論文の内容の要旨

Topology of gap nodes in multi-orbital superconductors

（多軌道超伝導体におけるギャップノードのトポロジー）

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The concept of topology was introduced in condensed matter systems to apply to quantum Hall systems and other gapped fermionic systems. Recently, it has been extended to gapless, or nodal superconductors. Inspired by these developments, we investigate topological perspective of gap nodes in multi-orbital superconductors. In a usual single-band model, electrons form either spin-singlet or spin-triplet Cooper pairs. In multi-orbital superconductors, their Cooper pairs have more complicated structure beyond spin-triplet bound states due to extra degrees of freedom such as orbital, sublattice, layer and valley. Thus, multi-orbital superconductors may have a new gap topology.

First, we address the issue of how nodeless fully gapped superconducting states are realized in multi-orbital systems even when gap nodes are expected from symmetry. Monolayer FeSe on $SrTiO_3$ substrate is a candidate of nodeless *d*-wave superconductor, and its pairing originates from a small but finite spin-orbit coupling.

Our work highlights the annihilation of gap nodes due to spin-orbit coupling and demonstrates that the nodal charge is protected by a chiral symmetry. We investigate the evolution with decreasing spin-orbit coupling from a nodal state to the nodeless state from a viewpoint of topology. We show that this evolution depends strongly on the orbital degrees of freedom in Cooper pairs. In particular, there are two types of *d*-wave pairs, orbitally trivial usual d_{xy}-wave and orbitally nontrivial with no momentum dependence, which we call orbitally trivial and orbitally nontrivial, respectively. Both pair has same B_{2g} symmetry in point group D_{4h}. This symmetry dictates the gap nodes in the k_x and k_y axis. In both cases, the gap nodes are characterized by a $\mathbb{Z}$ invariant and carry ± 2 topological charges related to a chiral symmetry. However, their charge distribution in the momentum space is different between the two cases, and this results in different evolutions when these nodes annihilate to form a nodeless state.

When the orbitally trivial pairing is dominant, points on the same axis in the momentum space have the topological charges with a same sign (same sign pair state). On the other hand, when the orbitally nontrivial pairing is dominant, the adjacent nodal points on each axis have the topological charges with opposite signs (opposite sign pair state). As the spin-orbit coupling decreases, in the case of opposite sign pair state, the nodal points can merge and are annihilated directly in pairs of neighboring nodes because they have opposite charges. However, nodal points in the same sign pair states cannot annihilate directly. We find that this annihilation occurs through an involved mechanism. Indeed, as the interband spin-orbit coupling decreases, new nodal points are first created near the old one. As the spin-orbit coupling further decreases, some nodal points stay while other nodal points move off the k_x or k_y axis. With further decreasing the spin-orbit coupling, they continue to move and annihilate in pairs with other nodes moving from another direction. Both same sign pair and opposite sign pair states exhibit different Andreev flat bands spectra at sample edges.

Furthermore, we show that it is possible to probe other types of nodal states by applying in-plane magnetic field. This field leads to the emergence of topologically protected nodal points and nodal line of energy dispersion, which are characterized by a $\mathbb{Z}_2$ invariant. We emphasize that these line and point gap nodes appear even when the spin-orbit coupling is weak.

Second, we address the issue of how we realize a new type of gap nodes in multi-orbital superconductors and its application. Multi-orbital superconductors with even-parity inversion and broken time-reversal symmetry may have a Fermi surface of Bogoliubov quasiparticles at zero energy, which is called Bogoliubov Fermi surface. Bogoliubov Fermi surfaces are inflated from point or line nodes and they are characterized by a $\mathbb{Z}_2$ invariant related to particle-hole conjugate (C) and parity (P) symmetries. However, their experimental signatures have not yet been explored. We apply this idea to the heavy-fermion superconductor UPt_3.

The pairing symmetry of UPt_3 is still under hot debate. One plausible candidate of its gap symmetry is two-dimensional representation E_{2u} in the point group D_{6h}. However, unless impurity effects are taken into account, this gap symmetry cannot explain the behaviors of its thermal conductivity in the B phase, which shows that a finite value of κ/T and also a finite ratio of the in-plane to c-axis thermal conductivity at very low temperatures.

With symmetry consideration, we propose the pairing that belongs to E_{1g} representation in point group D_{6h}. This is a mixing of spin-singlet d-wave, spin-triplet in-plane p- and out-of-plane f-wave pairing. We discuss the Fermi surfaces near the *Γ*- and the *A*-point in Brillouin zone in the normal state. We show that the in-plane *p*-wave pairing amplitude needs to be finite to realize the Bogoliubov Fermi surfaces. These Bogoliubov Fermi surfaces have nontrivial $\mathbb{Z}_2$ invariant defined by *CP* symmetry, and therefore we expect these are robust against the perturbations that preserve any *CP* symmetry. Moreover, these Bogoliubov Fermi surfaces give rise to a finite density of states at zero energy. It is worthwhile to emphasize that the Bogoliubov Fermi surfaces appear as an intrinsic effect. That is, amplitude of *p*-wave pairing in bulk controls the size of the Bogoliubov Fermi surfaces. Although the residual density of states has been interpreted as a result of impurity scattering, our symmetry analysis suggests that it is worthwhile to experimentally revisit this interpretation.

We further investigate thermal conductivity by using the Boltzmann theory with the relaxation time approximation. We show that the Bogoliubov Fermi surfaces explain a finite κ/T and also an anisotropy of thermal conductivity at $T = 0$.