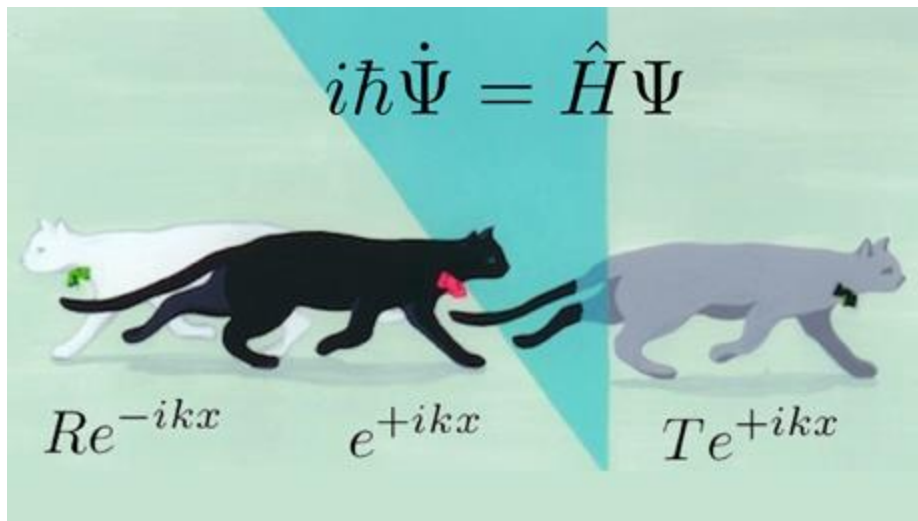


Exploring Quantum Physics

Instructors: Charles W. Clark and Victor Galitski

Quantum Gases

Part 3. Degenerate Fermi-Dirac gases



How to apply quantum mechanics to many-particle systems?

www.nobelprize.org



Enrico Fermi
1901-1954

1938 Nobel Prize in Physics
"for his demonstrations of the existence of new radioactive elements produced by neutron irradiation, and for his related discovery of nuclear reactions brought about by slow neutrons".

Fermi (1926):

- start with an ideal gas
- construct quantum states of motion for a gas atom
- assume that at most one atom can occupy any given quantum state*
- use statistical mechanics to calculate properties of gas in thermal equilibrium

*Fermi-Dirac statistics, which apply to **fermions**



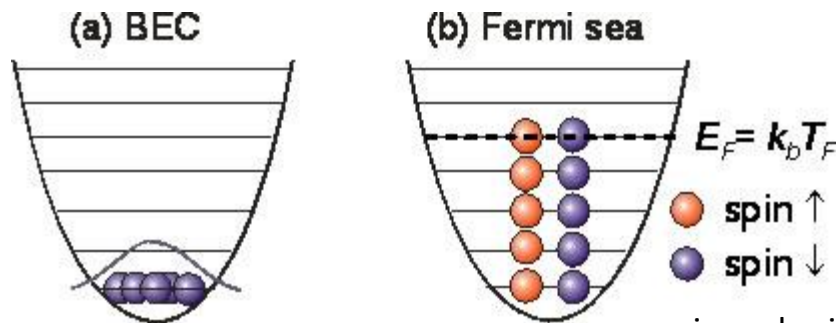
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The ideal Fermi-Dirac gas

Fermi worked this out for the 3D isotropic harmonic oscillator potential

Additional materials/On the quantization of the monoatomic ideal gas



greiner.physics.harvard.edu

- In contrast to bosons, levels are all filled up to the **Fermi energy E_F** , even at zero temperature
- This is what makes matter hard!

The ideal Fermi-Dirac gas

www.nobelprize.org



Many important implications of Fermi's idea!

Additional materials/The story of two atoms

$$M_{\text{limit}} \approx \left(\frac{hc}{G} \right)^{3/2} \frac{1}{m_{\text{H}}^2}$$

Planck constant

Speed of light

Gravity

Mass of hydrogen atom

Subramanyan Chandrasekhar
1910-1995

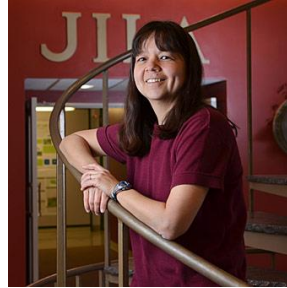
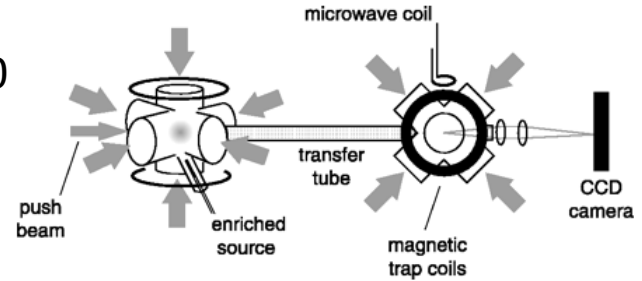
1983 Nobel Prize in Physics
"for his theoretical studies of
the physical processes of
importance to the structure
and evolution of the stars".

- Chandrasekhar: electron degeneracy pressure determines upper mass limit of stable stars
- This implies the existence of black holes!

Experimental attainment of a quantum degenerate Fermi gas

Fermi's construction realized in 1999

- $\sim 10^6$ atoms of potassium-40 (^{40}K) in a 3D harmonic oscillator trap



Deborah Jin

1968 -

MacArthur Fellow

Member of US National

Academy of Sciences

“Onset of Fermi Degeneracy in a Trapped Atomic Gas,” B. DeMarco and D. S. Jin, *Science* **285**, 1703 (1999)

Invideo quiz

Why is the isotope potassium-40 (^{40}K) a fermion ?

Potassium-40 is a composite quantum system made up of an even number of fermions

Potassium-40 really isn't a fermion, but it is cheaper to use than potassium-41, which IS a fermion and is pretty much the same in all other respects

Potassium-40 is an atom with 40 nucleons in its nucleus and 19 electrons in its electron shells. That's a total of 59 fermions, an odd number, so overall it is a fermion (correct)

Experimental attainment of a quantum degenerate Fermi gas

Fermi's construction realized in 1999

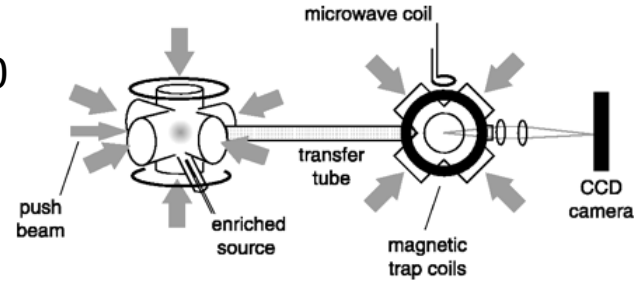
www.nist.gov



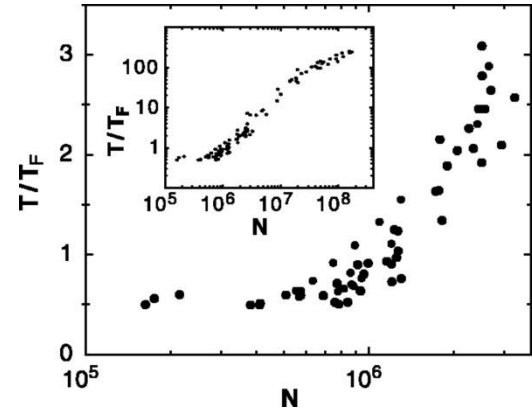
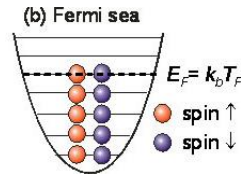
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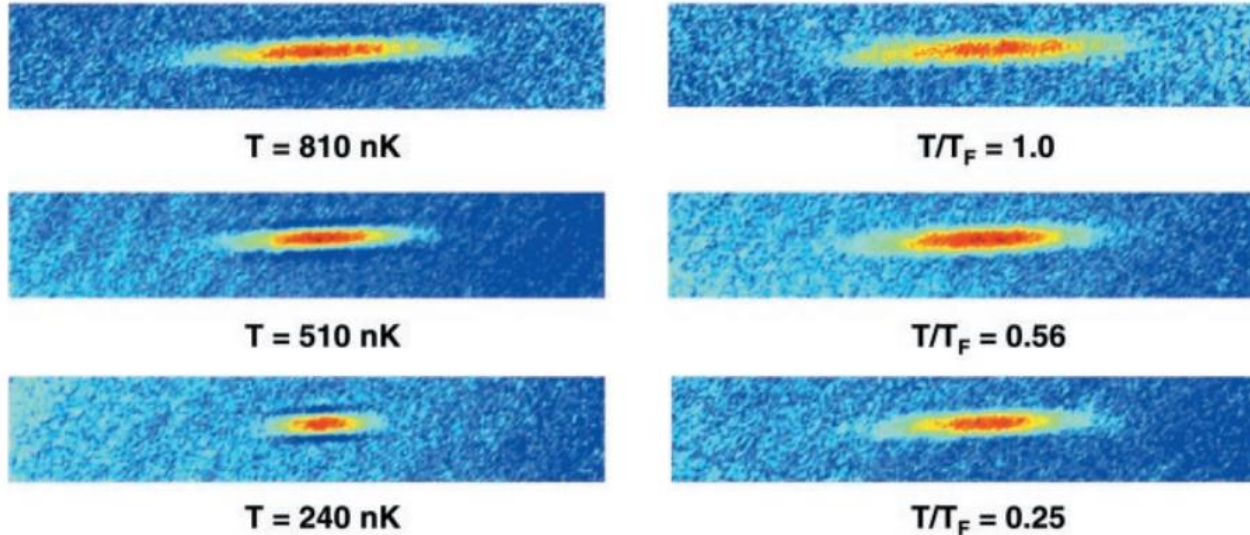
- Evaporative cooling encounters hard wall for temperatures below T_F



“Onset of Fermi Degeneracy in a Trapped Atomic Gas,” B. DeMarco and D. S. Jin, *Science* **285**, 1703 (1999)

Sympathetic cooling of fermions by bosons

^7Li and ^6Li cooled in the same trap



“Observation of Fermi Pressure in a Gas of Trapped Atoms,” A. G. Truscott *et al.*, Science **291**, 2570 (2001)

Invideo quiz

Which of the two isotopes lithium-6 (${}^6\text{Li}$) and lithium-7 (${}^7\text{Li}$) is a fermion?

They each have three electrons, so they are both fermions

They each have three electrons, so neither is a fermion

When you account for the number of nucleons in the nucleus, lithium-6 is the fermion (correct)

When you account for the number of nucleons in the nucleus, lithium-7 is the fermion

Sympathetic cooling of fermions by bosons

^7Li and ^6Li cooled in the same trap

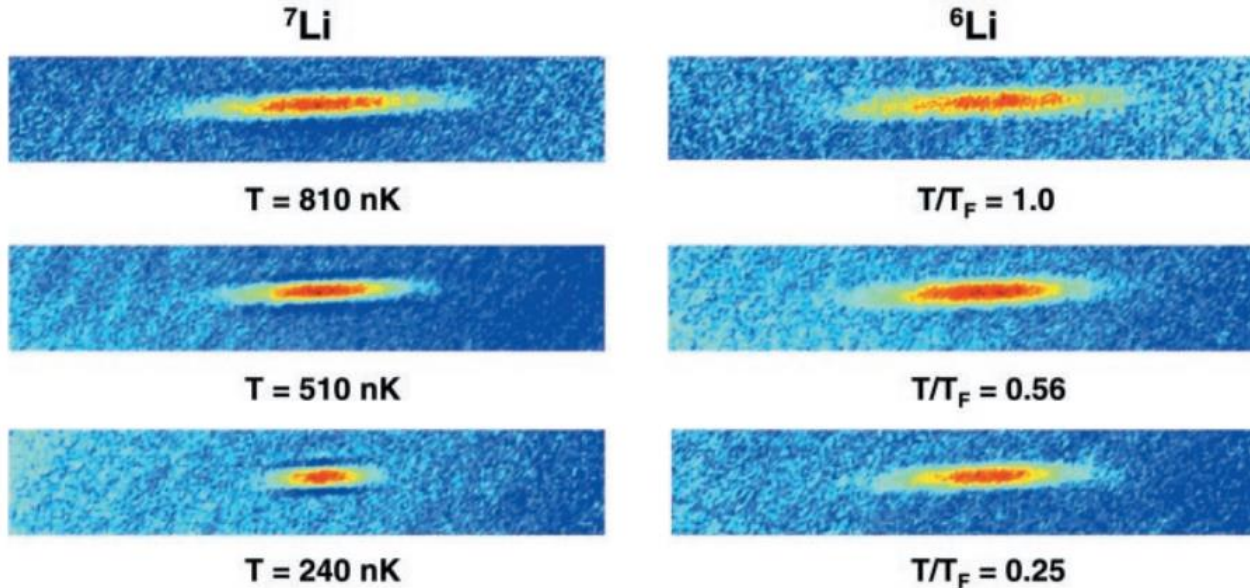
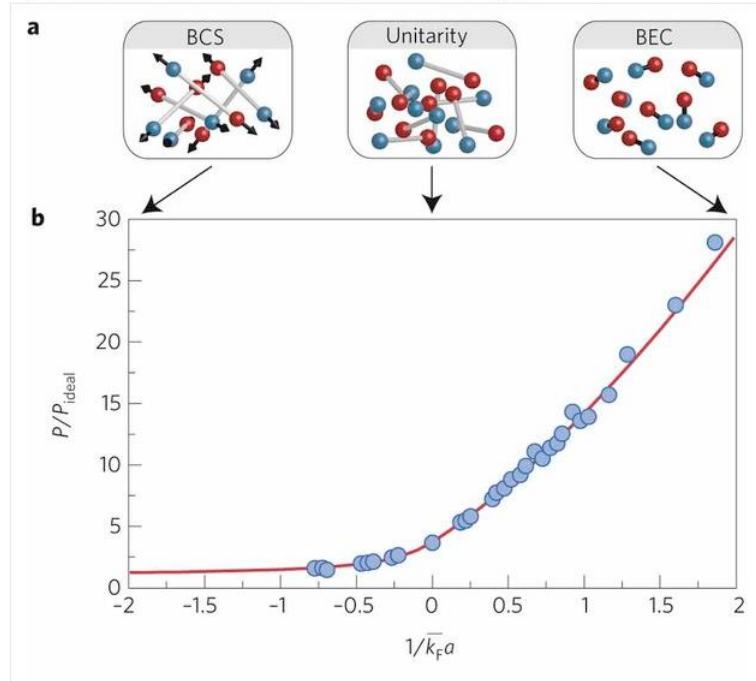


Fig. 1. Two-dimensional false-color images of both ^7Li and ^6Li clouds. At $T/T_F = 1.0$, the two clouds are approximately the same size, but as the atoms are cooled further, to $T/T_F = 0.56$, the Bose gas contracts, whereas the Fermi gas exhibits only subtle changes in size. At $T/T_F = 0.25$, the size

“Observation of Fermi Pressure in a Gas of Trapped Atoms,” A. G. Truscott *et al.*, Science **291**, 2570 (2001)

Connection between superconductivity and Bose-Einstein condensation

Figure 1: Equations of state of interacting ultracold Fermi gases.



“Quantum simulations with ultracold quantum gases,” I. Bloch, J. Dalibard and S. Nascimbène, *Nature Physics* **8**, 267 (2012)

- Superconductivity based on Cooper pairs of electrons (BCS: Bardeen-Cooper – Schrieffer)
- BEC: a condensate of bosons that are composed of fermions
- As pairs become more strongly correlated, we can see the “BCS – BEC crossover”