In solid state physics, the combination of huge number of particles and Coulomb interactions makes a detailed understanding of the many-body phenomena very difficult. Typical approach in condensed-matter physics is to introduce simplified model systems for the complex many-body problem: one attempts to formulate minimal models which include few crucial degrees of freedom necessary to reproduce the observed physical behavior. Yet, such models are the result of several assumptions and approximations. Therefore, the model's ability to provide a correct description of the system's key properties needs to be verified.

Ultracold quantum gases in optical lattices emerged as a promising experimental platform toward further understanding of solid state systems. The basic idea is to cool a dilute atomic gas down to quantum degeneracy and introduce the gas into an optical lattice, which is created by interference of counter-propagating laser beams. Due to the atom-light interaction, the atoms feel a periodical potential. The role of the electrons moving in a crystal is then taken by the atoms, while the crystalline structure is formed by the optical lattice. This *artificial solid* is a defect-free environment and has high controllability of parameters in the system. The concept to study a quantum system by choosing a physically different, but fully controllable system with the same properties originates from Richard P. Feynman, who called this strategy *quantum simulation*. The first experimental demonstration was made with the observation of the superfluid to Mott-insulator transition for bosonic atoms. This experiment ensures the capability of ultracold atoms to simulate and study quantum phases within the Bose-Hubbard model, and promoted a series of further experimental studies.

Not only the standard lattices such as a square lattice and cubic lattice, but also more complex lattices with multiple lattice sites per unit cell have been realized by optical means, providing unique physics owing to their special band structure and orbital degrees of freedom. One dimensional optical superlattice is the simplest example, where the superexchange energy is directly measured. As for two dimensional systems, an optical honeycomb lattice, optical triangular lattice, optical checker board lattice, optical kagome lattice are so far realized.

In this thesis, we present the experimental realization of an optical Lieb lattice for ultracold ytterbium(Yb) atoms. The Lieb lattice geometry is a square lattice with additional sites at each bond center. Such a structure is identical to the three-band *d*-*p* model, which describes the $\mathrm{CuO_2}$ plane of high-T_c superconductors. The Lieb lattice has a flat band and Dirac cones in the energy spectrum. Emergence of flat-band ferromagnetism in the lattice at sufficiently low temperature was rigorously proved. Ultracold Fermi gases in an optical Lieb lattice is a promising experimental platform to study such ordered state.

Our first work during the course of this thesis was to demonstrate novel manipulation and detection of a BEC in a flat band by developing a dynamically tunable optical Lieb lattice. In a Lieb lattice, a flat band appears due to destructive interference of the tunnelings. It is a fascinating question whether a Bose-Einstein condensate (BEC) is stable in a flat band. Experimental study for this question is hampered by the fact that a flat band is in an excited state in the case of the Lieb lattice. We have developed a method to coherently transfer a BEC of $^{174}\mathrm{Yb}$ into the flat band of Lieb lattice, and studied the stability of the BEC loaded in the flat band. We also investigate the inter-sublattice dynamics of the system by projecting the sublattice population onto the band population. This measurement shows the formation of the localized state in the flat band. In addition, almost arbitrary superposition of band eigenstates can be prepared, which drives coherent oscillation modes in the Lieb lattice and enables mapping out the band gap. This high controllability inspired our second work, where we measure the lowest three bands of an optical Lieb lattice for a BEC in a momentum-resolved manner. A BEC, which is initially prepared around zero quasimomentum in the lattice, is transported to a desired quasimomentum by applying a constant force. The energy dispersion of the lowest band is reproduced by integrating the measured group velocities. The excited band energy is reconstructed by measuring the gap from the lowest band with the same quasimomentum, which can be extracted from the oscillation of the sublattice populations after preparing a superposition of the band eigenstates. It is revealed that the second band, which should be flat in a single-particle description, is shifted and distorted around the Brillouin zone edge as the interaction strength increases.

A Lieb lattice system has a mathematical analogy to a three-level system with Λ-type transition. Momentum-dependent tunnelings in the Lieb lattice play a role of Rabi couplings in the three-level system and detunings can be mimicked by energy offsets of each sublattice. Most interestingly, a localized state in a flat band of the Lieb lattice corresponds to the dark state in the three-level system. By adiabatically changing the tunneling amplitudes in a counter-intuitive order, we coherently transfer atoms from one sublattice to another without populating the intermediate sublattice, which can be regarded as a spatial analogue of stimulated Raman adiabatic passage (STIRAP). We also successfully observe a matter-wave analogue of Autler-Townes doublet effect using the optical Lieb lattice. The demonstrated techniques are useful to prepare exotic many-body states in optical lattices. For example, at the half point of the STIRAP in the Lieb lattice, all atoms reside in the flat band. This might be a general scheme applicable to other lattices with flat bands.

Finally, we report on the observation of nearest-neighbor antiferromagnetic spin correlations of a Fermi gas with SU($\mathcal{N}$) symmetry trapped in an optical dimerized lattice. Quantum magnetism originates from the superexchange interaction between quantum-mechanical spins. By using a dimerized cubic configuration, we enhance the superexchange coupling within the dimer, which gives rise to an excess of singlets compared with triplets consisting of two different spins. We introduce the Fermi gas of ^{173}Yb into the lattice. This isotope is characterized by SU($\mathcal{N} = 2I + 1$) symmetric repulsive interaction for nuclear spin $I = 5/2$. For this large-spin system, a Pomeranchuk cooling effect is enhanced: large-spin degrees of freedom can effectively cool down the system by absorbing the entropy from motional degrees of freedom. The precise control of the spin degrees of freedom provided by optical pumping technique enables us a straightforward comparison between SU(2) and SU(4). Our main finding is that larger singlet-triplet imbalance is observed in a dimerized cubic lattice for the SU(4) spin system compared with SU(2) as a consequence of the Pomeranchuk cooling effect. In the field of ultracold atoms in optical latttices, this Pomeranchuk cooling method was already demonstrated in the paramagnetic SU(6) fermionic Mott-insulator, but no experimental study of this effect on the quantum magnetism was reported, which is clearly demonstrated in this work. This result is an important step towards the realization of novel SU($\mathcal{N} > 2$) quantum magnetism.