OIST Workshop

Coherent Control of Complex Quantum Systems

11 May 2013 Okinawa

Ultracold Ytterbium Atoms in an Optical Lattice

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Quantum Simulation

Hubbard Model:

\[ H = -J \sum_{<i,j>} c_i^+ c_j + U \sum_i n_{i\uparrow} n_{i\downarrow} \]

→ Magnetism, Superconductivity
Quantum Simulation
Using ultracold atoms in an Optical Lattice

\[ H = -J \sum_{\langle i, j \rangle} a_i^+ a_j + U \sum_i n_{i\uparrow} n_{i\downarrow} + \sum_i \varepsilon_i n_i \]

→ clean system, high controllability, various geometry, etc
Quantum Simulation
Using **Ytterbium** atoms in an Optical Lattice

\[ H = -J \sum_{<i,j>} a_i^+ a_j + U \sum_i n_{i\uparrow} n_{i\downarrow} + \sum_i \varepsilon_i n_i \]
Outline

Quantum Simulation of Strongly-Correlated States
- dual Mott insulator of Boson and Fermion
- SU(6) Mott insulator
- high-resolution spectroscopy of SF-Mott insulator transition

Resonant Control of Interaction:
- anisotropy-induced Feshbach resonance between $^1S_0$ and $^3P_2$ states

Prospects:
- Lieb lattice
- Yb-Li atomic mixture
Quantum Simulation of Strongly-Correlated States

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Prospects:
Lieb lattice
Yb-Li atomic mixture
## Unique Features of Ytterbium Atoms

### Rich Variety of Isotopes

<table>
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- **Attractive Interaction:**
  \[ a_{BF} = -4.3 \text{ nm} \]

- **Repulsive Interaction:**
  \[ a_{BF} = +7.3 \text{ nm} \]
“Strongly Interacting Dual Mott Insulators”


trigger theoretical studies

- arXiv:1205.4026v1  Ehud Altman, Eugene Demler, Achim Rosch
  “Mott criticality and pseudogap in Bose-Fermi mixtures”

- arXiv:1204.3988  Ippei Danshita and L. Mathey
  “Counterflow superfluid of polaron pairs in Bose-Fermi mixtures in optical lattices”
Unique Features of Ytterbium Atoms

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$^{173}$Yb (I=5/2) \[+5/2, +3/2, +1/2, -1/2, -3/2, -5/2\]

"origin of spin degrees of freedom is "nuclear spin"

$$H_{int} = \frac{4\pi\hbar^2a_s}{M}\delta(\vec{r}_1 - \vec{r}_2)$$  \[SU(6)\text{ system}\]

"Experimental realization is very difficult in solid state system"
Unique Features of Ytterbium Atoms

Theoretically, *Physics of large-spin Fermi gas* was extensively discussed

C. Wu *et al.*, PRL*91*, 186402(2003); C. Wu, MPL.*B20*, 1707(2006); C. Wu, PRL*95*, 266404(2005), etc


, etc

valence bond solid, spin liquid, etc

\[ \begin{align*}
\text{173} & \text{Yb (I=5/2)} \quad \text{+5/2} \quad \text{+3/2} \quad \text{+1/2} \quad \text{-1/2} \quad \text{-3/2} \quad \text{-5/2} \\
\end{align*} \]

“origin of spin degrees of freedom is “*nuclear spin”*

\[ H_{\text{int}} = \frac{4\pi\hbar^2}{M} a_s \delta(\vec{r}_1 - \vec{r}_2) \quad \text{SU(6) system} \]

“Experimental realization is very difficult in solid state system”
SU(6) Fermion

The first quantum gas with SU(N>2) symmetry

$^{173}\text{Yb}:SU(6)$

[Optical Stern-Gerlach Spin-Separator]

[S. Taie et al., PRL105, 190401(2010)]

SU(6) Hubbard model

[T. Fukuhara et al., PRL 98, 030401 (2007)]
Lattice Modulation Technique

“doublon production rate $\Gamma$ is a sensitive probe of $T_{\text{lattice}}$”

[D. Greif et al., PRL 106, 145302 (2011)]

$N=1.9 \times 10^4$, $11E_R$, $18\%\text{pp mod. } U/t=62.4$

$Lattice$ $Modulation$ $Technique$

$T_{\text{lattice}}=5.1t=16\text{ nK}$

$T_{\text{lattice}}=5.1t=16\text{ nK}$

$0.5$

$T_{\text{lattice}}=5.1t=16\text{ nK}$

$3\text{ nK}$

$T$: low

(in a harmonic trap)

$T$: high
Density and Entropy Distribution in a Trap


\[ T_{\text{lattice}} = 5.1 t = 16 \text{ nK} \quad U/t = 62.4 \]

Minimum (\(n=1\)):

\[ s = 1.81 \]

cf. \(\ln(6) = 1.79\)
"Lower temperature is achieved with larger spin system" [S. Taie et al, Nature Physics 8, 825(2012)]

**SU(6) versus SU(2)**

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"Enhanced Pomeranchuk Cooling of an Atomic Gas"

"isolated spin carries large entropy of \( \log(N) \)"
“Lower temperature is achieved with larger spin system”
[S. Taie et al, Nature Physics 8, 825(2012)]

“Enhanced Pomeranchuk Cooling of an Atomic Gas”
“isolated spin carries large entropy of log(N)”

Theory
SU(2) case: [F. Werner, et al, PRL.95, 056401(2005)]
Zi Cai et al., Pomeranchuk cooling of the SU(2N) ultra-cold fermions in optical lattices
Unique Features of Ytterbium Atoms

**Long-lived metastable state**
**Ultra-narrow Optical Transitions**

$^1S_0 \rightarrow ^3P_2 \sim 15 \text{ s (10-40 mHz)}$

$^1S_0 \rightarrow ^3P_0 \sim 23 \text{ s (15 mHz)}$

High-resolution laser spectroscopy
“We can spectroscopically resolve and independently control the single, double, and triple occupancy”
High-resolution laser spectroscopy is a powerful tool for the study of Bose-Hubbard phase diagram.
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\[ H = -J \sum_{\langle i, j \rangle} a_i^+ a_j + \frac{U}{2} \sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i \]

one important ingredient is missing

Independent Control of U
How to Control $U$ for alkali-atoms

**Magnetic Feshbach Resonance** $(^{2S_{1/2}} + ^{2S_{1/2}})$

Coupling between “Open Channel” and “Closed Channel”

Control of Interaction $(a_s)$

\[ a_s (B) = a_{bg} \left(1 - \frac{\Delta B}{B - B_0}\right) \]

[C. Regal and D. Jin, PRL 90, 230404(2003)]
How to Control $U$ for Yb atoms

Optical Feshbach Resonance for Yb atoms ($^{1}S_0 + ^{1}S_0$)

"Optical Feshbach Resonance Using the Intercombination Transition"
K. Enomoto, et al., PRL, 101, 203201 (2008),

“Submicron Spatial Modulation of an Interatomic Interaction in a BEC”

“Observation of a $p$-wave Optical Feshbach Resonance”
R. Yamazaki et al., PRA 87, 010704 (R) (2013)

There is a significant loss due to Photoassociation
Unique Features of Ytterbium Atoms

Long-lived metastable state

\[{\text{1S}}_{0}{\rightarrow^{3}\text{P}}_{0} \sim 23 \text{ s (15 mHz)}}

\[{\text{1S}}_{0}{\rightarrow^{3}\text{P}}_{2} \sim 15 \text{ s (10\text{-}40 \text{ mHz)}}

\[{507 \text{ nm}}\]

\[{507 \text{ nm}}\]

Another Useful Orbital States with Different Characters
Magnetic Feshbach Resonance ($^{174}$Yb)

[S. Kato et al., PRL 110, 173201(2013)]

$^{1}S_0 \leftrightarrow ^{3}P_2 (m=+2)$: $^{174}$Yb
Magnetic Feshbach Resonance \((^{170}\text{Yb})\)

\[ ^1S_0 \leftrightarrow ^3P_2(m= -2) \]: \(^{170}\text{Yb}\)

[S. Kato et al., PRL 110, 173201(2013)]

Anisotropy-induced Feshbach Resonance

[A. Petrov, E. Tiesinga, and S. Kotochigova, PRL(2012)]
Various Applications

Cooper Pairing between Different Electronic States;

- s-state: ⚫ ⚪ : p-state

Topological Superfluids:

- strong s-wave interaction + Spin-Orbit Interaction


Implementing Spin-Orbit Interaction between $^1S_0 - ^3P_2(^{174}Yb)$

$SOI \propto \sigma_y k_x$

“Boson: $^{87}\text{Rb}$” “Fermion: $^6\text{Li, }^{40}\text{K}$”

P. Wang et al., PRL (2012),
L. W. Cheuk et al., PRL (2012)

“Two-level system”
arXiv:1208.3055, Qi Zhang et al.,

$$Q = k_{x,L}, \quad |e, \uparrow \rangle = |^3P_2 \rangle$$

$$|g, \downarrow \rangle = |^1S_0 \rangle$$

$$\hat{P}^{(\text{quasi})} = \begin{cases} 
P_0 - \frac{\hbar Q}{2}, & |^3P_2 \rangle \\
P_0 + \frac{\hbar Q}{2}, & |^1S_0 \rangle 
\end{cases}$$

$q = P^{(\text{quasi})}/\hbar$
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Non-Standard Lattice-Lieb Lattice


\( \Delta = 0 \)

\[ E_0 = \Delta \]

\[ E_\pm(\Delta, k) \]

\[ \Delta \neq 0 \]

\[ \Delta = 0 \]

\[ \Delta \neq 0 \]

\[ E_\pm = \pm \sqrt{\Delta^2 + 4t^2 \{ \cos^2 (k_x a / 2) + \cos^2 (k_y a / 2) \}} \]

\[ V(x,y) = V_1 (\sin^2 k^L x + \sin^2 k^L y + \sin^2 2k^L x + \sin^2 2k^L y) \]

\[ + V_2 \left( \sin^2 \left[ k^L (x+y) + \frac{\pi}{2} \right] + \sin^2 \left[ k^L (x-y) + \frac{\pi}{2} \right] \right) \]

"proposal for optical lattice implementation" R. Shen et al., PRB 81, 041410(R), 2010
Simulation of Impurity System with Yb-Li atomic mixture

the hopping rate $t_{\text{Yb}} << t_{\text{Li}}$

localized impurity

Yb

delocalized carrier

“Anderson’s Orthogonality Catastrophe”


absorption spectrum

scattering length $\alpha < 0 \rightarrow$ no bound state

(b) (c)
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Thank you very much for attention

16 August  Mount Daimonji at Kyoto