Experiments on few fermion systems of ultracold atoms

…and the crossover to many-body systems

Workshop
Resonances and Non-Hermitian Quantum Mechanics in Nuclear and Atomic Physics
Trento, June 2014

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A tunable few-body system

How can one study few body effects?

Few-fermion systems in nature:
- atoms, nuclei
  - well defined quantum state
  - limited tunability of interaction

Artificial Quantum system:
- quantum dots
- atomic clusters
  - Wide tunability, but no „identical“ systems

→ Realize a well-controlled and tunable quantum system using ultracold atoms
Control at the single particle level

- Quantum control in a many-body system is becoming possible!

W. Bakr et al., Science 329, 547, 2010

→ We aim for bottom up approach:

Start with few-fermion system and then increase towards a many-body system

C. Weitenberg et al., Nature 471, 319-324, 2011
• Preparation and control of few-fermion systems

• Pairing in a few-fermion system with attractive interactions

• From few to many: Building a Fermi sea from single particles

• (Two fermions in a double well)
Outline

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High Fidelity Preparation

- 2-component mixture in reservoir $T=250\text{nK}$
- superimpose microtrap
  scattering $\rightarrow$ thermalisation
  expected degeneracy: $T/T_F = 0.1$

- switch off reservoir

$\Rightarrow$ count

+ magnetic field gradient in axial direction

Single atom detection

1 atom

2 atoms

4 atoms

8 atoms

1/e-lifetime: 250s

Exposure time 0.5s

1-10 atoms can be distinguished with high fidelity (> 99%)

High Fidelity Preparation

2 atoms

8 atoms

Lifetime in ground state ~ 60s

Interaction in 1D

3D

$3D a_{3D} [10^3 a_0]$

magnetic field [G]

1D

$1D g_{1D} [10 a_{1D} h (ω_{perp})]$

magnetic field [G]

radially strongly confined

aspect ratio: $ω_{||} / ω_{perp} \rightarrow 1:10 \rightarrow 1D$

Z. Idziaszek and T. Calarco, PRA 74, 022712 (2006)

\[ g_{1D} = \frac{2\hbar^2 a_{3D}}{ma_{\perp}^2} \frac{1}{1 - Ca_{3D} / a_{\perp}} \]

M. Olshanii, PRL 81, 938 (1998)
Studying few-body physics

\[ H = -\frac{\hbar^2}{2m} \sum_{i=1}^{N} \frac{\partial^2}{\partial x_i^2} + \frac{1}{2} m \omega_{\parallel}^2 \sum_{i=1}^{N} x_i^2 + g_{1D} \sum_{i<j}^{N} \delta(x_i - x_j) \]

tunability of the interpart. interaction

g_{1D} \rightarrow +0 \quad g_{1D} \rightarrow \pm \infty
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Probing the system

Observe tunneling dynamics:

- Tilt the trap such that the highest-lying states have an experimentally accessible tunneling time of about 10-1000ms.

From the observed tunneling time scale we can then infer the total energy of the system.
Attractive interactions

- Use this to determine the pairing energy
- Problem: tunneling of the two particles is correlated

Correlated tunneling

- Set up rate equation for tunneling
- Fit rate coefficients to the data (consistent with subsequent single particle tunneling)
Odd-even effect with ultracold fermions

- How does the energy of the system evolve for larger systems?
Prospects:

- Study non-perturbative regime
- Pairing in higher dimensions (2D, 3D)
- larger systems, superfluidity
• Preparation and control of few-fermion systems

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From few to many-body physics

How many is many?

Observable: Interaction energy vs. particle number and interaction strength
RF-Spectroscopy

\[ E_{\text{int}} \quad \rightarrow \quad E_{\text{HFS}} + E_{\text{int}} \]

\[
\begin{align*}
N=1, \quad g_{1D} &= -0.27 a_{||} \hbar \omega_{||} \\
\text{• free-free} \\
\text{• N=1, } g_{1D} &= -0.27 a_{||} \hbar \omega_{||}
\end{align*}
\]
Measure the interaction energy

A single impurity repulsively interacting with an increasing number of majority particles

The interaction energy diverges for $N_{\text{maj}} \to \infty$. Therefore rescale $E_{\text{int}}$ onto natural scale of a Fermi gas $E_F$ to obtain a dimensionless quantity:

$$E_{\text{int}} \to E_{\text{int}}/E_F$$

The interaction strength is rescaled with the Fermi momentum $k_F$ ($\sim 1$/interparticle spacing) to obtain a dimensionless quantity:

$$g_{1D} \to g_{1D}/k_F$$

$$g_{1D}/k_F \sim \gamma$$ the Lieb-Liniger parameter
Measure the interaction energy

\[ \mathcal{E} = \frac{\Delta E}{E_F} \]

- Non interacting
- Strongly repulsive

Analytic solution of the two particle problem

Analytic solution for an infinite number of majority particles
Adapted from homogeneous to trapped case by local density approximation

Measure the interaction energy

Four is Many!

\[ \varepsilon = \frac{\Delta E}{E_F} \]

\[ \varepsilon - \varepsilon_2 \]

-1/\( \gamma \)

non interacting

strongly repulsive

S.E. Gharashi et al.,
PRA 86, 042702 (2012)

see also:
Astrakharchik,
Conduit, T.-L. Ho,
Lewenstein, Rontani,
Santos, Zinner ...

A. N. Wenz, G. Zürn, S. Murmann, I. Brouzos, T. Lompe and S.
Jochim, Science 342, 457 (2013)
Outline

• Preparation and control of few-fermion systems

• Pairing in a few-fermion system with attractive interactions

• From few to many: Building a Fermi sea from single particles

• Realize a tunable potential
Creating a tunable potential

Acousto-optic deflector

AOD

RF

\( f_l, A_l \)

\( f_r, A_r \)

High-Resolution Objective

\(|L\rangle\)

\(|R\rangle\)

2\(\Delta\)
Tunneling in a double-well

Preparation

\[ \Psi_{\text{initial}} \rightarrow J \rightarrow \Psi_{\text{final}} \]

Detection scheme

\[ |\langle R | \Psi_{\text{final}} \rangle|^2 \]

\ (~1/2J \)

\[ U = 0 \]

\[ \psi_{1,2}(t) = \psi_1(t) \psi_2(t) \]

- Single-part. tunneling
- Calibration of \( J \)
Tunneling in a double-well

- Preparation
- Detection scheme

$U \neq 0$

$\Psi_{1,2}(t) \neq \psi_1(t) \psi_2(t)$

- Correlated tunneling
- Calibration of $U$
Measuring Energies in a DW

Conditional single-particle tunneling

Resonant pair tunneling

Measure amplitudes of single-particle and pair tunneling as a function of tilt
Preparation of the ground state

\[ \Delta \ll 0 \quad \rightarrow \quad \frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle) \quad \rightarrow \quad \Delta = 0 \quad \rightarrow \quad |RR\rangle \]

\[ \Delta \gg 0 \]

\[ \frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle) \]
The eigenstates

Spectrum of eigenenergies for the balanced case:

\[
\frac{1}{\sqrt{2}}(|LL\rangle + |RR\rangle)
\]

\[
\frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle)
\]
Occupation statistics

Number statistics for the balanced case depending on the interaction strength:

\[ \frac{1}{2} (|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle) \]
Occupation statistics

Number statistics for the balanced case depending on the interaction strength:

\[
\frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle)
\]

![Graph showing probability per well versus interaction energy U/J with single and double occupancy states labeled.](image)
Summary

• We can prepare and control few-fermion systems

• Observed Crossover from few- to many-body regime

• Next: Fermi-Hubbard physics
Creating imbalanced systems

How to prepare systems which are not balanced in spin?

• Go to 27G, where magnetic moment of state $|2\rangle$ vanishes
• Gradient only affects atoms in state $|2\rangle$
• Further changes between hyperfine states with RF transfer
$^6$Li level scheme
Feshbach resonances in $^{6}\text{Li}$
The ground state of the double well

One particle:
- basis $|L\rangle$ $|R\rangle$
- Ground state $\psi_S = \frac{1}{\sqrt{2}}(|L\rangle + |R\rangle)$

Two non-interacting particles:

$$\Psi_{1,2}(t) = \psi_1(t) \psi_2(t)$$

- Ground state at U=0

$$|\Psi\rangle = \frac{1}{2}(|L\rangle + |R\rangle)_1 \otimes (|L\rangle + |R\rangle)_2 = \frac{1}{2}(|L_1 L_2\rangle + |L_1 R_2\rangle + |R_1 L_2\rangle + |R_1 R_2\rangle)$$

$$= \frac{1}{2}(|LL\rangle + |LR\rangle + |RL\rangle + |RR\rangle)$$
Eigenenergies in the Hubbard Model

\[ \Delta = 0 \]

How to measure energy differences between eigenstates?

<table>
<thead>
<tr>
<th>State</th>
<th>$U \to -\infty$</th>
<th>$U = 0$</th>
<th>$U \to +\infty$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>a\rangle$</td>
<td>$\frac{1}{\sqrt{2}}(</td>
<td>LL\rangle +</td>
</tr>
<tr>
<td>$</td>
<td>b\rangle$</td>
<td>$\frac{1}{\sqrt{2}}(</td>
<td>LR\rangle +</td>
</tr>
<tr>
<td>$</td>
<td>c\rangle$</td>
<td>$\frac{1}{\sqrt{2}}(</td>
<td>LR\rangle +</td>
</tr>
<tr>
<td>$</td>
<td>d\rangle$</td>
<td>$\frac{1}{\sqrt{2}}(</td>
<td>LR\rangle +</td>
</tr>
</tbody>
</table>
\begin{align*}
\Delta \to -\infty & \quad |a\rangle = |LL\rangle, \\
& \quad |b\rangle = \frac{1}{\sqrt{2}} (|RL\rangle + |LR\rangle), \\
& \quad |c\rangle = |RR\rangle, \\
\Delta = 0 & \quad \frac{1}{2} (|LL\rangle + |RR\rangle + |LR\rangle + |RL\rangle), \\
& \quad \frac{1}{\sqrt{2}} (|LL\rangle - |RR\rangle), \\
& \quad \frac{1}{2} (|LL\rangle + |RR\rangle - |LR\rangle - |RL\rangle), \\
\Delta \to +\infty & \quad \frac{1}{\sqrt{2}} (|RL\rangle + |LR\rangle), \\
& \quad |RR\rangle, \\
& \quad |LL\rangle.
\end{align*}