Summary of thesis: Theoretical study of correlated topological insulators

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For many years, characterization of quantum phases has been done by the Ginzburg-Landau paradigm; quantum phases are characterized in terms of spontaneous broken symmetries and corresponding order parameters. Recently, however, it has become clear that some of quantum phases are out of this framework. This type of quantum phases show topologically nontrivial electronic states and cannot be adiabatically connected to topologically trivial phases. The remarkable difference between topological and ordinary insulators is existence of gapless edge modes which are source of intriguing behaviors, such as the quantized Hall conductivity, topological magnetoelectric responses, and realization of Majorana fermions as edge modes in topological superconductors. These novel behaviors attract both theorists and experimentalists, and nowadays such nontrivial phases provide a new research platform in condensed matter physics. As the results of extensive studies, the above-mentioned Z_2 topological insulators protected by time reversal symmetry are realized in HgTe quantum wells and bismuth-based compounds. Realization of Majorana fermions in topological superconductors is also reported in a one-dimensional quantum wire. In many cases, such nontrivial phases are studied as free fermion systems. However, intriguingly, their realization is proposed for *d*-, *f*- electron compounds. These discoveries trigger off explosive studies of topological phases in strongly correlated systems since strong correlations under the nontrivial condition are expected to yield exotic phenomena.

In this thesis, we have elucidated the basic properties of nontrivial phases in strongly correlated systems with particular emphasis on Mott transitions in topological insulators, correlation effects (e.g., Kondo effects) on topological magnetic phases, and the edge states in correlated systems. To accomplish our goal, we have employed non-perturbative and reliable methods, the dynamical mean field theory and the density matrix renormalization group.

To study Mott transitions in spin Hall insulators, we have employed dynamical mean field theory combined with the continuous-time quantum Monte Carlo method and have characterized the topological phase by the

spin Hall conductivity, which is quantized in the nontrivial phase at zero temperature. In this study the characterization of correlated topological phases in bulk systems has been done, and this is the first numerical evidence of correlated nontrivial insulators in bulk systems. Furthermore, we have elucidated properties of the phase transition; the topological insulator changes into a Mott insulator via a first order transition. This behavior is expected to be observed in topological insulators with geometrical frustration. In the absence of the frustration, magnetic order is favored. Topological properties of such phases have been also examined, and we have proposed that nontrivial antiferromagnetic insulators can be realized in two-dimension under the spin quantized condition. Besides, we clarify that electron correlations can stabilize the nontrivial phases.

There is another type of insulator in *f*- electron compounds, which is referred to as the Kondo insulator. In these systems, the RKKY interaction and the Kondo effect play an essential role. As the results of our study in such heavy fermion systems, it has been found that even in metallic systems, a nontrivial phase can be realized and that RKKY and Kondo effects stabilize it in spite of its tiny energy scale. Moreover, we have pointed out that such a new topological phase hosts edge states of non-Tomonaga-Luttinger-liquid behaviors, which can be characterized by NMR experiments.

Correlation effects on gapless edge states and topological phase transitions have been also addressed. In study of correlated topological insulators in one-dimension, we have reported on the following novel phenomena. (i) Only collective excitations show gapless edge modes. Furthermore we have established an unconventional topological phase transition accompanied by gapless collective excitations in bulk rather than by the gapless single particle excitation. Here, we would like to emphasize that these behaviors are in sharp contrast to those observed in non-interacting topological insulators.

Although in this thesis, we have elucidated several basis or essential properties, there are still various important issues to be addressed, which are left as future works. For example, establishment of interaction induced topological phases, quest for new topological phase (e.g., fractional topological insulators in three-dimensions). We hope that obtained knowledge is useful and contributes to study of topological aspects of strongly correlated systems.