Summary of thesis: Quantum Many-Body Dynamics of the Bose-Hubbard System with Artificial and Intrinsic Dissipation

Takafumi Tomita

Dissipation - coupling to the environment - is ubiquitous in nature and plays an essential role in quantum systems. It can cause decoherence of quantum states; thus, it limits the coherent dynamics. Therefore, protection of the quantum states from coupling to the environment is has been a crucial issue in quantum engineering. On the other hand, dissipation can be used as an efficient tool for the preparation and manipulation of desired quantum states. Therefore, understanding and controlling open quantum many-body systems has become increasingly important.

Thanks to their exquisite controllability, cold-atom quantum simulations have been successfully used to engineer various Hamiltonians of intensive theoretical interest. For these well-isolated and closed quantum many-body systems, various quantum phases are realized, and the transitions among those phases have been successfully observed. In addition, several recent experiments have extended the applicability of quantum simulators to Liouvillian dynamics of open quantum systems by introducing coupling to the environment, namely, dissipation.

In this thesis, we present a series of experimental studies of a Bose-Hubbard system with the dissipation of particle losses using ultracold ytterbium (Yb) atoms in a three-dimensional (3D) optical lattice. Because the two-body interaction is fundamental and crucial for the emergence of the novel quantum states and many-body physics such as quantum phase transition, it is important to investigate the effect of two-body dissipation on quantum many-body systems in the way that the strength of dissipation can be widely controlled.

First, we report the investigation of the dissipative Bose-Hubbard system with two-body inelastic atom loss with controllable strength, which is implemented by introducing a single-photon photo-association (PA) process. The inelastic collision rate, which characterizes the strength of the dissipation, can be controlled by varying the intensity of the PA beam. In the dynamics subjected to a slow ramp-down of the optical lattice, we find that strong on-site dissipation favors the Mott insulating state: the melting of the

Mott insulator is delayed, and the growth of the phase coherence is suppressed by the strong dissipation. This can be understood as the quantum Zeno effect, that is, the strong dissipation suppresses the unitary dynamics of the system. The highly controllable dissipation allows us to study the quench dynamics for investigating non-equilibrium quantum dynamics. The experimental results are compared with theoretical analysis and numerical calculation, which quantitatively capture the novel behavior presented in the experiments.

Second, we report the realization of a dissipative Bose-Hubbard system with Yb atoms in the metastable $^3P_2$ state. Because the collision between two metastable atoms induces a change in the internal degrees of freedom, the Yb atoms in the $^3P_2$ state have an intrinsically large inelastic collision rate, which induces dissipation. We fully characterize the system by measuring the scattering length between two $^3P_2$ atoms by developing a new scheme called the double excitation method. To overcome the difficulty of making Bose-Einstein condensate (BEC) in the dissipative metastable state, first we create a BEC in the ground state $^1S_0$ and form a unit-filling Mott insulator in the 3D optical lattice. Then we coherently transfer the Mott insulator in the $^1S_0$ state into the $^3P_2$ state, resulting in successful formation of the Mott insulator in the dissipative $^3P_2$ state. With this Mott insulator as an initial state, we investigate the atom loss behavior and find that the atom loss is suppressed by the strong correlation, which is attributed to both the on-site interaction and the inelastic loss. Also, this novel scheme of the initial state preparation enables us to observe the phase coherence as we decrease the potential depth of the lattice, and we quantitatively reveal that the formation of a sizable phase coherence is suppressed by the dissipation.