Summary of thesis: Theoretical Study of Exotic Quantum Phenomena in Odd-Parity Multipole Ordered Phase

Takanori Hitomi

Multipole order is one of the major topics in condensed matter physics. There are vast studies for even-parity multipole order in d-and f-electron systems. Recently, the subject of multipole physics is extended to odd-parity multipole order which may occur in locally noncentrosymmetric systems. Owing to the parity mixing in the wave function and odd-parity crystalline electric field, the odd-parity multipole may be activated by a sublattice-dependent antisymmetric spin-orbit coupling (ASOC). Previous studies, i.e., magnetic quadrupole order in zigzag chains [1], magnetic toroidal order in a honeycomb lattice [2], magnetic hexadecapole order in a tetragonal crystal with G-type antiferromagnetic order [3], have revealed exotic magnetoelectric responses induced by the sublattice-dependent ASOC.

In this thesis, we have studied the thermodynamic stability and the magnetoelectric response in an odd-parity electric octupole (EO) ordered state. We have considered a bilayer system and constructed the forward scattering model by taking into account a layer-dependent Rashba ASOC [4]. The forward scattering interaction is treated with use of the mean field approximation.

For the thermodynamic stability, we focus on the effect of layer-dependent ASOC on the stability of multipole order. By calculating the multipole susceptibility, it has been revealed that the ASOC plays an important role on the multipole order. The EO order is stabilized by the large layer-dependent ASOC, which decreases the kinetic energy due to the bilayer coupling. Furthermore, we calculated the phase diagram under a magnetic field and demonstrated the parity-breaking quantum critical point. In the EO ordered state, the asymmetric band structure induced by the in-plane magnetic field has been demonstrated.

Since the multipole moment characterizing the EO state belongs to the D_{2d} point group lacking the space inversion symmetry, it is expected that a characteristic magnetoelectric response occurs in the EO ordered state. According to a recent report [5], a spin-orbit coupled metal $Cd_2Re_2O_7$ is one of the candidate materials of the EO phase. With application to $Cd_2Re_2O_7$ in mind, we aim to explore the magnetoelectric response in the EO ordered

state, and investigate the magnetoelectric effect (Edelstein effect) and spin Hall effect in the bilayer system. By calculating the magnetoelectric coefficient and spin Hall conductivity with use of the Kubo formula, we obtained following consequences: (1) the magnetic moment characterized by the symmetry of the EO moment is induced by the electric field, (2) the spin Hall conductivity is drastically enhanced in the EO state.

Furthermore, we have studied the bilayer cuprates, $YBa_2Cu_3O_{7-x}$ (YBCO), which is categorized into the high-T_c superconductors. A change of nematicity has been detected by the magnetic torque measurement at a temperature higher than the onset temperature of charge density wave state [6]. Moreover, the optical measurements, such as a linear dichroism [7] and second-harmonic optical anisotropy [8], have pointed out the broken inversion symmetry. These experimental results imply the possibility of the EO order in the pseudogap regime. We have clarified the "hidden order" in YBCO by analyzing the bilayer Rashba model with a weak two-fold anisotropy. From the calculation of the spin susceptibility, we have demonstrated a kink in the temperature dependence of the magnetic torque at the phase transition point of EO order. We also showed the reduction of the spin susceptibility. These results are consist with experimental observations. Interestingly, it is shown that the two-fold magnetic anisotropy is significantly enhanced in the superconducting state because the Van Vleck susceptibility is highly anisotropic. Possible experimental test of magnetic anisotropy and characteristic magnetoelectric responses has been proposed.

References

[1] Y. Yanase, J. Phys. Soc. Jpn. **83**, 014703 (2014).
[2] S. Hayami, H. Kusunose, and Y. Motome, Phys. Rev. B **90**, 024432 (2014).
[3] H.Watanabe, and Y. Yanase, Phys. Rev. B. **96**, 064432 (2017).
[4] T. Hitomi, and Y. Yanase, J. Phys. Soc. Jpn. **85,** 124702 (2016).
[5] J. W. Harter, Z. Y. Zhao, J.-Q. Yan, D. G. Mandrus, and D. Hsieh, Science **356**, 295 (2017).
[6] Y. Sato, S. Kasahara, H. Murayama, Y. Kasahara, E.-G. Moon, T. Nishizaki, T. Loew, J. Porras, B. Keimer, T. Shibauchi, and Y. Matsuda, Nat. Phys. **13**, 1074 (2017).
[7] Y. Lubashevsky, L. Pan, T. Kirzhner, G. Koren, and N. P. Armitage, Phys. Rev. Lett. **112**, 147001 (2014).
[8] L. Zhao, C. A. Belvin, R. Liang, D. A. Bonn, W. N. Hardy, N. P. Armitage, and D. Hsieh, Nat. Phys. **13**, 250 (2017).