Phase structure of two-dimensional topological insulators by lattice strong-coupling expansion†

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Topological insulators have recently attracted a great interest in the field of materials physics, which are characterized by the topologically protected gapless modes localized on the boundary of the system. The effect of electron correlation in such an electronic system has always been an important problem. Even in non-topological Dirac fermion systems, such as graphene, it has been proposed that a sufficiently strong electron-electron interaction can lead to a spontaneous breaking of some symmetries of the system and a dynamical generation of band gap.

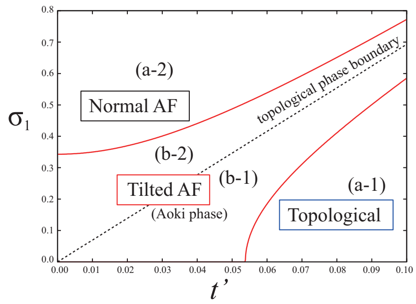

Fig. 1. The phase diagram of the Kane-Mele model in the (t', σ_1)-space. One of the Dirac cones loses its band gap at the phase boundary.

In this report, we study the effect of a sufficiently strong electron-electron interaction on the topological phase structure of 2D quantum spin Hall insulators. By the techniques of strong-coupling expansion of lattice gauge theory, we observe the behavior of the spontaneous antiferromagnetic (AF) order in the strong-coupling limit of the interaction. As a result, we find that the topological phase structure is modified from that of the noninteracting system by the emergence of a new "tilted AF" phase in-between the normal insulator and the topological insulator phases as shown in Fig. 1. Here we use the "modified" mass σ_1, instead of the bare mass (staggered magnetic field) m, and t' is the spin-orbit counpling constant. As a consequence of the interplay between the electron-electron interaction and the spin-orbit interaction, there appears a new "tilted antiferromagnetic (AF)" phase, where the imaginary part of the order parameter becomes nonzero ($\sigma_2 \neq 0$), between the normal AF phase and the topological phase.

The AF order is not parallel to the direction pointed by the spin-orbit interaction and the staggered magnetic field in the spin SU(2) space in the tilted AF phase. σ_1 and σ_2 are antiferromagnetic (AF) orders corresponding to two directions in the remnant U(1) spin space, which we denote M_z and M_x here. If we extend this argument to the full SU(2) spin space, another direction M_y is restored, so that the tilted AF acquires U(1) degree of freedom in choosing its direction, which may result in a massless Nambu-Goldstone mode (Fig. 2).

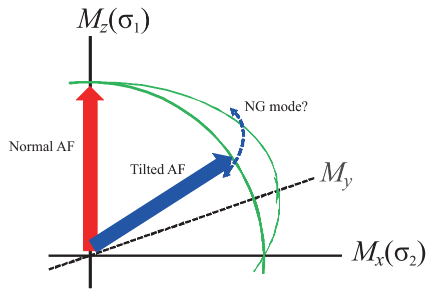

Fig. 2. Schematic picture of the order parameters derived in this study. It is expected that a gapless NG mode appear when the full SU(2) is restored.

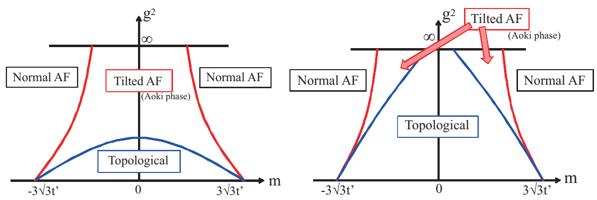

Fig. 3. The schematic phase structure of a graphene-like system with the spin-orbit interaction, conjectured in analogy to that of lattice QCD with the Wilson fermion formalism, for (left) $t' < t'_C$ and (right) $t' > t'_C$.

We also show the analogy between the phase structure of topological insulators and that of the strongly coupled lattice QCD with the Wilson fermion formalism in Fig. 3. In this analogy, σ_1 and σ_2 correspond to $\langle \bar{\psi}\psi \rangle$ and $\langle i\bar{\psi}\gamma_5\psi \rangle$. The tilted AF phase is similar to the so-called "Aoki phase" in lattice QCD in that both of them are characterized by an order parameter orthogonal to the external source term in the continuous symmetry space.[1)] Such an analogy may help us understand the behavior of topological insulators with an electron-electron interaction from the strong-coupling to the weak-coupling regime.

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References

1) S. Aoki, Phys. Rev. **D30** (1984) 2653; Nucl. Phys. **B314** (1989) 79.