Ferromagnetic Superconductivity

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Ferromagnetism and superconductivity had been though to be mutually competitive phenomena, since the large internal field easily destroys the Cooper pair for conventional superconductivity. We study the new superconductivity in uranium compounds, such as URhGe, UCoGe, which can microscopically coexist with ferromagnetism. The triplet-state of pairing allows superconductivity with a large upper critical field H_{C2}. Related to the ferromagnetic spin fluctuation and metamagnetism, re-entrant superconductivity is observed at high magnetic fields in URhGe, where the field-dependent effective mass is enhanced. The pressure study of UCoGe reveals the novel pressure-temperature phase diagram, where the superconductivity survives even in the paramagnetic phase.

The discoveries of superconductivity in the ferromagnetic phase in UGe_2, URhGe and UCoGe were spectacular events in the field of unconventional superconductivity despite the fact that this possibility was predicted long ago. Triplet pairing is presumably generated by the ferromagnetic fluctuation. More surprisingly, field re-entrant superconductivity was found near the metamagnetic transition in URhGe.

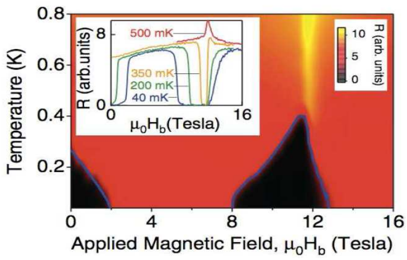

Fig.1: Re-entrant superconductivity of URhGe.

To clarify the interplay between the mass enhancement, low field superconductivity and re-entrant superconductivity in URhGe, we have grown high quality single crystals and performed resistivity measurements with fine tuning of pressure, temperature and magnetic field.

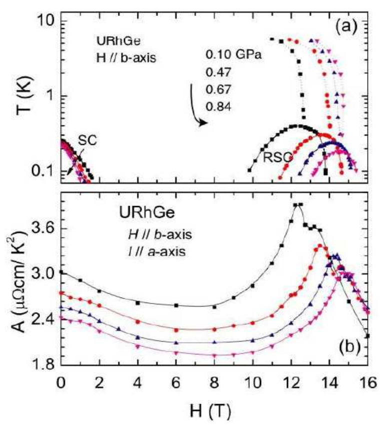

Fig. 2: (a) T-H phase diagram of superconductivity (SC) and re-entrant superconductivity (RSC) in URhGe at several pressures. (b) Field dependence of the coefficient of T2 term, which is proportional to the square root of effective mass.

With increasing pressure, the re-entrant superconducting phase shifts to the higher fields and completely collapses at 1.8GPa (see Fig.1). Correspondingly, the A coefficient of the resistivity ($\rho=\rho_0+AT^2$) shows a maximum around the re-entrant superconductivity and decreases with pressure. This result clearly demonstrates that the enhancement of the effective mass, which is at zero order proportional to $A^{1/2}$, induces the re-entrant superconductivity. A model with a two component contribution of the effective mass (the correlated mass, origin of superconductivity , and the renormalized band mass) gives an excellent description of superconductivity at low field as well as for H reentrant superconductivity. URhGe with its rather small ordered moment is far more easy to describe than UGe_2 where the ordered moment is near one Bohr magneton

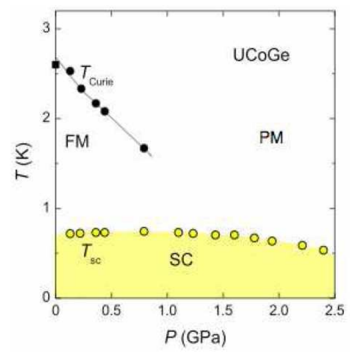

Fig.3: Temperature-pressure phase diagram of UCoGe.

The coexistence of superconductivity and ferromagnetism in UCoGe was discovered in 2008 in Amsterdam. The new perspective is that it allows studies of the persistence of superconductivity in the paramagnetic phase. While the ferromagnetic superconductor, UCoGe has the same crystal structure as URhGe, it seems to reveal a quite different temperature-pressure phase diagram from the theoretical predictions (Fig. 3).The ferromagnetism collapses at Pc ~ 1GPa, but the superconductivity is quite stable, even above Pc, indicating that superconductivity appears also in the paramagnetic phase. A new theory taking into account the symmetry and spin-orbit coupling is developed to explain this phase diagram.

With these three different cases, we have a unique opportunity to clarify the field of ferromagnetic superconductors. Furthermore each of them presents specificities in the general perspectives of quantum phase transitions. For example in UGe_2 , we can now make detailed studies on the first order transition line between two ferromagnetic states which starts under pressure at a critical end point near 0.9 GPa , we can also look carefully to the ferromagnetic paramagnetic line near its critical end point.