Phase separation of exotic superfluids in a chain of high spin ultracold atoms

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International Workshop
on Cold Gases in Quantum Information
June 30 - July 1, 2015, Bilbao

In collaboration with:

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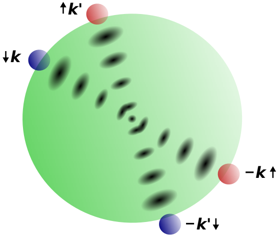
Homogeneous vs. inhomogeneous pairing



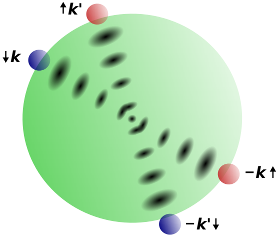
Bardeen, Cooper, Schrieffer (1957)

BCS pairing

- 2 species of fermionic particles.
- $\mathbf{Q}_{COM} = 0 \rightarrow$ homogeneous op.
- Spin singlet $S = 0$.
- Particles close to the Fermi surface.

Bardeen, Cooper, Schrieffer (1957)

BCS pairing



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- $\mathbf{Q}_{COM} = 0 \rightarrow$ homogeneous op.
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Effect of applied/generated magnetic field:

Small Zeeman field

no effect on the BCS pairs

1st order phase transition.

Large enough Zeeman field

ferromagnetic normal state

Chandrasekhar (1962), Clogston (1962)

Fulde, Ferrell (1964), Larkin, Ovchinnikov (1964)

FFLO pairing

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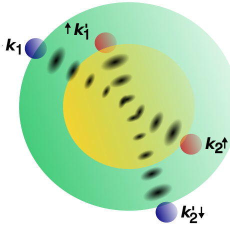
Homogeneous vs. inhomogeneous pairing

Fulde, Ferrell (1964), Larkin, Ovchinnikov (1964)

FFLO pairing



- 2 species of fermionic particles.
- $\mathbf{Q}_{COM} \neq 0 \rightarrow$ inhomogeneous op.
- Spin singlet $S = 0$.
- Particles close to the Fermi surface.

Small Zeeman field

no effect on the BCS pairs

1st order phase transition.

Intermediate Zeeman field

depairing state

2nd order phase transition.

Large enough Zeeman field

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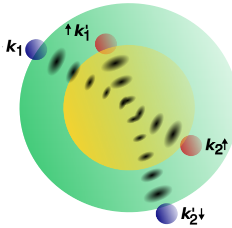
Homogeneous vs. inhomogeneous pairing

Fulde, Ferrell (1964), Larkin, Ovchinnikov (1964)

FFLO pairing



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Experimental studies with ultracold atomic systems:

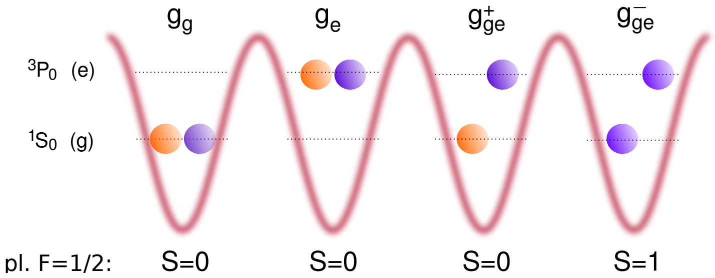
Zwierlein, et al. (2006);
Partridge, et al. (2006);
Schunck, et al. (2007);
Liao, et al. (2010);

and more...

- Simulation of orbital degree of freedom with fermionic ultracold atoms
- 1D systems – confinement induced resonance
  - Chain of two-orbital Yb-173 atoms
    [E. Sz. PRB (2013), and in preparation]
  - Spin polarized 4-component fermionic chain
    [Barcza, E. Sz., Solyom, Legeza, PRA (2012), EPJ ST (2015), and in preparation]
- Summary

Simulation of orbital degree of freedom with fermionic ultracold atoms

- Spin-F atoms in an optical lattice.
- Electronic ground state and metastable excited state.
- Charge neutral atoms → SU(N=2F+1) symmetric interaction.



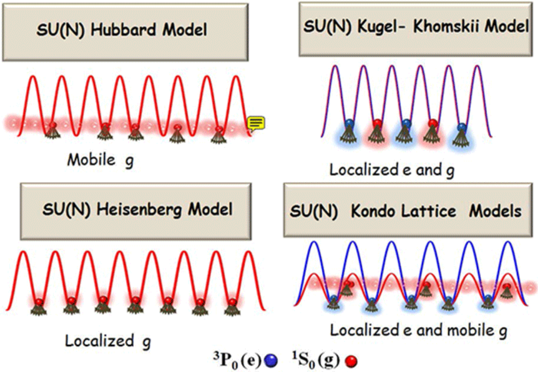
[Gorshkov, et al. (2010); Scazza, et al. (2014); Cappellini, et al. (2014); Zhang, et al. (2014)]

Simulation of orbital degree of freedom with fermionic ultracold atoms

- Spin-orbit coupled system
  - Eg. transition metals: Kugel-Kohmskii model
- Various mixtures of light and heavy particles, impurity models heavy fermion systems
  - Periodic Anderson model, Kondo lattice model
- One orbit systems

  SU(N) Hubbard and

  Heisenberg models



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One-dimensional systems

a_{3D}	^{87}Sr	^{173}Yb
a_g	96.2 a_B	199.4 a_B
a_e	176 a_B	306.7 a_B
a_{ge}^{+}	169 a_B	219.5 a_B
a_{ge}^{-}	68 a_B	3300 a_B

Confinement induced resonance:

Coupling constant in a 1D optical lattice:

$$g = \frac{2\hbar^2}{m}\frac{1}{a_\perp^2}\frac{a_{3D}}{1 - c\frac{a_{3D}}{a_\perp}},$$

- Tuning of the confining potential ($a_\perp = \sqrt{\hbar/m\omega_\perp}$).
- 2-orbital system $\rightarrow$ 4 resonances.
- Typical confining:
  - $\omega_\perp \approx 100$ kHz $\rightarrow a_\perp^{Yb} \approx 680\ a_B$.
  - $\omega_\perp$ to be changed up to 0.5-1 MHz.

Low energy behavior of Yb-173 atoms: F=5/2, SU(6)

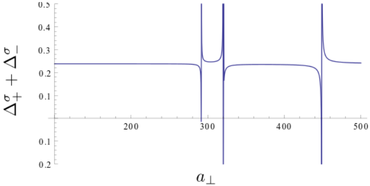
Field theoretical RG treatment, and bosonization

Asymptotic behavior of the correlation functions $\rightarrow$ dominant order

Phase diagram as a function of population and the confining potential:

Competing orders:

- $\mathcal{O}_{ADW} \sim |r|^{-\Delta_-^{\kappa} - \Delta_+^{\kappa}}$
- $\mathcal{O}_{pFFLO} \sim |r|^{-\Delta_-^{\sigma} - \Delta_+^{\sigma}}$
- $\mathcal{O}_{SDW} \sim |r|^{-\Delta_-^{\kappa} - \Delta_+^{\kappa} - \Delta_-^{\sigma'} - \Delta_+^{\sigma'}}$



E. Szirmai, PRB (2013), and in preparation

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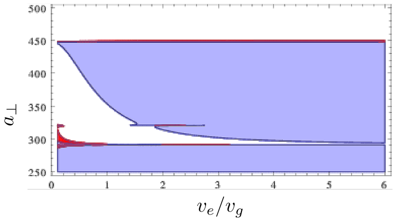

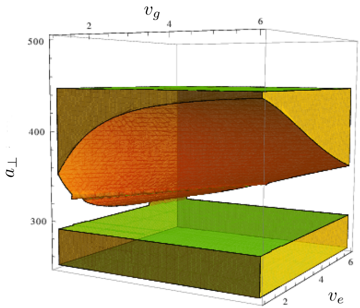

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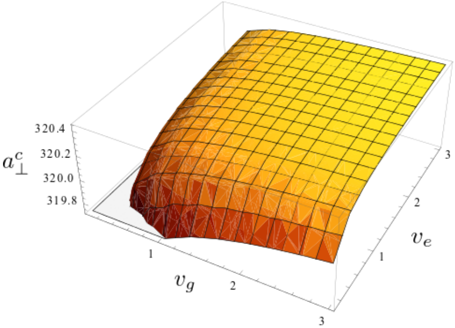
Phase separation - preliminary results

Phase separation:
presence of heavy and light particles + strong repulsive interaction.



- Close to each resonances.
- Properties of the segregated phase depend on the populations and $a_\perp$.
- 1st order transition with divergent compressibility.
- $\sqrt{1 \pm g_c^{ge} \sqrt{\kappa_g \kappa_e}} = 0.$

E. Szirmai, PRB (2013), and in preparation

Polarized 4-component fermions on a 1D chain

- 1 orbital state $\rightarrow$ 1 scattering length – tuned to the attractive regime by transverse confinement.
- Spin imbalance: nonzero total magnetization S^z_{tot}.

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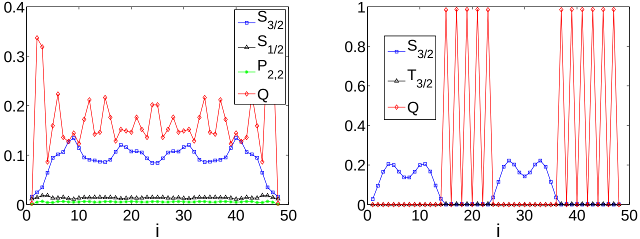
Phase diagram predicted by weak coupling analysis:

Barcza, E. Sz., Solyom, Legeza, PRA (2012), EPJ ST (2015), and in preparation

Polarized 4-component system – DMRG analysis

Density distribution along the chain:



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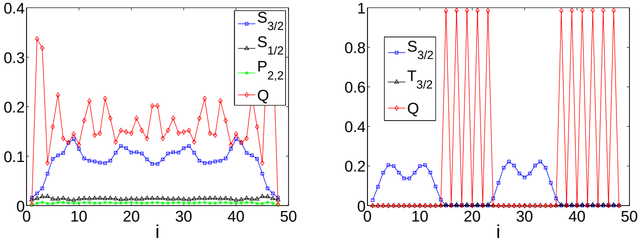
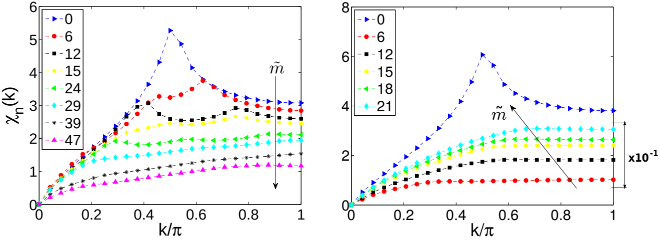


Density-density correlations $\to$ static structure factor



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Summary

- High spin fermionic chains where the interactions are tuned via changing the transverse confinement.
- Two-orbital Yb-173 isotopes:
    - The system can be driven into an orbital-FFLO state.
    - Phase separation is expected close to the resonances.
- Spin polarized 4-component fermions:
    - Formation of SU(4) quartets in a ferromagnetic background.
    - Phase separation of the composite (spin neutral) particles and the spin carrier particles for strong enough attractive interaction.