Hydrodynamics in a Degenerate, Strongly Attractive Fermi Gas

Duke Physics
Atom Cooling and Trapping

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Outline

- Degenerate Fermi Gases
- All-Optical Cooling Method
- Hydrodynamic Expansion
- Evidence for Superfluid Hydrodynamics
- Conclusions

We begin by reviewing the reasons for interest in degenerate Fermi gases, both noninteracting and strongly interacting. Then we describe our all-optical cooling and trapping method for creating the samples. Finally, we describe our observations of hydrodynamic expansion of the gas, and evidence for superfluid hydrodynamics in the trapped gas.

Trapped Degenerate Fermi Gases

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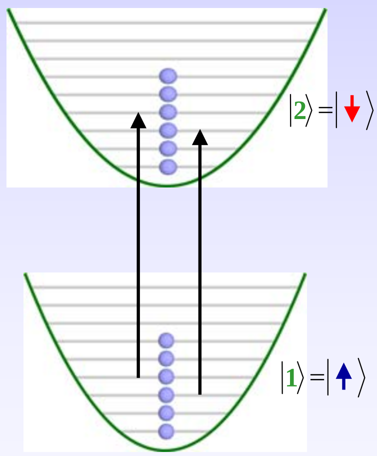
Hyperfine Transitions in an Optical Trap



Fermions in Same Superposition State are Noninteracting (Gibble and Verhaar)

Fermionic atoms in the same superposition of hyperfine spin states are noninteracting. For this reason, fermionic atoms have potential applications in new atomic clocks where interactions are suppressed.

Strongly-Interacting Fermi Gases Mimic Exotic Systems in Nature

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A BUNCH OF DEGENERATES

A degenerate gas of fermions occurs in diverse situations, as described below:

■ Superconductors: The electrons are degenerate and form loosely correlated Cooper pairs, which produce the superconductivity. Something similar must happen in high-temperature superconductors, but that process remains a mystery.

■ Neutron stars: The refusal of neutrons (which are fermions) to occupy identical quantum states generates a repulsion that prevents the star from collapsing under its own immense weight. A similar repulsion stabilizes the laboratory-made degenerate fermi gases against collapse.

– High-Temperature Superconductors
– Neutron Stars
– Strongly-Interacting Matter
– Quark-Gluon Plasma – Elliptic Flow

■ Quark-gluon plasma: As created at the Relativistic Heavy Ion Collider at Brookhaven National Laboratory, the exploding cloud of free quarks (which are fermions) and gluons has properties similar to a gas of fermionic atoms released from the confines of a trap.

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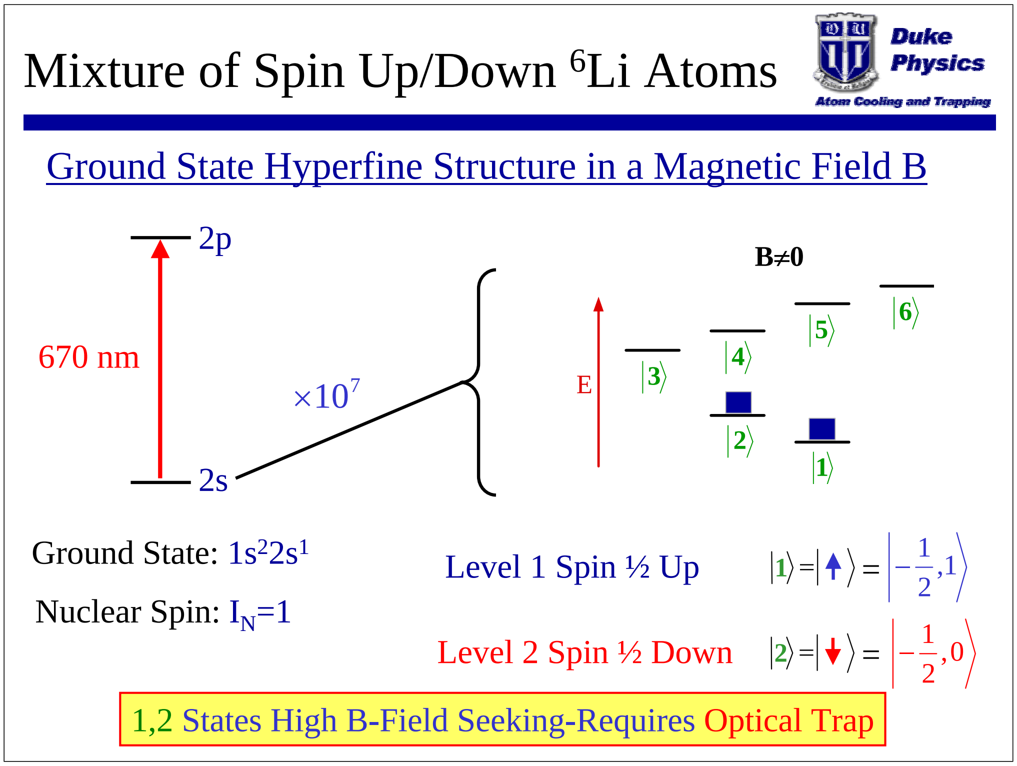
Fermionic atoms also can be made to interact strongly by exploiting a Feshbach resonance. In this case, a gas comprised of strongly interacting spin-up and spin-down atoms mimics a variety of exotic systems in nature, ranging from high temperature superconductors to nuclear matter. The elliptic flow exhibited by a quark-gluon is closely related to the anisotropic hydrodynamic expansion of a mixture of strongly interacting spin-up and spin-down atoms.



We employ lithium-6 atoms in a 50-50 mixture of the two lowest hyperfine states in a magnetic field. The spin-up and spin-down states have the same electron spin down and different nuclear spin. Both states are repelled from magnetic traps and require optical traps for study.

Controlling Interactions with a Feshbach Resonance

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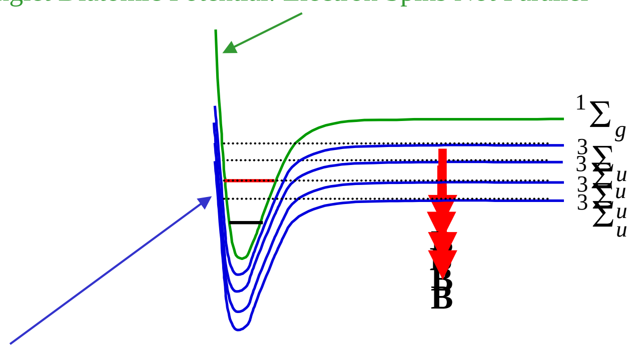
Resonant Coupling between Colliding Atom Pair – Bound Molecular State

Singlet Diatomic Potential: Electron Spins Not Parallel



Triplet Diatomic Potential: Electron Spins Parallel

Zero Energy Scattering Length $a_S \rightarrow \pm\infty$

Strong, magnetically tunable interactions are produced using a Feshbach resonance. Normally, a pair of lithium atoms forms a diatomic molecule in the singlet electronic state (green), where the electron spins are not parallel. One diatomic molecular state is shown in red. However, the trapped states have parallel electron spins, and therefore collide in a triplet electronic state (blue). Normally, the atoms approach each other and bounce off of the potential inner wall. However, by tuning an applied magnetic field, the total energy of the colliding atoms can be tuned, because the triplet state has a magnetic moment. When the total energy of the colliding pair coincides with the energy of the bound molecular state in the singlet potential, the molecular amplitude becomes large, causing the scattering length to increase. The scattering length at zero energy determines the distance over which the wavefunction of the colliding atoms is modified.

*Feshbach Resonance for 1-2 Mixture

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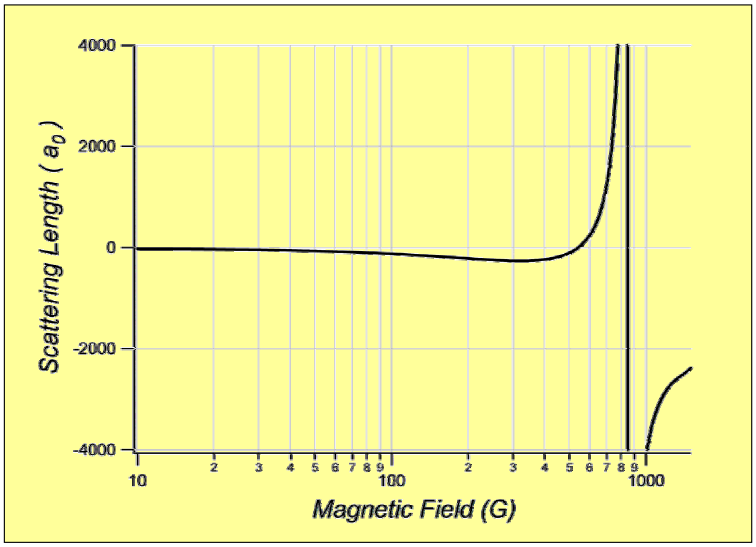
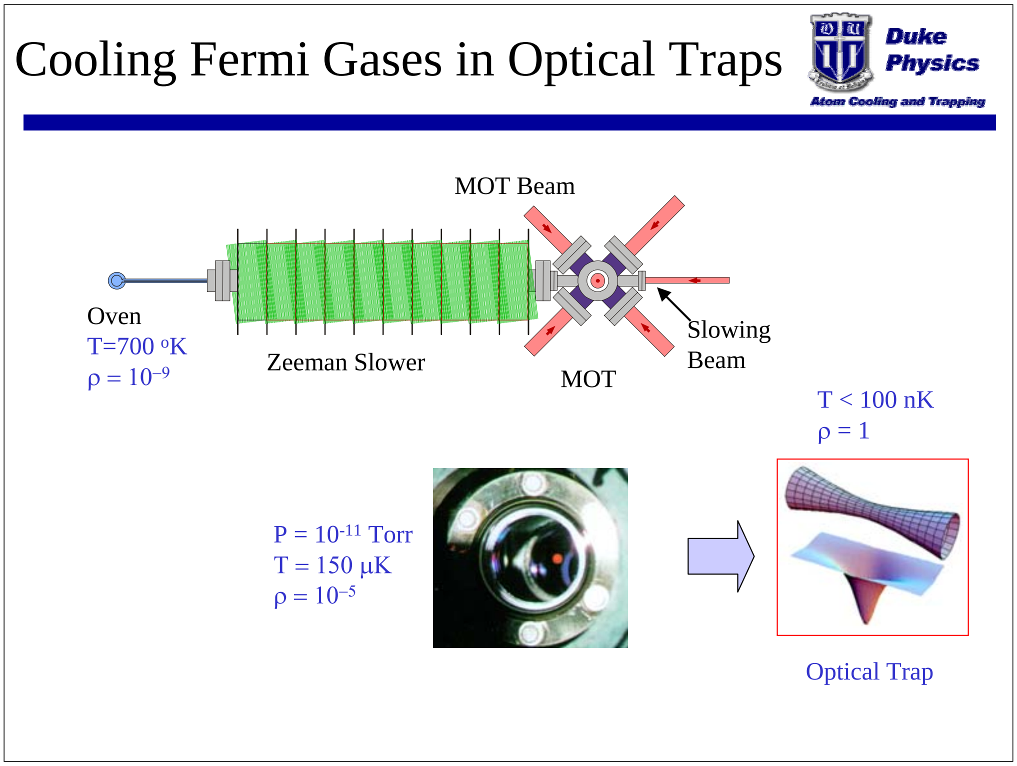


*M. Houbiers, *et al*., Phys. Rev. A **57**, 1497 (1998)

The scattering length is plotted as a function of magnetic field. Near 850 G, there is a resonance in which the scattering length ranges from extremely large and positive to extremely large and negative. At 530 G, the scattering length passes through zero, producing a sample of noninteracting atoms.



Our approach to producing a degenerate, strongly interacting gas differs from that of most other groups, in that we employ all-optical trapping and cooling methods. The optical trap is loaded from a standard magneto-optical trap which is produced from a slowed atomic beam.

Optical Trap

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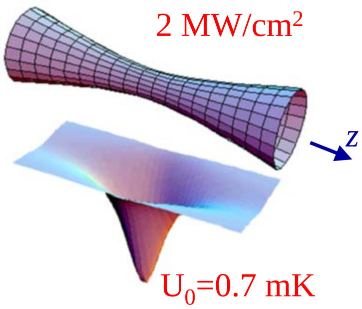
Focused Gaussian Laser Beam

$$U = -\frac{1}{2}\alpha\,\overline{E_0^2}\,\frac{1}{1+(z/z_0)^2}\,e^{-2r^2/w_0^2}$$



The optical trapping potential is proportional to the product of the static polarizability and the laser intensity. Approximately 65 watts of CO_2 laser power is focused to a radius of 50 micrometers, producing an intensity of 2 megawatts per square centimeter, and trap depth of 0.7 mK. The length of the trap is approximately a millimeter.

Ultrastable CO_2 Laser Trap

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- Stable Commercial Laser

- Typical Trap Parameters

$P = 65\ \mathrm{W}$ $\quad \omega_0 = 47\ \mu\mathrm{m}$, $z_0 = 0.7\ \mathrm{mm}$

$I_0 = 2.0\ \mathrm{MW/cm^2}$ $\quad U_0 = 0.7\ \mathrm{mK}$

$\nu_r \cong 6.6\ \mathrm{kHz}$ $\quad \nu_z \cong 340\ \mathrm{Hz}$

- Negligible Optical Heating
  - Scattering Time: 1/2 hour
  - Optical Heating: 18 pK/s
- Extremely Low Noise
  - Intensity Noise Heating

$$\Gamma^{-1} \geq 2.3 \times 10^4\ \mathrm{sec}$$

- Ultra-High Vacuum
  - Pressure: $< 10^{-11}$ Torr
  - Heating: < 5 nK/sec
  - Lifetime: 400 sec

We use a 140 watt CO_2 laser from the lidar industry. The laser is exceptionally stable, with a noise-induced heating time of 23 thousand seconds. The long wavelength and large detuning from resonance yields a light scattering rate of only two photons per hour and negligible optical heating. The trap lifetime is 400 seconds.

Experimental Apparatus

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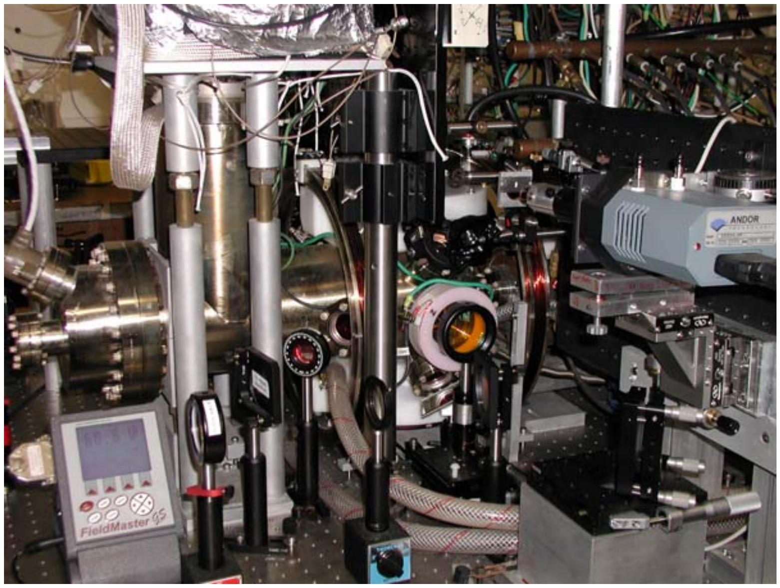

The lens in the foreground is used to focus the CO_2 laser beam into the vacuum system. A camera is used to record absorption images of the cloud.

Optical Trap Loading

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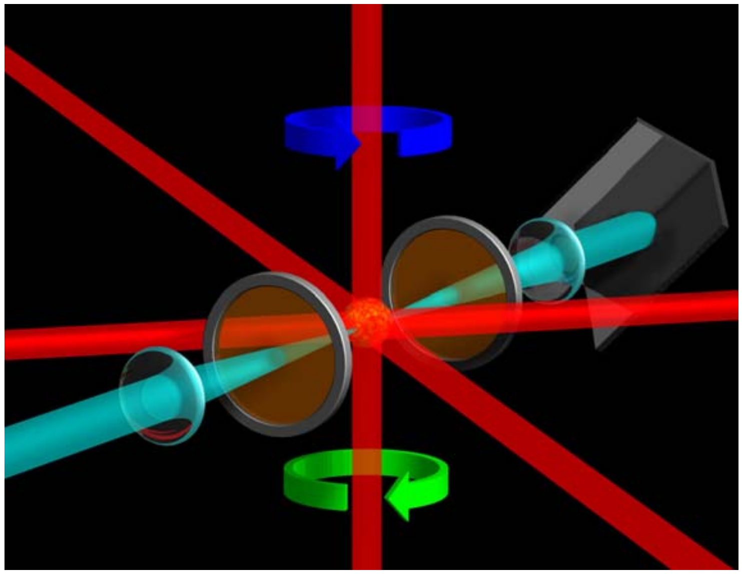

To reiterate the loading procedure, the CO_2 laser trap is first loaded from a magneto-optical trap. To increase the loaded number of atoms, the CO_2 laser beam is retroreflected using a rooftop mirror.

Forced Evaporation

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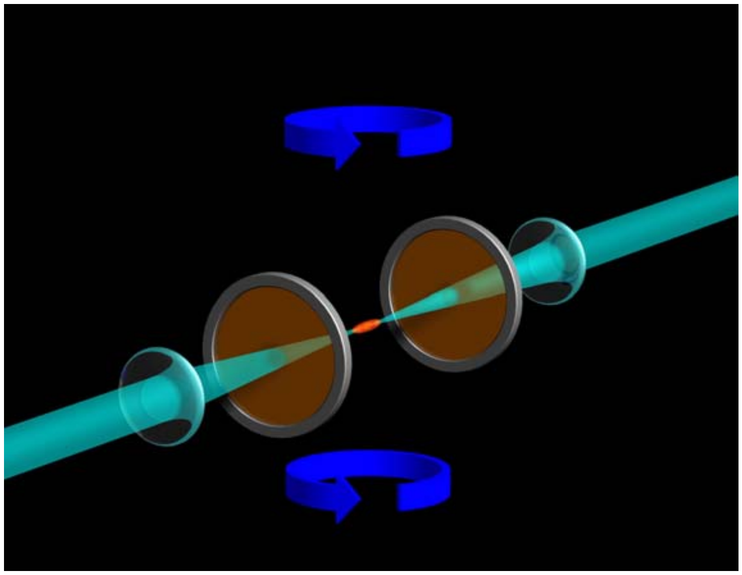

Next, the optical beams are extinguished and a magnetic field is applied to tune the gas into the Feshbach resonance region. Forced evaporative cooling is accomplished by lowering the trap laser intensity.

Timing Sequence for Evaporation

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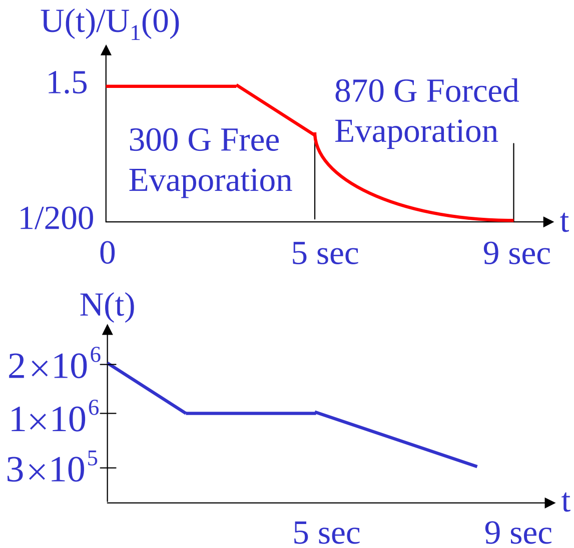

Scaling Laws:

$$\frac{\rho_f}{\rho_i} = \left(\frac{U_i}{U_f}\right)^{1.3} = 10^3$$

$$\frac{N_f}{N_i} = \left(\frac{U_f}{U_i}\right)^{\frac{3}{16}} = \frac{1}{2.7}$$

First, a 300 G magnetic field is applied at fixed trap depth. Then the trap is lowered at a field of 870 G, near the Feshbach resonance to produce a degenerate sample in a few seconds. Typically 2 million atoms are loaded. After free evaporation, 1 million atoms remain. Finally, after forced evaporation the number of atoms is reduced by a factor of 3, to 300 thousand, consistent with a scaling law model we have developed.

Cooling a Strongly-Interacting Fermi Gas

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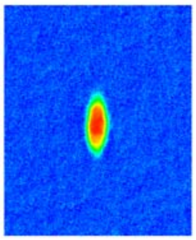
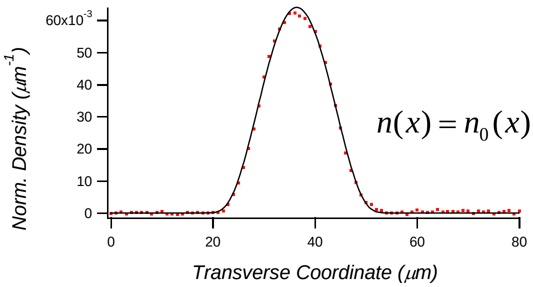
Evaporate for 3.5 s at 910 G:

t = 0.2 ms after release





$$n(x) = n_0(x) + \left(\frac{T}{T_F}\right)^2 n_2(x)$$

$T/T_F = 0.09$
T = 0.7 μK at full trap depth U_0
T = 50 nK at $U_0/200$

Temperature is determined by fitting the transverse distribution of the expanded cloud to a Thomas-Fermi distribution for a noninteracting gas. Temperatures less than 0.1 of the Fermi temperatures are obtained.

Superfluidity in Atomic Fermi Gases

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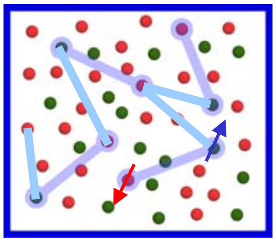
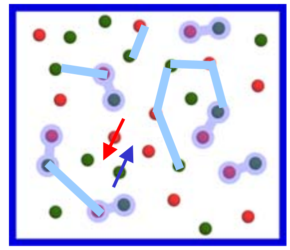
- Magnetically tunable interactions via Feshbach Resonance
- Theory BCS Pairing ^{6}Li: Houbiers, et al., PRA **56**, 4864 (1997).



$$\eta_C \approx \exp\left(\frac{-L}{|a_S|}\right) << 1$$

$$T_C = \eta_C T_F$$

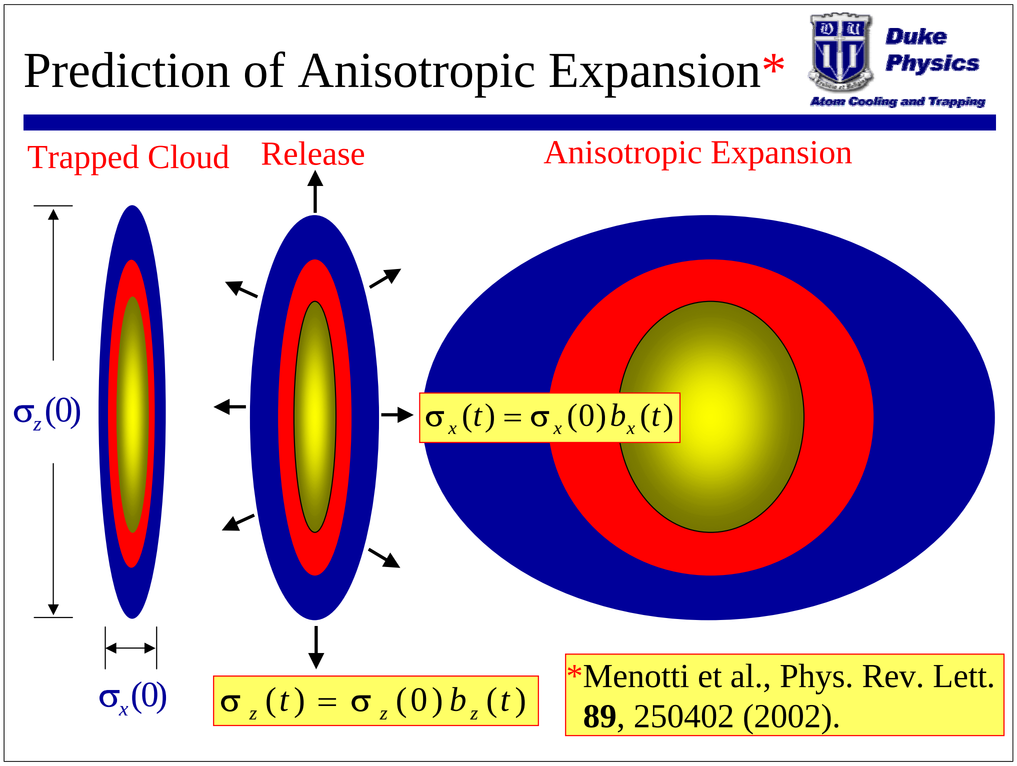


$$\eta_C \approx 0.2 - 0.5$$

- On Resonance: Super-High T_C Superconductivity!

M. Holland, *et al.* Phys. Rev. Lett. **87**, 120406 (2001)
E. Timmermans, *et al.* Phys. Lett. A **285**, 228 (2001)
Y. Ohashi *et al.* cond-mat/0201262 (2002)

Tunable interactions enable new studies of superfluidity in the strongly interacting gas. The first theory of superfluidity in an atomic Fermi gas was done by a collaboration between the groups of R. Hulet and H. Stoof. They applied BCS theory to lithium-6. Recent theories of superconductivity in strongly interacting atomic Fermi gases suggest very high transition temperatures, a large fraction of the Fermi temperature. Such a transition, scaled to a condensed matter system would correspond to a superconductor which could operate at thousands of degrees, far above room temperature.



One possible signature of superfluidity was predicted to be anisotropic expansion after release from the optical trap. The gas is expected to expand strongly in the transverse direction, while remaining nearly stationary in the axial direction.

Can Pauli Blocking Suppress Collisions?

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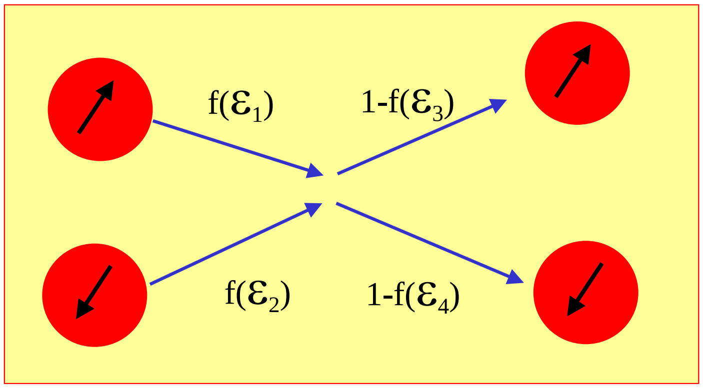
Collision cannot occur if the final state is occupied:



$$\Gamma_{coll} = \gamma \left(\frac{T}{T_F}\right)^2 \rightarrow 0$$

as $T \rightarrow 0$

$f(\varepsilon)$ is the occupation probability

The observation of anisotropic expansion is a signature of superfluidity if the gas is in the collisionless regime. Otherwise, the anisotropy can arise from collisional hydrodynamics. However, collisions are suppressed at low temperatures by Pauli blocking. In this case, colliding atoms cannot enter occupied energy levels, and the collision rate declines as the square of the temperature.

Pauli Blocking in a Harmonic Trap

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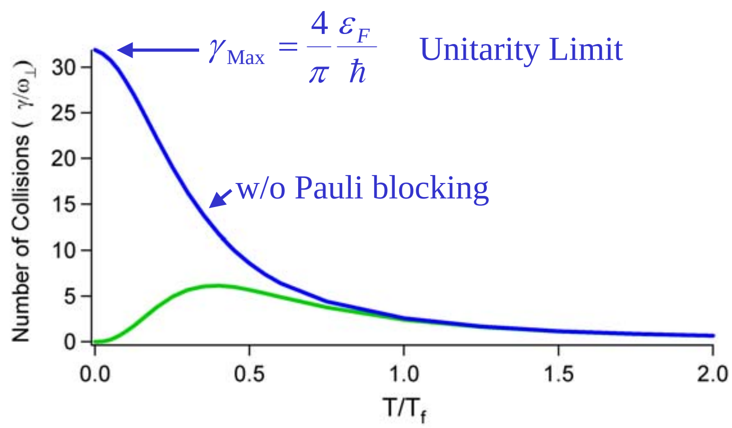
Depletion rate with and without Pauli Blocking:



The blue curve shows how the collision rate of a unitarity-limited gas varies with temperature in the absence of Pauli blocking. With Pauli blocking, the collision rate is suppressed as shown by the green curve. Hence, by operating at temperatures of 0.15 TF or less, the collision rate of the trapped gas is suppressed. Nevertheless, an expanding gas may become collisional as the Fermi surface is deformed. Recent modeling suggests however, that this mechanism is not sufficient to produce strongly hydrodynamic expansion.

Axial Expansion at 910 G

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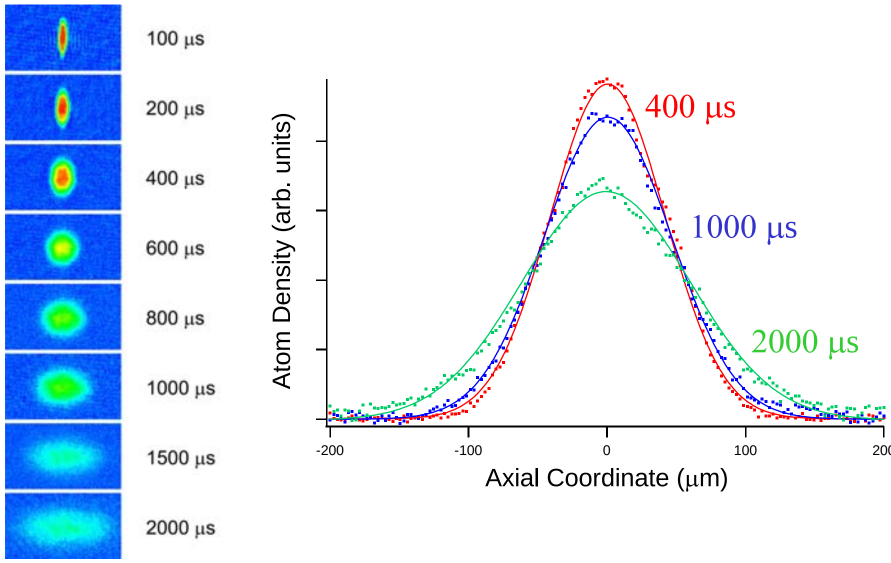
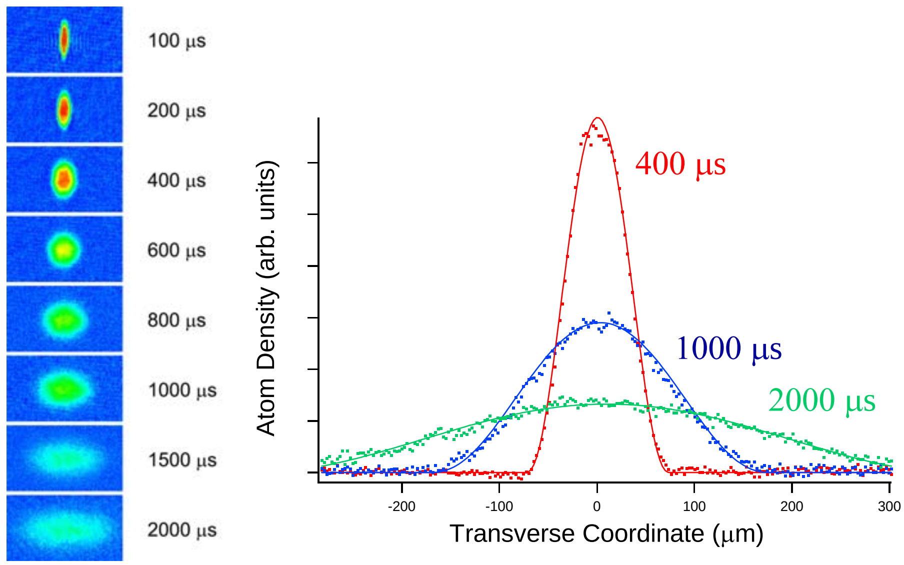


After release from the trap, the gas exhibits strongly anisotropic expansion, characteristic of nearly perfect hydrodynamics. The axial distributions remain nearly stationary.

Transverse Expansion at 910 G



By contrast, the transverse distributions expand rapidly.

Transverse and Axial Widths vs Time

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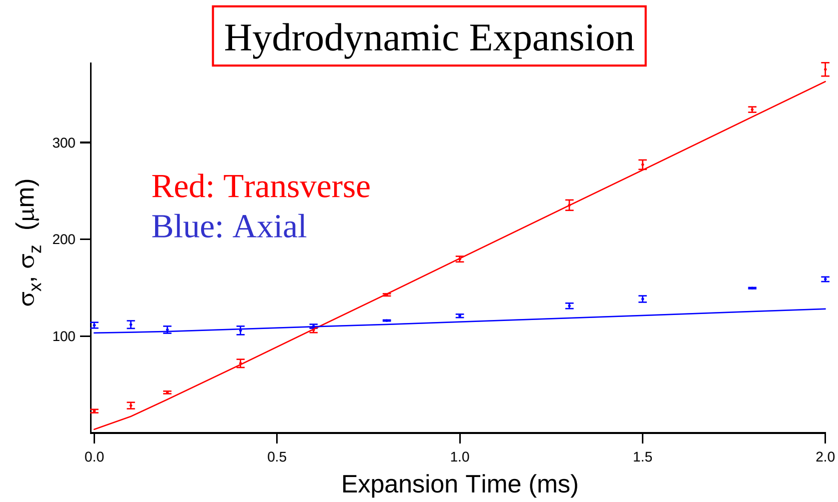
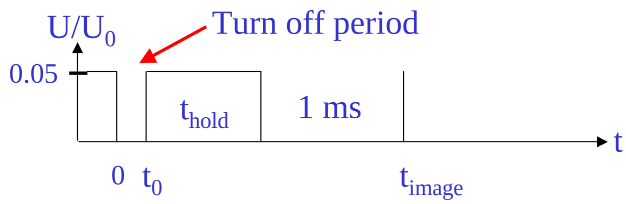


The fit of the observed expansion data is in very good agreement with hydrodynamic theory.

Breathing Mode in a Trapped Fermi Gas



$$t_0 = \frac{1}{16}\frac{2\pi}{\omega} \qquad \frac{T_i}{T_F} \cong 0.1-0.15 \quad \Rightarrow \quad \frac{\Delta T}{T_F} \cong 0.05$$

Measure the Breathing Mode Oscillation Frequency and Damping Time versus Temperature

To avoid issues of deforming the Fermi surface in observing hydrodynamic expansion, we have instead measured the radial breathing mode frequencies and damping times. The breathing mode of the trapped gas is excited by briefly turning off the trap. The corresponding energy input corresponds to 0.05 TF when the trap is extinguished for 1/16 of a radial oscillation period, and is reduced to 0.01 TF when the trap is off for only 1/32 of a period.

Collective Modes in a Trapped Fermi Gas

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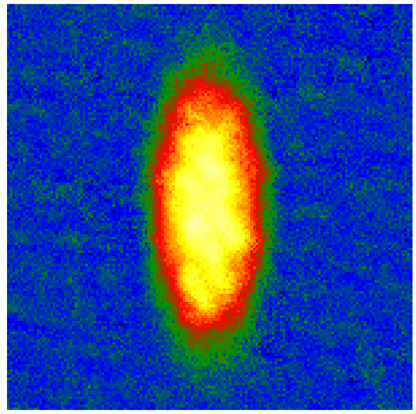
B = 870 G

$\frac{T_i}{T_F} = 0.1 - 0.15$



After the breathing mode is excited, the gas is held for a variable time, and then allowed to expand for 1 ms, after which it is imaged to show the oscillation.

Breathing Mode in a Trapped Fermi Gas

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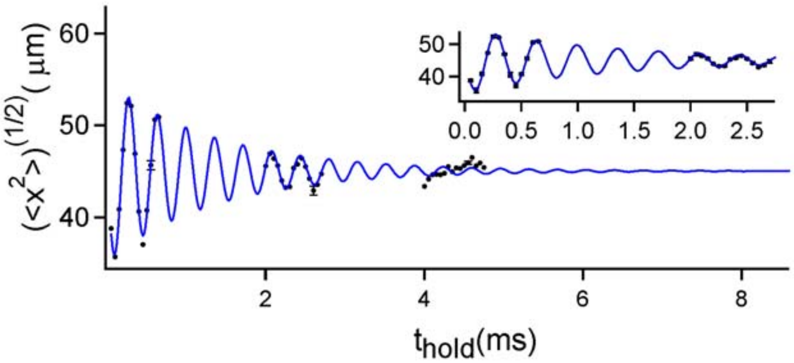
B = 870 G $\quad \frac{T_i}{T_F} = 0.50$



At a temperature of 0.5 TF, the oscillation decays in 1.4 ms.

Breathing Mode in a Trapped Fermi Gas

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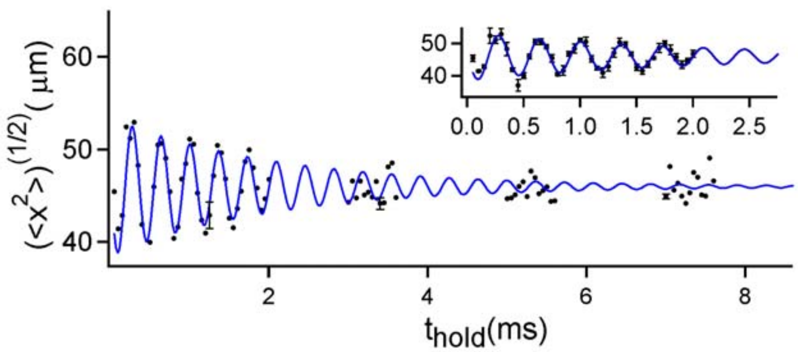
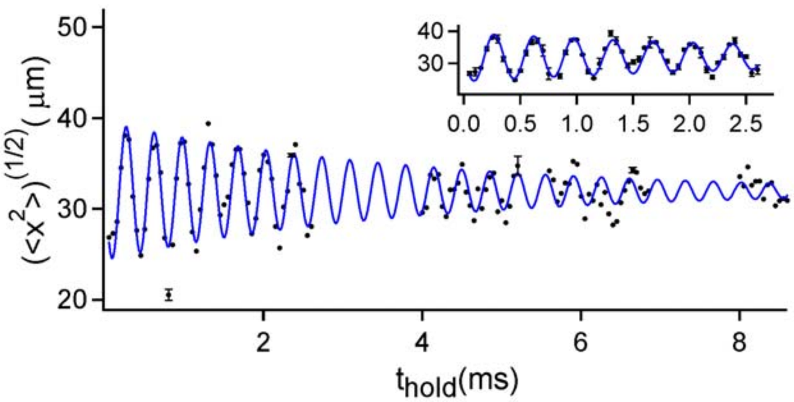
B = 870 G $\quad \frac{T_i}{T_F} = 0.33$



At 0.33 TF, the decay time increases to 2 ms.

Breathing Mode in a Trapped Fermi Gas

B = 870 G $\quad \dfrac{T_i}{T_F} = 0.17$



Finally, at a temperature of 0.17, the gas decays in 4 ms.

Breathing Mode Frequency

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Measured Oscillation Frequencies of Noninteracting Atoms:

$$\omega_x = 2\pi \times 1600 \text{ Hz}$$
$$\omega_y = 2\pi \times 1500 \text{ Hz}$$

Predicted Frequency for Hydrodynamic Fermi Gas:

$$\omega_{\text{Hydro}} = \sqrt{\frac{10}{3}\omega_x \omega_y} = 2\pi \times 2830 \text{ Hz}$$

Measured Oscillation Frequency for Sinusoidal Fit:

$$\omega_{\text{Meas}} = 2\pi \times 2840 \text{ Hz}$$

At 870 G, the measured frequency of the breathing mode is in very good agreement with that expected for a hydrodynamic gas in the unitarity limit.

The predictions are based on the oscillation frequencies measured for atoms in the noninteracting gas.

Breathing Mode Frequency vs B-Field

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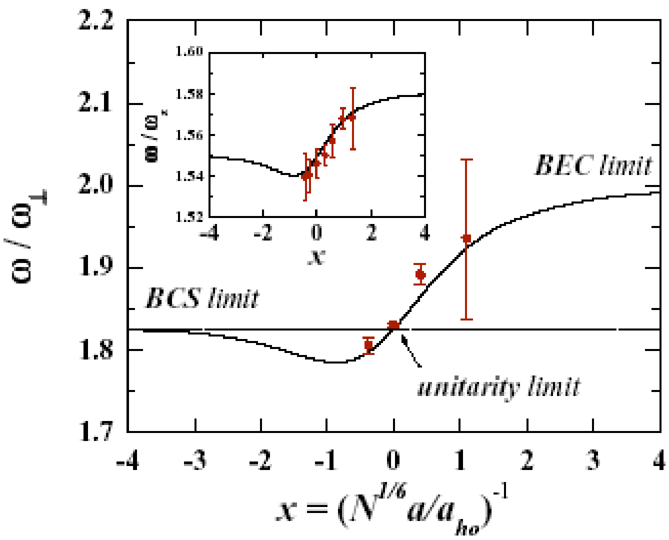
Hui Hu, A. Minguzzi, Xia-Ji Liu, and M. P. Tosi



Feshbach at 850 G

cond-mat/0404012
(Apr 2004)

The magnetic field dependence of the breathing mode frequencies is shown for the radial direction (lower) measured by our group and for the axial direction (measured by the Innsbruck group). If the Feshbach resonance is located at 850 G, the agreement is reasonably good.

Breathing Mode Frequency vs B-Field

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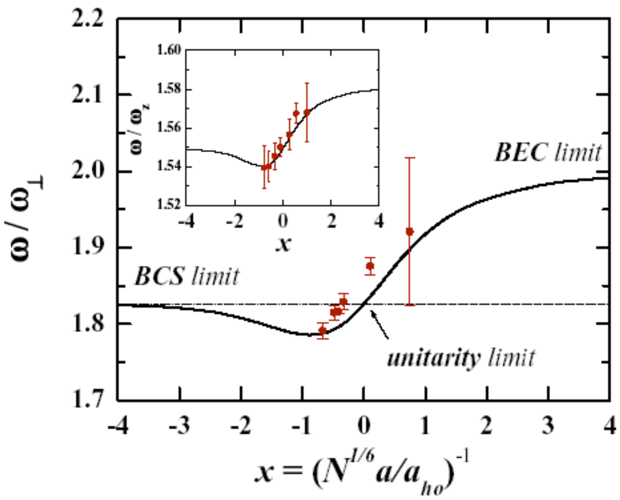

Feshbach at 822 G

cond-mat/0404012
(Apr 2004)

Moving the Feshbach resonance to 822 G produced worse agreement with the radial measurement. However, the measured frequencies display the predicted trend and are still hydrodynamic.

Damping Time of the Breathing Mode

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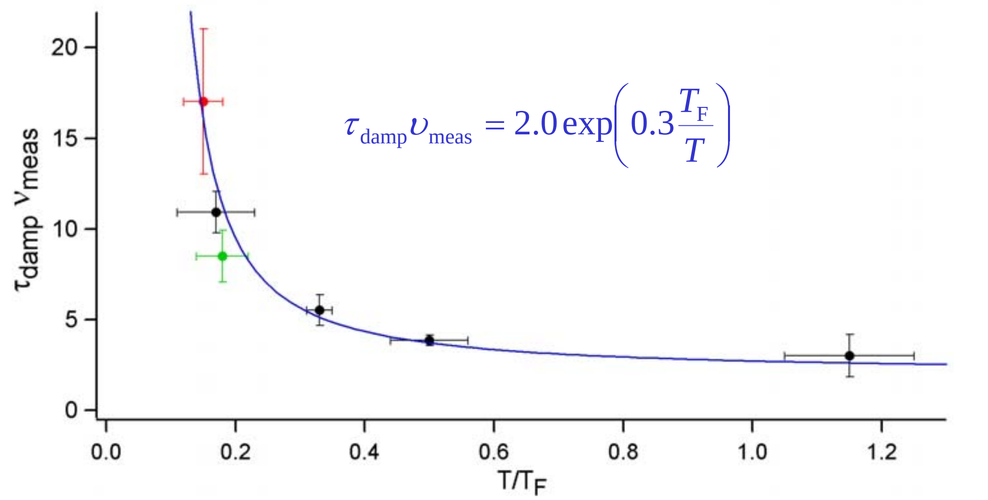

The damping time shows a rapid increase with decreasing temperature.

The red and green data points are taken with the duration of the trap turn off set to 25 microseconds, while all other data is taken at 50 microseconds. The green point is taken at approximately four times the trap depth, and it is at approximately twice the frequency.

Summary

- All-Optical Production of Degenerate Fermi Gas
  - Efficient evaporation near Feshbach resonance
  - Very low T/T_F

Hydrodynamics of a Strongly-Interacting Fermi Gas

- Observation of Anisotropic Expansion
  - For low T, collisions may not explain hydrodynamics
- Trapped Atom Hydrodynamics
  - Collisionally-damped hydrodynamic spectra at high T
  - Hydrodynamic breathing modes weakly-damped as T is reduced
  - First evidence for superfluid hydrodynamics in a Fermi gas

In summary, we use all-optical methods with evaporative cooling near a Feshbach resonance to produce a strongly interacting degenerate Fermi gas.

We observe hydrodynamic behavior in the expansion dynamics. At low temperatures, collisions may not explain the expansion dynamics.

We observe hydrodynamics in the trapped gas. Our observations include collisionally-damped excitation spectra at high temperature which were not discussed above. In addition, we observe weakly damped breathing modes at low temperature. The observed temperature dependence of the damping time and hydrodynamic frequency are not consistent with collisional dynamics nor with collisionless mean field interactions. These observations constitute the first evidence for superfluid hydrodynamics in a Fermi gas.