Quantum Simulation Using Ytterbium Atoms in an Optical Lattice

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Quantum Simulation

Simulation of Quantum System

Interesting quantum system

difficult → Classical computer

efficient → Quantum computer (Controllable quantum system)

Electrons In a Crystal Lattice

analogy

Cold Fermionic Atoms In an Optical Lattice

Unique features

Excellent controllability of various parameters
Lack of undesirable impurities

Quantum Simulation of high-T_c SC using Cold Fermionic Atoms in an Optical Lattice

W. Hofstetter, *et al.*, PRL. 89, 220407 (2002).

The cold fermionic atoms in an optical lattice are described by the Hubbard Hamiltonian:

$$H = -t\sum_{\langle i,j\rangle,\sigma} c^{\dagger}_{i,\sigma}c_{j,\sigma} + U\sum_{i} n_{i,\uparrow}n_{i,\downarrow}$$

Tunneling between adjacent sites

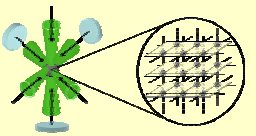
Onsite interaction of atoms

$$t = E_R \frac{4}{\sqrt{\pi}}\xi^3\exp(-2\xi^2) \qquad U = E_R a_s k\sqrt{\frac{8}{\pi}}\xi^3$$

$$\xi \equiv (V_o/E_R)^{1/4} \qquad E_R \equiv (\hbar k)^2/2m$$

a_s : Scattering length
k : Wave number of the lattice beams
V_0: Lattice potential depth

Widely recognized as a model of strongly correlated electron systems such as high-T_c cuprate superconductors.



Controllable Parameters

Hubbard model		Atomic system
• Tunneling	: t	Lattice potential by the laser intensity
• Onsite interaction	: U	(Optical) Feshbach Resonance
• Filling factor	: <n>	Atom density
• Temperature	: T	Temperature of atoms

Ytterbium (Yb)

- Only nuclear spin in the ground state: $^1S_0$ (S=0)
  less sensitive to stray magnetic field: small decoherence
- Ultranarrow optical transition: $^1S_0$-$^3P_0$ $^1S_0$-$^3P_2$
  possibility to detect weak interaction: superconducting gap
- A variety of isotopes (5 Bosons and 2 Fermions)

Bose-Fermi Mixtures in an Optical Lattice

H. P. Büchler and G. Blatter, PRL. 91, 130404 (2003),
M. Lewenstein, *et al.*, PRL. 92, 050401 (2004),
L. Mathey *et al.*, PRL. 93, 120404 (2004),
D.-W. Wang, M. D. Lukin, E. Demler, PRA. 72, 051604(R) (2005),
L. Pollet, *et al.*, PRL. 96, 190402 (2006).

Spin-3/2 Fermionic Atoms in Optical Lattices

H.-H. Tu, *et al.*, PRB. 76, 014438 (2007).

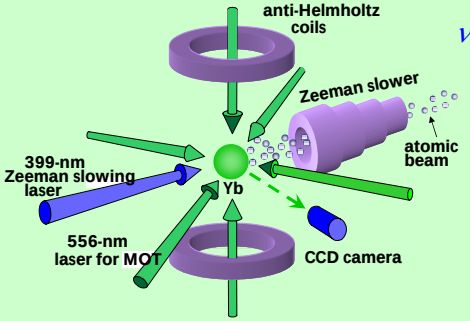
Fermion: ^{171}Yb (14.3%, I=1/2), ^{173}Yb (16.2%, I=5/2)
Boson: ^{168}Yb (0.13%), ^{170}Yb (3.05%), ^{172}Yb (21.9%), ^{174}Yb (31.8%), ^{176}Yb (12.7%)

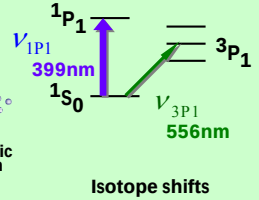
Nuclear spin I=0 for bosonic isotopes

Our group previously obtained BEC: Takasu, *et al.*, PRL 91 040404.

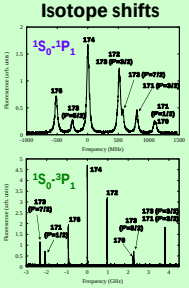
Experimental Procedure

Laser Cooling and Trapping





Isotope shifts

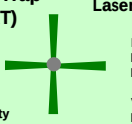


MOT Atom Number : ~10^7
Temperature: 15~40μK
Atom Density: 10^{12}cm^{-3}

Evaporative Cooling in the Crossed FORT

10^7 atoms in MOT ⇒ 10^6 in FORT

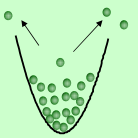
Optical Trap (FORT)



Laser Wavelength: 532 nm
Laser Power: up to ~5.5 W

Horizontal FORT
Beam waist: 14 μm
Potential depth: up to 650 μK

Vertical FORT
Beam waist: 85 μm
Potential depth: 18 μK

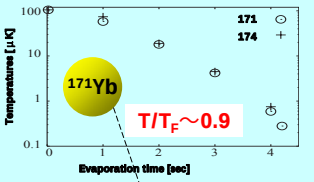


Thermalizing elastic collisions are important to perform efficient evaporative cooling

Cooling to Quantum Degeneracy

^{168}Yb

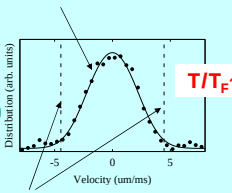
^{171}Yb



T/T_F~0.9

Sympathetic Cooling with ^{174}Yb

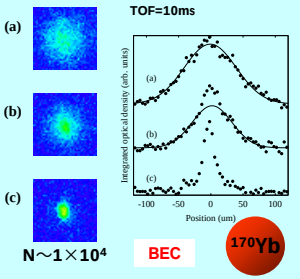
Fermi-Dirac distribution



T/T_F~0.4

Fermi velocity v_F=4.4 μm/ms

^{173}Yb



N~1×10^4

BEC

^{170}Yb

BEC-FDG Mixture

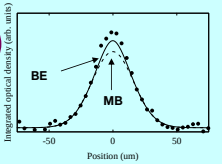
$N_{173} = 6\times10^3$ T_{173} = 140nK (T/T_F~0.45)
$N_{174} = 3\times10^4$ T_{174} = 80nK < T_c BEC

Fukuhara, *et al.*, PRL 98, 030401.

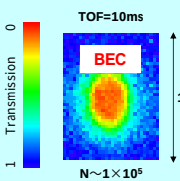
^{174}Yb

Sympathetic Cooling with ^{174}Yb

^{176}Yb



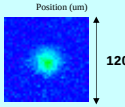
"BEC-BEC mixture"



N~1×10^5

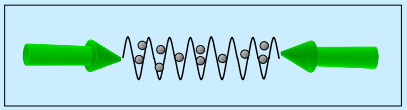
^{172}Yb

N_{176}=1×10^4
PSD_{176}>2.6



Optical Lattice

A standing wave created by counter-propagating beams causes a periodic potential for atoms.

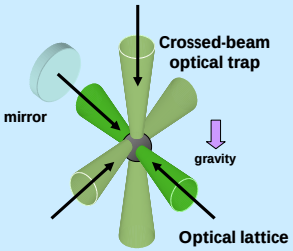


Optical lattice parameter
Laser wavelength: 532 nm → Period of lattice sites: 266 nm
Beam waist: 20 μm (Spatial mode is cleaned by using optical fiber)
Laser Power: up to 100 mW → Lattice potential depth: up to 40 E_R

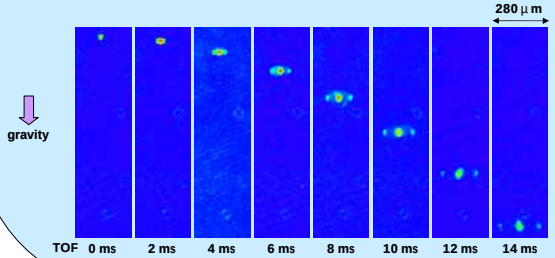
BEC in a 1D Optical Lattice

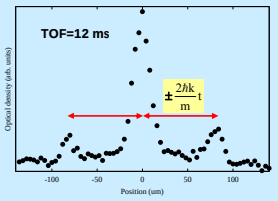
After creating ^{174}Yb BEC in the crossed-beam optical trap, we loaded the BEC into one-dimensional optical lattices by ramping up the intensity of the lattice beam.

~ 20 sites $N_{total} \sim 3 \times 10^4$



Free expansion of an array of BECs Interference patterns

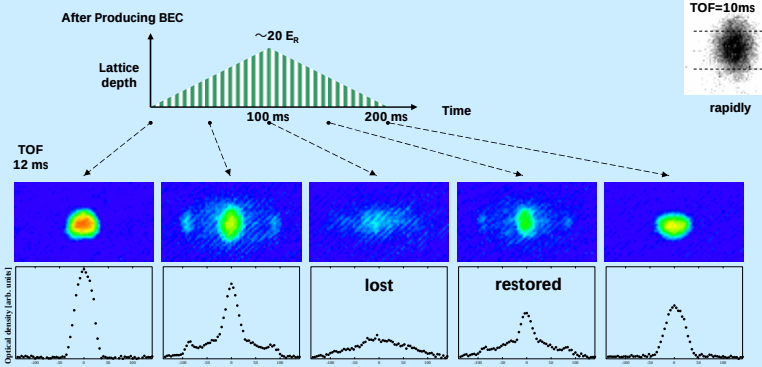




k : Wave number of the lattice beams
m : Atomic mass
t : Expansion time

"Number Squeezed State"

When the lattice depth was increased, the interference pattern was lost.

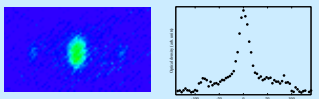


The number of atoms decreased probably due to three-body recombination lasses.

The loss of coherence was mainly due to suppressed number fluctuation.
→ Number Squeezed state

Bose-Fermi Mixture in Optical Lattices

We investigate change in the interference pattern of a released ^{174}Yb BEC by mixing fermionic ^{173}Yb impurity atoms into the BEC.

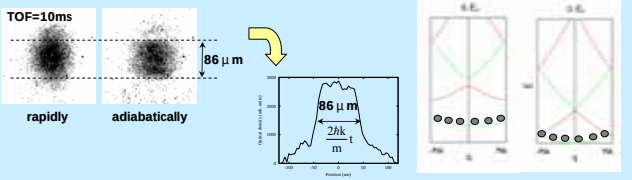


~ 8×10^3 ^{173}Yb impurity atoms
$N_{173}/N_{174} \sim 0.4$

Significant change has not been observed.

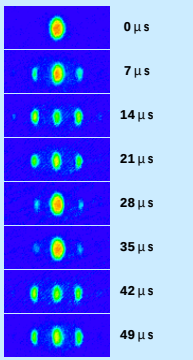
Observation of 1st Brillouin Zone

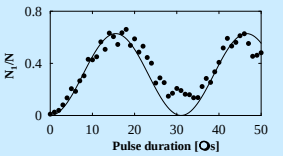
Mapping the quasi momentum to the free particle momentum by adiabatically decreasing the lattice depth.



Pulsed Optical Lattice

We observed the diffraction of a ^{174}Yb BEC by a pulsed standing light wave.





After the lattice beam is suddenly turned on, almost all the atoms are distributed over states of the two lowest-energy even bands.
↓
The oscillation frequency corresponds to the energy difference between the two band.

We can precisely determine the lattice depth by using this pulsed lattice technique.

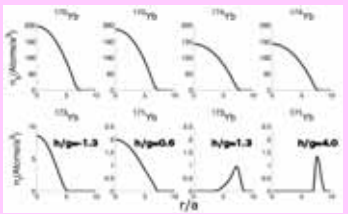
Quantum degenerate mixture

Ultracold atomic gases system is quite suitable for understanding quantum many-body system and one unique feature of this system is that a variety of mixtures can be investigated.

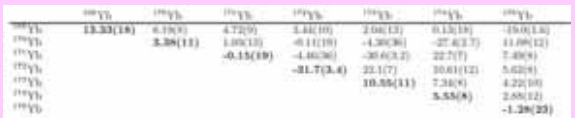
Yb A variety of isotopes (5 Bosons and 2 Fermions)

Ex. Bose-Fermi Mixture (Phase separation)

$N_B=10^5$
$N_F=10^3$
$\omega=2\pi\times500$ Hz
T=0 K



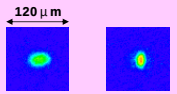
Scattering lengths for Yb isotopic combinations are evaluated by photoassociation spectroscopy and mass scaling.



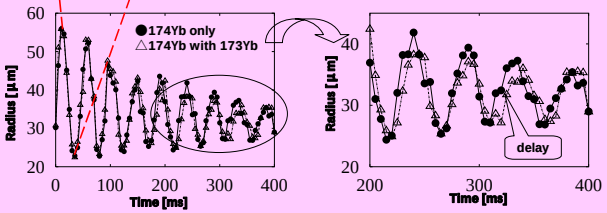
[Kitagawa, *et al.*, arXiv:0708.0752]

Quadrupolar Oscillations

We excited quadrupolar oscillations in a Bose-Fermi mixture of ^{174}Yb-^{173}Yb by changing trapping potential and observed oscillations of ^{174}Yb BEC with/without ^{173}Yb atoms.



$N_{174}=3\times10^4$ (Half of atoms is condensed.)
$N_{173}=1\times10^4$ T=100nk



When we mixed ^{173}Yb atoms, a delay of the oscillations was observed.

Summary

- Production of a variety of degenerate gases and mixtures of Yb isotopes
- Loading ^{174}Yb BEC into 1D optical lattices
  - Interference patterns
  - Number squeezing
  - Mixing Fermionic inpurity
- Observation of 1st Brillouin Zone
- Calibration of the lattice potential by pulsed lattice
- Investigating collective oscillations in a Bose-Fermi mixture

Future plan

- Realizing BEC and degenerate Fermi gas in 3D optical lattice and observing the Mott-insulator transition
- Further cooling in optical lattices (Sideband cooling)
- Investigating behavior of Bose-Fermi mixture in optical lattices
- Understanding mixtures of quantum many-body system
  Stability (collapse), Structure (phase separation), and Dynamics (collective mode)