



UTe₂: A New Spin-Triplet Pairing Superconductor

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Superconducting ferromagnets provide a fruitful playground to study exotic forms of Cooper pairing. Recently, a new superconductor at the verge of ferromagnetic order has been reported: UTe₂. Now researchers from Tohoku University, Kobe University and CEA/Grenoble have joined efforts and uncover an unconventional superconducting state.

Superconductivity and magnetism are two of the most striking “everyday” examples of macroscopic states of matter that directly reflect the complexity and exquisiteness of quantum electronic matter. Particularly interesting are situations where both states of matter meet, such as in cuprates and pnictides, where superconducting transition temperatures exceeding 100 K provide a longstanding quantum puzzle. Another striking example is the family of superconducting ferromagnets: UGe₂, URhGe, and UCoGe (Table I). These materials show long-range ferromagnetic order with a low Curie temperature, but at even lower temperatures superconduct, hence $T_{sc} < T_{Curie}$. Magnetism in these *5f*-electron metals is of itinerant nature, which allows for superconductivity and ferromagnetism to be carried by the same electrons. This implies magnetism and superconductivity occupy the same sample volume and coexist on the microscopic scale.

In the past decade, the family of superconducting ferromagnets has become a versatile tool-box for examining novel, exotic superconducting phenomena. A comprehensive review paper has been published in JPSJ recently [6]. An impressive body of experimental evidence has been collected which demonstrates superconductivity is due to an exotic Cooper-pair state, i.e., spin-triplet (or rather odd-parity) pairing ($L = 1, S = 0$). This is to be contrasted with spin-singlet pairing ($L = S = 0$) for most common superconductors that are described by the standard Bardeen–Cooper–Schrieffer (BCS) model. Spin-triplet pairing is tightly connected to an exotic pairing mechanism for superconductivity: the Cooper pairs are mediated via spin fluctuations rather than by electron–phonon coupling.

A qualitative explanation for the occurrence of superconductivity in itinerant ferromagnets is offered by spin fluctuation models [7,8]. In the simplest way, the magnetic behavior is described by a mean-field theory in terms of a Hubbard-type exchange interaction parameter \bar{I} and a Stoner enhancement factor $S = 1/(1 - \bar{I})$. When \bar{I} is tuned to its critical value $\bar{I} \rightarrow 1$, a second-order phase transition occurs

from the paramagnetic to the ferromagnetic state. Near the quantum critical point, the exchange of longitudinal spin fluctuations mediates spin-triplet superconductivity. In the ferromagnetic phase, exchange splitting of the Fermi surface gives rise to a separation in majority and minority spin sheets. Superconductivity is therefore restricted to the equal-spin pairing (ESP) states $|\uparrow\uparrow\rangle$ ($L_z = 1$) and $|\downarrow\downarrow\rangle$ ($L_z = -1$), which form on the different Fermi surface sheets in the presence of a sizeable exchange splitting.

In November last year, Ran et al. [5] reported a new superconductor with strong ties to the family of superconducting ferromagnets: UTe₂. UTe₂ with a T_{sc} of 1.6 K, does not show the spontaneous magnetization connected to ferromagnetic order, but is positioned exactly at the locus where the ferromagnetic and paramagnetic phases meet in the global phase diagram of ferromagnetic superconductors. Evidence for this critical location has been extracted from the magnetization process, that is well described by the Belitz–Kirkpatrick–Vojta theory of metallic ferromagnetic quantum criticality. Measurements of the superconducting phase reveal properties that make a strong case for spin-triplet pairing, especially (i) the extremely large values of the upper critical field, H_{c2} , that largely exceed the Pauli limit for spin-singlet superconductivity, $H^P = 1.86 \times T_{sc}$, and (ii) a temperature independent ¹²⁵Te NMR Knight shift upon cooling through T_{sc} , where a decrease is expected for spin-singlet pairing due to the concomitant decrease of the spin susceptibility.

Sparked by the e-print of Ran et al. Aoki and collaborators immediately turned to their crystal growth labs and, in a blink of the eye, prepared high quality UTe₂ single crystals, thereby benefitting from earlier work [9]. Resistivity, specific heat and magnetoresistance experiments were conducted immediately, and the results have been reported in JPSJ online on March 27 [10]. The publication, importantly, confirms the novel superconducting features of UTe₂ [5]. One of the striking results is the electronic specific heat $C_e(T)$ around the superconducting transition, traced as $C_e(T)/T$ versus T in Fig. 1. Bulk supercon-

Table I: Superconducting ferromagnets and their characteristic parameters: Curie temperature, T_C , superconducting transition temperature, T_{sc} , ordered moment, m_0 , Curie–Weiss effective moment, p_{eff} , and linear coefficient in the specific heat, γ . In the last row is listed UTe₂, a superconductor at the verge of ferromagnetic order.

Material	Structure	T_C (K)	T_{sc} (K)	m_0 (μ_B/U atom)	p_{eff} (μ_B/U atom)	γ (J/mol K ²)	Ref.
UGe ₂	orthorhombic	53	0.8 ^a	1.5 <i>a</i>	2.9	0.032	1
URhGe	orthorhombic	9.5	0.25	0.42 <i>c</i>	1.8	0.160	2
UIr	monoclinic	46	0.1 ^b	0.50 $[10\bar{1}]$	2.4	0.049	3
UCoGe	orthorhombic	3	0.6	0.07 <i>c</i>	1.7	0.057	4
UTe ₂	orthorhombic	→0	1.6	→0	2.8	0.117	5

^aat a pressure of 1.2 GPa; ^bat a pressure of 2.7 GPa

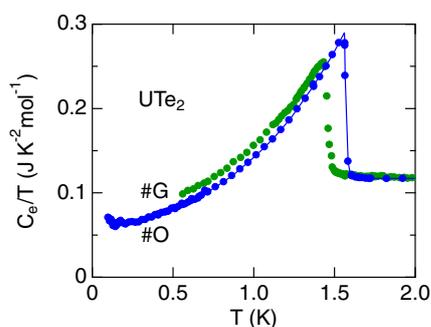


Fig. 1. Specific heat of UTe_2 around the superconducting transition for two different crystals #O and #G. Note the finite $C_e/T \approx \gamma_n/2$ for $T \rightarrow 0$ indicates superconducting pairing takes place on half of the Fermi surface only.

ductivity is clearly demonstrated by the large and sharp step in the specific heat with $\Delta C_e(T)/\gamma_n T_{sc} = 1.51\text{--}1.57$ for two different crystals. Here γ_n is the (normal-state) Sommerfeld coefficient that attains the enhanced value of 117 mJ/mol K^2 , which indicates UTe_2 is a heavy-electron metal. Surprisingly, $C_e(T)/T$ for $T \rightarrow 0$, deep in the superconducting phase, does not go to zero, but levels off at a finite value $\gamma_n/2$. The customary interpretation of a finite γ_n value is that the electrons in part of the crystal do not pair-up and contribute to the superconducting condensate, but remain normal. However, in this case it is expected $\Delta C_e(T)/\gamma_n T_{sc} \approx 0.715$, which is half of the standard weak-coupling value (1.43) in the BCS model. This leads to the appealing conclusion that superconducting pairing is restricted to the (spin-polarized) half of the Fermi surface only, and results in an exotic equal-spin pairing state $|\uparrow\uparrow\rangle$ (or $|\downarrow\downarrow\rangle$). Hence the Cooper pairs carry a magnetic moment. Such a superconducting state is termed non-unitary [5].

Aoki et al. also find extremely large H_{c2} -values for their UTe_2 crystals, although there are some important differences compared to the data presented in Ref. 5. From an analysis of H_{c2} , the field variation of the coupling parameter $\lambda(H)$, which is a measure of the pairing strength, is deduced. This, in turn, provides further evidence for spin-fluctuation mediated superconductivity.

These first experiments on the new superconductor, UTe_2 , at the border of ferromagnetic order, provide convincing evidence for unconventional superconductivity. A new laboratory instrument to investigate and test theories for spin-triplet superconductivity has been added to the quantum matter tool-box.

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News and Comments on “**Unconventional Superconductivity in Heavy-Fermion UTe_2** ” [D. Aoki, A. Nakamura, F. Honda, D. Li, Y. Homma, Y. Shimizu, Y. J. Sato, G. Knebel, J.-P. Brison, A. Pourret, D. Braithwaite, G. Lapertot, Q. Niu, M. Vališka, H. Harima, and J. Flouquet, *J. Phys. Soc. Jpn.* **88**, 043702 (2019)]