Microscopic evidence for a chiral superconducting order parameter in the heavy fermion superconductor UTe$_2$

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Spin-triplet superconductivity is a condensate of electron pairs with spin-1 and an odd parity pair wavefunction$^1$. A particularly interesting manifestation of triplet pairing is a chiral p-wave state which is topologically non-trivial and a natural platform for realizing Majorana edge modes$^{2,3}$. Triplet pairing is however rare in solid state systems and so far, no unambiguous identification has been made in any bulk compound. Since pairing is most naturally mediated by ferromagnetic spin fluctuations, uranium based heavy fermion systems containing f-electron elements that can harbor both strong correlations and magnetism are considered ideal candidate spin-triplet superconductors$^{4-10}$. In this work we present scanning tunneling microscopy (STM) studies of the newly discovered heavy fermion superconductor, UTe$_2$ with a $T_{sc}$ of 1.6 K$^{11}$. We find signatures of coexisting Kondo effect and superconductivity which show competing spatial modulations within one unit-cell. STM spectroscopy at step edges oriented at 0°- and 45° with respect to the a-axis show signatures of chiral in-gap states, predicted to exist on the boundary of a topological superconductor, which have not been observed to date. Combined with existing data indicating triplet pairing, the presence of chiral edge states suggests that UTe$_2$ is a strong candidate material for chiral-triplet topological superconductivity.
Uranium-based heavy fermion compounds such as UPt$_3$$^{12}$, UGe$_3$$^{13}$, URhGe$^{14}$, and UCoGe$^{15}$ are fertile ground for unconventional superconductivity since the coexistence of magnetism and superconductivity in these materials makes them ideal candidates for realizing spin-triplet pairing$^{4-10}$. However, having an extremely low superconducting (SC) transition temperature $T_{sc}$ and a SC phase that is either buried deep within the ferromagnetic phase or appears only under high pressure has hampered a deeper investigation of the nature of the SC order parameter in these systems$^{10}$. Recently, superconductivity with a transition temperature $T_{sc} = 1.6K$ was discovered in the heavy fermion Kondo system, UTe$_2$$^{11}$. The experiments report several striking properties$^{11,16-19}$: a $^{125}$Te Knight shift in nuclear magnetic resonance measurements which is temperature independent across $T_{sc}^{11}$; the upper critical field ($H_{c2}$) largely exceeding the Pauli limit$^{11,16}$; two reentrant SC phases in very high magnetic field$^{17}$; and strong nearly critical ferromagnetic fluctuations$^{11,18,19}$. These striking observations suggest a spin-triplet pairing scenario. Moreover, the specific heat ($C/T$) drops only to about half of its normal state value in the SC state, independent of sample quality$^{11,16}$. The large residual Sommerfeld $\gamma$-coefficient has led to speculations of exotic nonunitary pairing. The discovery of superconductivity in UTe$_2$ presents a novel candidate system to study spin-triplet superconductivity and its interplay with the Kondo effect, and potentially provides a unique opportunity to observe the long-sought chiral Majorana modes predicted to exist on the surfaces of chiral spin-triplet superconductors.

In this work we report a microscopic investigation of UTe$_2$ by scanning tunneling microscopy/spectroscopy (STM/STS), which reveals strong evidence for chiral spin-triplet pairing symmetry. UTe$_2$ crystallizes into an orthorhombic structure with a space group $I\text{m}m\text{m}$ (No. 71)$^{20,21}$. After considering the bond distance between U, Te1, and Te2 (Fig.1a and Extended Data Fig. 1), one easy-cleave surface is the (011) plane. As seen from the top view, the (011) plane consists of chains of both Te1 and Te2, as well as U-atoms along the [100] direction. Consequently, both Te2 and Te1 are visible in the STM topography (see Fig. 1b) and form one dimensional (1D) chains along the $a$-axis. In this cleave plane, the Te1 rows are slightly higher than the Te2 rows (Te2 being 6.5 pm below the Te1 layer), which is seen in the topography as alternating rows of bright and dark chains.

Since the normal state of UTe$_2$ is a heavy fermion metal, our first task is to look for signatures of the underlying Kondo effect. Figure 1c shows an averaged $dI/dV$ spectrum obtained on a clean surface. In addition to an overall V-shape in the LDOS that extents up to few hundred meV (Extended Data Fig. 2), we observe a peak-dip feature with the peak position around -6 mV. The lineshape of the peak-dip feature is reminiscent of Fano line shapes observed in STM data on a single Kondo impurity$^{22}$. However, as with other heavy fermion materials, UTe$_2$ constitutes a Kondo lattice system, developing a nearly flat band of almost localized heavy quasiparticle states near $E_F$ at low temperatures, with a coherence temperature of roughly 30 K$^{19}$. This nearly localized band is likely responsible for the resonance feature$^{23}$ shown in Fig. 1c. A more detailed analysis of the resonance line shape is included later in this paper as well as in the Extended Data.
Fig. 3. Similar features have been observed in YbRh$_2$Si$_2$\textsuperscript{24}, CeCoIn$_5$\textsuperscript{25}, and SmB$_6$\textsuperscript{26}, which have been interpreted in terms of a Kondo lattice peak.

Zooming into a much smaller, 1 meV, energy range, we observe the suppression of the LDOS with symmetric coherence peaks located around ±0.25meV, as shown in Fig. 1d. We associate this feature with the SC gap, as it is suppressed upon approaching the upper critical field ($H_{c2}$) in magnetic fields (Extended Data Fig. 4), which clearly connects it with superconductivity. However, the tunneling conductance does not go to zero as would be expected for a fully -gapped superconductor, but instead shows the presence of a rather large density of gapless excitations. By comparing the spectra to other materials with a similar $T_{sc}$ we can show that the residual LDOS at zero bias is too large to be ascribed to a thermal smearing effect (Extended Data Fig. 4). The large residual density of states is also confirmed by spectra obtained with a SC tip. By inserting a normal tungsten tip into the sample, we can pick up a small flake of SC UTe$_2$. The resulting superconductor-insulator-superconductor tunnel junction doubles the observed gap size in the $dI/dV$-spectrum (blue curve in Fig. 1d). Still, ~50% to 60% of the LDOS at zero bias remains. This residual density of states may arise both due to a background density of unpaired electrons as well as due to low-energy quasiparticle excitations. While a nonunitary pairing state\textsuperscript{11} or a hidden order\textsuperscript{16} may be invoked to explain a remnant density of unpaired electrons, there is another intriguing possibility that could generate states inside the SC gap. Similar to proposals for candidate spin- triplet superconductors UPt$_3$\textsuperscript{27,28} and Sr$_2$RuO$_4$\textsuperscript{29,30}, chiral dispersing surface states (also known as chiral surface Andreev bound states\textsuperscript{3}) with sub-gap energies are constrained to exist by topology in superconductors with a non-zero Chern number\textsuperscript{31-33}. The experimental signature of such chiral surface states would be a non-vanishing DOS inside the SC gap. We will revisit this possibility later.

A distinct property of strongly correlated materials is the fierce competition between various interactions, especially in the quantum critical regime\textsuperscript{34}. UTe$_2$ is believed to be located in the vicinity of a quantum critical point as evidenced by the critical scaling of the magnetization\textsuperscript{11}. Unlike other uranium-based superconductors, UTe$_2$ exhibits a paramagnetic ground state hosting both strong ferromagnetic fluctuations and Kondo coupling\textsuperscript{18,19}. Utilizing STM, we can directly image the competition or coexistence of different order parameters in real space. Figure 2d and 2e show line cuts across the surface from Te1 to Te2 in the energy range of the Kondo resonance and the SC gap, respectively. We find that both the Kondo lattice peak and SC gap show real space modulations within the unit cell. $dI/dV$ maps at -6 mV and 0 mV (Fig. 2 b and c) affirm that these periodic modulations are a general feature of this system. Intriguingly, a comparison between Fig. 2 a, b, and c indicates that while the modulation wave vectors of the LDOS at -6 mV and 0 mV are locked to the atomic structure of Te chains, the height of the peak we attribute to the Kondo resonance and the depth of the SC gap are anticorrelated.
To further characterize the behavior of the Kondo resonance, we fit the peak-dip feature by a Fano lineshape\(^{35}\):  
\[
dJ/dV(V) \propto \frac{((V+E_0)/\Gamma+qK)^2}{1+((V+E_0)/\Gamma)^2}
\]  
This formula describes tunneling between a localized many-body states at \(E_0\) and an itinerant continuum, where \(\Gamma\) is proportional to the width of the Kondo resonance and \(qK\) is the Fano parameter. The results of fitting presented in Table S1 reveal a monotonic decrease of \(|qK|\) from Te1 to Te2 sites, suggesting that the Kondo coupling is much stronger on the Te1 site than on the Te2 site. This seems natural since the nearest U-Te1 distance is shorter than U-Te2 distance, so the coupling to the U \(f\)-electrons is stronger for the Te1 sites. A similar spatial modulation of the Kondo resonance was also observed in \(\text{URu}_2\text{Si}_2\), and thought to be connected with the unsolved mystery of the “hidden order” phase\(^{36,37}\). Interestingly, while the strength of the Kondo resonance is reduced from Te1 chains to Te2 chains, the magnitude of the SC gap, \(\Delta\), is enhanced by about 2.5 times (Extended Data Fig. 5). A short-range modulation of the SC gap in zero magnetic field is rarely observed, except in the case of a pair density wave (PDW) in cuprate superconductors such as \(\text{La}_{2-x}\text{Ba}_x\text{CuO}_4\)\(^{38}\) and \(\text{Bi}_2\text{Sr}_2\text{CaCuO}_{8+x}\)\(^{39}\). However, since the gap modulation does not break any of the lattice symmetries it is not in line with the typical scenario of a spontaneous PDW, which leaves the origin of these intra-unit cell SC gap modulations and its connection to the Kondo resonance as open questions for future work.

Our next step it to elucidate the nature of the SC order parameter in \(\text{UTe}_2\). To do this we exploit the possibility that step edges could provide crucial information on the pairing symmetry of unconventional superconductors. Our \(dI/dV\) measurements at single step edges along the \(a\)-axis (Fig. 3d and e) reveal spectra with unusual asymmetric lineshapes (Fig. 3g and h); a peak-dip feature that conspicuously breaks the particle-hole (p-h) symmetry expected for Bogoliubov quasiparticles. As shown in Fig. 3g and h, the asymmetric resonance can appear either above or below the \(E_F\), depending only on the orientation of the step edge. To describe this apparently “chiral” phenomenon, we classify the single step edges using the vector normal to the side surface of the step. Step edges with a normal in the [01-1] direction may be classified as \(n\)-type (corresponding spectra color coded in blue) and those with a opposite normal vector as \(p\)-type (spectra color coded in red) (see Fig. 3a and b). Let us now consider two pairs of step edges on two distinct surfaces as shown in Fig. 3d and e. The topology of the two surfaces is clearly different with one hosting a terrace in the middle (Fig. 3d) and the other a trench (Fig. 3e). Regardless of this difference, as the data show, it is the direction of the normal to the step edge that determines the lineshape. On \(n\)-type step-edges (blue curves), a peak is seen below \(E_F\) at \(E_{\Delta_n} = -0.2\) mV, while \(p\)-type step-edges (red curves) show peaks at \(E_{\Delta_p} = +0.2\) mV.

Additional data show that these resonances are intimately tied to superconductivity. First, as shown in Fig. 4a, the peak like features on the \(p\)- and \(n\)-type edges occur inside the SC gap at symmetric energies above and below \(E_F\). Second, our temperature dependence measurements (Fig. 4b) show that the resonance attenuates steadily with increasing temperature, disappearing just below \(T_c\). As shown in Extended Data Fig. 6, this behavior cannot be attributed to thermal smearing. First, simple thermal smearing of the 300 mK data would produce an attenuated but
robust peak at 1.5 K, while our peak disappears at 1.5 K. Second, thermal smearing would cause the peak position to shift to higher energies. However, the peak position in our data stays constant or even slightly decreases with temperature. This translates into a peak position that moves to lower energies at higher temperatures which is consistent with a shrinking SC gap. The resonance is thus an in-gap state existing only in the SC phase.

The connection to superconductivity is further demonstrated, by studying the evolution of the resonance in a magnetic field. $dI/dV$ maps along the step edges are shown in figure 4d. The maps reveal that the resonances become steadily weaker upon application of a magnetic field and become difficult to detect at 10T (Fig. 4d) below $H_{c2}$\textsuperscript{17}. These combined data indicate that the resonances can be identified as in-gap bound states, which are sensitive to the phase of the SC order parameter\textsuperscript{32}. Additionally, from data on more than 20 step edges, we determine that the microscopic details of the step edge such as its termination at Te1 or Te2 or the step edge density (Extended Data Fig. 7 and 8) do not affect the bound state asymmetry, which is solely controlled by the direction (n- or p-type) of the step edge as discussed earlier. The universal behavior of the resonances indicates that the asymmetry is not controlled by local properties that depend on microscopic details. The switch from $E_h$ to $E_p$ for n- and p-type step edges thus dictates that the SC order parameter must have a vector associated with it, which means that superconductivity in UTe\textsubscript{2} must have a complex chiral order parameter like the well-known $p+ip$ SC state\textsuperscript{46}.

While this in itself is a significant finding, the deviation from $p$-$h$ symmetry of the in-gap states provides further insights on the SC state. In general, the integrated density of states in a superconductor preserves $p$-$h$ symmetry for in-gap energies, even though the relative intensities of the resonances may be different (see Supplementary Text 2 for a discussion on Yu-Shiba states). The observed asymmetry is thus remarkable and as we will see in the following discussion, imposes even stronger constraints on the order parameter.

The expected $p$-$h$ symmetry in a superconductor suggests two possible explanations for the asymmetry using mechanisms that involve the tunneling process. A kinematic picture based on symmetry considerations is shown schematically in Extended Data Fig. 9. To explain the data, we consider the surface of a chiral $p$-wave superconductor (topological superconductor). The surface of such a superconductor is expected to host topologically protected surface states with a dispersion such that states with opposite momenta (along a certain direction within the surface plane) necessarily have opposite energies\textsuperscript{3,40,41} (Extended Data Fig. 9b). As theoretically discussed by Kobayashi et. al\textsuperscript{42}, such surface states are constrained to exist for all directions of the chiral axis, except when it is parallel to the surface normal. Tunneling into these surface states at locations far from a step edge (which averages over all momentum directions) would give a $p$-$h$ symmetric spectrum with a finite density of states inside the SC gap as we observe. The step edges however break reflection symmetry in a way to allow preferential tunneling into states with positive or negative momenta (Extended Data Fig. 9c). Depending on the direction of the normal to the step edges this momentum selectivity would probe energy states below or above
$E_r$ thus giving rise to peaks above or below $E_r$ as seen in our data. Note that this scenario only works for chiral states where the sign of the momentum is tied to the sign of the energy.

Another possibility is that the asymmetric line shapes represent Fano resonances of chiral Andreev bound states (ABS)\textsuperscript{43} at the step edges of an unconventional superconductor (Supplementary Text 1). The Fano lineshape would represent tunneling into the localized in-gap ABS interfering with a continuum that may arise either from nodal quasiparticles (if a node exists) or from the normal electrons in this system that do not participate in superconductivity. Fitting the resonance to a Fano lineshape reveals that the energy of the ABS are within error close to zero bias (Extended Data Fig. 10). The two in-gap bound states only differ by the sign of the Fano parameter $q \propto \frac{\langle \Phi | T | i \rangle}{\langle \psi | T | i \rangle}$, where the numerator and denominator represent tunneling into the localized states and the continuum, respectively. The fittings yield $q \approx \pm 1$ for $p$-type ($n$-type) step edges. From the definition of $q$, a sign change in $q$ requires a $\pi$-phase shift between the ABS wavefunctions on the two step edges. To obtain this phase shift, we invoke a chiral superconductor with its chiral axis along the surface normal. As seen in figure 4e, in this case there is a $\pi$-phase shift between the incoming Cooper pairs for $p$- and $n$-step edges, which directly determines the relative phase of the resulting ABS on the two step edges, which in turn determines the sign of the Fano parameter.

Keeping these two scenarios in mind, we measure the LDOS at step edges oriented at $\sim 45^\circ$ with respect to the $a$-axis (Fig. 3 f,i) which show a nearly symmetric zero-bias-voltage peak. This zero-bias feature is robust and is observed all along the edge as shown in Fig. 3i. Within the Fano scenario, the data demonstrate the existence of zero-bias ABS on both diagonal- and parallel-step edges, indicating that a $\pi$-phase shift occurs in the SC order parameter at step edges oriented at both $0^\circ$- and $45^\circ$ with respect to the $a$-axis. These observations exclude $s$- and $d$-wave pairing symmetry\textsuperscript{44,45}. $S$-wave pairing cannot generically provide zero-bias ABS. For the $d$-wave order parameter (Supplementary Text 2 and Extended Data Fig. 11), zero-bias ABS would appear for step edges oriented in the direction of one of the gap nodes but should disappear when the step-edge is rotated by $45^\circ$. Within the Fano scenario therefore, our data are most consistent with a chiral complex order parameter of the $p+i\sigma$ type\textsuperscript{46}. The zero bias resonance is also consistent with the momentum selective tunneling scenario. Step edges in other directions with respect to the $a$-axis should necessarily show a different lineshape since the preferentially tunneling conditions would change.

Both scenarios explaining the phenomenology of the asymmetric in-gap resonances require a chiral order parameter of the $p+i\sigma$ type which would give rise to chiral dispersing surface/edge states. The difference between them is essentially a choice of the direction of the chiral axis\textsuperscript{42}. In the Fano scenario, the chiral axis is along the surface normal while in the kinematic momentum selective tunneling scenario, the chiral axis can be in any direction but the normal. We note that
further identification of the exact form and orientation of the chiral order parameter requires a deeper theoretical analysis based on the crystal symmetry, spin-orbital coupling, and magnetism.

Our data on UTe$_2$ show many intriguing features in this heavy fermion superconductor which suggest a highly unusual SC state. The anti-correlated intra unit-cell modulation of the Kondo resonance and superconductivity is an indication of competing interactions in the quantum critical region and further theoretical modeling is needed to understand the origins and full implications. The step edge data provide strong evidence for the presence of chiral modes existing inside the SC gap which are theorized to occur on the surfaces/edges of topological superconductors. In combination with the temperature independent Knight shift across $T_{sc}$, very large upper critical field of $\sim 40$ T, and evidence for ferromagnetic fluctuations, our data are most consistent with UTe$_2$ being a triplet-chiral superconductor. Since chiral symmetry is linked to time reversal symmetry in a superconductor, the next step is to look for broken time-reversal symmetry in the SC state of UTe$_2$. 
Methods

Single crystals of UTe$_2$ were synthesized with the chemical vapor transport method using iodine as the transport agent. Elements of U and Te with atomic ratio 2:3 were sealed at one end of an evacuated quartz tube, together with 3 mg/cm$^3$ iodine. The ampoule was gradually heated up and hold in the temperature gradient of 1060/1000 °C for 7 days, with source materials at the hot end. It was then furnace cooled to the room temperature, and mm size crystals were accumulated at the other end. The crystal orientation was determined by Laue diffraction. Samples were all cleaved in situ at ~77 K and in ultra-high vacuum chamber. After cleaving, sample are directly transferred to the STM. All STM measurements were performed below 4 K using annealed tungsten tips. STS spectra were collected using a standard lock-in technique at a frequency of 913 Hz.

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**Figure 1**

**Crystal structure and spectroscopic properties of UTe$_2$**.  

**a**, Unit cell of UTe$_2$. Our data reveal that the (011) plane is the easy-cleave plane. **b**, STM topography of the exposed (011) plane of UTe$_2$. Te1-chains (bright dots) and Te2-chains (dim dots) can be distinguished. The inset shows the position of Te1 and Te2 atoms. **c**, $dI/dV$-curve of UTe$_2$ showing the Kondo resonance ($I_{\text{set}}=150$ pA, $V_b=50$ mV). A typical asymmetric Fano lineshape is observed, the black arrow marks the Kondo lattice peak at -6 mV. The inset sketches the cotunneling effect which gives rise to the Fano lineshape. **d**, $dI/dV$-curve taken within a small bias voltage range showing the superconducting gap. The red and blue curves were obtained with a normal tungsten-tip (W-tip) and tip with UTe$_2$ flake, respectively. Spectra are measured at 0.3K, 0 Tesla. ($I_{\text{set}}=50$ pA, $V_b=2$ mV, $V_{\text{mod}}=60$ $\mu$V).
**Figure 2**

**Intra-unit cell spatial modulation of Kondo resonance and superconductivity.**

- **a**: 2x4 nm$^2$ topography of UTe$_2$.
- **b, c**: $dI/dV$-map in the same area as topography at -6 mV (b) and 0 mV (c).
- **d, e**: $dI/dV$-curves measured at the points denoted in a. Inset to d shows the experimental data (dots) and the corresponding fits to Fano lineshapes (black dashed line). The black dashed lines in e are fittings to Dynes function. Detailed information on the fit parameters is included in the extended data.
Figure 3

“Chiral” in-gap bound states in UTe$_2$. a-c, Schematic of surfaces with a terrace, a trench, and a diagonal step-edge (oriented at 45° with respect to the $a$-axis). $n$-type and $p$-type step-edges are defined in the figures. d-f, Topographies of UTe$_2$ with terrace, trench and 45° step-edge. The length of the yellow scale bar is 4 nm. The linecuts of the topographies are shown below and reveal step heights of 5.5 Å corresponding to single-steps. g-i, $dI/dV$ spectra measured at the positions marked by dots in the topographies. The dashed lines mark the peak positions. Curves are equally shifted for clarity. Data sets were obtained at 0.3 K and zero field.
Figure 4 | Phenomenology of in-gap states and connection to superconductivity. a, A comparison of the \( \text{d}I/\text{d}V \)-curve obtained on a clean surface (green dashed line), \( n \)-type (blue curve) and \( p \)-type (red curve) step-edge. b, Temperature dependent \( \text{d}I/\text{d}V \)-curves measured on the \( n \)-type step-edge. c, topography of UTe\(_2\) surface (35x10 nm\(^2\)) with a wide trench. d, magnetic field dependent \( \text{d}I/\text{d}V \)-maps on this area are measured from 0T to 10T. The maps shown depict the density of states differences between positive and negative bias voltages at each location, i.e., \( \text{d}I/\text{d}V(r,V_0)-\text{d}I/\text{d}V(r,-V_0) \) with \( V_0 = 0.2 \) mV. The successive maps at higher fields show that the “chiral” bound states gradually disappear with increasing magnetic field. e Illustration of ABS forming at the step edge of an isotropic chiral \( p \)-wave superconductor. The color ring represents the SC phase in momentum space. Andreev reflection (AR) and normal reflection (NR) are depicted around the step edge. The schematic illustrates the phase shift between the incoming Cooper pairs for \( p \)- and \( n \)-step edges.