UTe_2: A new Topological Superconductor?

1. **Nearly ferromagnetic spin-triplet superconductivity**
   Authors: S. Ran, C. Eckberg, Q-P. Ding, Y. Furukawa, T. Metz, S. R. Saha, I-L Liu, M. Zic, H. Kim, J-P. Paglione & N. P. Butch
   Science, 6454, 365 (2019)

2. **Chiral superconductivity in heavy-fermion metal UTe_2**
   Authors: L. Jiao, S. Howard, S. Ran, Z. Wang, J. O. Rodriguez, M. Sigrist, Z. Wang, N. P. Butch & V. Madhavan
   Nature, 579 , 523 (2020)

3. **Multicomponent superconducting order parameter in UTe_2**
   Authors: I. M. Hayes, D. S. Wei, T. Metz, J. Zhang, Y. S. Eo, S. Ran, S. R. Saha, J. Collini, N. P. Butch, D. F. Agterberg, A. Kapitulnik & J. Paglione
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Recommended with a Commentary by Piers Coleman and Tamaghna Hazra, Center for Materials Theory, Rutgers University

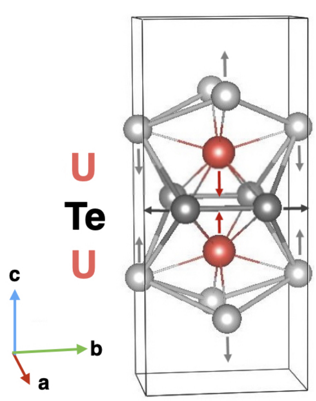

Figure 1: Structure of UTe_2, figure from [1].

Since the discovery of triplet-paired superfluid He-3 fifty years ago, physicists have been fascinated by the prospect of its superconducting analogs. This interest has been piqued with the realization that triplet-paired condensates can develop a non-trivial topology, with protected surface states. The recent discovery of an very unusual superconductor, UTe_2[2], with chiral surface states and an upper critical field that rivals high temperature superconductors, has driven an explosion of new interest [1, 3]. Here we provide a short commentary on recent developments.

UTe_2 is an orthorhombic crystal, with two uranium atoms in each primitive unit cell, as shown in Fig. 1. Despite its modest 1.5K transition temperature, superconductivity survives up to 35 Tesla[4] (Fig. 2a.) for fields in the b-c plain. Moreover, at 35° to the b-axis, parallel to the b-c face diagonal a re-entrant superconducting phase develops between 40 and 60 Tesla. Large upper-critical fields are a hall-mark of triplet pairing: singlet pairing is Pauli-limited to fields where the Zeeman energy is smaller than gap, but in UTe_2, H_{c2} exceeds its Pauli limit by an order of magnitude; triplet pairing is further corroborated by the absence

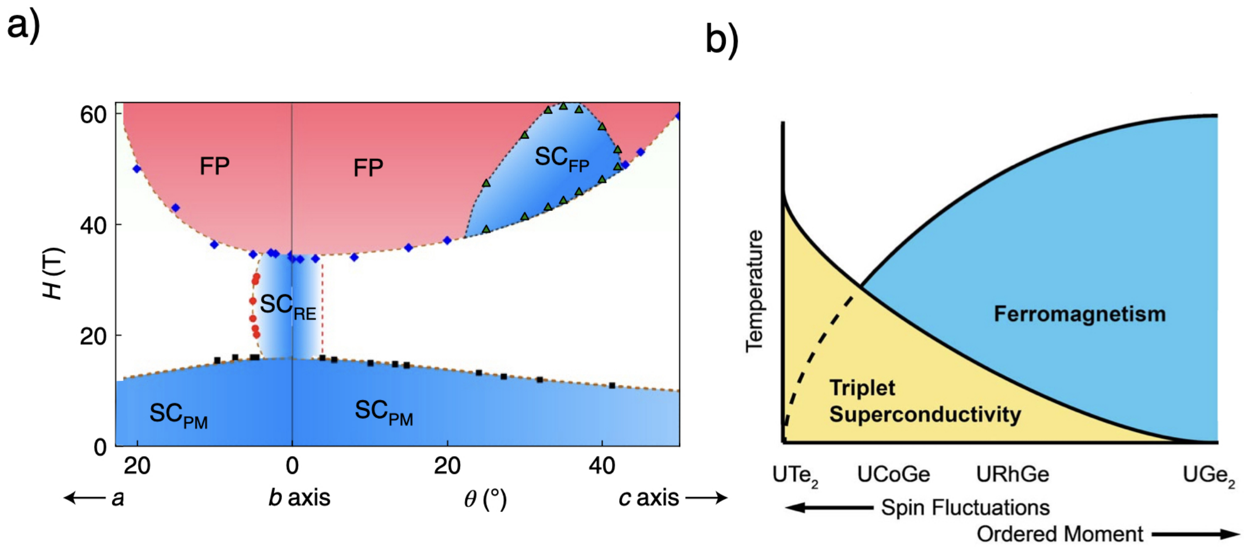

Figure 2: a) Phase diagram of UTe_2 for fields in the a-b and b-c plane, showing superconducting phases in blue. b) Evolution of magnetism and superconductivity in the family of U-based superconductors. Figs from [2, 4].

of a significant Knight shift in the nuclear magnetic resonance[2, 5]. UTe_2 belongs to a family of triplet-paired heavy fermion compounds UGe_2, UCoGe and URhGe[6], but unlike the others, in which superconductivity co-exists with ferromagnetism, it is paramagnetic, with an easy-axis magnetic susceptibility that diverges at low temperatures, suggesting[2] that it lies at a ferromagnetic quantum critical point (2(b)).

In a triplet superconductor, the gap function is a Pauli-matrix in spin space with a quantization axis determined by a d-vector $\mathbf{d}(\mathbf{k})$

$$\Delta_{\alpha\beta}(\mathbf{k}) = \mathbf{d}(\mathbf{k}) \cdot \boldsymbol{\sigma}_{\alpha\beta}, \qquad (\mathbf{d}(\mathbf{k}) = -\mathbf{d}(-\mathbf{k})) \tag{1}$$

In the simplest case, $\mathbf{d}(\mathbf{k})$ is real, giving rise to Cooper pairs quantized with $m_d = 0$ along the axis $\mathbf{d}$ (Fig. 3a). Time-reversal breaking pairing is described by the complex superposition of two real d-vectors $\mathbf{d}(\mathbf{k}) = \mathbf{d}^1(\mathbf{k}) + i\mathbf{d}^2(\mathbf{k})$. where the intersection of the two spin-planes, given by $\mathbf{d}^2 \times \mathbf{d}^1$ defines the quantization axis of the Cooper-pair $|\uparrow\uparrow\rangle$ magnetization (Fig. 3b). Such time-reversal breaking states give rise to orbital moments. In UTe_2 at high fields, we can be confident that the pairs are of this type, but could such a state develop spontaneously at zero field? In UTe_2, crystal symmetry adds an important nuance to this discussion, for group theory dictates that the two d-vectors must transform as irreducible representations of the orthorhombic (D_{2h}) point-group. Normally, we would expect that $\mathbf{d}^{1,2}$ to be members of a two dimensional representation, but the D_{2h} symmetry group has only one-dimensional representations, so we expect that if the ground-state breaks time-reversal symmetry,

$$\mathbf{d}(\mathbf{k}) = \mathbf{d}^{\Gamma_1}(\mathbf{k}) + i\mathbf{d}^{\Gamma_2}(\mathbf{k}), \tag{2}$$

where $\Gamma_{1,2} \in \{A_{1u}, B_{1u}, B_{2u}, B_{3u}\}$ are selected from the four odd-parity, irreducible representations of an orthorhombic crystal. Based on various different measurements, different symmetry combinations have been proposed.

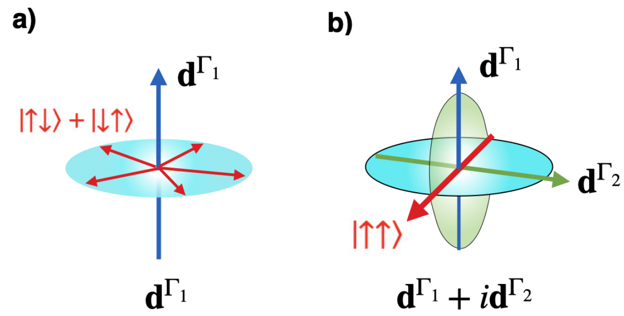

Figure 3: a) Single d-vector describes an unpolarized triplet state, b) complex d-vector, involving the superposition of two different representations $\{\Gamma_1, \Gamma_2\}$ generates parallel-spin pairing.

Early indication of such broken time-reversal symmetry was inferred from an anomalously huge linear specific heat $C_V = \gamma_S T$ in the superconducting state, roughly one half of the normal state value[2], as if only one spin component of the electron fluid is unpaired. Subsequently Ref. [5] observed a plateau in the NMR relaxation rate $1/T_1T$ below T_c at one-fourth the normal state value, until 0.2K when $1/T_1T$ drops further. These observations, along with the similarity of the re-entrant superconductivity among the family of heavy-fermion superconductors, led Ref. [7] to propose that time-reversal symmetry is spontaneously broken at the onset of superconductivity, with a order parameter $\mathbf{d}(\mathbf{k}) = (\mathbf{b} + i\mathbf{c})(k_b + ik_c) \equiv \mathbf{d}^{A_{1u}} + i\mathbf{d}^{B_{3u}}$, motivated by analogy with He-3.

The time-reversal breaking was soon established by Kerr effect measurements in Ref. [8]. The position of point gap nodes in the order parameter along the a axis was inferred from an array of thermodynamic and transport measurements[9, 10]. However, with improvements of sample quality, γ_S has dropped to below 5% of the normal state[11], while mysteriously, the thermal conductivity κ in the superconductivity reveals no linear-in-temperature component $\kappa \sim T$ expected of a quasiparticle Fermi surface[9]. This is still an unresolved issue, but the prevailing view is that the nodal excitations are robust, but that the linear specific heat is more likely associated with localized excitations created by disorder.

Seeking further insight, in [12] the authors carried out a detailed set of scanning tunneling microscopy (STM) experiments on UTe_2. These measurements measurements revealed a dip-hump "Fano"-line shape in the dI/dV curves that are a well-known a consequence of the Kondo effect in heavy fermion systems. But further analysis of the low energy spectra revealed a surprise: when the scanning tip was positioned above surface step edges along the a-axis, a small asymmetric wiggle in the density of states,

$$\Delta\left(\frac{dI}{dV}\right) = \Phi(\alpha eV), \qquad (\alpha = \pm), \tag{3}$$

was observed in the spectrum, i.e a feature in the spectrum that reverses its dependence on voltage depending on the sign of the chirality $\alpha = \hat{\mathbf{a}}.(\hat{\mathbf{n}} \times \hat{\mathbf{m}})$ of the edge, where $\hat{\mathbf{n}}$ and $\hat{\mathbf{m}}$ are the normal to the surface and step edge respectively, so that "step ups" and "step downs" in the scan had voltage-reversed signals (See Fig 4b). The authors interpreted this chirality as a result of a chiral surface state, with an energy that depends linearly on momentum, circulating unidirectionally around the $\hat{\mathbf{a}}$ axis, along the surface of the superconductor. This paper proposed a gap function of the form $\mathbf{d} = \mathbf{d}^{B_{1u}} + i\mathbf{d}^{B_{2u}}$.

In [8], the authors set out to directly detect the presence of spontaneous time-reversal symmetry breaking in superconducting UTe_2 by measuring the Kerr rotation of reflected light. When light was reflected along the c-axis they found a Kerr effect; moreover, by

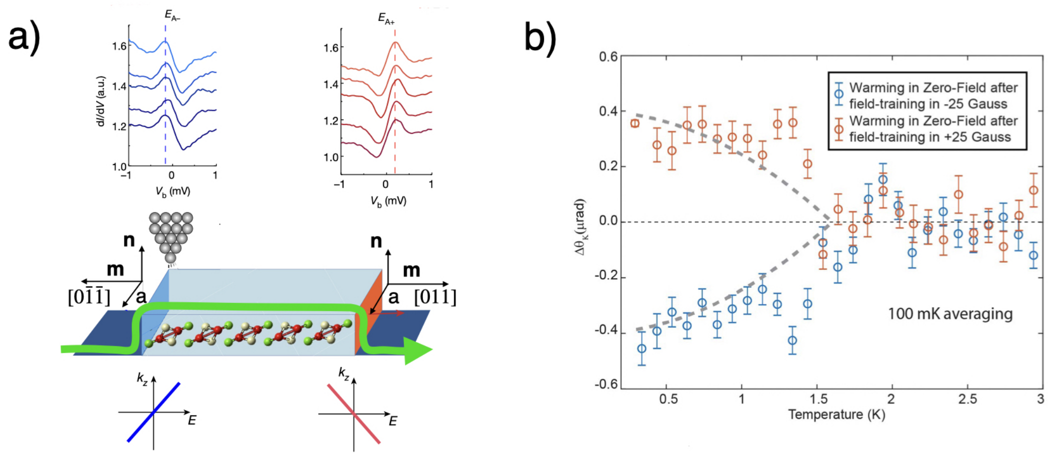

Figure 4: a) Voltage-asymmetric tunneling density of states observed at steps of opposite chirality α after [12], b) field-trained Kerr effect for field along the c-axis after [8].

applying a field on the c-axis, the Kerr rotation could be "trained", indicating the development of a spontaneous magnetization along the c-axis.(Fig 4b) To confirm this result, the group measured the specific heat capacity in a field, and observed that the phase transition is split by a field. This poses a conundrum, because the STM results had suggested a magnetization along the a-axis. To resolve the issue, the authors proposed an ingenious resolution, suggesting that the chiral edge states seen in the STM result from the formation of a Weyl superconductor. Weyl metals form when a topological insulator is exposed to broken time-reversal or inversion symmetry, resulting in a quantum material with Fermi arcs on its surface. The authors suggest that in a state where $\mathbf{d} = \mathbf{d}^{B_{2u}} + i\mathbf{d}^{B_{3u}}$, gapless Weyl cones will form in the superconductor.

An obvious unsolved problem posed by UTe_2 is its huge 60T upper critical field. Normally, an estimate of the orbital upper-critical field is obtained by extrapolating dHc/dT_c to zero temperature, a number of order $20T$ along the b-axis. Somehow, the effective coherence length of the superconductor reduces at high fields. Lebed[13] has suggested that one mechanism is the development of a two dimensional electron fluid at high temperatures, yet UTe_2 is a three dimensional system and there is no natural geometric reason for this to occur at 35^0 to the b-axis.

Perhaps the greatest problem posed by this system is one of symmetry. The broken time reversal symmetry forces upon us a two-component condensate composed of two different symmetry representations. Generically, Cooper pairs of different symmetry will condense at different temperatures, producing a two-stage jump in the specific heat capacity. While the specific heat does develop a double peak in a magnetic field, no such jump has been seen in zero field in samples grown by the prescription outlined in [14]. Moreover, the application of pressure[15] does not split the transition, ruling out the possibility of an accidental degeneracy. This represents a major enigma for our current understanding and may force us to think in terms of a radically different class of order parameter.

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