Quantum magnetism with few cold atoms

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States of matter

- What are the key ingredients for high-Tc superconductivity?
- Can we “simulate“ some of them?

http://en.wikipedia.org/wiki/High-temperature_superconductivity
Related phenomena

- **2D structure**: study phase transition and phase correlation
  
- **effective magnetic interaction**
  exchange interaction

The Heisenberg model:

\[ \hat{H} = -J_{\text{ex}} \sum_{\langle j,k \rangle} \hat{S}_j \cdot \hat{S}_k \]

first order correlation function \( g_1(r) \)

M. Ries et al., PRL 114, 230401 (2015)

Spin order on a lattice

Many body system at high temperature

For positive J:

1D: (Bethe-Ansatz, DMRG, ...)

2D and large N, anisotropic $J_{\text{ex}}$, ... difficult...
The cold gases approach

- **Reduce the complexity** of a system as much as possible until only the essential parts remain!
  (e.g. consider only nearest neighbor interaction)

- **Tunability of interaction**: vary s-wave scattering length $a$ by Feshbach resonances

- **Shape** of the external **confinement**
  (optical dipole traps, lattices)
A lattice for ultracold atoms

- Shape a lattice potential with light

\[ H_t = -J^t \sum_{s=\{\uparrow, \downarrow\}} \left( \mathcal{C}_{L,s}^\dagger \mathcal{C}_{R,s} + \mathcal{C}_{R,s}^\dagger \mathcal{C}_{L,s} \right) \]
A lattice for ultracold atoms

- Shape a lattice potential with light

\[
H_{\text{int}} = U \sum_{i=\{L,R\}} n_{i,\uparrow} n_{i,\downarrow}
\]
A lattice for ultracold atoms

- For large enough $U/J^t$: Mott-insulating state is reached, fixed particle number per site

Tunneling $J^t$

On-site interaction $U$
Fermionic Mott insulators

D. Greif et al., arXiv:1511.06366
M. Greiner group, Harvard
Control ordering?

- Energy scale relevant for ordering: Superexchange

\[ H = -J_{ex} \sum_{(j,k)} \hat{S}_j \cdot \hat{S}_k \]

\[ J_{ex} = 4 \, J^t \frac{2}{U} \]

Challenge: low enough entropy to observe long range correlation

Our Idea - Bottom up approach:
Create this fundamental building block

...and scale system up
Outline

• Preparation and control of few-fermion systems

• Two fermions in a double well potential

• Finite antiferromagnetic spin chains without a lattice
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• Preparation and control of few-fermion systems

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Prepare finite, deterministic samples, where all degrees of freedom are controlled
Pauli principle: each single particle state not occupied by more than one Fermion

Control over the quantum states of the trap → Control over particle number

Requirement:
• highly degenerate Fermi gas
• control over the trap depth more precise than level spacing
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%)

F. Serwane et al., Science 332, 336 (2011)
High Fidelity Preparation

2 atoms

8 atoms

F. Serwane et al., Science 332, 336 (2011)

Lifetime in ground state ~ 60s >> 1/ω

fluorescence normalized to atom number

counts

88.5%
Interaction in 1D

3D

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

magnetic field [G]

1D

\[ g_{1D} [10 a_{\text{perp}} \hbar \omega_{\text{perp}}] \]

magnetic field [G]

radially strongly confined

aspect ratio: \( \omega_{||} / \omega_{\text{perp}} \) 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)

G. Zürn et al., PRL 110, 135301 (2013)
Few atoms in a harmonic trap

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

control of the particle number

imbalanced

balanced

Measure the interaction energy

vary the number of majority particles

Determine: how many is many?

Resolution: ~ 1% of $E_F$

A. Wenz et al., Science 342, 457 (2013)
Realize systems with magnetic ordering...

We have full control of a harmonically trapped system.
Can we prepare an ordered state with similar fidelity and control?

→ We have very low entropy per particle!

Further requirement: Shape the trapping potential:

Start with the smallest possible system
Outline

- Preparation and control of few-fermion systems
- Two fermions in a double well potential
- Finite antiferromagnetic spin chains without a lattice
Creating a tunable potential

Acousto-optic deflector

AOD

\[ \text{RF}_L (f_L, A_L) \]
\[ \text{RF}_R (f_R, A_R) \]

High-Resolution Objective

\( |L\rangle \) \( |R\rangle \) \( 2\Delta \)
Tunneling in a double-well

Preparation

\[ \Psi_{\text{initial}} \]

Detection scheme

\[ \Psi_{\text{final}} \]

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

\[ U = 0 \]

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

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

\[ U \neq 0 \]

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

- Correlated tunneling
Measuring Energies in a double well

Conditional single-particle tunneling

Resonant pair tunneling

Measure amplitudes of single-particle and pair tunneling as a function of tilt

\[ \Delta > \frac{U}{J} \]
Preparation of the ground state

\[ \Delta \ll 0 \quad \frac{1}{2}(|L L\rangle + |L R\rangle + |R L\rangle + |R R\rangle) \quad \Delta = 0 \quad \frac{1}{2}(|L L\rangle + |L R\rangle + |R L\rangle + |R R\rangle) \quad \Delta \gg 0 \quad |R R\rangle \]
Two site Hubbard model - eigenstates

Spectrum of eigenenergies ($\Delta=0$)

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

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

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

S. Murmann et al., PRL 114, 080402 (2015)
Measuring energy differences

Method:
Trap modulation spectroscopy

\[ E \sim U + \frac{4J^2}{U} \]

S. Murmann et al., PRL 114, 080402 (2015)
Basic building block is realized:

- S=0 state.
- one particle per site
- control of super-exchange energy

Assemble antiferromagnetic ground state by merging several double wells
Outline

- Preparation and control of few-fermion systems
- Two fermions in a double well potential
- Finite antiferromagnetic spin chains without a lattice
A Heisenberg spin chain without a lattice...

.... in a single 1-D tube through strong repulsion!
Fermionization

G. Zuern et al., PRL 108, 075303 (2012)
A spin chain without a lattice

A Wigner-crystal-like state:

→ Mapping on a Heisenberg Hamiltonian - Theory by Frank Deuretzbacher
Realization of spin chain

Non-interacting  Repulsive  Attractive  Non-interacting

[Diagram showing energy vs. $-1/g_{1D} [a_{\parallel} \hbar \omega_{\parallel}]^{-1}$]

Gharashi, Blume, PRL 111, 045302 (2013)
Bugnion, Conduit, PRA 87, 060502 (2013)
Realization of spin chain

Non-interacting  Repulsive  Attractive  Non-interacting

Fermionization

Gharashi, Blume, PRL 111, 045302 (2013)
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Realization of spin chain

Non-interacting → Repulsive → Attractive → Non-interacting

Non-interacting

Fermionization

Gharashi, Blume, PRL 111, 045302 (2013)
Bugnion, Conduit, PRA 87, 060502 (2013)
Realization of spin chain

At resonance: Spin orientation of rightmost particle allows for identification of state

Distinguish states by:
- Spin densities
- Level occupation
Measurement of spin orientation

Non-interacting system

Ramp on interaction strength

Energy \([\hbar \omega_{||}]\)

\[-1/g_{1D} \left[ a_{||} \hbar \omega_{||} \right]^{-1}\]
Measurement of spin orientation

Non-interacting system

Ramp on interaction strength

Spill of one atom

Energy $\hbar \omega_{||}$

$-1/g_{1D} \left[a_{||}\hbar \omega_{||}\right]^{-1}$

"Minority tunneling"

"Majority tunneling"
Measurement of spin orientation

Theory by Frank Deuretzbacher, Luis Santos, Johannes Bjerlin, Stephie Reimann

Note: data points in gray can be explained by CoM-Rel motion coupling
Measurement of occupation probabilities

Remove majority component with resonant light

Spill technique to measure occupation numbers

AFM has "most symmetric" spatial wavefunction

many levels required to describe the "kink"

S. Murmann et al., PRL 115, 215301 (2015)
We can prepare an AFM spin chain!

Important: We don’t really need to resolve this energy scale in our experiment! 
→ spin symmetry is fixed by initial preparation

\( J_i \propto \frac{1}{g_{1D}} n_i^3 \)

\(- \frac{1}{g_{1D}} [a_{||} \hbar \omega_{||}]^{-1}\)
Can we scale it up?

It will be extremely challenging to produce longer spin chains
• But: Can we couple many individual spin chains?

\[ J_{Ex_1} \quad J_{Ex_2} \]

Current work in progress…
Thank you for your attention!

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Combine 2D- and lattice geometry

We have another experiment:

- 2D gas with a lattice!

M. Ries et al., PRL 114, 230401 (2015)
Precise energy measurements

Radio Frequency spectroscopy

„bare“ RF – transition

RF – transition with interaction
CoM – Rel. motion coupling

\[ H(\mathbf{r}, \mathbf{R}) = T_{\text{REL}}(\mathbf{r}) + T_{\text{COM}}(\mathbf{R}) + V_{\text{REL}}(\mathbf{r}) + V_{\text{COM}}(\mathbf{R}) + U_{\text{int}}(\mathbf{r}) + W(\mathbf{r}, \mathbf{R}). \]

cubic and quartic terms in the potential

2-1 sample, detect majority
Creating imbalanced samples

(a) Graph showing the energy in MHz as a function of the magnetic field in Gauss. The graph includes two lines, one for $|2\rangle$ and one for $|1\rangle$, with a shaded region indicating the magnetic field region of constant magnetic moment $\mu = 1\mu_{\text{Bohr}} \times 10^{-2}$.
Eigenstates

\[ |AFM_3\rangle = \frac{1}{\sqrt{6}} \left( |\uparrow, \uparrow, \downarrow\rangle - 2|\uparrow, \downarrow, \uparrow\rangle + |\downarrow, \uparrow, \uparrow\rangle \right) \]

\[ |IM_3\rangle = \frac{1}{\sqrt{2}} \left( |\uparrow, \uparrow, \downarrow\rangle - |\downarrow, \uparrow, \uparrow\rangle \right) \]

\[ |FM_3\rangle = \frac{1}{\sqrt{3}} \left( |\uparrow, \uparrow, \downarrow\rangle + |\uparrow, \downarrow, \uparrow\rangle + |\downarrow, \uparrow, \uparrow\rangle \right) \]

\[ H_s^{(3)} = E_F^{(3)} 1 + \begin{pmatrix} -3J & 0 & 0 \\ 0 & -J & 0 \\ 0 & 0 & 0 \end{pmatrix} \]
Tunneling Model

Tunneling rate: 
\[ T_{i,f} \propto |\langle i | f, t \rangle|^2 E_{i,f} e^{-2\gamma(E_{i,f})} \]

Overlap of spin chains 
\[ |\langle i | f, t \rangle|^2 \]

Gamma-factor 
\[ \gamma(E_{i,f}) = \frac{1}{r} \int_{z_1}^{z_2} dz \sqrt{2m[V(z) - E_{i,f}]} \]

Probability to tunnel from \(|i>\) to \(|f>\) 
\[ P_{i,f} = \frac{T_{i,f}}{\left( \sum_{f'} T_{i,f'} \right)} \]
AOD setup

Acousto-optical deflector

Objective

Vacuum viewport

Light intensity distribution