Summary of thesis:

Study of the electronic states in heavy fermion compound URu_2Si_2

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In this thesis, we will focus on the unusual properties of the heavy fermion compound URu_2Si_2. This compound undergoes at 17.5 K a phase transition accompanying a huge amount of entropy loss, but no magnetic and structural ordering have been observed. Despite considerable experimental and theoretical efforts for more than a quarter century, the order parameter is not yet totally understood and therefore the phase is called ‘’hidden order phase’’. In general, a second-order phase transition causes a change in various types of symmetries, such as crystal, rotational, gauge and time reversal symmetries. Therefore the experimental determination of broken symmetries is the most essential step toward elucidating the nature of the hidden order phase transition. Recent magnetic torque measurements reveal the in-plane anisotropy of magnetic susceptibility, which suggests that the crystal C_4 rotational symmetry in the tetragonal URu_2Si_2 is broken below the hidden order transition. This newly suggested rotational symmetry breaking has raised several theoretical proposals, and calls for further experimental verifications by using other techniques.

One of the most direct ways of observing such symmetry breaking is to use X-ray diffraction, which sensitively probes the lattice symmetries. In solids we always have finite electron-lattice coupling, and when the electronic system breaks one of the symmetries of the crystal structure at the transition, then the same symmetry should also be broken in the lattice at the same time. If the electron-lattice coupling constant is small, the amount of lattice change (or distortion) may also be small, and experiments focusing on particular Bragg points may be required to achieve the highest resolution. In the previous crystal-structure studies on URu_2Si_2, no symmetry change has been detected for [h00] and [00l] directions. We therefore perform high-resolution synchrotron X-ray crystal-structure analysis for a high-angle (880) Bragg diffraction by four-circle diffractometer. These results reveal tiny but finite orthorhombic distortion of the order of 10^{-5} (or lattice constant change less than 100 fm), which is discussed in Chapter 3.

The nature of electronic orders in metals and semiconductors is, in general, closely related to the electronic structure, and the most essential information is the structure of Fermi surface. For the understanding of the nature of hidden order, it is indispensable to

determine how the electronic structure changes with the gap formation at the hidden order transition, and in particular it is important to clarify how this is related to the rotational symmetry breaking suggested by the torque measurements. We therefore perform cyclotron resonance measurements in the hidden order phase, which allows the full determination of angle-dependent electron-mass structure of the main Fermi-surface sheets. Furthermore, we find an anomalous splitting of the sharpest resonance line under in-plane magnetic-field rotation. This is most naturally explained by the domain formation, which breaks the fourfold rotational symmetry of the underlying tetragonal lattice. The results reveal the emergence of an in-plane mass anisotropy with hot spots along the [110] direction, which can account for the anisotropic in-plane magnetic susceptibility reported recently. These results are shown in Chapter 4.

Another important aspect of URu_2Si_2 is that the hidden order phase hosts the unconventional superconducting phase below the transition temperature T_{SC} = 1.4 K at ambient pressure. The cyclotron mass m_{CR} in the superconducting state has also been a subject of theoretical debate. Experimentally, however, this point has not yet studied mainly because the observation of cyclotron resonance in the superconducting state is difficult due to the limitation of microwave penetration depth which is usually short. By using a ^{3}He microwave cavity we are able to observe cyclotron resonance in the superconducting phase of URu_2Si_2. Contrary to the proposed temperature dependence, we find that the mass does not show any significant change below T_{SC}. We rather find that the scattering rate at low temperatures exhibits characteristic temperature dependence; it shows non-Fermi liquid-like quasi T-linear dependence followed by a sudden decrease below the vortex-lattice melting transition temperature, which has been determined by the resistivity measurements. This supports the formation of a coherent quasiparticle Bloch state in the vortex lattice phase. These results are shown in Chapter 5.

Finally we will summarize and conclude the our study in Chapter 6.