

(First session)

Degenerate Fermi gas (K-40, JILA, 1999)

DeMarco and Jin, Science 285 (1999) 1703

Strongly interacting fermi gas (Li-6, Duke, 2002)

O'Hara et al., Science 298 (2002) 2179

Pairing atoms into molecules (K, Cs, Li, Rb, Na, 2003)

Regal et al., Nature 424 (2003) 424

(Second session)

BEC-BCS experiment (2004-)

Selected early papers:

Regal et al., PRL 92 (2004) 040403

Bartenstein et al., PRL 92 (2004) 120402

Chin et al., Science 305 (2004) 1128

Question 1: why are Fermi gas experiments lagging behind BECs?

Question 2: why are interacting Fermi gas stable? Or are they?

Question 3: how can the BEC-BCS crossover be smooth when scattering length diverges?

Question 4: what is new in a strongly interacting fermi gas?

Q1 and Q2:

Laser cooling

Only 2 out of 9 alkali isotopes are fermionic. Both of them have issues.

K-40: low natural abundance 0.07% (actually not even stable) and inefficient cooling

Li-6: low abundance and 10x worse optical cooling only to 300~500 μ k.

Further investigation:

- Why there are so few fermionic isotopes?
- Why does not optical cooling work well on K-40 and Li-6?
- Recent progress in cooling Li-6 and K-40 (ENS, LENZ, Berkeley)

Magnetic/optical trapping and evaporation

High temperatures require deeper traps, especially Li needs > 100W focused to few 10 microns.

Fermions of the same spin do not interact at low temperatures, thus thermalization and evaporation ceases.

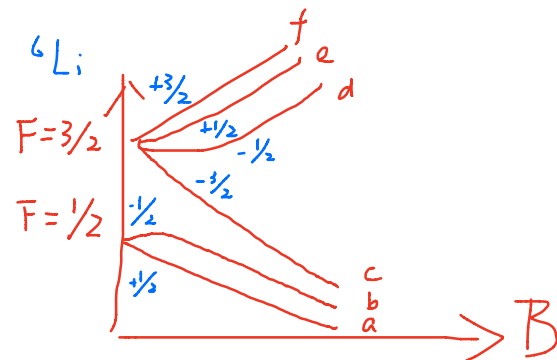
This means the sample will be an ideal fermi gas, which is boring!!

Solution: more than one component fermi gas

(Convention: a, b,c.... in the order of the Zeeman energy.)

Elastic collisions -> interaction

Inelastic collisions -> decay



Popular option 1: spin a and b

- aa, bb... are non-interacting (why?)
- ab can pair near a Feshbach resonance.
- Are there inelastic collisions?
 - $a + b \rightarrow a + a$??
 - $a + b + b \rightarrow ab + b$??
 - $a + a + b \rightarrow ab + a$??
 - $ab + ab \rightarrow$??

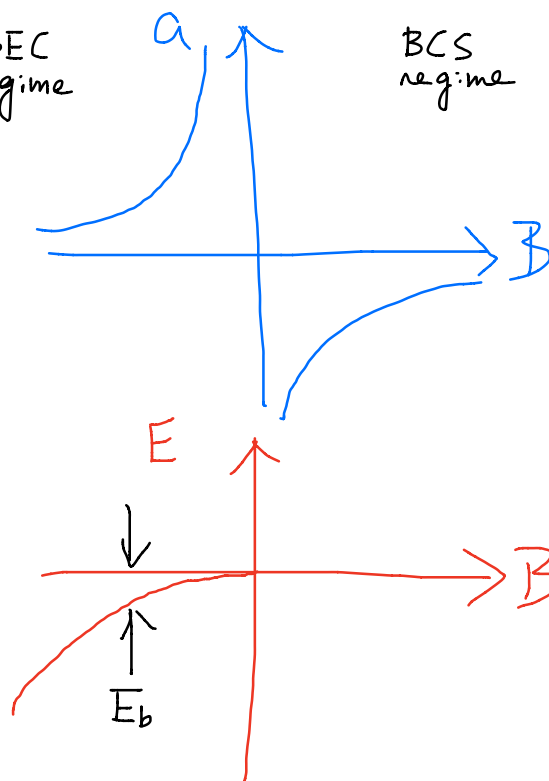
Other combinations: bc or ac or a b c. They are also of interest.

Q3: a smooth BEC-BCS crossover!?

Two body
Picture

BEC
regime

BCS
regime



scattering length

$$a = a_{bg} \left(1 - \frac{\Delta}{B - B_0} \right)$$

a_{bg} : background
scattering length

Δ : resonance width

B_0 : resonance position

Binding energy

$$E_b = \frac{\hbar^2}{m(a - \bar{a})^2}$$

m : atomic mass

\bar{a} : mean scattering length
 $\approx 0.95 r_{vdW}$

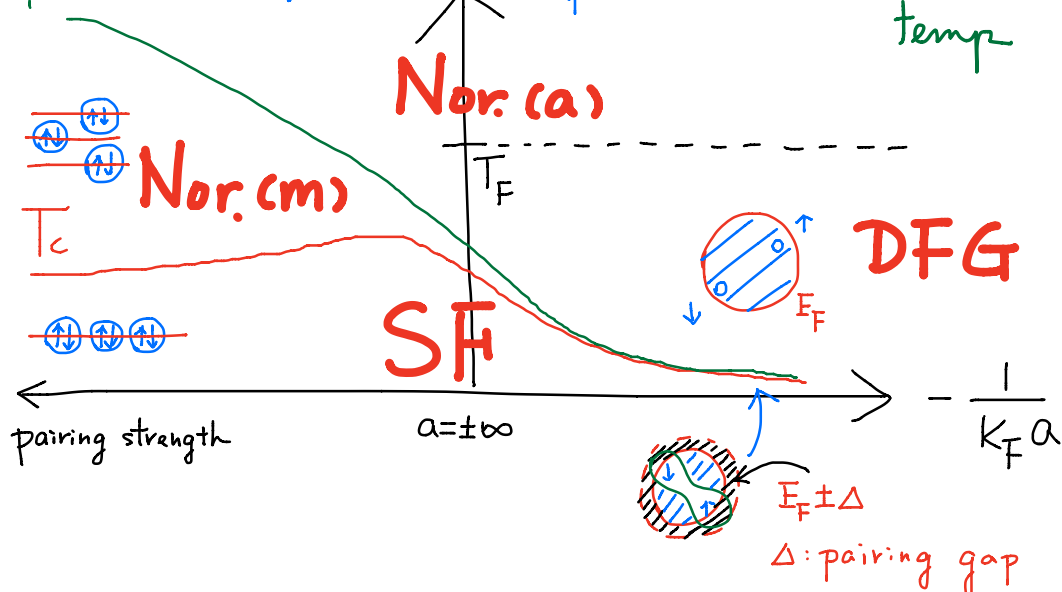
Many body picture

T^* molecular
BEC

BCS

T_c : SF temp.

T^* : pairing
temp



BEC regime:

When pairing energy is greater than Fermi energy, pair size is smaller than interparticle spacing. System is more like a collection of composite bosons. The ground state is a **molecular BEC**.

Expectation:

BEC of diatomic molecules Li_2 or K_2 just like atomic BEC.

How do diatomic molecules interact? Why are diatomic BECs stable?

BCS regime:

When pairing energy is weak compared to Fermi energy, system remains normal well below fermi temperature, and pairing and **BCS superfluid** transitions happen at the same time $\Delta \sim kT_c = kT^*$ (BCS theory).

Expectation:

BCS theory should apply, but trap and finite particle # might give a stringent condition to experimentally realize atomic BCS superfluid.

Use BCS theory result and estimate how many particles you need to see a gap larger than the vibrational spacing in a harmonic trap or in a box?

BCS-BEC crossover: **molecular BEC connects to BCS superfluid**

Expectation:

On resonance, everything looks somewhat like that of a regular Fermi gas, but T_c is proportional to Fermi temperature. T^* is expected to be higher than T_c (not confirmed).

Since a diverges, the only length scale is the interparticle spacing $\sim 1/k_F$. It is expected all energies scale with Fermi energy of free fermions.

Frontier of quantum gas research: few-and many-body physics

Homework CC1

Due in two weeks (3/25/2014)

1. Answer two of the following three questions in one page. Provide references if you do not find an intuitive way to elaborate your argument.

- Why there are so few fermionic isotopes in stable alkali atoms?*
- What is the fundamental reason that optical cooling does not work as well on K-40 and Li-6 as on, say, Rb?*
- Describe the key ideas in recent breakthroughs in sub-Doppler cooling Li-6 and K-40.*

Hint: for b & c, you may start with recent relevant publications ('11~'13) in Giovanni Mondugno's group in LENZ, Christopher Salomon's group at ENS, or Holger Mueller's group at UC Berkeley.

2. Consider N fermionic atoms with spin up, and N with spin down in a 3D spherical harmonic trap $V(r)$ with trap frequency ω . The average occupancy number of a state i for non-interacting bosons/fermions is

$$n_i = \frac{1}{e^{(E_i - \mu)/kT} \mp 1}.$$

- In the BCS limit (non-interacting Fermi gas), show that the ground*

state density profile is $n_F(r) = \frac{1}{3\pi^2} \left(\frac{2m}{\hbar^2} \right)^{3/2} [\mu - V(r)]^{3/2}$, and

$\mu = E_F = \sqrt[3]{6N} \hbar \omega$ is the chemical potential.

- In the unitarity limit, the above results require only minor corrections! Why? And what are the minor corrections?*
- An important result from BCS theory is that the gap is given by*

$$\Delta = \frac{g}{2^2} E_F e^{-\pi/2 k_F |a|}.$$

In typical fermi gas experiments, $N \sim 100,000$, how deep into the BCS regime can one go before the Cooper pairs are limited by the trap?

