Supersolid phases in imbalanced atomic Fermi gases

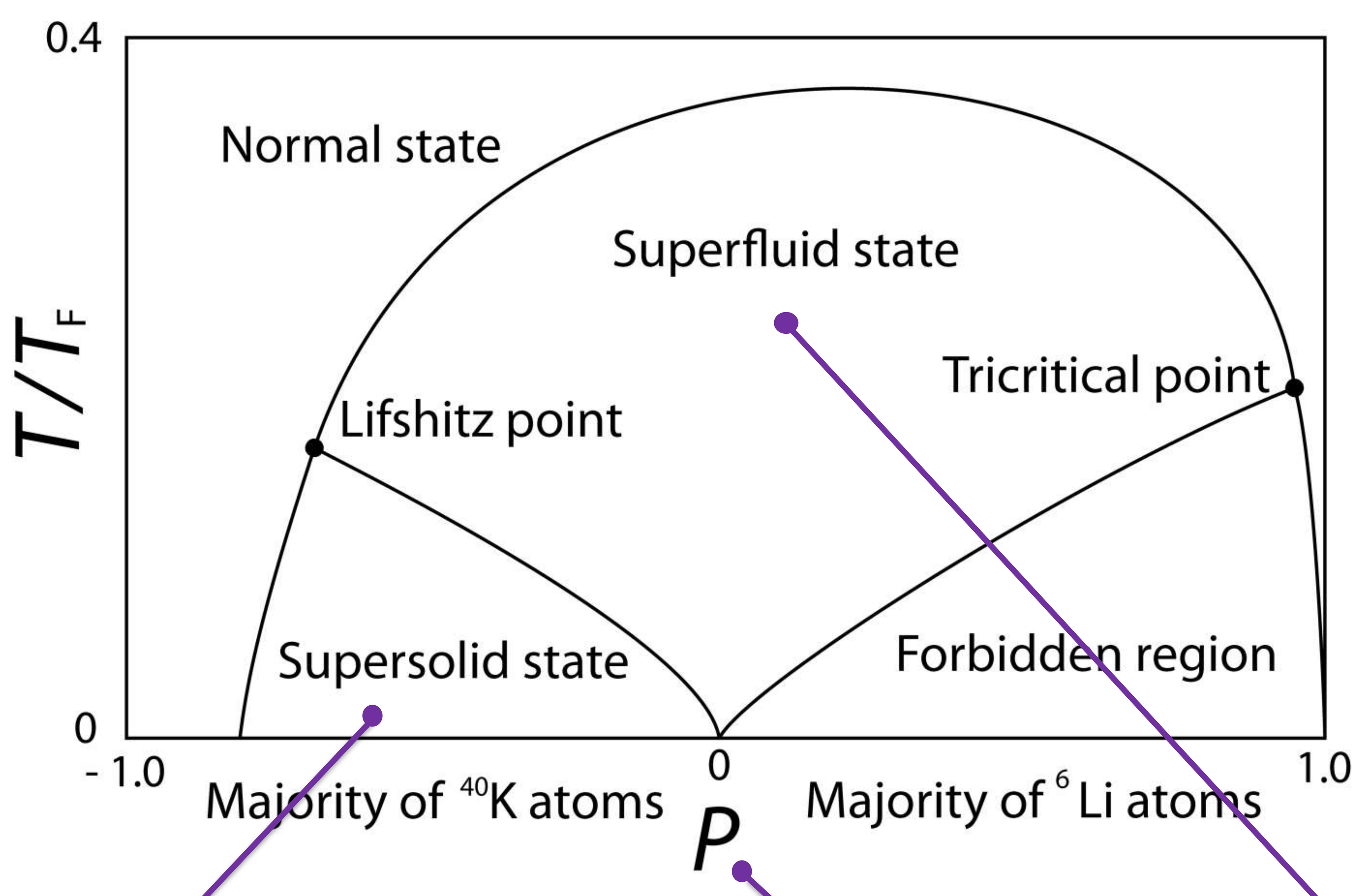
Universiteit Utrecht

Jildou Baarsma and Henk Stoof

Fermions can not occupy the same quantum state and can therefore only form a superfluid state after forming so-called Cooper pairs. A Cooper pair is a pair of two fermions from different (spin) species. This phenomenon has been studied extensively both experimentally and theoretically in gases of cold atoms. In cold atom experiments, not only the temperature can be controlled, but also the interaction strength between atoms and even the polarization of a Fermi gas. This resulted in a complete phase diagram for a Fermi gas consisting of a single species of atoms present in two spin states.

The next possibility is to study a Fermi gas consisting of two different species of atoms. We study a polarized mixture of ^{6}Li and ^{40}K atoms.

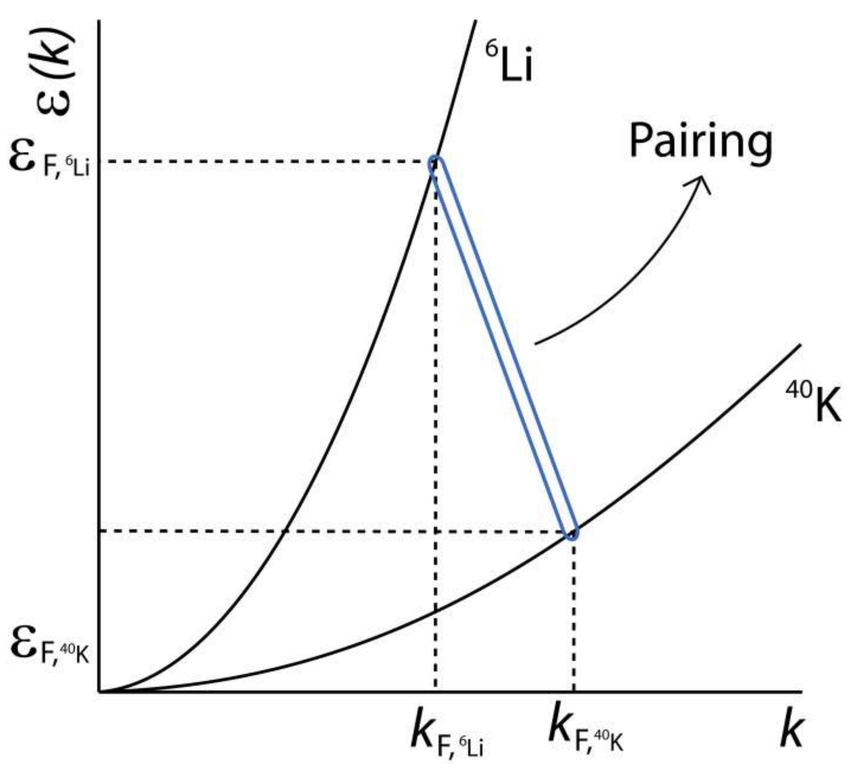
Mixture of ^{6}Li and ^{40}K



The phase diagram of a Fermi mixture consisiting of ^{6}Li atoms and ^{40}K atoms. For small polarizations the phase transition from a normal state to a homogeneous is continuous. For a majority of ^{6}Li atoms there is a tricritical point below which the phase transition is discontinuous. This discontinuity causes the forbidden region below the tricritical point.

For a majority of ^{40}K atoms a phase transition to a supersolid occurs. The point where the normal, superfluid and supersolid state meet is called a Lifshitz point.

Supersolid



In the supersolid phase Cooper pairs are made up of a ^{6}Li atom and a ^{40}K atom with different momenta. Thus, the pairs have an effective momentum. This causes a standing wave in the superfluid, giving also a periodicity in the densities. Thus, the superfluid is also a solid.

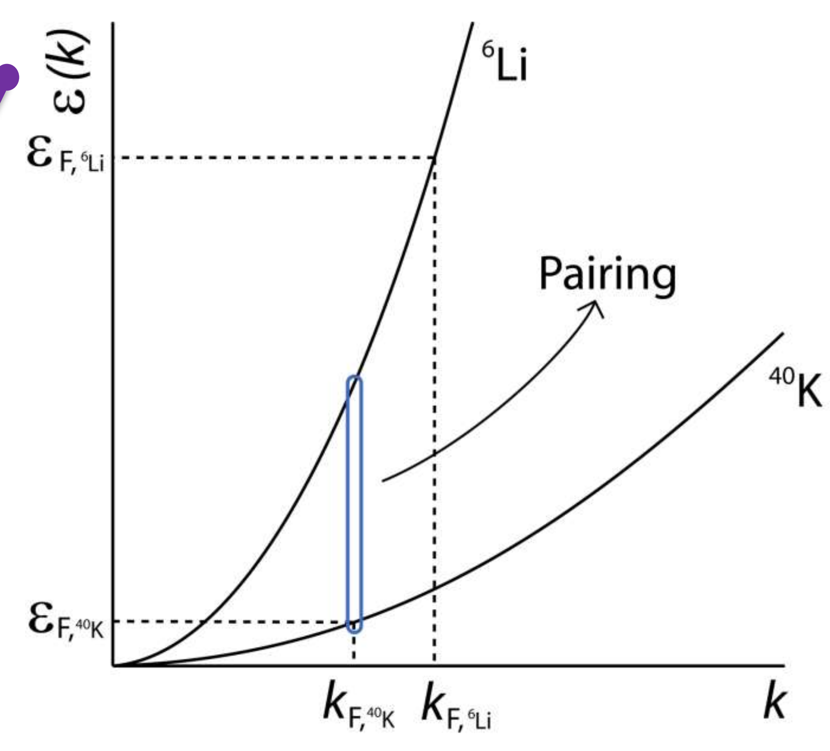
$$P = \frac{n_+ - n_-}{n_+ + n_-}$$

n_+: density ^{6}Li atoms

n_-: density ^{40}K atoms

$$\varepsilon_\sigma(\mathbf{k}) = \frac{\hbar^2 \mathbf{k}^2}{2m_\sigma}$$

Superfluid



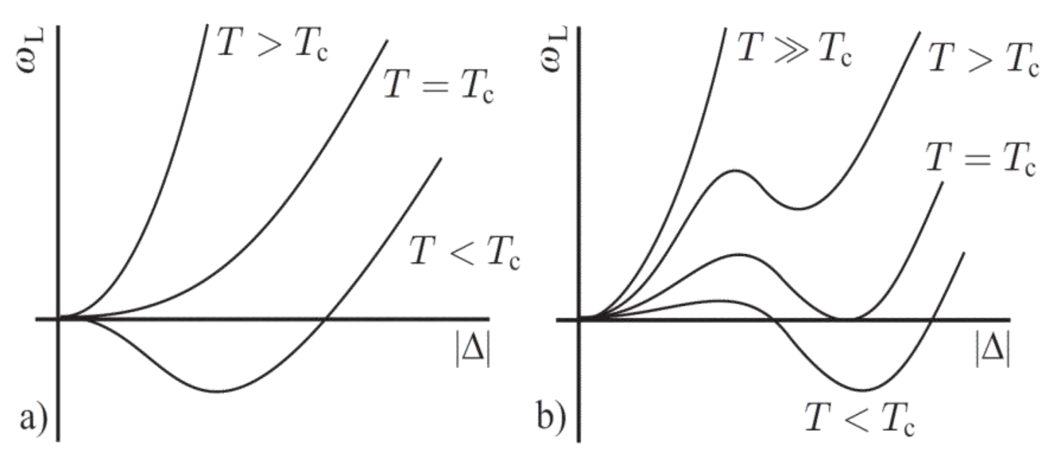
In a single species Fermi gas atoms with the same momentum also have the same energy. In a mass-imbalanced mixture this is not the case and forming a Cooper pair therefore costs more energy.

Theory

In order to describe a phase transition we introduce an order parameter, that is on average related to the density of Cooper pairs:

$$\langle \Delta(\mathbf{x}) \rangle = V_0 \left\langle \hat{\psi}_-(\mathbf{x}) \hat{\psi}_+(\mathbf{x}) \right\rangle$$

Then we can calculate the thermodynamic potential, which plays the role of a Landau free energy. From the thermodynamic potential we can determine the phase diagram.



Superfluid

A fermion with momentum **k** couples to a fermion with momentum –**k**. The order parameter thus becomes:

$$\Delta(\mathbf{x}, \tau) = \Delta$$

With this ansatz for the order parameter we calculate the thermodynamic potential:

$$\omega_L(|\Delta|)$$

Supersolid

A fermion with momentum **k** couples to a fermion with momentum –**k + q** or to a fermion with momentum **–k-q**. The order parameter becomes:

$$\Delta(\mathbf{x}) = \Delta(\mathbf{q}) \cos(\mathbf{q} \cdot \mathbf{x})$$

With this ansatz for the order parameter (LO) we calculate the thermodynamic potential.

$$\omega(|\Delta(\mathbf{q})|)$$

References: M.W. Zwierlein *et al.*, Science **311**, 492 (2006); G.B. Partridge *et al.* Science **311**, 503 (2006); K.B. Gubbels *et al.*, Phys. Rev. Lett. **103**, 195301 (2009); J.E. Baarsma *et al.*, Phys. Rev. A **82**, 013624 (2010)