Summary of thesis

Two-Orbital Quantum Gases in an Optical Lattice: Interorbital Spin-Exchange dynamics and Spin-Space Quantum transport

Koki Ono

In this thesis, a series of experiments on ultracold atomic Fermi gases with orbital degrees of freedom in an optical lattice is described.

Ultracold atomic gases in an optical lattice have reproduced paradigmatic models of condensed matter physics such as the Hubbard model, demonstrating the ability of quantum simulation. Recently, two-electron atoms such as ytterbium (Yb) and strontium (Sr) have received much attention due to the existence of the long-lived metastable states $^3P_0$ and $^3P_2$ optically coupled to the ground state $^1S_0$. This intriguing internal structure can provide the platform for the quantum simulation with orbital degrees of freedom.

The Kondo effect is a prominent example of the quantum many-body phenomenon highlighting a relevant role of the orbital and spin degrees of freedom. It manifests itself as a screening of a localized magnetic moment by itinerant fermions, which forms a many-body singlet, called the Kondo singlet. Thus far, several schemes for the quantum simulation of the Kondo effect using two-electron atoms have been proposed. However, the previous works reported that the interorbital spin-exchange interactions between the $^1S_0$ and $^3P_0$ states are ferromagnetic for the fermionic isotopes of ^{173}Yb and ^{87}Sr. This suggests that these isotopes are not suitable for the realization of the Kondo system since an antiferromagnetic coupling between the orbitals plays an important role in the emergence of the Kondo effect. We focus on another fermionic isotope of ^{171}Yb and investigate the collisional properties of the ^{171}Yb atoms in the $^1S_0$ and $^3P_0$ states by the clock transition spectroscopy in a three-dimensional (3D) magic-wavelength optical lattice with a wavelength of 759.4 nm. We measure the interorbital *s*-wave scattering lengths in a spin singlet $a_{eg}^{+} = 255(13)a_0$ and in a triplet $a_{eg}^{-} = 355(6)a_0$, with a_0 being the Bohr radius. This result indicates that the interorbital spin-exchange interaction of ^{171}Yb is antiferromagnetic.

In addition, we observe the interorbital spin-exchange dynamics in a two-orbital lattice system, where the $^1S_0$ atom is itinerant in a tube, and the $^3P_0$ atom is localized in 0D. The two-orbital lattice system consists of a one dimensional (1D) near-resonance optical lattice with a wavelength of 650.7 nm and the 2D magic-wavelength optical lattice. The 1D near-resonance optical lattice gives a strong confinement to the $^3P_0$ atom and is superimposed along the axis of the 2D array of the tube traps created by the 2D magic-wavelength optical lattice, realizing a quasi (0+1) D system. We successfully observe the depolarization of the $^1S_0$ atoms due to the spin-exchange interaction with the $^3P_0$ atoms, opening the route to the quantum simulation of the Kondo effect.

Furthermore, this thesis presents the demonstration of spin-space quantum transport induced by an atomic quantum point contact. Quantum transport is ubiquitous in physics. So far, quantum transport between terminals has been extensively studied in solid state systems from the fundamental point of views such as the quantized conductance to the applications to quantum devices. Recent works have demonstrated a cold-atom analog of a mesoscopic conductor by engineering a narrow conducting channel with optical potentials, which opens the door for a wealth of research of atomtronics emulating mesoscopic electronic devices and beyond. We realize an alternative scheme of the quantum transport experiment with ytterbium atoms in the two-orbital optical lattice system. Our system consists of a multi-component Fermi gas and a localized impurity, where the current can be created in the spin space by introducing the spin-dependent interaction with the impurity. We demonstrate a rich variety of localized-impurity-induced quantum transports, which paves the way for atomtronics exploiting spin degrees of freedom.