Spin-imbalanced quasi-2D Fermi gases

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Outline

Introduction

• Creating layered quasi-two dimensional Fermi gases:
  – Meaning of quasi-2D?

Experiments

• Radio-frequency spectroscopy of quasi-2D Fermi gases:
  – Failure of dimer and 2D-BCS theories
  – 2D Fermi-polaron model

• Thermodynamics of quasi-2D Fermi gases:
  – Density, pressure, and temperature in spin-imbalanced mixtures
  – Phase transition of spin-imbalanced mixtures to a balanced core
Creating a Quasi-2D Fermi Gas

- CO\textsubscript{2} laser:
- Standing wave
- Mirror

\(~1000\text{~atoms/site, 5.3~}\mu\text{m spacing}\)

**Individual optical imaging**
Atoms in Standing Wave Trap
Two-Dimensional Gas

\[
\sin^2\left(\frac{2\pi z}{\lambda}\right) + \frac{-m\omega^2\rho^2}{2U_0} + \frac{1}{1 - e^{\frac{-m\omega^2\rho^2}{2U_0}}}
\]

2D Transverse Fermi Energy

\[
\mu_{\perp 0} = E_F \equiv h\nu_\perp \sqrt{2N_0}
\]

- True 2D if: \(\mu_{\perp 0} = E_F \ll h\nu_\perp\)
- 3D if: \(\mu_{\perp 0} = E_F \gg h\nu_\perp\)
Quasi-Two-Dimensional Gas

True 2D if:

\[ \mu_{\perp 0} = E_F \ll \hbar \nu_z \]

Quasi-2D if:

\[ E_F \approx \hbar \nu_z \]
Quasi-2D Fermi Gases

Search for high temperature superconductivity in *layered* materials:

- In copper oxide and organic films, electrons are confined in a quasi-two-dimensional geometry
- Complex, strongly interacting many-body systems
- Phase diagrams are not well understood
- Exotic superfluids in spin-imbalanced systems

**Enhancement** of the superfluid transition temperature *compared to true 2D* materials:

- Heterostructures and inverse layers
- Quasi-2D organic superconductors
- Intercalated structures and films of transition metals
Optically-Trapped $^6$Li Atoms

$^6$Li Fermi Gas

![Diagram of optical trapping and magnetic field](image)

![Graph showing energy vs. magnetic field](image)
Radio Frequency Spectroscopy

\[ E_b(a_s, \nu_{\text{trap}}) - \text{dimer binding energy} \]
RF 12-to-13 spectrum at 720 G

Calculated dimer binding energies:

\[ E_{b}^{12} = 145 \text{ kHz} \]

\[ E_{b}^{13} = 2.9 \text{ kHz} \]
RF 12-to-13 spectrum at 832 G

Bare atomic transition

Bound to bound transition

$E_{b}^{12} - E_{b}^{13}$

$E_{b}^{12} = 7.25 \text{ kHz}$

$E_{b}^{13} = 0.81 \text{ kHz}$

Dimer theory fails!
Many-body physics?
BCS Theory in Two Dimensions

**BCS-Two dimensions:** (Randeria 1989)

Predicts radio-frequency transition with frequency $\omega$:

$$\hbar\omega = \sqrt{\mu_\perp^2 + \Delta^2} - \mu_\perp$$

Gap equation: $E_b = \sqrt{\mu_\perp^2 + \Delta^2} - \mu_\perp$

$h\omega = E_b$  **Dimer Spectrum!**

No many-body effects on the spectrum!
Fermi-Polaron Gas (Chevy)

\[ \langle \psi \rangle_{\text{polaron}} = \phi_0 \downarrow, p = 0 \langle FS \uparrow \rangle + \sum_{kq} \phi_{kq} \downarrow, q - k \langle FS \uparrow; 1_k \uparrow 0_q \uparrow \rangle \]

single spin down  cloud of particle-hole pairs
Comparison of Polaron Model with Measurements

\[ h\Delta \nu_{\text{dimer}} = E_{b12} - E_{b13} \]
\[ h\Delta \nu_{\text{polaron}} = E_{p12} - E_{p13} \]

<table>
<thead>
<tr>
<th>B(G)</th>
<th>(v_z) (kHz)</th>
<th>(\Delta \nu_{\text{meas}}) (kHz)</th>
<th>(\Delta \nu_{\text{dimer}}) (kHz)</th>
<th>(\Delta \nu_{\text{polaron}}) (kHz)</th>
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<td>179</td>
<td>44.5</td>
<td>33.2</td>
<td>48.3</td>
</tr>
</tbody>
</table>
Measure Column Density:

\[ n_c(x) = \int_{-\infty}^{\infty} dy \, n_{2D}(\sqrt{x^2 + y^2}) \]

Transverse Density Profiles: \( n_{2D}(\rho) \)
Column Densities versus $N_2/N_1$

**Majority state:** $N_1 \cong 800$ per site

- $E_b = 2D$ dimer binding energy

**Minority state:** $N_2 \leq N_1$

- $E_F = 2D$ ideal gas Fermi energy

- **832 G** $\frac{E_F}{E_b} = 6.6$

- **775 G** $\frac{E_F}{E_b} = 0.75$

[Graphs showing column densities versus $x/R_{TF1}$ for different values of $N_1$ and $N_2$.]

$\text{site per 800} \cong N$

[$N_1 \leq 12$]

[$N_2 \leq N_1$]

[$E_b = 2D$ dimer binding energy]

[$E_F = 2D$ ideal gas Fermi energy]
Quasi-2D Fermi Gas Temperature

\[
n_{2D}^{(n)}(\rho) = \frac{2N}{\pi R^2} \tilde{T} \ln \left[ \frac{1 + e^{[\tilde{\mu}_n - \tilde{U}(\rho)]/\tilde{T}}}{1 + e^{[\tilde{\mu}_n - \tilde{U}_0]/\tilde{T}}} \right]
\]

Total 2D-Density

\[
n(\rho) = \sum_n n_{2D}^{(n)}(\rho)
\]

Normalization determines \(\mu_0\)

Fit Column Density:

\[
n_c(x) = \int_{-\infty}^{\infty} dy n(\sqrt{x^2 + y^2})
\]

\[
\mu_n = \mu_0 - n \hbar \omega_z
\]
Quasi-2D Fermi Gas Spatial Profiles

- $E_F/E_b = 2.1$
  - $N_2/N_1 = 0.1$
  - $N_2/N_1 = 0.5$
  - $N_2/N_1 = 1$
  - Fit $n = 0$ only
  - $n = 0$ contribution
  - $T/T_F = 0.21$
  - $T/T_F = 0.18$
  - $T/T_F = 0.14$

- $E_F/E_b = 6.6$
  - Fit $n = 0, 1, 2$
**Majority and Minority Radii**

- $E_b = 2D$ dimer binding energy
- $E_F = 2D$ ideal gas Fermi energy

Ideal gas Thomas-Fermi radius - Majority

$$\frac{E_F}{E_b} = 6.6$$

$$\frac{E_F}{E_b} = 0.75$$
Majority and Minority Radii

\frac{E_F}{E_b} = 6.6

\varepsilon_F = \mu + \frac{E_b}{2}

\frac{E_F}{E_b} = 0.75

Ideal gas

2D-BCS—balanced
2D-Polaron Thermodynamics

Free energy density of imbalanced gas:

\[ f = \frac{1}{2} n_1 \varepsilon_{F1} + \frac{1}{2} n_2 \varepsilon_{F2} + n_2 E_p (2) \]

Polaron energy:

\[ E_p (2) = y_m (q_1) \varepsilon_{F1} \]

Ideal Fermi gas

Minority Polaron Energy

\[ \varepsilon_{F1} = \frac{2\pi \hbar^2}{m} n_1 \]

\[ q_1 \equiv \frac{\varepsilon_{F1}}{E_b} \]

\[ y_m (q_1) = \frac{-2}{\log(1 + 2q_1)} \]

Klawunn and Recati 2011

Chemical potentials:

\[ \frac{\partial f}{\partial n_1} = \mu_1 = \mu_{10} - U(\rho), \quad \frac{\partial f}{\partial n_2} = \mu_2 = \mu_{20} - U(\rho) \]

Pressure:

\[ p = n_1 \mu_1 + n_2 \mu_2 - f \]
Majority and Minority Radii

\[ \frac{E_F}{E_b} = 6.6 \]

\[ \frac{E_F}{E_b} = 0.75 \]

\( \frac{R}{R_{TFI}} \) vs. \( \frac{N_2}{N_1} \)

- Ideal gas
- Polaron model
- 2D-BCS—balanced
Predicted Density Profiles

\[ \frac{n_{2D}}{n_{\text{ideal}}} \]

\[ E_F/E_b = 0.75 \quad \text{N}_2/N_1 = 0.5 \]

[Graph showing density profiles with labels for Majority and Minority]
Transition to a Balanced Core?

Balanced Core 2D-Profile: \( \Delta n_{2D}(\rho) = A \Theta[\rho - R] \Theta[R_1 - \rho](1 - \rho^2 / R_1^2) \)

balanced core \( \rho < R \)

\[ N_2/N_1 = 0.35 \quad E_F / E_b = 0.75 \]
2D-Central Density Ratio

- Transition to balanced core:
  - Not predicted!

Polaron model

Ideal gas

\[ \frac{E_F}{E_b} = 6.6 \]
\[ \frac{E_F}{E_b} = 2.1 \]
\[ \frac{E_F}{E_b} = 0.75 \]
Summary

- BCS theory for a true 2D system **fails** in the quasi-2D regime.

- 2D polaron model explains several features of the density profiles in the quasi-2D regime.

- 2D polaron model with the analytic approximation is too crude to predict the transition to a balanced core.

- Measurements with imbalanced mixtures provide the first benchmarks for predictions of the phase diagram for quasi-2D Fermi gases.