Superfluidity in 2D atomic gases: BEC-BCS crossover

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INTRODUCTION

1. OVERALL AIM

In a fermionic ultracold atomic gas at the BEC-BCS crossover there could be a modulated superfluid Fulde-Ferrel-Larkin-Ovchinnikov (FFLO) phase. The FFLO phase is difficult to realise experimentally in 3D atomic gases but in 2D is expected to be more prominent. There are similarities of the system to electron-hole bilayers.

SPECIFIC AIMS OF THIS PROJECT

- Search for FFLO phases in 2D atomic gases
- Find the phase diagram of a free and harmonically trapped gas
- Consider population and mass imbalance

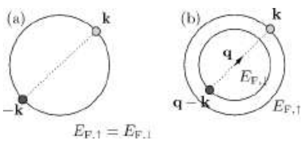

Fig. 1. A Cooper pair in (a) a BCS state, (b) a FFLO instability. Different shading denotes particle species, Fermi surfaces are shown by solid lines and pairing momentum by the by solid lines and pairing momentum by the dotted line.

2. FFLO INSTABILITY

A FFLO superfluid phase with a spatially modulating order (gap) parameter is formed from mismatched fermion species (spin-up ↑ and down ↓), shown in Fig. 1.

(a): With equal Fermi surfaces the Cooper pairs have no total momentum.

(b): Population imbalance (or a ratio of masses) means Fermi surfaces are mismatched so Cooper pairs have non-zero total momentum **Q**. This results in a modulating order parameter and a spatially varying state.

3. ANALYTICAL APPROACHES

Two complementary approaches were followed to express energy in terms of the order parameter Δ_q:

Ginzburg-Landau approach: Expand the thermodynamic potential as $\Phi=\sum_q \alpha_q|\Delta_q|^2$, if $\alpha_q<0$ it is favourable for $\Delta_q\neq 0$ – an FFLO instability.

Single Fourier component approach: The exact thermodynamic potential $\Phi(\Delta_Q)$ is minimised with respect to a single wave vector **Q** and the order parameter Δ_Q.

FREE SYSTEM

Possible phases: **SF:** balanced superfluid phase. **FFLO:** textured superfluid phase. **FP:** fully polarised normal (that is a free Fermi gas) phase. **PP:** partially polarised normal phase. **ZP:** no particles.

Control parameters: Mass ratio $r=m_\downarrow/m_\uparrow$, particle chemical potentials $\mu_\uparrow=\mu+h$ and $\mu_\downarrow=\mu-h$, and binding energy of particle pairs E_b.

4. WITHOUT FFLO

In the Fig. 2 phase diagram, the order parameter is constrained to be uniform, that is **Q=0**.

As the ratio of masses r is increased the phase diagram becomes skewed, the centre of the SF phase is the locus $\mu/h=(r+1)/(r-1)$, where the species Fermi surfaces are perfectly matched.

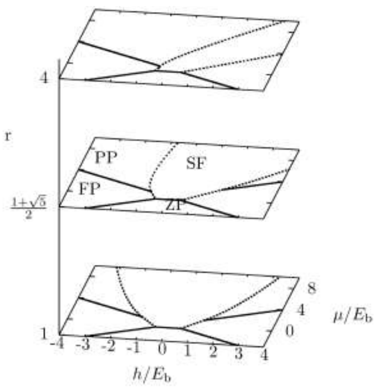

Fig. 2. Free system phase diagram. Second (first) order transitions are shown by solid (dotted) lines.

5. WITH FFLO PHASE

In the Fig. 3. phase diagram the FFLO instability encroaches into the partially polarised normal state (PP) but not the superfluid (SF).

There is a first order transition from the FFLO instability into the SF state and a second order transition from the PP state into the FFLO instability, agreeing with a previous Fourier analysis [2].

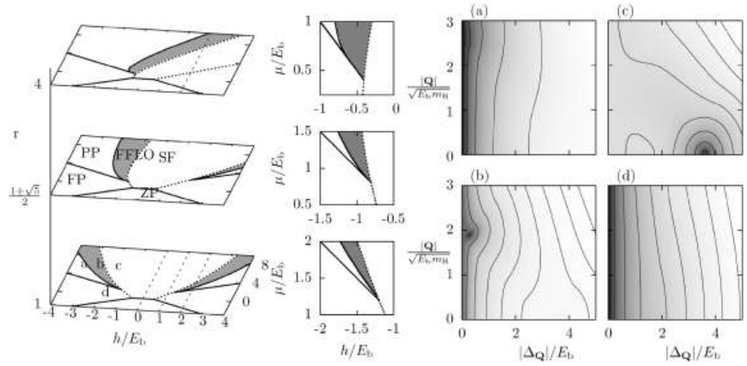

Fig. 3. *Left*: The phase diagram of a free system with variable mass ratios. The FFLO regions are shaded grey. Continuous transitions are shown by solid lines, first order by dotted lines. *Centre*: The FFLO terminus at each mass ratio. *Right*: Sample thermodynamic potential surfaces, dark regions have more negative thermodynamic potential (more favourable).

TRAPPED SYSTEM

6. HARMONIC POTENTIAL

A rich range of radial density profiles of the system in a harmonic trap are shown in Fig. 4. The trap is treated with the local density approximation with an effective chemical potential $\mu(\mathbf{R})=\mu_0-V(\mathbf{R})$ corresponding to the straight line trajectories shown in Fig. 3.

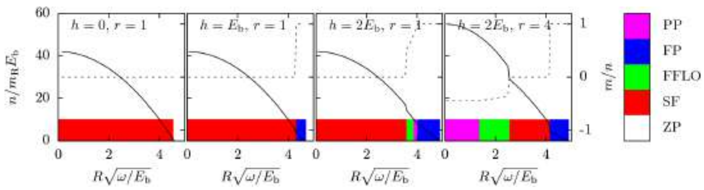

Fig. 4. Radial density profiles in four identical harmonic traps with different population imbalance h and mass ratio r. Solid lines show radial density based on the primary y-axis, the dashed line shows the local population imbalance based on the secondary y-axis. The bottom band shows the extent of the phases that are labelled with the defined colours.

CONCLUSIONS

- An analytical expression for the thermodynamic potential of a 2D two-component atomic Fermi gas was derived
- The FFLO transition phase boundary was found analytically
- The free system phase diagram was analysed in detail, a second order transition was seen from the PP into the FFLO phase.
- Trapped systems have a rich range of possible density profiles

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