Spin-Triplet Superconductivity in UTe_2

Spin triplet superconductivity in UTe_2 is now one of the hottest topics in condensed matter physics. In two years (2019-2020), the international collaboration project on UTe_2 were carried out and many important results have been published. Here we present our results focusing on field-reentrant superconductivity, which appears at high magnetic fields.

Superconductivity of heavy fermion UTe2 was discovered only recently at the end of 2018 and attracted enormous attention. In this project we focus on the high quality single crystal growth of UTe_2 and the magnetic and electronic properties under extreme conditions (low temperature, high field, high pressure) using the various experimental technique in order to clarify the spin-triplet superconductivity.

UTe_2 is a heavy fermion paramagnet with the body-centered orthorhombic structure with the space group *Immm*. Although the global inversion symmetry exists in the crystal structure, the local inversion symmetry is broken, indicating that the inversion center is located not at the U site but at the middle of the two U atoms of the next nearest neighbors. The structure without local inversion symmetry will generally give rise to the various interesting physical properties, such as the non-trivial parity of superconducting order parameters, electrical current induced phenomena, and non-reciprocal conductivity. Indeed, UTe2 shows a variety of superconducting and magnetic properties on the basis of this unique structure.

Although UTe_2 is a paramagnet, the similarity to ferromagnetic superconductors, that is URhGe and UCoGe, has been pointed out from the beginning, meaning that UTe_2 might be located at the ferromagnetic end in the spin-triplet superconductors. This is a good starting point to understand UTe_2. One of the most remarkable points in both systems is the huge and anisotropic upper critical field H_{c2}. Figure1 shows the angular dependence of H_{c2} in URhGe, UCoGe and UTe_2. In URhGe, the field-reentrant superconductivity appears for the field along b-axis (hard-magnetization axis). Similarly, the acute enhancement of H_{c2} is observed in UCoGe for a and b-axes (hard magnetization axes). The superconducting critical temperatures are 0.25 and 0.6K for URhGe and UCoGe, respectively. Of course, these unusual behaviors of H_{c2} cannot be explained by the conventional BCS theory, indicating spin-triplet superconductivity with the odd parity. Since superconductivity is realized in the ferromagnetic state, the ferromagnetic fluctuations, which are sensitive to the field direction with the Ising magnetic property, play a role for the "glue" of the superconducting Cooper pairs.

In UTe_2, H_{c2} is again huge and anisotropic, as shown in Fig.1(c). T_c is about 1.7K, but H_{c2} is ranging from 7 to 35T depending on the field direction, highly exceeding the Pauli limit (~3T) based on the weak coupling BCS theory. This is a strong support for spin-triplet superconductivity in UTe_2. An important

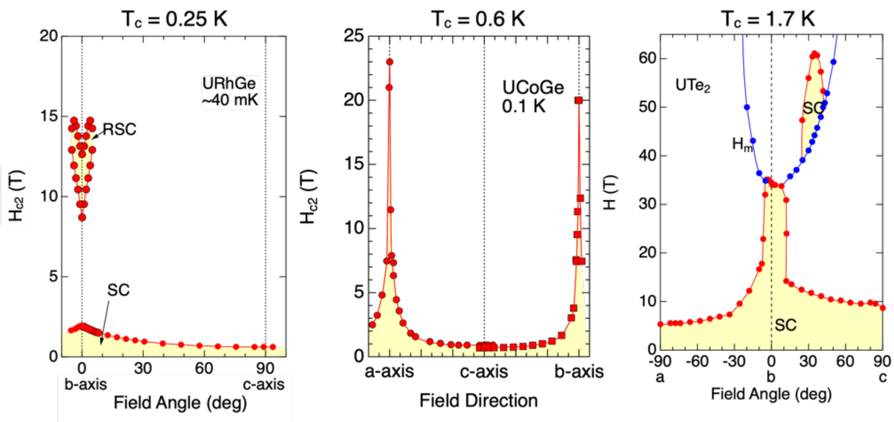

Fig. 1 Angular dependence of the superconducting upper critical field H_{c2} in ferromagnetic superconductors (URhGe, UCoGe) and UTe_2

question is what is the origin of the pairing glue, because UTe_2 is a paramagnet and the ferromagnetic fluctuations are not trivial.

When the field is applied along b-axis, field-reentrant superconductivity is observed as shown in Fig.2(a) [1]. T_c is reduced with increasing field up to 15T, but it is enhanced again with further increasing field. Finally superconductivity is abruptly suppressed at 35T due to the first order metamagnetic transition Hm associated with the drastic change of the electronic state.

Surprisingly, when the field is tilted by 27 deg from b to c-axis retaining perpendicular to easy magnetization axis, superconductivity appears at high fields region (40-60T) above H_m, as shown in Fig. 2(b). This totally unusual H_{c2} behavior at so-called "magic angle" cannot be explained neither by the conventional BCS theory nor by a spin-triplet scenario based on the simple ferromagnetic fluctuations. In the polarized paramagnetic state (PPM), the electronic state is drastically changed, indicating the Fermi surface reconstruction as evidenced by the Hall effect and thermopower experiments. Above H_m in the spin-polarized regime, one can naively expect the suppression of ferromagnetic fluctuations, if it exits. However, regarding other fluctuations, such as antiferromagnetic fluctuations, valence instabilities and Fermi surface instabilities, the field response below/above H_m is not very clear. The reappearance of superconductivity at high fields at magic angle may suggest the existence of multiple fluctuations in this system. In fact, recent high field magnetization measurements clearly demonstrated that the field response of effective mass is quite different between b-axis and the magic angle from the analysis based on the thermodynamics [2]. The multiple fluctuations are also inferred from the magnetic susceptibility and magnetization measurements under pressure [3].

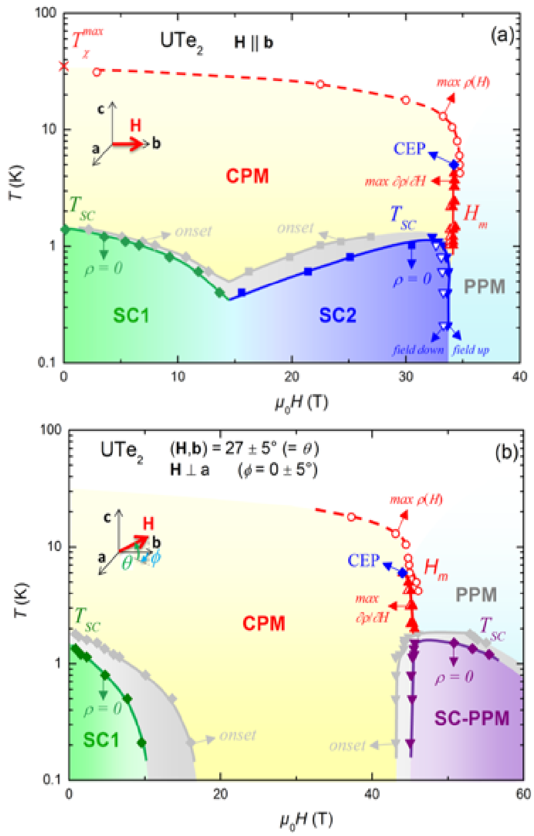

Fig. 2 temperature-field phase diagrams for the field along b-axis (a) and for the field tilted by 27 deg from b to c-axis (b) in UTe_2. SC, CPM and PPM denote superconductivity, correlated paramagnetic state and polarized paramagnetic state, respectively. [1]

This project was performed in strong international collaboration between IMR, CEA-Grenoble, LNCMI-Toulouse, LNCMI-Grenoble, ILL, ESRF, KIT together with domestic collaborations with JAEA, Kyoto University, ISSP, Osaka University, Hokkaido University.

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