Unitarity in periodic potentials and correlated s-wave Cooper pair insulators

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Pseudogap: quantum vortex liquid?


Vortex dynamics theory in cuprates:


Unitarity in periodic potentials & correlated s-wave Cooper pair insulators
Is there a universal picture?

• Correlated superconductors & pseudogap
  – QED3 (Tesanovic, Franz, Vafek, Herbut...)
  – Nodal liquid (Balents, Fisher, Nayak)
  – Competing orders (Tesanovic, Balents, Sachdev...)

• What about electrons?
  – Why pairing correlations in the normal state? What does it mean?

• A universal theory of pairing correlations?
  – Insight from unitarity? (BEC-BCS crossover)
Interacting fermions in a lattice

- SF-I pairing transitions
  - (p) ..... particle dominated
  - (h) ..... hole dominated
  - (ph) .. relativistic

- Tuning parameters
  - Chemical potential $\mu$
  - Interaction strength $U$
  - Lattice potential & depth $V$

\[
S = \sum_n \int \mathcal{D}k \ f_{n,k,\alpha}^\dagger (-i\omega + E_n(k)) f_{n,k,\alpha}
\]

\[
+ \sum_{n_1m_1} \sum_{n_2m_2} U_{n_1n_2}^{m_1m_2} \int \mathcal{D}k_1 \mathcal{D}k_2 \mathcal{D}q f_{m_1,k_1+q,\alpha}^\dagger f_{n_1,k_1,\alpha} f_{m_2,k_2-q,\beta}^\dagger f_{n_2,k_2,\beta}
\]

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RG: Only particles or holes

Exact renormalization group:

\[ \frac{dE_g}{dl} = 2E_g \]

\[ \frac{dU}{dl} = (2 - d)U - \Pi U^2 \]

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RG: Both particles & holes

Intra-band Cooper

Inter-band Cooper

Exciton

Ext. s-wave resonating singlet (iron-based superconductors)

RG: $\varepsilon=d-2$ expansion
– 17 tractable fixed points

Unitarity in periodic potentials & correlated s-wave Cooper pair insulators
• Universality class of the SF-I transition
  – bosonic mean-field or XY: 
    \(d=2\), or strong coupling in \(d>2\)
  – pair-breaking:
    weak coupling in \(d>2\):

Mott-band insulator distinction

- Non-analytic change in the excitation spectrum
- Non-equilibrium phase transition
- Driven condensate: Cooper-pair laser


\[ \rho(E, P) = \frac{1}{\sqrt{V}} \sum_n \delta(E - E_n) \delta(P - P_n) \]

\[ \rho'(k) = \lim_{\Delta \epsilon \to 0} \lim_{\Delta_p \to 0} \int d\delta \epsilon \int d^d \delta p \frac{1}{\sqrt{V}} \sum N \rho(N \epsilon_k + \delta \epsilon, N p_k - \delta p) \]
Pseudogap in cuprates

- Microscopic pairing mechanism (?)
  - Short-range AF correlations $\Rightarrow$ gap (antinodal)
  - Weak effective attractive interaction from pair-hopping (antinodal)

- Superconductivity + low temperature + $d=2$ $\Rightarrow$ “BEC regime”

- Complications due to $d$-wave pairing
  - Low energy fermions have small DOS
  - Low energy bosons have large DOS, dominate response
  - Nodal pairbreaking occurs, but anomalously slow (?)
Conclusions

• Renormalization group in band insulators
  – Fixed points ⇒ scattering resonances
  – Run-away flow ⇒ correlated (bosonic Mott) insulators
  – Implications for non-equilibrium

• Generic ingredients for Cooper pair mottness
  – “Independent” gap for fermionic excitations
  – Effective attractive interactions between fermions
  – Proximity to a superconducting phase
  – Low temperatures + $d=2$, or strong interactions in $d>2$