Summary of thesis：
Kondo Effect and Topological Phenomena in Ultracold Atoms

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The rapid development of laser-cooling technique in past a few decades has enabled us to cool the atomic gases down to a nano-Kelvin scale and observe numerous intriguing quantum many-body phenomena. The significant feature of this system is that the Hamiltonian of the atomic cloud is described by simple models with high accuracy and the parameters of the system can be controlled almost perfectly by using the laser or magnetic fields. By highlighting this feature, ultracold atoms are often called "quantum simulators", which reproduce the behavior of the prototypical models of condensed matter physics using table-top experiments. In addition to these features, ultracold atoms can also realize intriguing models which are hardly realized in solid state systems. Thus one of the fascinating aspects of cold atoms is to discover new quantum many-body phenomena which are difficult to find in the ordinary models in solid state physics. Once the emergence of the new phenomena is established, it certainly helps our understanding of the quantum many-body systems and also provides a starting point to realize such new phenomena in solid-state setups.

In this thesis, we propose several setups to realize intriguing quantum many-body phenomena in ultracold atoms, and thereby investigate their properties in details. Our setups utilize the peculiar properties of cold atoms, but have a close connection with the phenomena in solid state physics. First, we propose that ultracold atoms offer a novel platform to study the Kondo effect, which is a prototypical example of strong correlation effects in condensed matter physics. We demonstrate that intense laser application to atoms can coherently induce a novel Kondo effect in ultracold atomic gases. In this setup, a long-lived electronic excited state of alkaline-earth(-like) atoms play a central role, and the Kondo effect is induced by optical transitions between the electronic ground state and the excited state. One of the highlighted features here is that we can investigate the Kondo effect in nonequilibrium situations under the laser irradiation. Thus we address whether the Kondo effect survives or not in the nonequilibrium situations. We demonstrate that the optically coupled two internal states are dynamically entangled to form the Kondo singlet state, and they actually overcome the heating effect caused by the irradiation. Furthermore, it is shown that the laser-induced Kondo effect has several peculiar properties, which cannot be realized in ordinary solid-state systems. For example, a lack of SU(N) symmetry in the optical

coupling gives spin-selective heavy fermion liquids in which higher spin components have larger effective masses in the Kondo lattice system. We further found that the laser-induced Kondo effect has unusual spin states different from the well-known Kondo singlet. This unusual Kondo state is certainly distinct from the ordinary Kondo singlet state, if we assume the spin rotational symmetry around a particular axis.

Next, we show that the cold-atom realization of the Kondo lattice can host a topological phase protected by symmetries in one spatial dimension with tightly confined optical lattices. This phase is reminiscent of the celebrated Haldane phase in spin chains, but here the charge degrees of freedom play a key role on the fate of the topological phase. We uncover the role of various symmetries on the phase diagram of the one-dimensional Kondo lattice using bosonization methods and strong-coupling pictures of the ground states. As a result, the one-dimensional Kondo lattice provides a typical example of a crossover from a fermionic topological phase in weakly interacting regime to a bosonic topological phase in the strong coupling limit. Ultracold alkaline-earth(-like) atoms are therefore a promising candidate to realize the symmetry-protected topological phase with strong correlations.

Furthermore, we consider a phenomenon called topological pumping, which is a manifestation of topological nature of quantum states in transport phenomena. Although the topological pumping was theoretically predicted almost 30 years ago, it is realized only recently using the controllability of cold atoms in optical lattices. Here we focus on the fact that the topological pumping is composed of non-interacting particles and has a strong relationship with the integer quantum Hall effect. Since the quantum Hall effect has more fascinating properties in interacting systems, such as the fractional quantum Hall effect, it is natural to ask whether the connection between the topological pumping and the quantum Hall effect is also held in interacting systems. In this thesis, based on a quasi-one-dimensional limit of quantum Hall states on a thin torus, we propose a systematic scheme to construct interaction-induced topological pumping which is possibly realized in cold-atom setups.