# Multiple Superconducting Phases in Novel Spin-Triplet Superconductor $UTe_2$

We discovered multiple superconducting phases in the novel spin-triplet superconductor $UTe_2$ under a magnetic field and pressure. Owing to the thermodynamic response shown by AC calorimetry measurements, *H*-*T* phase diagrams under pressure were determined for the field along the *a*-axis in the orthorhombic structure. The unusual enhancement of the upper critical field $H_{c2}$ was observed as a consequence of multiple superconducting phases. This behavior of $H_{c2}$ requires the state of the superconducting order parameter to be more complex than the spin-triplet state with equal-spin pairing.

Heavy fermion superconductivity in $UTe_2$ has attracted much attention because of recently discovered superconducting phenomena. $UTe_2$ is a paramagnet with a heavy electronic state in the proximity of the ferromagnetic order. The microscopic coexistence of ferromagnetism and superconductivity has already been established for uranium-based compounds, namely $UGe_2$, URhGe, and UCoGe. The newly discovered $UTe_2$ has many similarities with these ferromagnetic superconductors. One of the highlights of $UTe_2$ and ferromagnetic superconductors is the huge superconducting upper critical field $H_{c2}$. In $UTe_2$, when the field is applied along the hard magnetization axis (*b*-axis), the superconducting phase persists at an extremely high field up to 35 T, which is one order of magnitude larger than usually expected at the superconducting transition temperature 1.6 K. Furthermore, the $H_{c2}$ curve displays field re-entrant behavior; $T_c$ at 35 T is two times higher than that at 15 T. Therefore, spin-triplet superconductivity is expected because $H_{c2}$ can be enhanced by tuning the ferromagnetic fluctuation without the Pauli paramagnetic effect. Another important aspect of spin-triplet superconductivity is the spin degree-of-freedom. In this case, multiple superconducting phases are theoretically expected, as is well known in superfluid $^3$He. However, obtaining experimental evidence for multiple superconducting phases is a difficult task.

We performed AC calorimetry measurements under pressure and for the field along the easy-magnetization axis (*a*-axis) in $UTe_2$ to clarify whether the superconducting phases are a thermodynamic response. Figure 1 shows the *H*-*T* phase diagram at 0.54 GPa for the *H* ∥ *a*-axis. The superconducting transition temperature was enhanced to $T_c$ = 2.5 K compared with that at ambient pressure ($T_c$ = 1.6 K). When the field was increased, $T_c$ decreased with a strong convex curvature. At temperatures below 0.4 K, $H_{c2}$ abruptly increased and reached 8 T at 0 K. This $H_{c2}$ curve was also confirmed by magnetoresistance [2]. The Pauli limitation exhibited by $H_{c2}$ could be attributed to the appearance of the Fulde–Ferrell–Larkin–Ovchinnikov (FFLO) state, in which the pair-breaking due to the Pauli paramagnetic effect is reduced. However, this is unlikely because the FFLO state never produces the sharp kink observed in $UTe_2$. Moreover, $UTe_2$ is a three-dimensional superconductor, different from the two-dimensional iron-based superconductor. Most importantly, the abrupt increase in $H_{c2}$ emerged as a prolongation of the lower superconducting transition existing at zero field, where no paramagnetic limitation exists. Our results demonstrate multiple superconducting phases, which may require different order parameters for each phase. Several theoretical models to explain this phase diagram have been proposed based on the existence of point node gaps at ambient pressure indicated by field-angle resolved specific heat measurements [3].

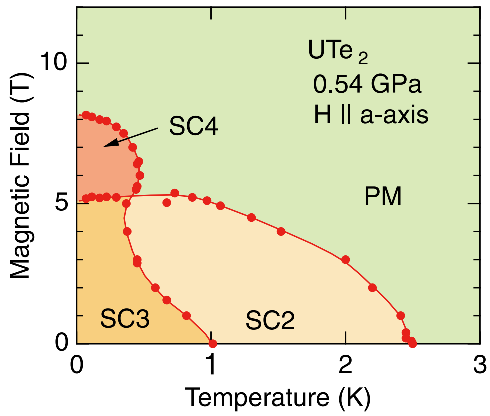


Fig. 1 *H*-*T* phase diagram for *H* ∥ *a*-axis at 0.54 GPa [1]. PM, SC denote paramagnetism and superconductivity, respectively

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