Quantum Simulation Using Ultracold Ytterbium Atoms in an Optical Lattice

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ABSTRACT

I will describe our on-going projects in our lab for quantum simulation research of quantum many-body systems using ultracold two-electron atoms of ytterbium (Yb) atoms in an optical lattice, which provides unique possibilities in quantum simulation research. After a brief introduction of the unique features of Yb atoms, we will describe several important results, including the formation of a novel SU(N) Mott insulator, matter-wave localization in a Lieb lattice, topological charge pumping, realization of a quantum simulator based on an impurity system with an Yb-Li(Lithium) atomic mixture, and development of a novel quantum gas microscope.

INTRODUCTION

Quantum Simulations Using Ultracold Atoms

Recently, the technique of manipulating individual single quantum systems such as an atom, ion, and photon has made dramatic progress. The development of an ultra-precise atomic clock is one illustrative example. In contrast to individual quantum systems, many functional materials (e.g., high-Tc superconductors) are strongly-correlated quantum many-body systems, which are studied by various approaches in order to obtain an accurate understanding of their novel behaviors. However, quite often, even a qualitative understanding is difficult to obtain for such quantum many-body systems. In addition, topological materials have recently attracted much attention for fundamental research and applications.

Under these circumstances, a system of ultracold atoms in an optical lattice (see Fig. 1) is regarded as an ideal quantum simulator of quantum many body systems, because it possesses a high-degree of controllability of system parameters and it is a quite clean system, free of lattice defects and impurities. It is greatly expected that we can offer indispensable guidelines for novel functional materials, by developing quantum simulation techniques that will enable us to obtain a quantitative understanding of strongly-correlated many-body systems, using this ideal system of ultracold atoms in an optical lattice. The system is also quite useful for the ideal realization of novel topological phases. Thus, in multiple areas, quantum simulation research can make a significant impact on our society.

Up to now, by using quantum gases of alkali atoms, quantum phase transitions for bosons have been thoroughly studied, and anti-ferromagnetic ordering for fermions has been now observed by a quantum gas microscopy, which is a recently developed method of site-resolved imaging of individual single atoms. The apparent next step is to lower the temperature of atoms, realizing the expected d-wave superfluidity. In addition to the impor-

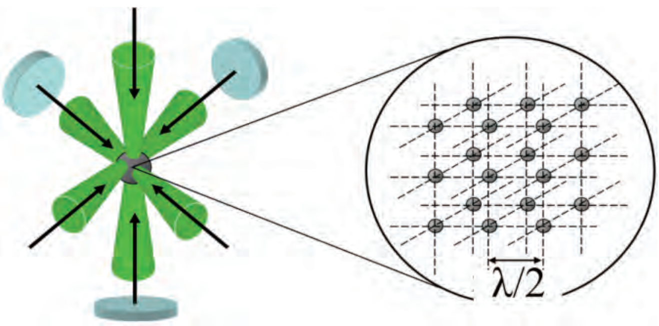

Fig.1: An optical lattice (periodic potential for atoms created by standing waves of light).

tant steps of temperature lowering and the development of measurement and control techniques, a rich variety of interesting research topics are currently being studied, such as topological physics and low-non-equilibrium dynamics.

Basic properties of two-electron atoms of Ytterbium

Instead of using popular alkali-atoms, we have studied quantum degenerate gases by using two-electron atoms of ytterbium(Yb), because Yb atoms have many unique features that are advantageous in the study of quantum simulation. In the following sections, we will describe the basic properties of two-electron atoms of Yb. It is noted that some properties are common to two-electron atoms of alkaline-earth-metal atoms. Detailed information on how to generate ultracold Yb atoms can be found in Ref. [1] and [2].

One of the unique features of Yb atoms is the existence of a rich variety of isotopes: two fermions (^{171}Yb and ^{173}Yb) and five bosons (^{168}Yb, ^{170}Yb, ^{172}Yb, ^{174}Yb, and ^{176}Yb). We have so far successfully created Bose-Einstein condensates (BEC) of ^{168}Yb, ^{170}Yb, ^{174}Yb, and ^{176}Yb, Fermi degenerate gases of ^{171}Yb and ^{173}Yb, Bose-Bose mixtures of ^{168}Yb-^{174}Yb and ^{174}Yb-^{176}Yb, a Fermi-Fermi mixture of ^{171}Yb- ^{173}Yb, and Bose-Fermi mixtures of ^{170}Yb- ^{173}Yb, ^{174}Yb- ^{173}Yb, and ^{174}Yb- ^{171}Yb.

Another unique feature of Yb atoms is the novel energy structure associated with two valence electrons. The two valence electrons result in the spin-singlet ground state $^1S_0$ and the metastable spin-triplet states $^3P_0$ and $^3P_2$, as in shown in Fig. 2. The lifetimes of these metastable states are on the order of 10 s., which are long enough for most cold atom experiments. As a result, these metastable states can be considered as useful orbital states in the Hubbard model. In addition, there are only weakly allowed intercombination transitions with the linewidths on the order of 10 mHz. In fact, we have successfully performed high-resolution laser spectroscopy of quantum many-body states in an optical lattice [3].

SU(N) SYMMETRIC FERMI GAS

The isotope of ^{173}Yb has a spin 5/2 originated from the nuclear spin. Since the inter-atomic interaction of the ground state is independent of the nuclear spin, this system has a high spin symmetry of SU(6). This implies that the spin population should be conserved, for example, even in the presence of inter-atomic collision. Experimentally we have confirmed that the spin population is actually conserved in a harmonic trap. It should be noted that before the realization of cold atoms, theoretical aspects of the physics of SU(N) with N larger than 2 have been already investigated.

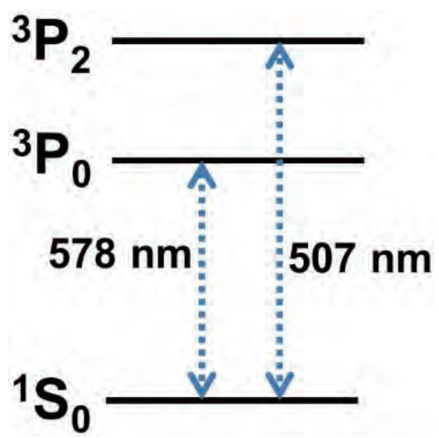

Fig. 2: Relevant energy levels of an Yb atom, connected with ultra-narrow optical transitions.

By adiabatically loading a deeply Fermi degenerate gas of ^{173}Yb with 6-spin components[4] into an optical lattice, we successfully create a strongly-correlated system of a Mott insulator state with SU(6) symmetry [5]. Furthermore, a lower temperature is obtained for the SU(6) system compared with those for SU(2), with the same initial entropy in a harmonic trap, which can be explained as the atomic analogue of a Pomeranchuk cooling effect, which is known as an important cooling method for liquid ^{3}He. The result is shown in Fig. 3. During the adiabatic loading process, the entropy flows from the motional degrees of freedom into those of spin, which results in the cooling of the system.

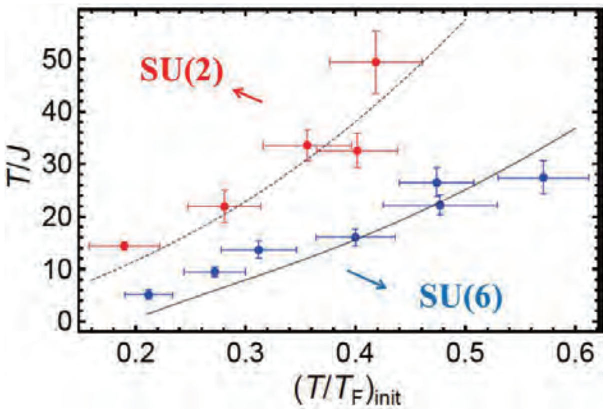

Fig. 3: Pomeranchuk cooling effect for a Fermi gas in an optical lattice.

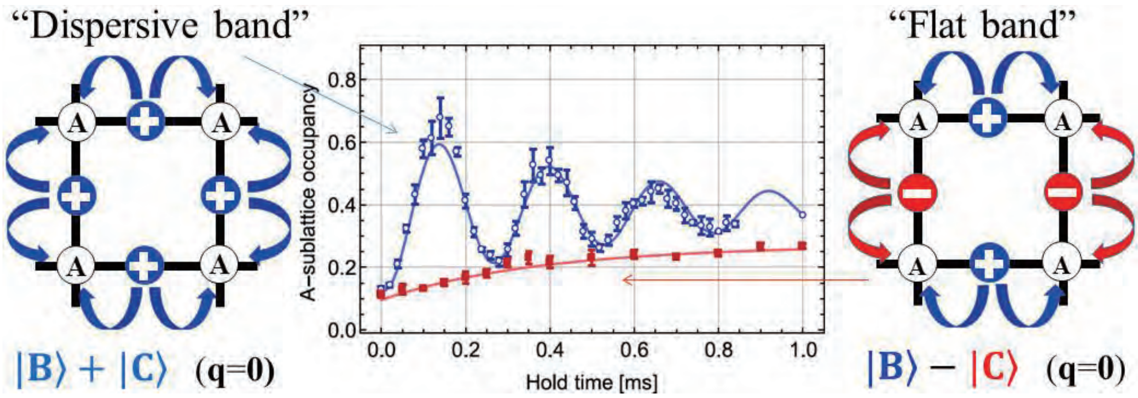

Fig. 5: Localization of matter wave in a flat band.

It is noted that the lowest entropy for one site almost reaches the value of $k_B\log(6)$, which is the value expected for an uncorrelated spin. This indicates that this temperature regime is close to the observation of the onset of the quantum magnetism of an SU(6) system. The apparent next step is, therefore, the study of novel SU(N) quantum magnetism by lowering the atomic temperature.

OPTICAL LIEB LATTICE

By using several lasers, we can create various non-standard optical lattices, i.e. lattices other than cubic or square optical lattices, such as triangular, honeycomb, and kagome lattices, which have been successfully demonstrated for alkali-metal atoms. In particular, by combining three different kinds of optical lattices, we successfully realize an optical Lieb lattice[6], in which there are three sites in a unit cell, as shown in Fig. 4. The Lieb lattice has a unique band structure in which there is a flat band and so it is especially important to explore the physics of flat-band ferromagnetism and super-solids. It is also noted that the Lieb lattice configuration is basically the same as that of the CuO_2 two-dimensional plane of high-T_c cuprate superconductors.

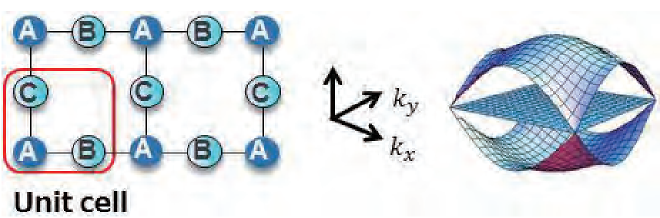

Fig. 4: Lieb lattice structure(left) and the band structure(right).

The successful formation of the Lieb lattice is confirmed by the characteristic pattern of the matter wave interference of BEC. By manipulatinga bosonic matter-wave in the Lieb lattice, in particular, by controlling the population and phase on each lattice site, we successfully demonstrate the coherent transfer of atoms in the lowest dispersive band into the second flat band and observe the frozen motion of atoms on a specific sublattice, which is a manifestation of the localization of atoms in a flat band[6]. This is shown in Fig. 5.

The next target is to explore the exotic phases expected in the flat band, such as itinerant ferromagnetism, novel superconductivity for fermions, and a super-solid for bosons.

TOPOLOGICAL CHARGE PUMPING

The high controllability of ultracold atoms in an optical lattice can be also applied for the study of topological quantum physics. So far there have been nice experiments which explored topological physics using cold atoms. In the case of spatial 2D systems, Hofstadter Hamiltonian and Haldane models are realized. Recently, a system of spatial 1D and 1 more synthetic dimension has been realized, leading to the observation of the chiral edge state. In our work, we realized a spatial 1D and temporal 1D system, leading to the observation of Thouless topological charge pumping[7], which shares the same topological features with a two-dimensional quantum Hall effect.

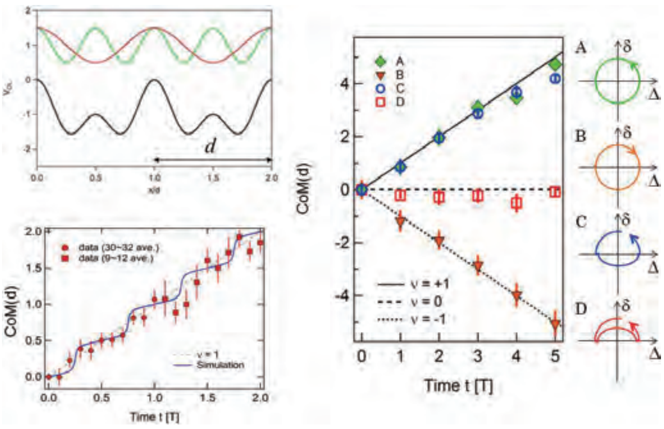

Fig. 6: Topological Thouless charge pumping. Dynamical super-lattice(left top). Shift of center-of-mass of an atom cloud as a function of number of pumping cycle (left bottom). Charge pumping for various pumping schemes A, B, C, and D(right).

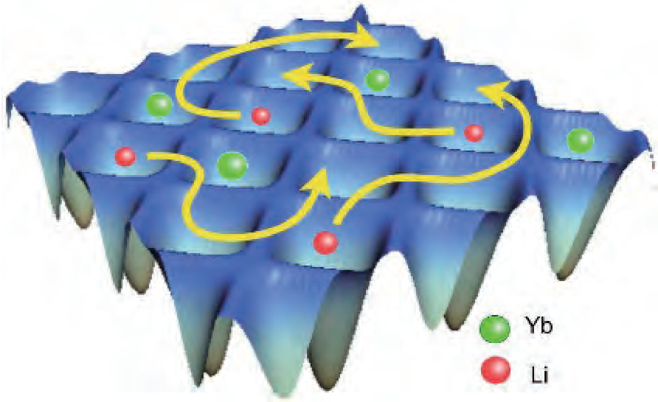

Fig. 7: Yb-Li quantum sim ulator of impurity system.

More specifically, in our work, we utilize the dynamical controllability of our optical super-lattice system, as shown in Fig. 6, and realize a continuous quantum Rice-Mele pumping of cold fermionic ^{171}Yb atoms. In particular, we successfully reveal the topological feature of this charge pumping[7] by taking various trajectories of the system parameters which are different in topology in the parameter space, shown in Fig. 6.
We can extend our charge pumping scheme to investigate the effect of disorder and interaction. The rich internal degrees of freedom of an Yb atom will also allow us to realize a spin pump with a spin-orbit coupling.

ENGINEERED IMPURITY: YBLI MIXTURE

An impurity plays a crucial role in condensed matter physics in phenomena like Anderson localization and the Kondo effect, and it is still important to develop a deeper understanding of these phenomena. Ultracold atomic gases in optical lattices can provide intriguing opportunities to study impurity problems with excellent controllability. For this purpose, we studied a quantum degenerate mixture of Yb atoms and a fermionic isotope of lithium (^{6}Li) atoms in an optical lattice [8], shown in Fig. 7. This mixture has a large mass ratio of about 29. On the one hand, Yb is well localized in an optical lattice and can be considered to be a localized impurity. On the other hand, ^{6}Li is light and as it is so well delocalized in an optical lattice, it is considered as an itinerant carrier. Therefore, this offers an ideal system of controlled impurity in a Fermi system.

In our recent work [8], we measured inelastic loss rates of the collisions between Yb in the metastable $^3P_2$ state immersed with the Fermi sea of the ground state ^{6}Li.

We have clearly observed fast decay of Yb($^3P_2$) and have determined Yb($^3P_2$)-Li inelastic loss coefficients in various magnetic fields, indicating Feshbach resonances.

High controllability of the internal state of Yb atoms in an optical lattice by a resonant laser light beam provides the great possibility of dynamical aspects of response of impurity. We can study, for example, the non-equilibrium behavior of a Fermi sea, known as a problem of Anderson's orthogonality catastrophe.

QUANTUM GAS MICROSCOPE

In addition to the sharpening of a quantum simulation technique that utilizes a global or ensemble measurement and control of a quantum many-body system, it also should be important to develop an advanced quantum control technique such as an individual quantum feedback control based on an individual quantum non-demolition(QND) measurement of single atoms in an optical lattice. By successfully combining these two technologies, it is possible to realize an ultimate quantum simulator for a quantum many-body system. We consequently expect the emergence of a new physics of quantum state control of quantum many-body systems.

We have already developed a quantum gas microscope for Yb atoms with a destructive fluorescence detection method[9], and quite recently have demonstrated the site-resolved imaging of single atoms in an optical lattice by

Faraday quantum gas microscopy, which utilizes a dispersive, QND-like interaction of Faraday effect. A typical image is shown in Fig. 8. Boosting the performance of Faraday quantum gas microscopes to a minimally destructive regime will be an important first step toward the realization of the above-mentioned ultimate quantum simulator.

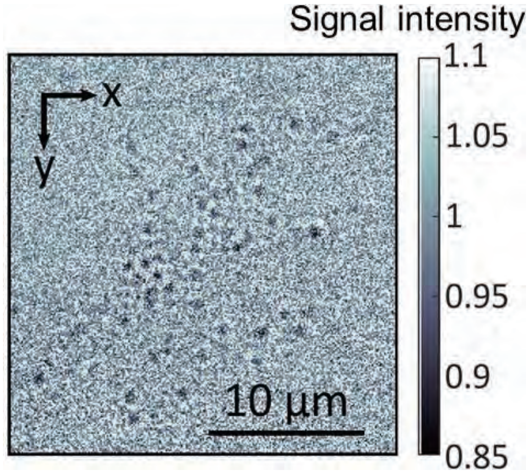

Fig. 8: Site-resolved image of single atoms with Faraday quantum gas microscopy.

CONCLUSION

In this article we describe several important results related to quantum simulation of the Hubbard model using ultracold Yb atoms in an optical lattice. We describe the formation of a novel SU(N) Mott insulator, the localization of a matter wave in a flat band of an optical Lieb lattice, the observation of topological Thouless charge pumping, the creation of a quantum simulator based on an impurity system with a Yb-Li atomic mixture, and the development of a novel quantum gas microscope.

In addition, we have recently studied the behavior of a quantum many-body state under strong dissipation. In particular, we investigated in detail the effect of strong dissipation on the superfluid-Mott insulator quantum phase transition.

The non-equilibrium dynamics of atoms in an optical lattice is also studied by exploiting the unique ability of a Yb atom system.

Furthermore, by performing an ultra-precise photoassociation spectroscopy of BEC of various Yb isotopes in a harmonic trap, we can set the limit on non-Newtonian short-range gravity.

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