Ultracold atoms in an optical lattice - an ideal simulator of strongly-correlated quantum many-body system -
Quantum Optics Group
Kyoto University

R. Yamamoto
P125

Dr. Namiki
(GCOE PD)

S. Watanabe
P121

T. Nishio
P71

Y. Seki
P82

H. Hara
P10

Y. Nakamura
P66

Dr. Takasu
P104

NTT:
K. Inaba
M. Yamashita
Research Objectives of Our Group in GCOE program

Application of atoms to investigating

1) quantum information (science)

and

2) (aspects of) fundamental physics

(integrating optical and atomic experiments with elementary particle theories)
We have initiated a new research project:

“Test of Gravity at Nano-meter Scale by using Bose-Einstein Condensate”
from the discussion with prof. Ando (special AP of GCOE)

Current status:

- Inhomogeneity
- Reproducibility
- Controllability

Precise measurement of binding energies of “molecule” to detect possible effect of gravity

“Revealed Insufficiency of simple mass-independent Potential”
Application of atoms to investigating

1) quantum information (science)

and

2) (aspects of) fundamental physics
(integrating optical and atomic experiments with elementary particle theories)

Quantum Simulation of Hubbard Model
Quantum Simulation of Strongly-Correlated System

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
Quantum Gas Microscope
YbLi
Spin-Orbit Interaction
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Quantum Simulation

“Interesting”

Many-body Quantum System

Hubbard Model:

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

\[ \sum_{i,j} t_{i,j}, U \]

\[ i-th, j-th \]

\[ \rightarrow \]

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

$$H = -J \sum_{<i,j>} a_i^+ a_j + \frac{U}{2} \sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i$$

→ clean system, high controllability, various geometry, etc

“Optical lattice”
= periodic potential for atoms generated by standing wave of laser light

In fact, there are many QS experiments using Alkali-atoms
Quantum Simulation
Using Ytterbium atoms in an Optical Lattice

\[ H = -J \sum_{<i,j>} a_i^+ a_j + \frac{U}{2} \sum_i n_i(n_i - 1) + \sum_i \varepsilon_i n_i \]

\[ \lambda_{\text{lattice}} = 532 \text{ nm} \]

\[ \varepsilon_i \text{ are the energy levels} \]

\[ \lambda_{\text{lattice}} = 532 \text{ nm} \]

\[ \text{distance} = 266 \text{ nm} \]
# Unique Features of Ytterbium Atoms

## Rich Variety of Isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass Number</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{168}\text{Yb}$</td>
<td>168</td>
<td>0.13%</td>
</tr>
<tr>
<td>$^{170}\text{Yb}$</td>
<td>170</td>
<td>3.05%</td>
</tr>
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<tr>
<td>$^{176}\text{Yb}$</td>
<td>176</td>
<td>12.7%</td>
</tr>
</tbody>
</table>

- **Boson**
- **Fermion**

### Attractive Interaction:
- $a_{BF} = -4.3$ nm
- $a_{BB} = +3.4$ nm
- $a_{FF} = +10.6$ nm

### Repulsive Interaction:
- $a_{BF} = +7.3$ nm
- $a_{BB} = +5.6$ nm
- $a_{FF} = +10.6$ nm
By loading the BF mixtures into 3D optical lattice, we successfully create **“Strongly Interacting Dual Mott Insulators”**


**Trigger theoretical studies**


### Unique Features of Ytterbium Atoms

#### Rich Variety of Isotopes

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**$^{173}\text{Yb}$ (I=5/2)**

- $+\frac{5}{2}$
- $+\frac{3}{2}$
- $+\frac{1}{2}$
- $-\frac{1}{2}$
- $-\frac{3}{2}$
- $-\frac{5}{2}$

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

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

SU(6) system

“Experimental realization is very difficult in solid state system”
The first quantum gas with SU(N>2) symmetry

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

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

Optical Stern-Gerlach Spin-Separator for nuclear spin

[S. Taie et al., PRL 105, 190401 (2010)]
Lattice Modulation Technique

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

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

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

\[ T_{\text{lattice}} = 5.1t = 16 \text{ nK} \]

\[ T_{\text{lattice}} = 5.1t = 16 \text{ nK} \]

\( U_{FF} \)

We could successfully create SU(6) Mott Insulator
“Lower temperature is achieved with larger spin system”
[S. Taie et al, Nature Physics 8, 825(2012)]

SU(6) versus SU(2)

“Enhanced Pomeranchuk Cooling of an Atomic Gas”

“isolated spin carries large entropy of log(N)”

Theory (T > t):
Unique Features of Ytterbium Atoms

*Long-lived metastable state*

*Ultra-narrow Optical Transitions*

\[ \begin{align*}
\text{1S}_0 & \quad \text{3P}_0 \quad \text{3P}_2 \\
507 \text{ nm} & \quad \sim 15 \text{ s (10~40 mHz)} \\
578 \text{ nm} & \quad \sim 23 \text{ s (15 mHz)} \\
\end{align*} \]

High-resolution laser spectroscopy
Spectroscopy of Atoms in a Mott Insulating State

“We can spectroscopically resolve and independently control the single, double, and triple occupancy”

$\sim 2(U_{eg} - U_{gg})$

$\sim U_{eg} - U_{gg}$
Spectroscopy of Superfluid-Mott Insulator Transition

Theory (NTT) and Experiment (Kyoto)

\[ E_R = \frac{\hbar^2 k^2}{2m} \]
High-resolution laser spectroscopy is a powerful tool for the study of SF-Mott insulator transition.
Quantum Simulation of Strongly-Correlated System

dual Mott insulator of Boson and Fermion
$SU(6)$ Mott insulator
high-resolution spectroscopy of SF-Mott insulator transition

Resonant Control of Interaction:
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Quantum Gas Microscope
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Spin-Orbit Interaction
Quantum Simulation
Using Ytterbium atoms in an Optical Lattice

\[ H = -J \sum_{\langle i, j \rangle} a_i^+ a_j + \frac{U}{2} \sum_i n_i (n_i - 1) + \sum_i \epsilon_i n_i \]

\[ \lambda_{\text{lattice}} = 532 \text{ nm} \]

one important ingredient is missing

Independent Control of \( U \)

\[ \lambda_{\text{lattice}} = 532 \text{ nm} \]

\[ 266 \text{ nm} \]
How to Control $U$ for alkali-atoms

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

Coupling between “Open Channel” and “Closed Channel” results in Resonant 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** ($^1S_0 + ^1S_0$)

"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”

“Manipulating Higher Partial-Wave Interatomic Interaction with an Optical Feshbach Resonance”
R. Yamazaki et al., arXiv:1210.2567

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

**Long-lived metastable state**

$\text{Long-lived metastable state}$

$^3\text{P}_2 \sim 15 \text{ s (10\text{~}40 \text{ mHz})}$

$^3\text{P}_0 \sim 23 \text{ s (15 \text{ mHz})}$

$^1\text{S}_0$

$507 \text{ nm}$

$578 \text{ nm}$

Another Useful Orbital States with Different Characters
Magnetic Feshbach Resonance between $^1S_0$ and $^3P_2$

“$^1S_0 \leftrightarrow ^3P_2(m=+2)$”: $^{174}$Yb

“$^1S_0 \leftrightarrow ^3P_2(m=-2)$”: $^{170}$Yb


We can study various interesting physics with resonant interaction
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Prospects:
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Quantum Gas Microscope
YbLi
Spin-Orbit Interaction
“Non-Standard Lattice-Lieb Lattice”

\[ \Delta = 0 \]

\[ E_+ (\Delta, k) \]
\[ E_0 = \Delta \]
\[ E_-(\Delta, k) \]

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

“proposal for optical lattice implementation”
R. Shen et al., PRB 81, 041410R, 2010

\[ \lambda_1 = 532 \text{ nm} \]
\[ \lambda_2 = 1064 \text{ nm} \]
Developing Yb Quantum Gas Microscope

Boson, Fermion, Bose-Fermi Mixture
Simulation of Impurity System with Yb-Li atomic mixture

the hopping rate \( t_{Yb} << t_{Li} \)

localized impurity

Yb

delocalized carrier

Li

**Anderson Hubbard Model**

\[
H = -J \sum_{<i,j>,m=\uparrow,\downarrow} c_{i,m}^{\dagger} c_{j,m} + U \sum_i n_{i,\uparrow} n_{i,\downarrow} + \sum_i W_i n_i
\]

\[
W_i = \begin{cases} 
W & \text{(with Yb)} \\
0 & \text{(without Yb)} 
\end{cases}
\]

**High-resolution Spectroscopy:**

**Anderson Orthogonality Catastrophe**
Simulation of Impurity System with Yb-Li atomic mixture

the hopping rate \( t_{\text{Yb}} << t_{\text{Li}} \)

localized impurity

Yb

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**Anderson Hubbard Model**

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\[
W_i = \begin{cases} 
W & \text{(with Yb)} \\
0 & \text{(without Yb)}
\end{cases}
\]

“Superfluid-Mott insulator Transition of Yb”

0 \( E_R \)  10 \( E_R \)  15 \( E_R \)  20 \( E_R \)
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Prospects:
Lieb lattice: implementation of 2D super-lattice
Quantum Gas Microscope: fluorescence imaging with dual molasses
YbLi: optical lattice setup for impurity problem
spin-Orbit Interaction
Thank you very much for attention

16 August  Mount Daimonji at Kyoto