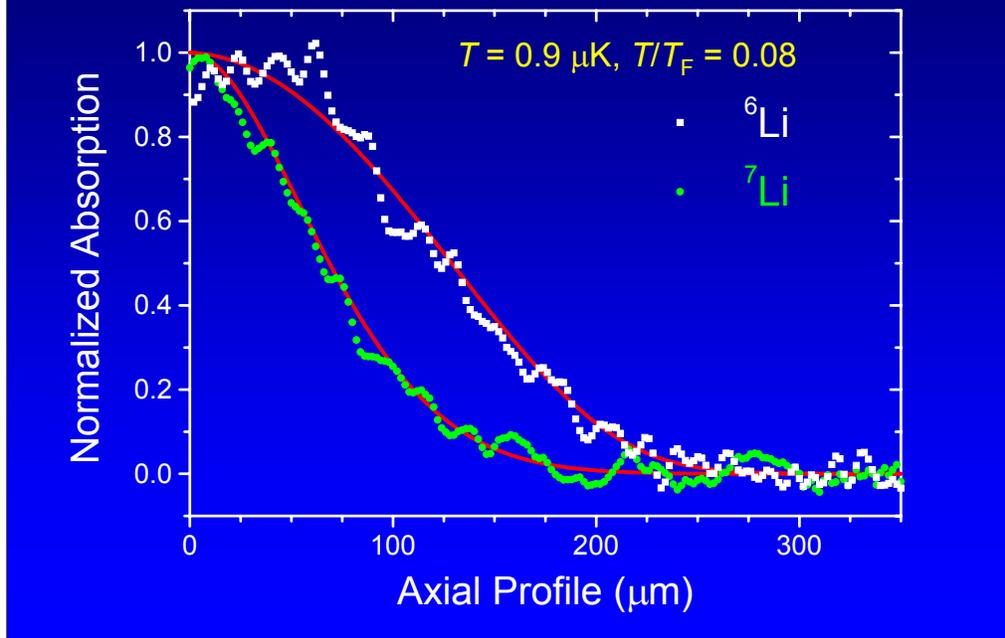
These are profiles of the density distributions for both bosons and fermions. The isotopes are in thermal equilibrium.

Cooper pairing requires a large, attractive interaction. Because of the Fermi symmetry, a two-spin state incoherent mixture is needed. The lowest two Zeeman sub-levels exhibit a Feshbach resonance, that enables tunability of the interaction strength and sign, as shown in the next slide.
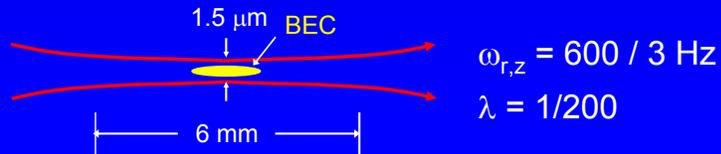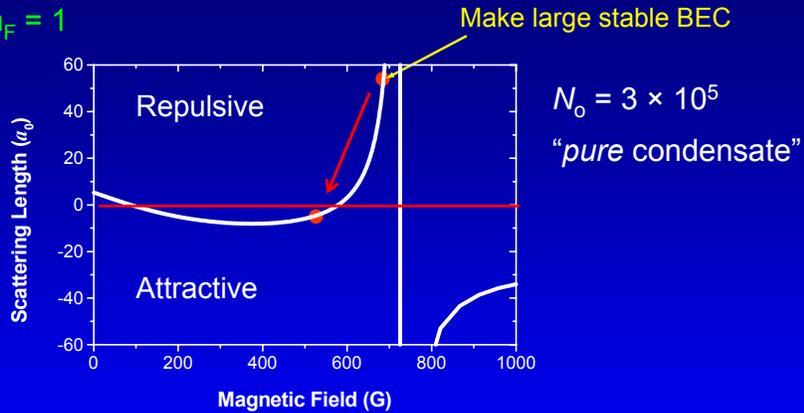
Feshbach Resonance
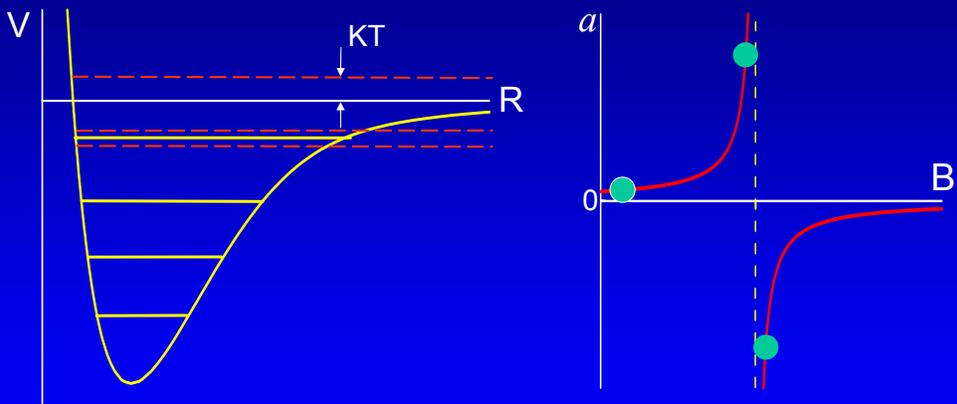
Tune dissociative state into resonance with a bound molecular state

A Feshbach resonance is a magnetically tuned collisional resonance in which an open channel of two colliding free atoms is tuned near a molecular bound state. The scattering length is large and positive when the molecular state is bound, while it becomes large and negative when the molecule is unbound.

⁷Li Feshbach Resonance

F = 1, m_F = 1

Make large stable BEC

Repulsive

Attractive

Scattering Length (a_0)

Magnetic Field (G)

$N_0 = 3 \times 10^5$

"*pure* condensate"

1.5 μm BEC

6 mm

$\omega_{r,z}$ = 600 / 3 Hz

λ = 1/200

This is an example of a Feshbach resonance in the boson, lithium-7. We trapped the atoms in an optical trap and formed a Bose condensate by tuning to a field where the scattering length is positive. The field is then reduced to where the interactions are weakly attractive. If the confinement is effectively one-dimensional the condensate will form matter wave solitons.

K.E. Strecker *et al.*, *Nature* **417**, 150 (2002)
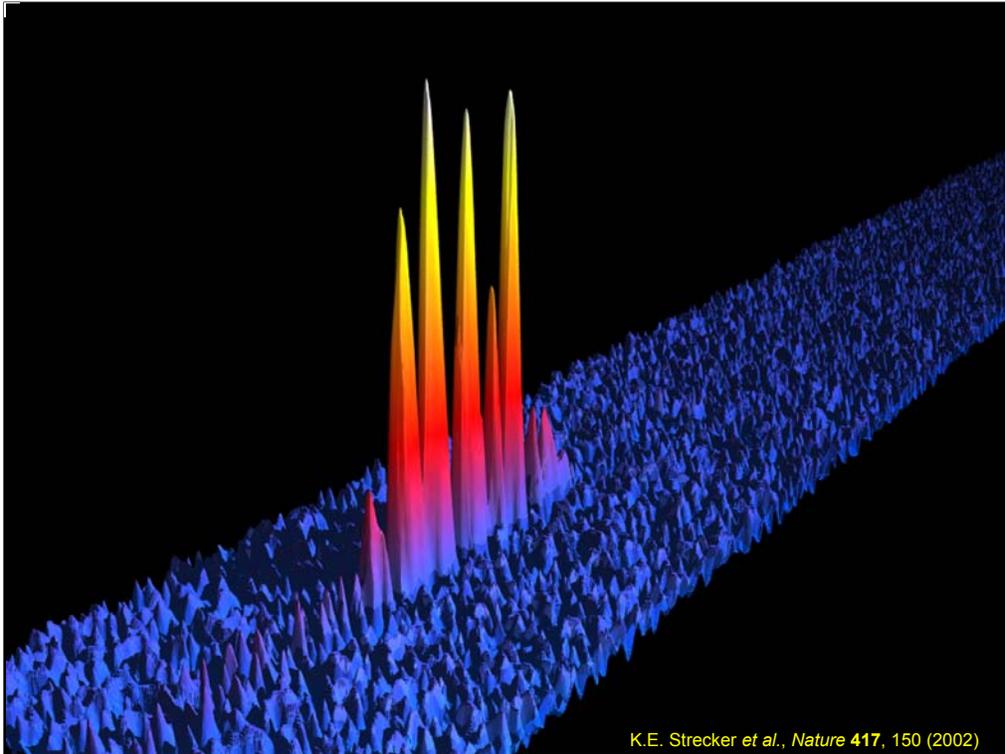
This is an image of the resulting solitons. Each peak is Bose-Einstein condensate in which wave-packet dispersion is balanced by attractive interactions.
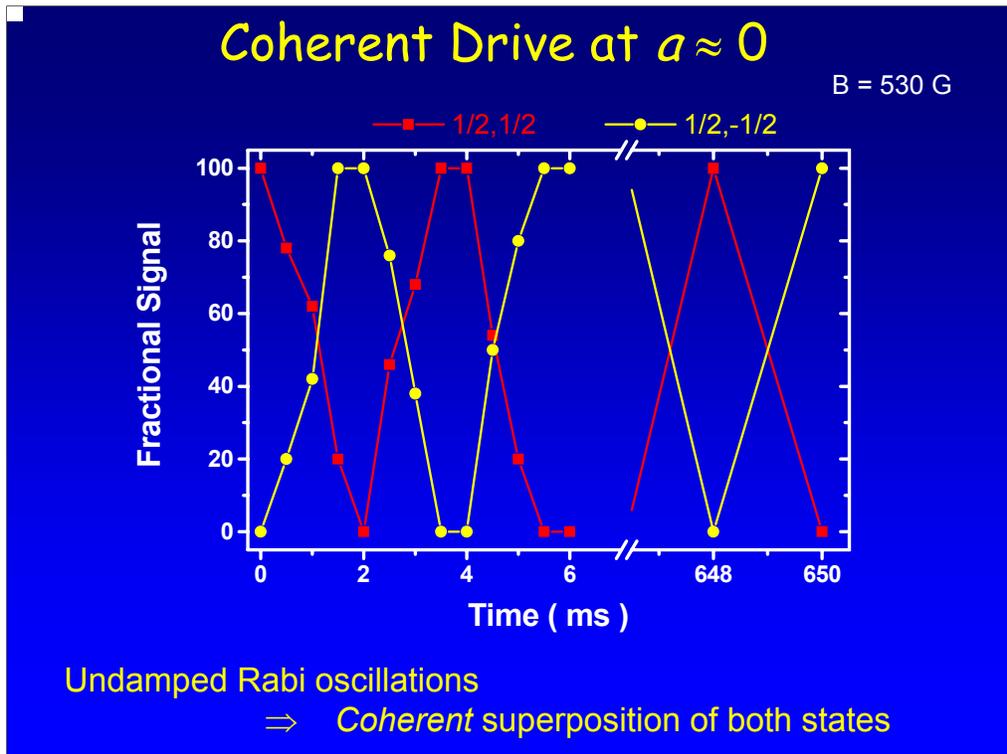
Tunable Interactions in ⁶Li
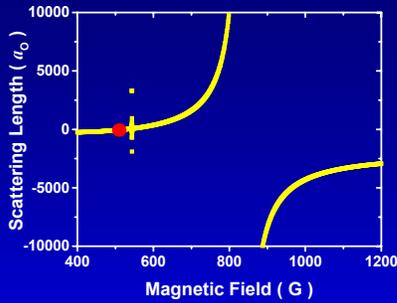
- Feshbach resonance in ⁶Li
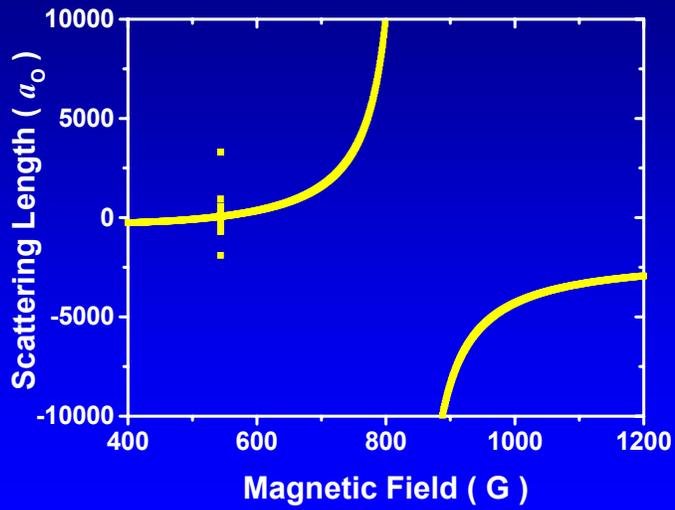
Houbiers, Stoof, McAlexander, Hulet, PRL **57**, R1497 (1998)

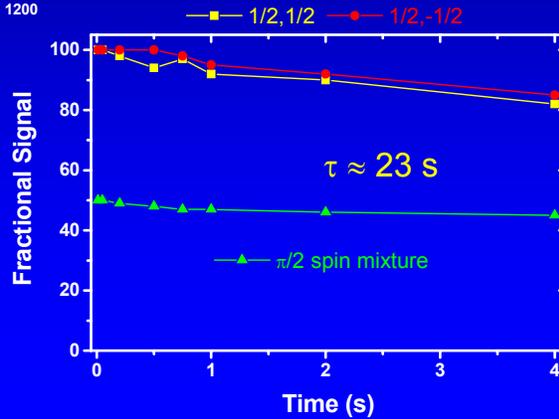This is the calculated Feshbach resonance for lithium-6.

As said previously, ultracold fermions will not interact unless they are in an *incoherent* superposition. We found that making such a superposition was not trivial to create. Starting with all the atoms in the lowest sublevel ($F=\frac{1}{2}$, $m_F=\frac{1}{2}$), we used *rf* to drive the transition to the next sublevel ($F=\frac{1}{2}$, $m_F=-\frac{1}{2}$). We found that the population oscillated coherently for many seconds, without decohering for the lifetime of the atoms in the trap (~20 s).
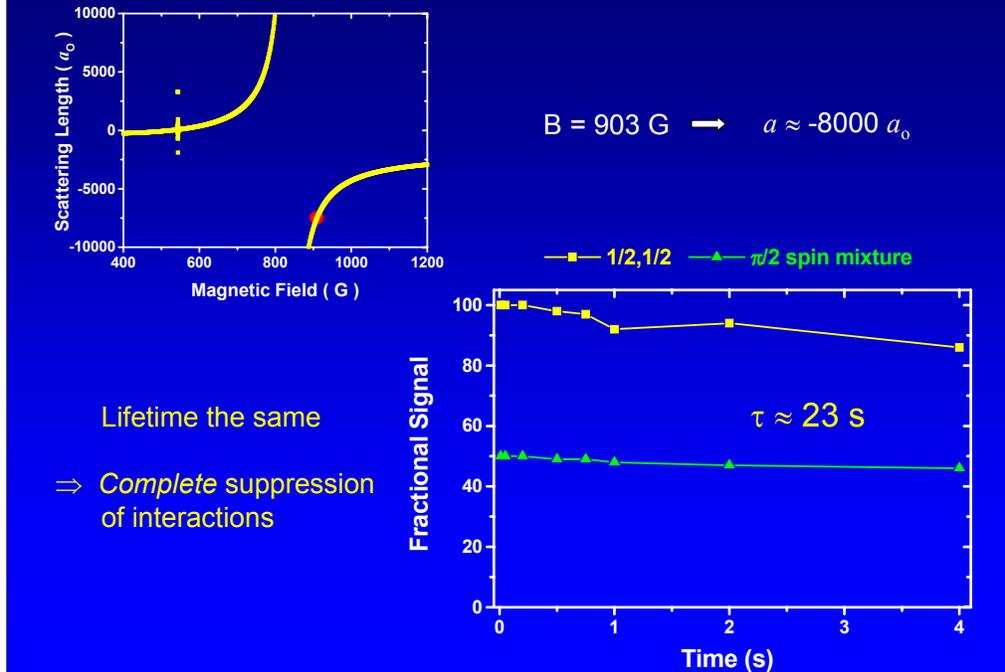
Lifetime of Coherent Mixture at $a \approx 0$

B = 530 G ➡ $a \approx 0$

$\tau \approx 23$ s

Lifetime of each spin state *and* spin mixture is same

Scattering Length (a_0) vs Magnetic Field (G)

Fractional Signal vs Time (s)

Legend: ■ 1/2,1/2 — ● 1/2,-1/2 — ▲ $\pi/2$ spin mixture

We tuned the magnetic field to 530 G, where $a \approx 0$, and created a 50% mixture in each spin state. The lifetime of the mixture, was the same as a pure states.

Next, we tuned the field to 903 G where the scattering length has an extremely large magnitude. In this case, we would expect an interacting gas to have a very short lifetime in the trap because as the atoms elastically scatter and evaporate out of the short trap. Incredibly, we again find the lifetime of the 50/50 mixture is the same as that of a pure state. This demonstrates that each atom in the coherently prepared mixture is identical and again, Fermi statistics prevents interaction. We believe that the long coherence time are evidence of extreme magnetic field homogeneity.

Noisy rf Drive

Broadened rf pulse gives damped Rabi oscillations
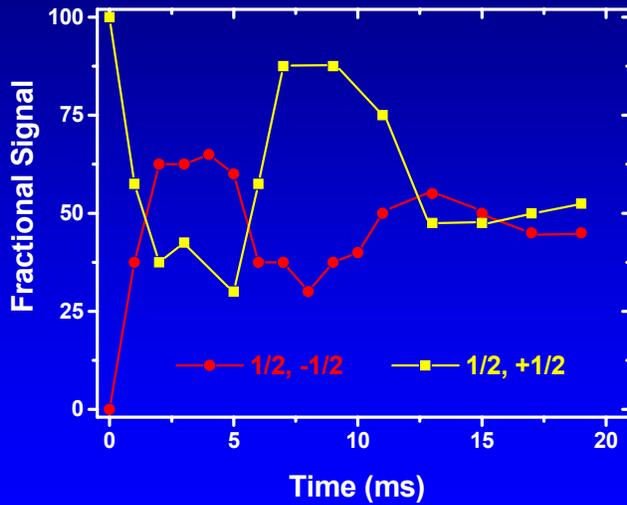
Lifetime at 900 G: $\tau \approx 1$ s

An rf field in which white noise is added to spectrally broaden it results in damped Rabi oscillations. Although such dynamics are indicative of decoherence they can also occur in a completely coherent system, such as this one. We would expect that the coherent Rabi oscillations would revive sometime after the initial damping at 20 ms.

Summary

- Dual evaporation gives 50 million fermions at $T = 0.1\ T_F$

- Demonstrated suppression of interactions by coherent superposition - applicable to atomic clocks

- Looking for evidence of Cooper pairing and superfluidity
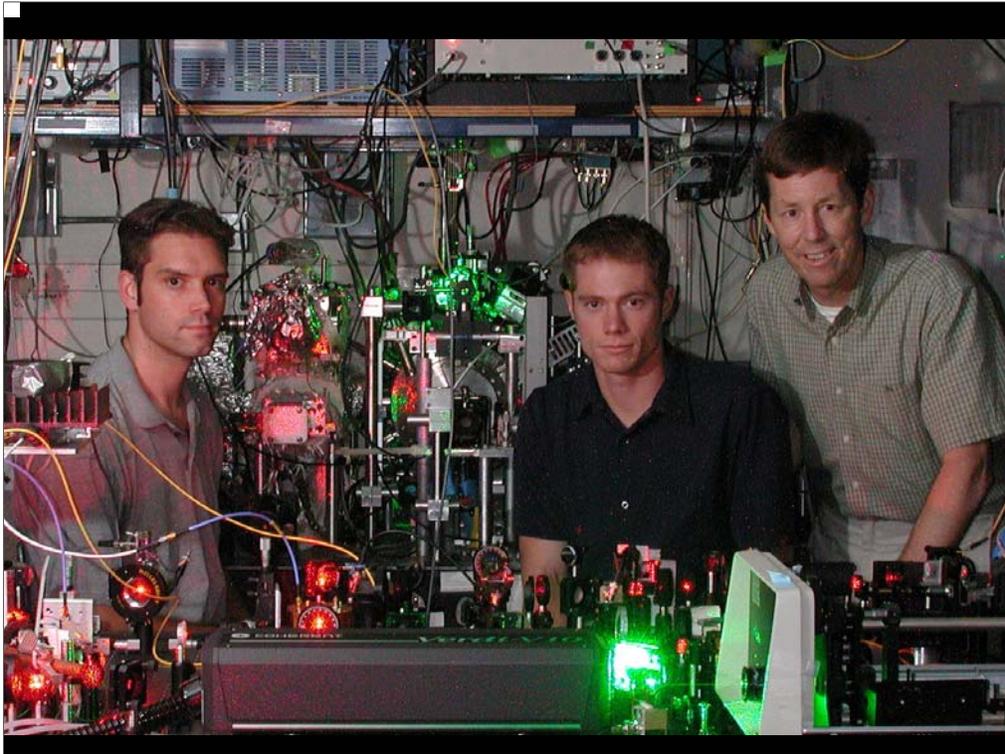
The two guys, left and center, are Kevin Strecker and Guthrie Partridge, who performed the experiments discussed in this talk.