Probing superfluid and 2D Fermi gases

Outline

3D Critical velocity

Homogeneous 2D Fermi gases

Equation of state

Momentum Distribution
Landau’s critical velocity

\[ v_c = \min_k \left( \frac{\epsilon(k)}{\hbar k} \right) \]

BEC

BCS
BEC-BCS crossover

![Graph showing the crossover between BEC and BCS regimes.](Image)
The critical velocity

- strong correlations
- knowing ground state not enough
- \( v_c \) and \( T_c \) matter
- phonons, pair breaking, vortices

Critical velocity
Critical velocity and speed of sound

W. Weimer et al., PRL 114, 095301 (2015); V. Singh et al. PRA 93, 023634 (2016)
Simulations by Vijay Singh & Ludwig Mathey

Ground state from Monte Carlo, dynamics with truncated Wigner method,

- trapping
- inhomogeneous vertical density
- finite temperature
- finite attractive stirrer depth
- circular stirrer motion
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Reducing dimensions

2D Fermi: Turlapov, Vale, Köhl, Zwierlein, Thomas Jochim, Bakr, …
Reducing dimensions

\[ \frac{5}{2} \hbar w_z \]
\[ \frac{3}{2} \hbar w_z \]
\[ \frac{1}{2} \hbar w_z \]

\[ E_F, k_B T \ll \hbar \omega_z \]
\[ 5 \text{kHz} \ll 10 \text{kHz} \]

2D Fermi: Turlapov, Vale, Köhl, Zwierlein, Thomas Jochim, Bakr, …

3D Fermi in box: Zwierlein Group

\[ \theta = 10.4^\circ \]
\[ D = 50 \mu\text{m} \ldots 200 \mu\text{m} \]

Plane Wave

Bessel Region

Ring Region
Creating a steep ring without disorder inside

Simplest setup

Fiber Tip

10° Axicon

10° Axicon

Stray Light

\( f_1 = 8 \text{mm} \)

Steeper, less stray light inside

Fiber Tip

10° Axicon

10° Axicon

Movable 2° Axicon

Point of Optical Inversion

Intermediate Image Plane

\( f_{k1} = 8 \text{mm} \)

\( f_{k2} = 400 \text{mm} \)

Flatness and steepness

\( V(x) = Ax^\xi = Ax^{87\pm5} \)

75 img’s averaged

\( \sigma_n = 8.6\% \)
Tunable potential landscapes

- Digital micromirror array (DMD) imaged onto atoms
  - 25 pixels per resolved spot → 25 gray scales
  - A hardware extension was developed to generate truly static patterns [K. Hueck et al., RSI 88, 016103 (2017)]
  - Development of Matlab class to control the DMD [GitHub]

- For transport measurements through 2D
  - Disordered media
  - Josephson barrier/oscillations
  - Driven systems

- Embedded systems, Interfaces
Equation of state $n(\mu, T)$ of ideal Fermi gas

$\Delta n = \log \left[ 1 + \exp \left( \frac{\mu - \epsilon}{k_B T} \right) \right]$
Scale invariant equation of state $n(\mu, T)$

Theory: $n\lambda_{dB}^2 = \log[1 + \exp(\beta \mu)]$

2D EOS: Bose gases  Chin & Dalibard groups, Fermi gases: Turlapov, Vale, Jochim groups

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- Momentum Distribution – a nonlocal probe
To momentum space and back ...

free evolution in HO = rotation in phase space

Matter wave focussing: Bose: Walraven, Cornell, Bouchoule, van Druten groups
Fermions: Jochim group

Thermometry: $n(k) = f(k, T, \mu)$

$$f_{FD}(k) = \frac{1}{1 + \exp \left[ \beta \left( \frac{\hbar^2 k^2}{2m} - \mu_0 \right) \right]}$$

$k_{F,dens} = \sqrt{4\pi n_{2D}}$

$T/T_F = 0.31 \pm 0.02$
Pauli blocking in momentum space

box diameter $D \Rightarrow$ single k-mode occupies area $A_k = 16\pi / D^2$

Measure $n(k)$: If one atom per $A_k \Rightarrow$ unit occupation $f(k) = 1$

$f(k)$ saturates for increasing $n \Rightarrow$ evidence for Pauli blocking

Pauli blocking in momentum space: B. Mukherjee (Zwierlein group), PRL 118, 123401 (2017)  
Interacting 2D gases

Non-interacting expansion – remove one spin

free interacting expansion $t = 0$
spin removal pulse at $t = t_k$
free non-interacting exp $t = T/2$
Filling up higher vibrational levels

Increase atom number ⇒ central occupation in momentum $f(k)$ space should not change!

See also: P. Dyke et al., PRA 93, 011604 (2016), Vale Group

Summary

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Outlook

Hole dynamics

Poke out hole In k space
Back to real space Dynamics, wait
Look in k-space again Hole diffusion (Auger)?

Interacting and imbalanced gases

Coherence: $g_1$

Trap averaged momentum distribution $n(k) \xrightarrow{\text{Fourier}} g_1(r)$

P. A. Murthy et al., PRL 115, 010401 (2015), Jochim group
Collaboration: Vijay Singh, Ludwig Mathey
Previous members: Wolf Weimer, Kai Morgener