Nearly ferromagnetic spin-triplet superconductivity

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Nearly ferromagnetic spin-triplet superconductivity

Abstract
Spin-triplet superconductors potentially host topological excitations that are of interest for quantum information processing. We report the discovery of spin-triplet superconductivity in UTe2, featuring a transition temperature of 1.6 kelvin and a very large and anisotropic upper critical field exceeding 40 teslas. This superconducting phase stability suggests that UTe2 is related to ferromagnetic superconductors such as UGe2, URhGe, and UCoGe. However, the lack of magnetic order and the observation of quantum critical scaling place UTe2 at the paramagnetic end of this ferromagnetic superconductor series. A large intrinsic zero-temperature reservoir of ungapped fermions indicates a highly unconventional type of superconducting pairing.

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Spin-triplet superconductors potentially host topological excitations that are of interest for quantum information processing. We report the discovery of spin-triplet superconducting pairing state in UTe$_2$, featuring a transition temperature of 1.5 kelvin and a very large and anisotropic upper critical field exceeding 40 teslas. This superconducting phase stability suggests that UTe$_2$ is related to ferromagnetic superconductors such as UGe$_2$, URhGe, and UCoGe. However, the lack of magnetic order and the observation of quantum critical scaling place UTe$_2$ at the paramagnetic end of this ferromagnetic superconductor series. A large intrinsic zero-temperature reservoir of ungapped fermions indicates a highly unconventional type of superconducting pairing.

Spin-triplet superconductors potentially host topological excitations that are of interest for quantum information processing. We report the discovery of spin-triplet superconducting pairing state in UTe$_2$, featuring a transition temperature of 1.5 kelvin and a very large and anisotropic upper critical field exceeding 40 teslas. This superconducting phase stability suggests that UTe$_2$ is related to ferromagnetic superconductors such as UGe$_2$, URhGe, and UCoGe. However, the lack of magnetic order and the observation of quantum critical scaling place UTe$_2$ at the paramagnetic end of this ferromagnetic superconductor series. A large intrinsic zero-temperature reservoir of ungapped fermions indicates a highly unconventional type of superconducting pairing.
is strongly anisotropic, with the value along \( b \) exceeding the two orthogonal directions by a factor of 4 at 1 K. The zero-temperature limit of \( H_{c2} \) along \( b \) well exceeds the highest measured magnetic field of 20 T, and we conservatively estimate a value of 40 T on the basis of the curvature of the critical field in UCoGe (20). The \( H_{c2} \) value is very sensitive to the alignment of magnetic field along the \( b \) axis (fig. S5).

The upper critical field of a conventional singlet superconductor is restricted by both of the orbital and paramagnetic pair-breaking effects. The zero-temperature orbital limit in superconductors is often well described by the Werthamer-Helfand-Hohenberg (WHH) theory \( H_{orb} = 0.7dH_{c2}dT_c/T_c \) (27). Although it can account for the response to field along the \( a \) axis, the WHH model otherwise disagrees drastically with our experimental results, most prominently along the \( b \) axis, where the slope of \( H_{c2} \) at \( T_c \) is \( -17 \) T/K along \( b \), which leads to an expected \( H_{orb} = 20 \) T for this direction. The conventional paramagnetic zero-temperature limit is given by \( H_{para} = 1.86T_c \) (28), yielding \( H_{para} = 3 \) T for UTe\(_2\). In the zero-temperature limit, the experimental \( H_{c2} \) value well exceeds \( H_{para} \) in all three directions and by almost an order of magnitude along the \( b \) axis, excluding spin-singlet order parameters.

The violation of the orbital limit in directions perpendicular to the magnetic easy axis (the \( a \) axis) is consistent with the behavior of the ferromagnetic superconductors (29) and differs qualitatively from the relatively low \( H_{c2} \) values found in other paramagnetic triplet superconductors (8, 30). The unusual shape of the \( H_{c2} \) curve of UTe\(_2\) resembles those of UCoGe (26) and URhGe (31), in which ferromagnetic spin fluctuations are believed to mediate the superconducting pairs (25). Although the normal state of UTe\(_2\) is not magnetically ordered, the notable similarities suggest that its superconducting pairs are also mediated by ferromagnetic spin fluctuations, indicating that it is the end member of the series of ferromagnetic superconductors. When superconducting pairing is mediated by ferromagnetic spin fluctuations, the field dependence of the magnetization is coupled to the field dependence of the superconducting coupling strength (32), as verified in UCoGe and URhGe (33). The coupling strength \( \lambda \) as a function of magnetic field can be estimated based on the behavior of \( H_{c2} \) and \( \gamma \) (24). Especially prominent is the large increase in \( \lambda \) along the \( b \) axis of \( \sim50\% \) (fig. S6), which far exceeds the field-induced enhancement of \( \lambda \) in UCoGe (33).

Further confirmation of spin-triplet pairing in UTe\(_2\) comes from NMR measurements, which are sensitive to internal magnetic fields (Fig. 3D). No change of the peak position is observed in the \(^{125}\)Te-NMR spectra between normal and superconducting states, leading to a temperature-independent value of the \(^{125}\)Te Knight shift \( K \), which is proportional to the spin susceptibility of the quasiparticles forming the superconducting pairs. In singlet-paired superconductors, \( K \) decreases below \( T_c \), whereas in UTe\(_2\), \( K \) remains

Fig. 1. Structure of UTe\(_2\). (A) Global phase diagram of ferromagnetic superconductors; UTe\(_2\) is located at the paramagnetic end of the series. (B) A photo of a single crystal of UTe\(_2\) grown using chemical vapor transport method on the millimeter scale. (C) Crystal structure of UTe\(_2\), with U atoms in blue and Te atoms in gray. The U atoms sit on chains parallel to the [100] \( a \) axis, which coincides with the magnetic easy axis, illustrated by the magenta arrows.

Fig. 2. Normal state properties of UTe\(_2\). (A) Temperature dependence of magnetization for three different directions of magnetic field of 0.1 T. For the field in a direction, the gray dashed line is the fit to the power law in the low-temperature region, whereas the black dashed line is the fit to the Curie-Weiss law in the high-temperature region. (Inset) Magnetization as a function of applied field in three directions at 1.8 K. (B) Magnetization data at 1.8 K/\( T \) as a function of \( H/T \). (C) Temperature dependence of electric resistivity data in zero magnetic field with electric current applied along \( a \) and \( b \) axes. (D) \( M/T \) as a function of \( H/T^{1.5} \) for different temperatures. All the data collapse onto a single line. This scaling corresponds to the BKV theory of metallic ferromagnetic quantum criticality (see text).
constant on passing through $T_c$, signifying that the superconducting pair is a spin triplet (34, 35). The unconventional nature of the superconductivity in UTe$_2$ is also observed in the temperature dependence of $^{125}$Te nuclear spin-lattice relaxation rate $1/T_1$ (fig. S16). $1/T_1$ shows a deep drop below ~1 K without showing a Hebel-Slichter coherence peak in $1/T_1$ just below $T_c$, which is expected for conventional BSC superconductors. The temperature dependence of $1/T_1$ below $T_c$ follows a power law behavior $1/T_1 \propto T^2$ which is close to the $T/T_c \rightarrow T^2$ relation expected from the point-node gap structure (36, 37), consistent with the results of the specific heat measurement.

Having established clear evidence for spin-triplet pairing, one possible superconducting pairing symmetry consistent with a large fraction of ungapped electronic states of UTe$_2$ is the nonunitary triplet state, in which a two-component superconducting order parameter has two different energy gaps. However, such a state is generally not expected for paramagnetic, orthorhombic systems with strong spin-orbit coupling—this scenario applies to UTe$_2$ unless the effective spin-orbit coupling is demonstrated to be weak owing to special circumstances. No other standard archetype fits all measured properties of UTe$_2$ and any candidate state must account for the large field anisotropy, nodal gap structure, and the large residual electronic density of states, which are by themselves unusual. The high upper critical field itself suggests that the superconducting state resembles a condensate of equal spin pairs. One general possibility is band-selective superconductivity in a highly anisotropic electronic structure having multiple Fermi surfaces. Ongoing electronic structure measurements will help to determine whether such a description is applicable here. Regardless, explaining the relevance of ferromagnetic quantum criticality and the role of spin fluctuations will require further theoretical work.

The discovery of this superconducting state opens the door to advances in the study of spin-triplet pairing, topological electronic states, and their application to quantum information technology. As a paramagnetic version of ferromagnetic superconductors, UTe$_2$ is a promising topological superconductor (38) and may host Majorana excitations that can be detected by angle-resolved photoemission spectroscopy or scanning tunneling microscope (39).

**Fig. 3. Superconducting state properties of UTe$_2$.** Temperature dependence of (A) resistivity and (B) ac magnetization data at low temperatures showing bulk superconductivity. (C) Electric contribution to heat capacity (phonon contribution has been subtracted as explained in the supplementary materials) in zero field and 7 T divided by temperature, shown as a function of temperature, illustrating $\gamma$ in the superconducting and normal states. Magnetic field is applied along the a axis. (D) Temperature dependence of $^{125}$Te NMR Knight shift $K$ below and near $T_c$ of powdered UTe$_2$ sample (left axis) and of the resonance frequency $f$ of the NMR tank circuit confirming the superconducting state and $T_c$ (right axis). $H = 113$ T.

**Fig. 4. Upper critical field $H_{c2}$ of UTe$_2$.** (A to C) Color contour plots of resistivity value as a function of temperature and magnetic field, with magnetic fields applied along (A) the b axis, (B) the c axis, and (C) the a axis. The current is applied along the a axis. (D) The $H_{c2}$ value as a function of $T$ in three directions. Dotted lines represent the WHH fit of the $H_{c2}$ data. (E) Temperature-dependent resistivity data in magnetic fields applied along the b axis up to 20 T. Curves were measured using a constant magnetic field interval of 1 T.

**REFERENCES AND NOTES**

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SUPPLEMENTARY MATERIALS
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Materials and Methods
Supplementary Text
Figs. S1 to S16
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An unusual superconductor

In conventional, and in many unconventional, superconductors, the electrons that form Cooper pairs have spins pointing in opposite directions. An applied magnetic field can easily “break” such pairs—and destroy superconductivity—by aligning both spins in the same direction. In contrast, spin-triplet superconductors are much more resilient to magnetic fields. Very few candidates for such materials have been discovered. Ran et al. add to this select group by observing signatures of spin-triplet superconductivity, including a very large and anisotropic upper critical magnetic field, in the material UTe₂. Because spin-triplet superconductors may naturally exhibit topological superconductivity, this material may also be of interest in quantum computing.

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