Fermi surface instabilities and superconductivity in uranium compounds

Superconductivity is one of the most interesting topics in the strongly correlated electron systems. There are many uranium-based heavy fermion compounds which show exotic superconductivity with anomalous pairing. We present our recent results on uranium heavy fermion superconductors, focusing on the Fermi surface instabilities and Lifshitz transition

After the discovery of superconductivity on UBe_{13}, many interesting actinide superconductors have been reported, such as odd-parity superconductivity, coexistence with antiferromagnetism, "high-Tc" superconductivity, superconductivity with strong Pauli paramagnetic effect. In particular, ferromagnetic superconductivity attracts much interest, because the unconventional pairing with spin-triplet state should be realized.

URhGe is a ferromagnet with the Curie temperature T_{Curie}=9.5K. Superconductivity coexists with ferromagnetism below T_{sc}=0.25K[1]. When the field is applied along the hard-magnetization axis (b-axis), field-reentrant superconductivity is observed between 8 to 13T. The upper critical field of conventional superconductivity is in general determined by the Pauli limit and the orbital limit. The Pauli limit of URhGe is very small below 0.5T, thus the reentrant superconductivity observed at extremely high field is indeed unconventional, and is most likely due to the spin-triplet state with equal spin-paring which is free from the Pauli limit. In order to study the mechanism of reentrant superconductivity, we focus on the Fermi surfaces, which reveal the electronic state from the microscopic point of view. Figure 1 shows the field dependence of Hall resistivity and thermopower[2,3]. The abrupt change in Hall resistivity and thermopower signal at H_R indicates the reconstruction of Fermi surfaces in URhGe near the reentrant superconducting phase. Increasing the magnetic field further, we detected the quantum oscillations both in the thermopower and in the magnetoresistance, namely, Shubnikov-de Haas effect. The frequency, which is proportional to the cross-sectional area of Fermi surface, is field-dependent, indicating the Fermi surface instabilities near the reentrant superconductivity.

Another important aspect for the mechanism of reentrant superconductivity is the field-induced ferromagnetic fluctuation[4]. Figure 2 shows the field dependence of the spin-spin relaxation rate, $1/T_2$, which corresponds to the longitudinal spin fluctuation. The divergence of $1/T_2$ at H_R is a direct microscopic evidence for the development of spin fluctuation near the reentrant superconductivity.

In URhGe, both ferromagnetic fluctuations and Fermi surface instabilities are the key ingredients for reentrant superconductivity.

We also clarified the Fermi surface instabilities and Lifshitz transition at high fields in other heavy fermion superconductors[5,6,7]. In the ferromagnetic superconductor UCoGe, we observed successive anomalies at 4, 9, 16, 21T for the field along the easy-magnetization c-axis. At all anomalies, significant change of quantum oscillation frequencies and the effective masses was observed, revealing

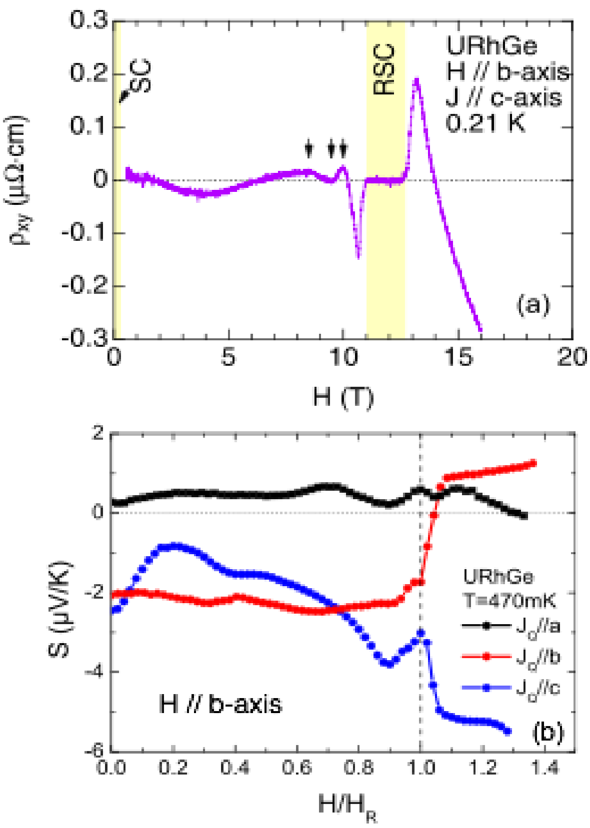

Fig. 1 Field dependence of Hall resistivity and thermopower for the field along b-axis in URhGe

the Fermi surface instabilities. This is consistent with the fact that UCoGe is a low carrier system with heavy quasi particles. In this case, the effective Zeeman energy is low, and the Fermi surfaces are easily changed by the magnetic field.
Uranium compounds have a large spin-orbit interaction and the dual nature of itinerant and localized 5f-electrons. Thus, small tuning parameters, such as magnetic field and pressure, can easily modify the ground state, and the novel quantum phase emerges.
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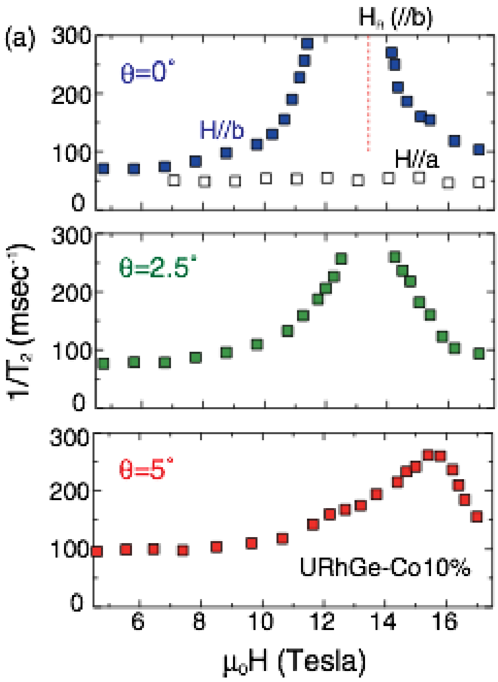

Fig. 2 Field dependence of spin-spin relaxation rate $1/T_2$ for H // b-axis in URhGe with 10% Co doping

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