Superfluidity in polarized Fermi gases through the BEC–BCS crossover

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Why cold atom gases?

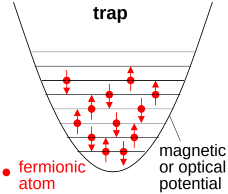
- Explore the limits of many-body theories used in nuclear physics by applying them to systems of cold atoms.
- Atomic clouds can simulate some complicated nuclear systems
- Only one parameter to describe the interaction strength: a (the scattering length in s-wave channel):

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

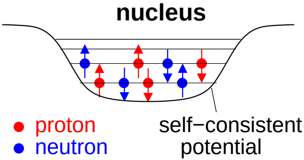
  B is the external magnetic field applied to the trapped atomic cloud

- Experiments on cold atoms don't require big and expensive experimental set-up

From an atomic gas to a nucleus



$\Leftrightarrow$



$N \sim 10^3 - 10^6$ (3D)
$T_F = \varepsilon_F / k_B \sim 10^{-6}$ K
$k_F^{-1} \sim 10^{-6}$ m
int. range $r \sim 10^{-4} k_F^{-1}$

$T_{exp} \to 0.1\, T_F$

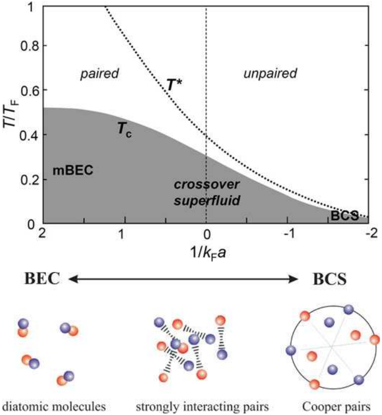
$A \sim 10 - 10^2$
$T_F \sim 10^{11}$ K
$k_F^{-1} \sim 10^{-15}$ m
$r \sim k_F^{-1}$

Superfluid phase!

Diluteness

Phase diagram of the BEC–BCS crossover

BOSONS | Phase diagram | FERMIONS



[R. Grimm, 2007]

Repulsive ($a > 0$)

Attractive ($a < 0$)

$^6\mathrm{Li}_2$

$^6\mathrm{Li}$

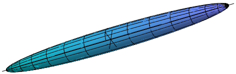
From a Bosonic to a Fermionic behaviour with the same system!

What kind of systems can be produced?

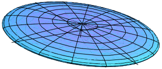
- Preparing an atomic (^{6}Li, ^{40}K,...) gas into 2 hyperfine levels (pseudospin): $|\uparrow\rangle$ and $|\downarrow\rangle$
- Optical trap (laser) or magneto-optical trap
- Simulating polarized matter: $N_\uparrow \neq N_\downarrow$
- Systems of two different atom species (different masses): useful for quark matter

Possibility to choose the geometry of the cloud

- Lasers + magnetic coils = trap potential with different frequencies:

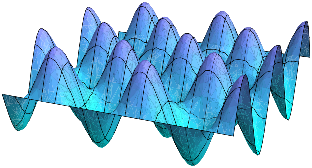


$\omega_x = \omega_y \gg \omega_z$
Cigar shaped



$\omega_x = \omega_y \ll \omega_z$
Pancake

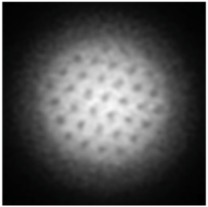
- Optical lattice: 2D, 1D gases!



Superfluidity in atom clouds and nuclei

Cold atoms

- Fermionic: Cooper pairs ($(k_F a)^{-1} < -1$)
- Bosonic: Bose–Einstein condensates ($(k_F a)^{-1} > 1$)
- Vortex lattices in rotating clouds have been observed



[MIT]

Nuclei

- 2 kinds of fermions (isospin)
- Smaller number of interacting particles
- Rotations!

Superfluidity in Fermionic gases

Balanced systems: $N_\uparrow = N_\downarrow$

- BCS below a critical temperature $\Rightarrow$ Cooper pairs: $k_{F\uparrow} = k_{F\downarrow}$

Unbalanced systems $N_\uparrow > N_\downarrow$

- New pairing appears: FFLO phase (1964)

Cooper pairs with non-zero total momentum

BUT

Not observed yet

- Coexistence with a fully polarized phase
- Maybe even in nuclear matter (at low densities) [Stein et al, PRC 86, 062801]

Description of the strong interacting regime

- BCS theory:
  - OK for $(k_F a)^{-1} < -1$
  - Near unitarity: critical temperature overestimated

  $\rightsquigarrow$ We need an other method to describe the interaction
- T-matrix approximation (Nozières–Schmitt-Rink (1985))
  - Ladder diagram approximation (beyond mean field)
  - OK with the BEC critical temperature ($(k_F a)^{-1} \gg 1$)
  - OK with the BCS critical temperature ($(k_F a)^{-1} \ll -1$)
  - To do: generalization to polarized systems
- Critical temperature given by Thouless criteria

$$\mathrm{Re}\,\Gamma^{-1}(0, \mathbf{0}, T = T_C^{\mathrm{BCS}}) = 0,$$

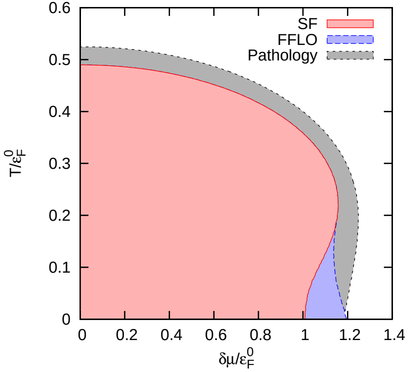
$$\mathrm{Re}\,\Gamma^{-1}(0, \boldsymbol{k}, T = T_C^{\mathrm{FFLO}}) = 0. \qquad \text{(NEW)}$$

Phase diagram of an imbalanced atomic Fermi gas

- FFLO found!
- Bad value of the spin susceptibility

$$\chi = \frac{\partial}{\partial \delta\mu}(\rho_\uparrow - \rho_\downarrow) < 0.$$

- Pathology even at $\delta\mu = 0$



- Cold atoms = an easy way to get clean and controlable systems of strongly correlated Fermions
- Study physics of some particular state of the nuclear matter:
  - Pairing correlations
  - Neutron stars
  - Collective modes

Trapped atomic gases:
a laboratory for thermodynamic and non-equilibrium processes for strongly correlated particles and with a lot of available data!