

Resonance from antiferromagnetic spin fluctuations for superconductivity in UTe_2

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Superconductivity originates from the formation of bound (Cooper) pairs of electrons that can move through the lattice without resistance below the superconducting transition temperature T_c (ref. ¹). Electron Cooper pairs in most superconductors form anti-parallel spin singlets with total spin $S = 0$ (ref. ²), although they can also form parallel spin-triplet Cooper pairs with $S = 1$ and an odd parity wavefunction³. Spin-triplet pairing is important because it can host topological states and Majorana fermions relevant for quantum computation^{4,5}. Because spin-triplet pairing is usually mediated by ferromagnetic (FM) spin fluctuations³, uranium-based materials near an FM instability are considered to be ideal candidates for realizing spin-triplet superconductivity⁶. Indeed, UTe_2 , which has a $T_c \approx 1.6$ K (refs. ^{7,8}), has been identified as a candidate for a chiral spin-triplet topological superconductor near an FM instability^{7–14}, although it also has antiferromagnetic (AF) spin fluctuations^{15,16}. Here we use inelastic neutron scattering (INS) to show that superconductivity in UTe_2 is coupled to a sharp magnetic excitation, termed resonance^{17–23}, at the Brillouin zone boundary near AF order. Because the resonance has only been found in spin-singlet unconventional superconductors near an AF instability^{17–23}, its observation in UTe_2 suggests that AF spin fluctuations may also induce spin-triplet pairing²⁴ or that electron pairing in UTe_2 has a spin-singlet component.

In conventional Bardeen–Cooper–Schrieffer (BCS) superconductors, electron–lattice coupling binds electrons into spin-singlet pairs below T_c without involving magnetism¹. In most unconventional superconductors, the proximity of superconductivity to static AF ordered states suggests AF spin fluctuations as a common thread that can pair electrons into spin singlets for superconductivity². For spin-triplet candidate heavy-fermion superconductors such as UGe_2 , URhGe and UCoGe , superconductivity arises through suppression of the static FM order or coexists with static FM order⁶. In unconventional spin-singlet superconductors, the resonance is a sharp magnetic excitation near an AF ordering wavevector in the superconducting state that peaks at a well defined energy E_r and an intensity that tracks the superconducting order parameter^{25,26}. Within the weak-coupling theory of superconductivity, the resonance is a bound state inside the particle–hole continuum gap, referred to as a spin exciton, that arises from quasiparticle excitations that connect parts of the Fermi surfaces exhibiting a sign change in the superconducting order parameter ($\Delta(\mathbf{k}) = -\Delta(\mathbf{k} + \mathbf{Q})$, where $\Delta(\mathbf{k})$ is the momentum ($\mathbf{k}$)-dependent superconducting gap and $\mathbf{Q}$ is the momentum transfer connecting the two gapped Fermi surfaces)^{2,25}. In this picture, the energy of the resonance is below the sum of the energies of the superconducting gaps of the two connecting Fermi surfaces, and its wavevector dependence contains signatures of the superconducting gap symmetry^{2,25}.

For uranium-based heavy-fermion superconductors near an FM instability⁶, although previous INS experiments have found FM spin

fluctuations, there is no evidence that these fluctuations are coupled to superconductivity^{27,28}. Similarly, although incommensurate and FM spin fluctuations were found in the spin-triplet candidate superconductor Sr_2RuO_4 , they do not couple to superconductivity, and therefore suggest that spin fluctuations alone are not sufficient to induce spin-triplet superconductivity^{29,30}. These results are consistent with nuclear magnetic resonance (NMR) Knight-shift measurements that indicate that superconductivity in Sr_2RuO_4 cannot arise from a pure spin-triplet pairing state³¹. Finally, for the spin-triplet superconductor candidate UPt_3 (ref. ³²), superconductivity appears to couple to very weak static AF order instead of to FM spin fluctuations³³. Therefore, there is no experimental evidence that superconductivity is coupled to FM spin fluctuations in any of these spin-triplet candidate materials^{27–33}.

We chose to study spin excitations in UTe_2 using INS because this technique can probe both FM and AF spin fluctuations and the effect of superconductivity on these excitations (Fig. 1a, b)¹⁹. UTe_2 sits at the paramagnetic end of a series of FM heavy-fermion superconductors^{7,8}, and is believed to be a spin-triplet superconductor for the following reasons: (1) Upper critical fields H_{c2} that exceed the Pauli limits along all crystallographic directions^{9,10}; (2) Muon spin relaxation/rotation measurements of coexisting FM spin fluctuations and superconductivity¹¹; (3) Scanning tunnelling microscopy evidence of chiral-triplet topological superconductivity¹²; (4) Exclusion of spin-singlet pairing from the ¹²⁵Te Knight-shift reduction below T_c measured by NMR¹³; and

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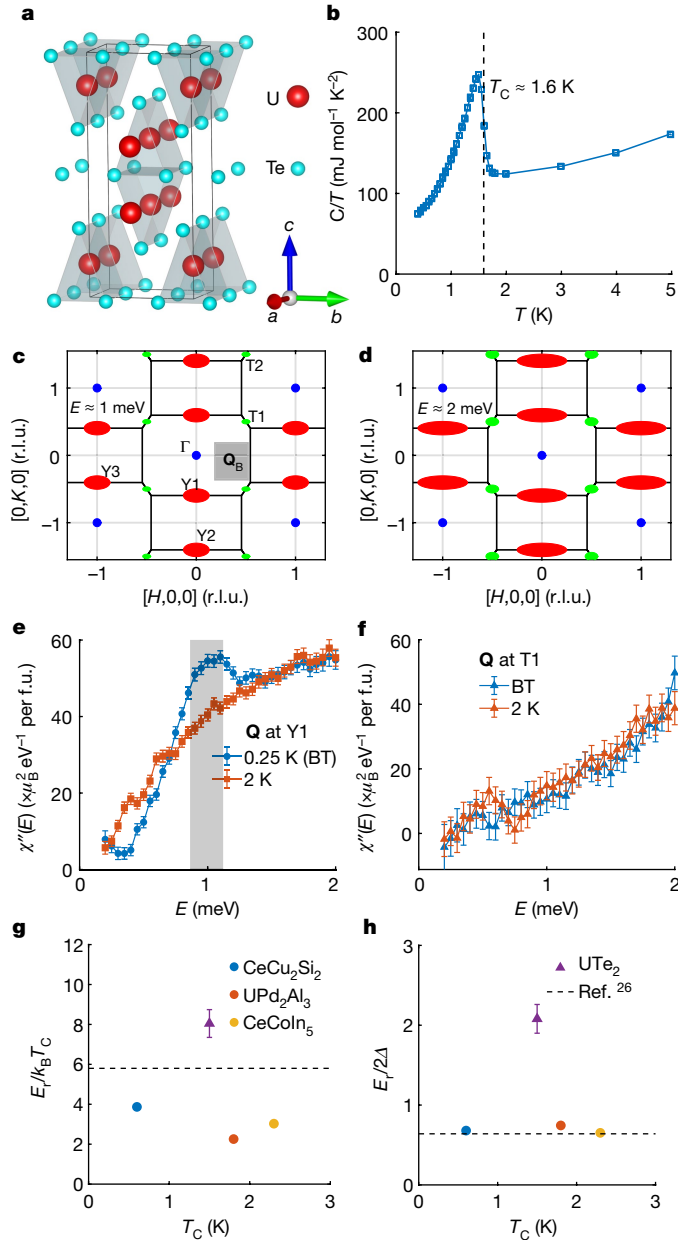


Fig. 1 | Crystal structure, heat capacity and a summary of INS results.

a, The crystal structure of UTe_2 . **b**, The heat-capacity data plotted as a function of temperature. A clear jump is observed at $T_c \approx 1.6$ K. **c, d**, Schematic plots of the INS pattern in the $[H, K, 0]$ plane at $E = 1$ meV (**c**) and $E = 2$ meV (**d**). Brillouin zones are marked with solid black lines, and the Γ points are marked with blue dots. Spin excitations are observed at high-symmetry points at Brillouin zone boundaries. The excitations at $Y1$ ($K = 0.59, H = 0$) and its symmetry-equivalent positions (red ellipses; $Y2$ is at $K = 1.41$) are coupled to superconductivity, as shown in **e, f**, $\chi''(E)$, where the data taken at BT and 2 K are integrated in a box of $H: \pm 0.12, K: \pm 0.18, L: \pm 0.5$ reciprocal lattice units (r.l.u.) at the $Y1$ position with an E step of 0.05 meV. A background taken at Q_B is subtracted from the integrated data to remove the incoherent scattering before making the Bose factor correction. Q_B has the same $|Q|$ as $Y1$ and is away from nuclear Bragg peaks and phonon modes. The background integration range is $H: [0.22, 0.58], K: [-0.27, 0.27], L: [-0.75, 0.75]$ r.l.u., as marked in **c** with the shaded box. **f**, $\chi''(E)$ at the $T1$ position is plotted for comparison with **e**; it does not couple to superconductivity. **g, h**, Comparison of the resonance energy of UTe_2 (this work) and its ratio to the superconducting energy gap¹² with other heavy-fermion superconductors: CeCu_2Si_2 ²³, UPd_2Al_3 ²⁰, CeCoIn_5 ^{22,35} and the universal relationship summarized in ref. ²⁶. The vertical error bars in **e, f** represent statistical errors of 1 standard deviation. The vertical error bars in **g** and **h** represent uncertainty in $E_r/k_B T_c$ and $E_r/2\Delta$, respectively.

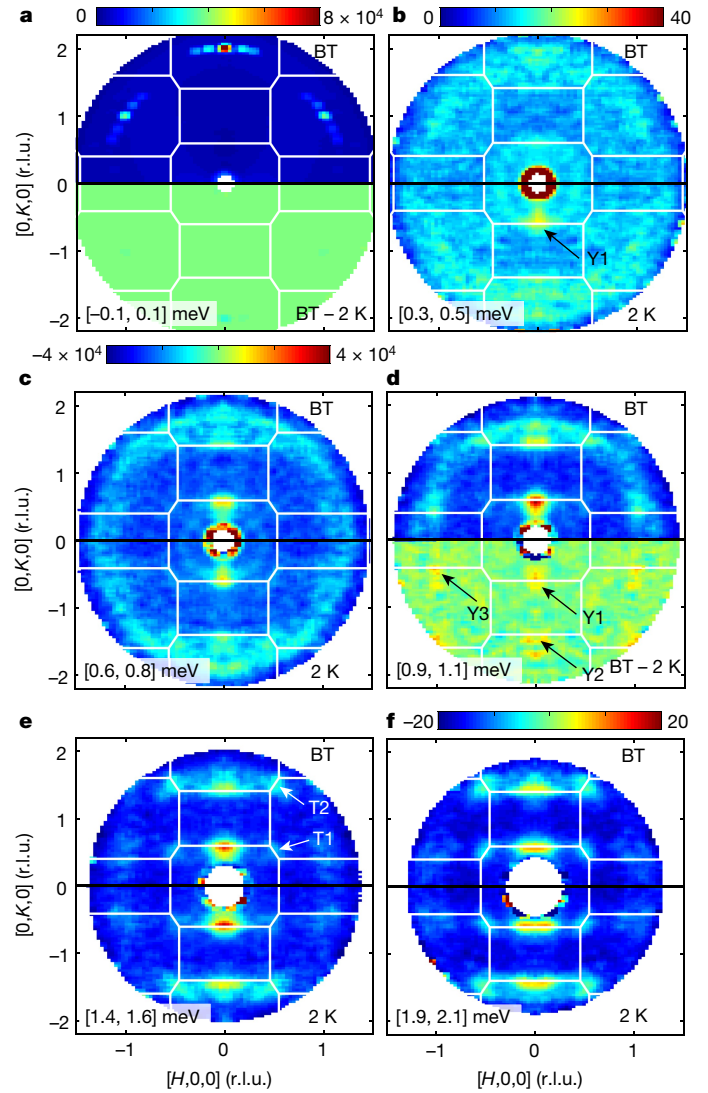


Fig. 2 | The wavevector, energy and temperature dependence of the scattering function $S(\mathbf{Q}, E)$ in the $[H, K, 0]$ plane. **a–f**, Constant-energy cuts of the symmetrized $S(\mathbf{Q}, E)$ with $E_0 = 3.32$ meV in the elastic channel, $E = 0 \pm 0.1$ meV (**a**); 0.4 meV (**b**); 0.7 meV (**c**); 1.0 meV (**d**); 1.5 meV (**e**); and 2.0 meV (**f**). Unsymmetrized raw data are available in Extended Data Fig. 4. The bin size is 0.035 r.l.u. along both the H and K directions. The integration range is ± 0.2 r.l.u. in L , and ± 0.1 meV in E . In each subplot, the upper panel shows data taken at BT. For **a** and **d**, the lower panel shows the subtraction of data taken at BT and 2 K. For **b, c, e** and **f** the lower panel shows data taken at 2 K. Brillouin zones are marked with solid white lines. High-symmetry positions at the Brillouin zone boundaries ($Y1, Y2, Y3, T1, T2$) are marked with arrows in **b, d** and **e**. In Figs. 2, 3, 4a–d, the unit of the colour bars is $(\frac{1}{2}g\gamma_n r_0)^{-2}$ mbarn meV^{-1} per Sr per f.u., where $g = 2$, and $\frac{1}{2}g\gamma_n r_0 = 2.695 \times 10^{-15}$ m ($\gamma_n = 1.91$, and $r_0 = 2.818 \times 10^{-15}$ m is the classical radius of the electron). The colour bars above and below **a** are for the upper and lower panel of **a**, respectively. The colour bar for **b, c**, upper panel **d, e**, and **f** is shown in **b**. The colour bar in lower panel **d** is shown below **d**.

(5) Breaking of time-reversal symmetry below T_c from a non-zero polar Kerr effect and evidence for two superconducting transitions in the specific heat¹⁴. Although these reasons provide circumstantial evidence for spin-triplet superconductivity, they are not conclusive proof that superconductivity in UTe_2 must be in a pure spin-triplet p -wave state. For example, although time-reversal symmetry breaking is seen by a non-zero Kerr effect, it is not confirmed by muon spin relaxation/rotation measurements; however, reasons why this might not have been visible have been discussed^{11,14}. Moreover, interpretation of the Knight-shift data from NMR measurements can be ambiguous because

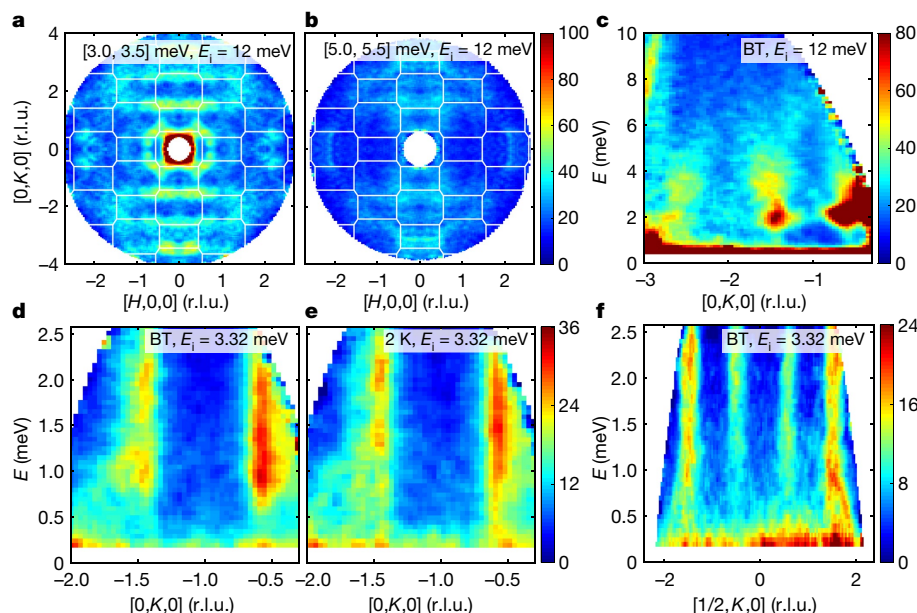


Fig. 3 | The wavevector and energy dependence of the scattering below and above T_c . **a, b**, Constant-energy cuts of the symmetrized scattering function $S(\mathbf{Q}, E)$ with $E_i = 12$ meV at $E = 3.25$ meV (**a**) and 5.25 meV (**b**) at BT. Brillouin zones are marked with solid white lines. Unsymmetrized raw data are available in Extended Data Figs. 5–6. The bin size is 0.04 r.l.u. along both the H and K directions. The integration range is ± 0.2 r.l.u. in L , and ± 0.25 meV in E . **c**, E – $\mathbf{Q}$ plot of $S(\mathbf{Q}, E)$ at $H = 0$ with $E_i = 12$ meV at BT. The integration range is ± 0.2 r.l.u. in H and ± 0.3 r.l.u. in L , the bin size along the K direction is 0.04 r.l.u., and the

E step is 0.1 meV. The flat band near $E = 2$ meV is due to multiple scattering from the sample environment with $E_i = 12$ meV, and is absent in data with $E_i = 3.32$ meV. **d–f**, E – $\mathbf{Q}$ plots of $S(\mathbf{Q}, E)$ with $E_i = 3.32$ meV, with $H = 0$ at BT (**d**), $H = 0$ at 2 K (**e**), and $H = 1/2$ at BT (**f**). The integration range is ± 0.1 r.l.u. in H and ± 0.3 r.l.u. in L , the bin size along K is 0.035 r.l.u., and the E step is 0.05 meV. The two strong-intensity regions around 1.3 meV and 2 meV in **e** are statistical fluctuations; see cuts in Extended Data Fig. 7d, e, as they do not appear in the data with $E_i = 2.5$ meV in Extended Data Fig. 6f.

the NMR signal only probes within a London penetration depth of the surface and therefore may not reflect bulk behavior³⁴.

On the other hand, there are indications that UTe_2 is near an AF instability instead of an FM order^{15,16}. In particular, our previous INS experiments within the $[0, K, L]$ scattering plane of UTe_2 reveal spin fluctuations at the incommensurate wavevectors $\mathbf{Q} = (0, \pm(K + 0.57), 0)$ and $(K = 0, 1)$ not far away from the Brillouin zone boundary¹⁶. The magnetic scattering is centered around $L = 0$ and dispersionless along the L direction, suggesting that spin fluctuations in UTe_2 are two dimensional in the $[H, K, 0]$ plane (Fig. 1c, d). Nevertheless, there is no evidence that they are coupled to superconductivity¹⁶.

Experimental data

Here we use INS to map out the spin excitations in UTe_2 in the $[H, K, 0]$ plane and show that superconductivity induces a resonance near the AF wavevector at an energy $E_r = 7.9k_B T_c$ (k_B , Boltzmann constant) and opens a spin gap at energies below the mode, analogous to what occurs in unconventional spin-singlet superconductors^{17–23}. Figure 1a shows the orthorhombic unit cell of UTe_2 (space group $Immm$)⁷. The bulk superconductivity of our samples is confirmed by heat-capacity measurements showing $T_c \approx 1.6$ K (Fig. 1b). Figure 1c shows Brillouin zones in reciprocal space within the $[H, K, 0]$ plane, where solid red ellipses (Y1, Y2, Y3) and green dots (T1, T2) are positions of spin excitations as a function of increasing energy (Fig. 1d). The blue solid dots are Γ points and nuclear Bragg peaks are at $(\pm 1, \pm 1)$. The energy dependence of the imaginary part of the local dynamical susceptibility $\chi''(E)$ near Y1, defined as $\chi''(E) = \int_{\text{BZ}} \chi''(\mathbf{Q}, E) d\mathbf{Q} / \int_{\text{BZ}} d\mathbf{Q}$ within a Brillouin zone where E is the excitation energy¹⁹, above and below T_c reveals a clear resonance and a spin gap in the superconducting state (Fig. 1e). On the other hand, $\chi''(E)$ near T1 shows no observable changes across T_c (Fig. 1f). Figure 1g, h compares the energy of the resonance mode with unconventional spin-singlet superconductors²⁶, indicating that the mode deviates from the current trend for these materials.

Figure 2a–f shows the wavevector dependence of elastic and inelastic scattering in UTe_2 as a function of increasing energy at base temperature (BT = 0.25 K) and above T_c ($T = 2$ K). In the elastic channel, we find nuclear Bragg peaks at the $(0, -2, 0)$ and $(1, \pm 1, 0)$ positions and no evidence of magnetic order at BT (Fig. 2a, Extended Data Fig. 4a, b). On increasing the energy to $E = 0.4 \pm 0.1$ meV, there is clear scattering at the Brillouin zone boundary position (Y1 point) in the normal state that is suppressed at BT (Fig. 2b). Upon further increasing energies to $E = 0.7 \pm 0.1, 1.0 \pm 0.1, 1.5 \pm 0.1$ and 2.0 ± 0.1 meV, spin excitations are still well defined along the $[0, K, 0]$ direction at Y points but broaden progressively along the $[H, 0, 0]$ direction (Fig. 2c–f). In addition, we see clear magnetic scattering at T points of reciprocal space for energies above $E = 0.7 \pm 0.1$ meV (Fig. 2c–f). Although the spin excitation intensity increases below T_c at $E = 1.0 \pm 0.1$ meV for all equivalent Y points (Fig. 1d), they are virtually temperature independent across T_c at Y points for energies above 1.3 meV and at T points for all energies.

Figure 3a, b summarizes the evolution of spin excitations for energies above $E = 2.1$ meV at BT. At $E = 3.25 \pm 0.25$ meV, spin excitations are still well defined along the $[0, K, 0]$ direction but extend to the entire Brillouin zone boundary along the $[H, 0, 0]$ direction (Fig. 3a). Finally, at $E = 5.25 \pm 0.25$ meV, they become weak and diffusive, but still centre around the Brillouin zone boundary broadly along the $[H, 0, 0]$ direction (Fig. 3b). The $\mathbf{Q}$ – E map along the $[0, K, 0]$ direction reveals clear spin excitations stemming from Y points that disappear above 7 meV (Fig. 3c). The temperature dependence of the scattering along the $[0, K, 0]$ direction across T_c is shown in Fig. 3d, e, where the superconductivity-induced spin gap and resonance are observed at the Y1 and Y2 points. The broad dispersive scattering from the $(0, -2, 0)$ nuclear Bragg peak is due to a temperature-independent acoustic phonon¹⁶. Figure 3f shows the $\mathbf{Q}$ – E map along the $[0.5, K, 0]$ direction. We see clear rod-like magnetic scattering stemming from the T points in reciprocal space above $E = 0.5$ meV (Fig. 3f), but these excitations do not respond to superconductivity (Extended Data Fig. 7).

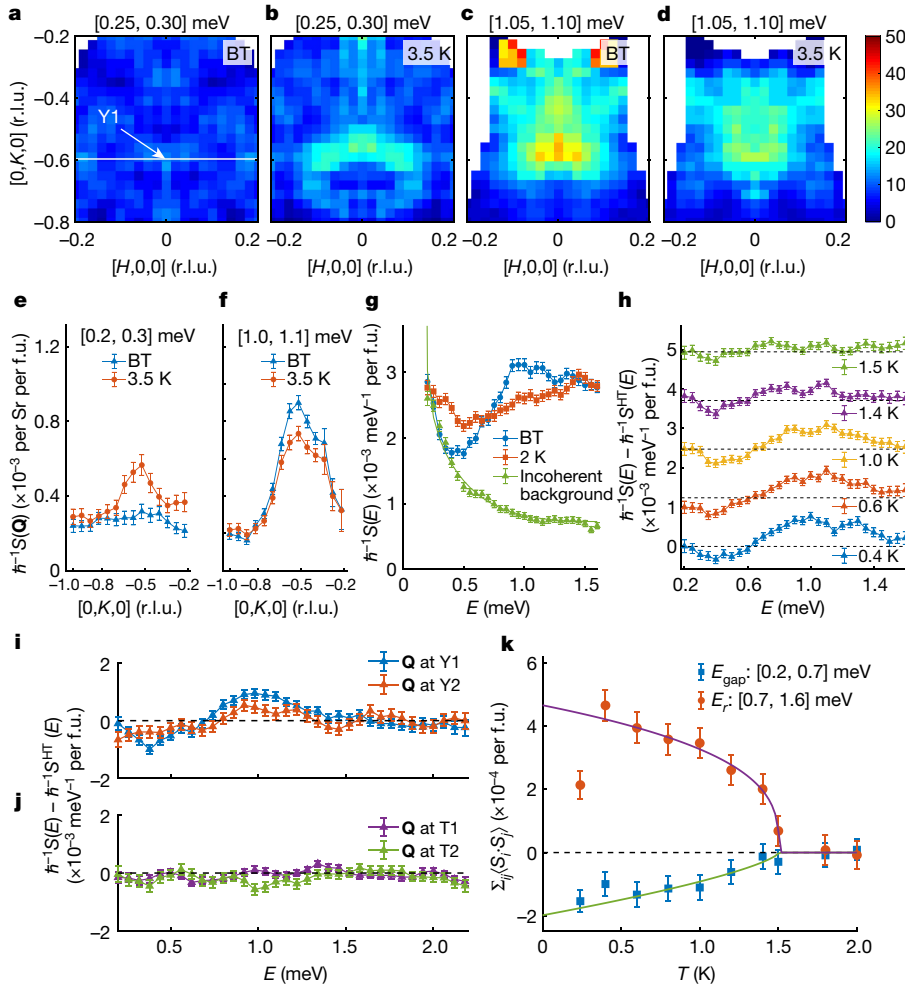


Fig. 4 | The wavevector, energy and temperature dependence of the scattering at Brillouin zone boundary points. **a–d**, Constant-energy cuts of the symmetrized scattering function $S(\mathbf{Q}, E)$ with $E_i = 2.5$ meV at $E = 0.25$ – 0.30 meV and BT (**a**); $E = 0.25$ – 0.30 meV and 3.5 K (**b**); $E = 1.05$ – 1.10 meV and BT (**c**); and $E = 1.05$ – 1.10 meV and 3.5 K (**d**). The bin size is 0.02 r.l.u. in H and 0.03 r.l.u. in K . The integration range is ± 0.3 r.l.u. in L . **e, f**, One-dimensional (1D) cuts of $S(\mathbf{Q})$ with $E_i = 2.5$ meV across Y1 along the K direction integrated in $E = 0.2$ – 0.3 meV (**e**) and $E = 1.0$ – 1.1 meV (**f**) at BT (blue triangles) and 3.5 K (red circles). The bin size is 0.06 r.l.u. in K . The integration range is ± 0.08 r.l.u. in H and ± 0.3 r.l.u. in L . **g**, 1D cuts of $S(\mathbf{Q})$ with $E_i = 3.32$ meV at Y1 along E at BT (blue circles) and 2 K (red squares). Incoherent background scattering integrated at $\mathbf{Q}_b$ is plotted in green triangles. **h**, 1D cuts of $S(\mathbf{Q})$ with high-temperature data ($S^{HT}(\mathbf{Q})$) subtracted. The cuts are taken at Y1 along E taken at 0.4 K (blue), 0.6 K (red), 1.0 K (yellow), 1.4 K (purple) and 1.5 K (green) with $E_i = 3.32$ meV. The high-temperature data are averaged over 1.8 K and 2 K data, both above T_c . Different temperature data in **h** are artificially shifted, with the dashed black line representing the base line for each temperature. The integration ranges in all the 1D cuts in **g, h** are: ± 0.1 r.l.u. in H , ± 0.15 r.l.u. in K , and ± 0.3 r.l.u. in L . The bin size in E is 0.05 meV. **i, j**, Temperature difference $S(E)$ at different Brillouin zone points. The integration is done around each Y and T point in a box of H : ± 0.1 , K : ± 0.15 , L : ± 0.3 r.l.u. with an E bin size of 0.06 meV. $E_i = 3.32$ meV. **k**, Magnetic scattering versus temperature at E_{gap} (blue squares) and E_r (red circles). The integration is done around Y1 in a box of H : ± 0.1 , K : ± 0.15 , L : ± 0.3 r.l.u. The solid line is a guide to the eye. The y axes in **e–j** are divided by the reduced Planck constant $\hbar = h/2\pi$ to have a dimension of E^{-1} . The vertical error bars in **e–k** represent statistical errors of 1 standard deviation.

To further demonstrate that spin excitations at the Y1 position are coupled to superconductivity, we carried out high-resolution measurements using an incident neutron energy of $E_i = 2.5$ meV. The wavevector-dependent scattering at $E = 0.275 \pm 0.025$ meV below T_c (Fig. 4a) and above T_c (Fig. 4b) reveals the opening of a spin gap in the superconducting state (Extended Data Fig. 6). For comparison, spin excitations at $E = 1.075 \pm 0.025$ meV are clearly enhanced below T_c at BT (Fig. 4c, d). Figure 4e, f shows $\mathbf{Q}$ cuts along the $[0, K, 0]$ direction at $E = 0.25 \pm 0.05$ meV and $E = 1.05 \pm 0.05$ meV, respectively. Although superconductivity in UTe_2 induces a spin gap and a resonance, it does not change the $\mathbf{Q}$ -dependent lineshape, as seen in the resonance of CeCoIn_5 (ref. ³⁵). Figure 4g shows energy-dependent scattering at the Y1 point together with the nuclear incoherent scattering backgrounds taken at the background wavevector position $\mathbf{Q}_b$ (Fig. 1c). We find clear evidence of a spin gap at BT below $E = 0.25 \pm 0.05$ meV and a resonance at $E_r = 7.9 k_B T_c$. Figure 4e, f shows the temperature dependence of $\chi''(E)$ at the Y1 and T1 positions, respectively, in absolute units, obtained by subtracting the incoherent scattering backgrounds, correcting for the Bose population factor, and normalizing the magnetic scattering to a vanadium standard. We note that the magnitude of the magnetic scattering in UTe_2 is similar to that of iron-based superconductors¹⁹. The temperature dependence of the spin gap and resonance is obtained by systematically subtracting the high-temperature data (the average of the $T = 1.8$ and 2 K data) from those at lower temperatures (Fig. 4h). At $T = 1.5$ K, the temperature-difference plot shows no visible feature. On cooling further below T_c , we find clear evidence for negative and positive scattering in the temperature-difference plots arising from

the opening of a spin gap and the emergence of a resonance, similar to other unconventional spin-singlet superconductors^{17–23}. Figure 4i shows similar temperature-difference plots between BT and 2 K obtained at Y1 and Y2 with $E_i = 3.32$ meV, again revealing the resonance at these equivalent positions. The absence of the resonance mode at T1 and T2 is shown in the temperature-difference plots of Fig. 4j. Finally, Figure 4k summarizes the temperature dependence of the scattering at Y1 for energies of $E_{\text{gap}} = 0.45 \pm 0.25$ meV and $E_r = 1.15 \pm 0.45$ meV. It is clear that the intensity gain of the resonance below T_c occurs at the expense of opening a spin gap at energies below it.

Discussion

To summarize the INS results in Figs. 2–4, the temperature dependence of $\chi''(E)$ at Y1 and T1 is plotted in Fig. 1e, f, respectively. In previous work, the energy of the resonance E_r for unconventional spin-singlet superconductors was found to be proportional to the universal value $E_r = 5.8 k_B T_c$ (ref. ¹⁸) or the superconducting gap Δ (ref. ²⁶). The values of $E_r/k_B T_c$ of spin-singlet heavy-fermion superconductors are well below the dashed line representing $E_r/k_B T_c = 5.8$, whereas $E_r/k_B T_c$ for UTe_2 is well above the dashed line (Fig. 1g). Assuming that UTe_2 has a superconducting gap of $\Delta = 0.25$ meV (ref. ¹²), $E_r/2\Delta \approx 2$ for UTe_2 is well above the expected universal dashed line of $E_r/2\Delta \approx 0.6$ (Fig. 1h)²⁶. Because the resonance energy is believed to be a direct measure of the electron-pairing strength, arising from the spin-singlet to spin-triplet excitations for spin-singlet superconductors²⁵, its observation in UTe_2 suggests that the system might also be a spin-singlet superconductor,

in contrast to previous work^{7–14}. By comparing magnetic scattering intensity at the Y1, Y2 and Y3 equivalent points in reciprocal space in Fig. 2c–f, we conclude that spin fluctuations are highly anisotropic in spin space with a large magnitude along the a -axis direction, thus suggesting the presence of a large spin–orbit coupling. Three $5f$ electrons of uranium in UTe_2 can display a dual localized and itinerant character similar to other U-based compounds^{36,37}, and so superconductivity can arise from some itinerant electrons, whereas magnetism comes about from other, more localized electrons. In this picture, the presence of the AF resonance in UTe_2 at an energy so different from other spin-singlet superconductors could simply be a consequence of the weak coupling between itinerant and localized electrons (Fig. 1g, h).

Alternatively, if we assume that UTe_2 is indeed a spin-triplet superconductor, our results reveal several important conclusions for the microscopic origin of spin-triplet superconductivity. First and foremost, the observation of a resonance in UTe_2 with $E_r \approx 7.9k_B T_c$ suggests that AF spin fluctuations with large spin–orbit coupling can drive spin-triplet superconductivity, clearly different from the current understanding that FM spin fluctuations are responsible for its superconductivity³⁸. Second, the observation of a superconductivity-induced spin gap at energies below E_r suggests that the superconducting order parameter may have a spin-singlet component with a sign change (possibly in the A_g state)³⁸. Third, within a spin-exciton picture of the resonance, we expect $E_r(\mathbf{Q}) < \min(|\Delta(\mathbf{k})| + |\Delta(\mathbf{k} + \mathbf{Q})|)$ (refs. ^{2,25}). Because scanning tunnelling microscopy experiments reveal a superconducting gap of $\Delta = 0.25$ meV (ref. ¹²), $E_r/2\Delta \approx 2$ in UTe_2 is much larger than $E_r/2\Delta = 0.64$ found in unconventional spin-singlet superconductors (Fig. 1h)²⁶. Fourth, our experimental observation of AF spin excitations extending up to about $E = 6$ meV in Fig. 3 suggests that the in-plane magnetic exchange coupling of UTe_2 has an energy scale about ten times the superconducting pairing energy of $2\Delta = 0.5$ meV, similar to copper oxide² and iron-based superconductors¹⁹. A crude estimation using Figs. 1b, e, 3c suggests that the saving of magnetic exchange energy in the superconducting state in UTe_2 is sufficient to account for the superconducting condensation energy determined from the heat-capacity anomaly across T_c (Extended Data Fig. 2)³⁹. Finally, the discovery of a resonance and normal-state spin excitations in UTe_2 , where charged quasiparticles can also be probed by angle-resolved photoemission spectroscopy⁴⁰, should open new avenues of research towards understanding the connection between spin excitations and Fermi surface topology in UTe_2 .

UTe_2 is a multi-band/orbital system, with superconducting pairing channels classified by the D_{2h} point group¹⁴. In such multi-band/orbital superconductors, the presence of additional orbital degrees of freedom expands the pool of symmetry-allowed spin-triplet and spin-singlet pairing candidates, which, in turn, implies that quasi-degenerate pairing channels are more probable than in the typical single-band cases. As outlined in Methods, AF spin correlations of UTe_2 , in the probable Γ_5^- f -ground manifold³⁷, allow for not only the usual spin-singlet pairing channel but also spin-triplet pairing channels. The spin-triplet pairing channels arise because the product of two Γ_5^- 's contains not only the spin-singlet matrix Γ_1 but also three spin-triplet matrices Γ_{2-4} , which transform as three one-dimensional non-trivial representations. Therefore, spin-triplet pairing states are allowed by the AF correlations in the manifold of Γ_5^- doublets. Furthermore, in the presence of AF correlations and when the spin–orbit coupling induces strong Ising anisotropy, as is the case for UTe_2 (ref. ⁷), the spin-triplet channel can become energetically competitive.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at <https://doi.org/10.1038/s41586-021-04151-5>.

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Methods

Single-crystal growth

Single crystals of UTe_2 were produced using an iodine vapour transport method similar to that described earlier⁷. U (99.98% purity) and Te (99.99% purity) were combined in the ratio 2:3 and sealed with iodine (3 mg cm^{-3} , 99.999% purity) in an evacuated quartz tube with a length of 10 cm and an inner diameter of 1.4 cm. The tubes were placed in a single zone furnace with the hot end (furnace center) held at $1,060^\circ\text{C}$ for four weeks. The natural temperature gradient of the furnace was adequate to promote vapour transport and to produce large single-crystal specimens of the type shown in Extended Data Fig. 1a. After the heating cycle, samples were naturally cooled to room temperature, removed from the quartz tube, and rinsed in ethanol. Samples were subsequently stored under vacuum in sealed quartz ampoules.

Heat-capacity measurements

The temperature-dependent heat capacity divided by temperature C/T for two samples is shown in Extended Data Fig. 2a. Similar to earlier reports, there is a second-order phase transition near $T_c \approx 1.6 \text{ K}$, which marks the onset of superconductivity. All samples measured from these growth experiments show this feature, but, as previously reported, some show a single transition whereas others exhibit a double transition¹⁴. At higher temperatures, the data follow a Fermi liquid temperature dependence $C/T = \gamma + \beta T^2$, where $\gamma \approx 111 \text{ mJ mol}^{-1} \text{ K}^{-2}$, consistent with earlier reports^{7,8}. We also find that the quantity $\Delta C/\gamma T_c \approx 1.54$, when it is determined using an equal entropy construction (Extended Data Fig. 2b). To estimate the superconducting condensation energy, we consider the expression $U(0) = (1/2)N(0)\Delta^2(0)$ where $N(0)$ is the density of states at the Fermi energy and is determined from the expression $\gamma = (\pi^2/3)k_B^2 N(0)$ and $2\Delta = 3.52k_B T_c$ relates the BCS superconducting energy gap to the transition temperature. From this, we estimate $U(0) \approx 150 \text{ mJ mol}^{-1}$, which is consistent with trends that are seen for other strongly correlated uranium-based superconductors⁴¹.

Neutron scattering

INS measurements on UTe_2 were carried out using the Cold Neutron Chopper Spectrometer (CNCS) at Oak Ridge National Laboratory⁴². The momentum transfer $\mathbf{Q}$ in three-dimensional reciprocal space is defined as $\mathbf{Q} = H\mathbf{a}^* + K\mathbf{b}^* + L\mathbf{c}^*$, where H, K and L are Miller indices and $\mathbf{a}^* = \hat{\mathbf{a}}2\pi/a$, $\mathbf{b}^* = \hat{\mathbf{b}}2\pi/b$, $\mathbf{c}^* = \hat{\mathbf{c}}2\pi/c$ with $a = 4.16 \text{ \AA}$, $b = 6.12 \text{ \AA}$ and $c = 13.95 \text{ \AA}$ of the orthorhombic lattice⁷. The crystals are naturally cleaved along the ab plane and form small flakes about $0.5\text{--}1 \text{ mm}$ thick and up to 1 cm long. We co-aligned 27 pieces (total mass 0.9 g) of single crystals on oxygen-free Cu plates using an X-ray Laue machine to check the orientation of each single crystal (Extended Data Figs. 1b, c, 3]. The crystal assembly is aligned in the $[H, K, 0]$ scattering plane as shown in Fig. 1c, d and mounted on a ^3He insert installed in the standard cryostat. The lowest temperature that can be reached in this setup is $\text{BT} = 0.25 \text{ K}$. INS data were collected with incident neutron energies set to $E_i = 12, 3.32$ and 2.5 meV in the Horace mode as specified in the legends of Figs. 1–4 (ref. ⁴³). The sample co-alignment resulted in three assembled peaks at each Bragg position with a 6-degree spread, as shown in Extended Data Fig. 4a, b. The strongest peak of the three contributes over 70% of the total Bragg peak intensity. The H, K coordinates used for data analysis were based on the position of the strongest peak. The symmetrized constant energy cuts shown in Figs. 2a–f, 3a, b, 4a–d are results of two reflection operations against the horizontal and vertical axes according to the space group $Immm$, which do not change the positions of the strongest assembled peaks but create copies of the two smaller peaks on the opposite side. The symmetrized data were only used for constant energy cuts. All the one-dimensional data shown in Figs. 1–4, Extended Data Figs. 1–7 are taken from the unsymmetrized raw data. Extended Data Figs. 4, 5, 6 show raw data obtained with $E_i = 3.32, 12$ and 2.5 meV , respectively, at different temperatures. Extended Data

Fig. 7 shows cuts around the FM Bragg peak and background positions at BT and 2 K , indicating no evidence of FM spin fluctuations in UTe_2 within our measurement sensitivity. We also checked possible existence of quasielastic magnetic scattering, as seen in AF-ordered UPd_2Al_3 (ref. ²¹), and find no evidence in UTe_2 , consistent with no static magnetic order in the system. The high-flux instrument mode was used to maximize the neutron intensity with the Fermi chopper and double-disk chopper frequency at 60 Hz and 300 Hz , respectively. The neutron scattering data are normalized to absolute units using a vanadium standard, which has an accuracy of approximately 30%.

Theory

In UTe_2 , as is typical of f -electron materials, the U atomic states are split by strong spin–orbit coupling and crystal-field effects into multiplets, which transform according to the double-valued irreducible representations of the D_{2h} point group. We will construct microscopic Cooper pairing candidates of well defined symmetry from products of momentum-dependent form factors such as p waves and matrices defined in the relevant multiplet space⁴⁴. The pairing matrices, which are obtained from the decomposition of the products of two multiplets, also transform as irreducible representations of the point group. This classification naturally restricts the number of symmetry-allowed pairing states by incorporating the spin–orbit coupling and crystal-field splitting for the U levels. Furthermore, by taking into account the relevant atomic structure of the paired electrons, pairing candidates constructed from our microscopic procedure go beyond the more common Landau–Ginzburg analysis, which relies only on a symmetry classification without reference to the pairing matrix structure. Our approach also provides a natural link to the topology of the superconducting state.

In this approach, the matrix structure in orbital/spin space⁴⁵, or similarly in multiplet space with strong spin–orbit coupling, provides the key to advancing new pairing states. To set the stage, we recall the approach in the previously studied case⁴⁴ of the prototypical heavy-fermion unconventional superconductor CeCu_2Si_2 . In that compound, various probes⁴⁴ point toward a ground-state Γ_7 Kramers doublet of the D_{4h} point group which emerges from the $\text{Ce } f$ electron via spin–orbit coupling and crystal-field splitting. Ref. ⁴⁴ showed that the matrix corresponding to spin-singlet pairing between two $\Gamma_7 f$ electrons transforms as the identity (Γ_1) irreducible representation of D_{4h} , which is featureless in the sense that it can be classified entirely via the symmetry of its form factor. However, the same procedure also predicted that, when paired instead with Γ_6 conduction electrons originating from the Cu d -electron states, the $\Gamma_7 f$ -electron multiplets give rise to a spin-singlet matrix that transforms as a Γ_3 irreducible representation; it changes signs under C_{4z} rotations and thus transforms non-trivially. In CeCu_2Si_2 , this pairing matrix, together with a featureless s -wave form factor, is equivalent to an unconventional $d + d$ pairing state consisting of intra- and inter-band d -wave components⁴⁵, reflecting the sign-changing nature of the irreducible representation. The $d + d$ pairing leads to a fully gapped Bogoliubov–de Gennes (BdG) spectrum at lower temperatures. This matrix pairing state proved successful in accounting for the spin resonance observed in CeCu_2Si_2 in inelastic neutron scattering, as well as in fitting the experimental data on London penetration-depth and specific-heat measurements that encode a hard gap in the low-energy BdG spectrum⁴⁶. A small but nonzero admixture of $\Gamma_6 f$ electrons in the ground state, as indicated by soft X-ray absorption spectroscopy⁴⁷, provides evidence for the degrees of freedom that underlie the proposed $d + d$ pairing.

Although less is known about the f -electron levels of UTe_2 at this stage, we can still construct and classify symmetry-constrained pairing channels for this compound using the same microscopic framework. A number of available ab initio studies^{16,48,49} point toward a predominant $Uj = 5/2, m_j = \pm 1/2$ doublet at low energies. These results are consistent with data from core-level photoelectron spectroscopy³⁷. They are also

compatible with the spin size extracted in this work: By assuming that the spin excitation spectral weight determined from the $E_i = 3.32$ meV data goes up linearly as a function of E up to 6 meV (the band top, which is determined by high- E_i data), we estimate the momentum- and energy-integrated spin spectral weight to be $-1.5\mu_B^2$ per U (μ_B , Bohr magneton) that, for g close to 2, is compatible with a spin size $1/2$. The double-valued irreducible representations of D_{2h} allow only for Γ_5 Kramers doublets⁵⁰. It is then natural to identify a Γ_5 doublet with the $Uj = 5/2, m_j = \pm 1/2$ states.

We can then proceed along the lines set out in ref.⁴⁴, and determine the possible pairing matrices via a decomposition of the product of two Γ_5 doublets. The products decompose as follows⁵⁰: $\Gamma_5 \times \Gamma_5 = \Gamma_1 + \Gamma_2 + \Gamma_3 + \Gamma_4$. (Note that the parity of the Γ_5 's is not specified, but it does not affect the decomposition.) In the above decomposition, the first term corresponds to a spin-singlet matrix, which transforms according to the identity Γ_1 representation. This component captures the standard result, namely that AF correlations promote spin-singlet pairing.

Our procedure also reveals a striking result: The decomposition also includes three spin-triplet matrices. The latter transform according to three one-dimensional, non-trivial Γ_{2-4} representations. We achieve our key results: AF correlations within the ground-state manifold of $U\Gamma_5$ can also lead to spin-triplet superconducting pairing. We re-iterate that, in arriving at this conclusion, it is crucial to account for the matrix structure of the pairing state.

We next turn to the energetics of the pairing states. A systematic study requires the knowledge of both the tight-binding parameterization of the noninteracting bands and the effective interaction parameters among the Γ_5 multiplets. When such parameters are known, we can determine and compare the ground-state energies of the different pairing channels, in the same way as used to show that the band-mixing $d+d$ (matrix spin-singlet) pairing state is energetically competitive^{44,45}. Given that the model parameters are not yet available, we resort to more general means to assess the stability of the spin-triplet pairing. A key feature is that the spin-orbit coupling of UTe_2 is such that the magnetic response is strongly Ising anisotropic⁷. For antiferromagnetically correlated systems that are highly Ising anisotropic, the spin-triplet channel can be energetically competitive, as captured in the microscopic calculations of pairing correlations in well defined Kondo systems⁵¹ and recently discussed in the context of superconductivity observed near a magnetic-field-induced heavy-fermion quantum critical point⁵².

Data availability

The data that support the plots within this paper and other findings of this study are available from the corresponding authors upon reasonable request.

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Author contributions P.D. and M.B.M. conceived the project. R.E.B. grew the single crystals and made specific-heat measurements on the crystals. The single crystals of UTe_2 were aligned using Laue X-ray diffraction by C.D., Y.D., C.M. and A.J.B. and characterized by means of powder X-ray diffraction by C.M., A.J.B. and Y.D. at UCSD. The INS experiments were carried out by A.P. in remote discussion with C.D. and P.D. The data analysis was carried out by C.D. and P.D. E.M.N. and Q.S. contributed to the theoretical idea that AF spin fluctuations may facilitate spin-triplet superconductivity. The paper was written by P.D., C.D., R.E.B., E.M.N. and Q.S., and all coauthors made comments on the paper.

Competing interests The authors declare no competing interests.

Additional information

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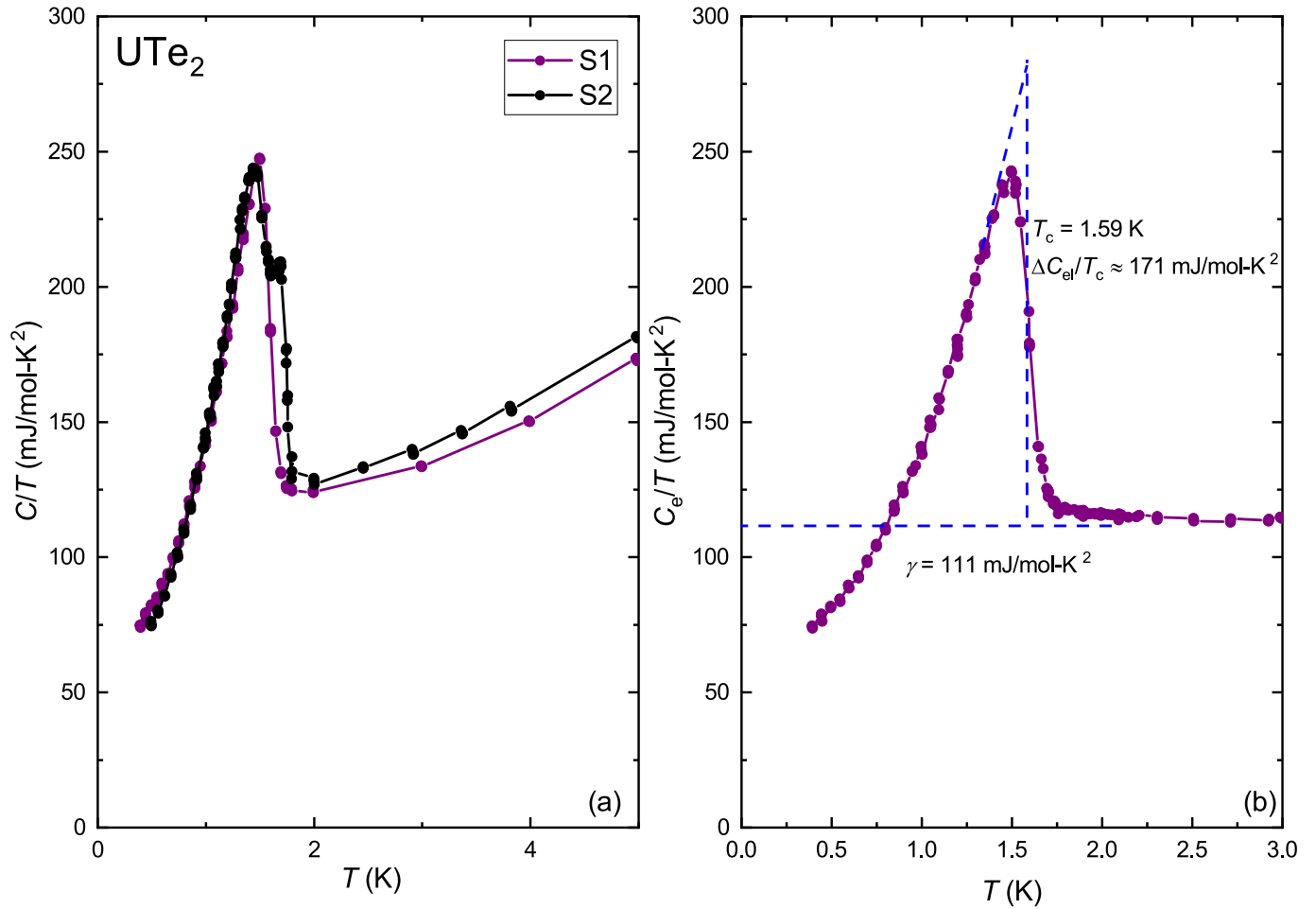
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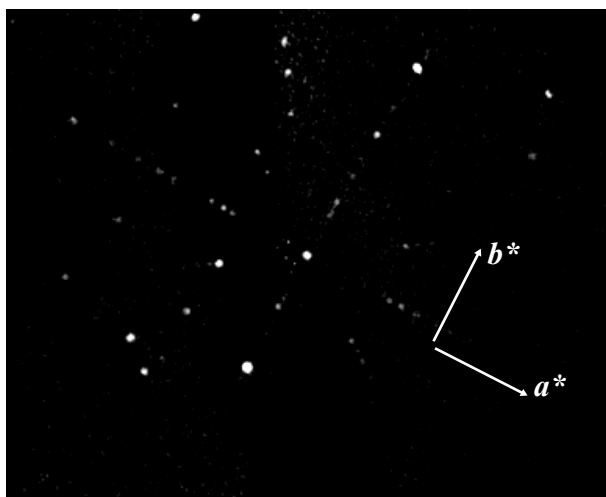


Extended Data Fig. 1 | Pictures of the UTe_2 single crystals used in the INS experiment. **a**, A typical piece of UTe_2 single crystal of 10 mm by 3 mm by 3 mm in size. The direction of the longest edge is the intersection of $[1, 1, 0]$ plane and $[0, 0, 1]$ plane. **b, c**, 27 pieces of UTe_2 single crystals co-aligned on two oxygen-free Cu sample plates. The total mass is 0.9 grams.

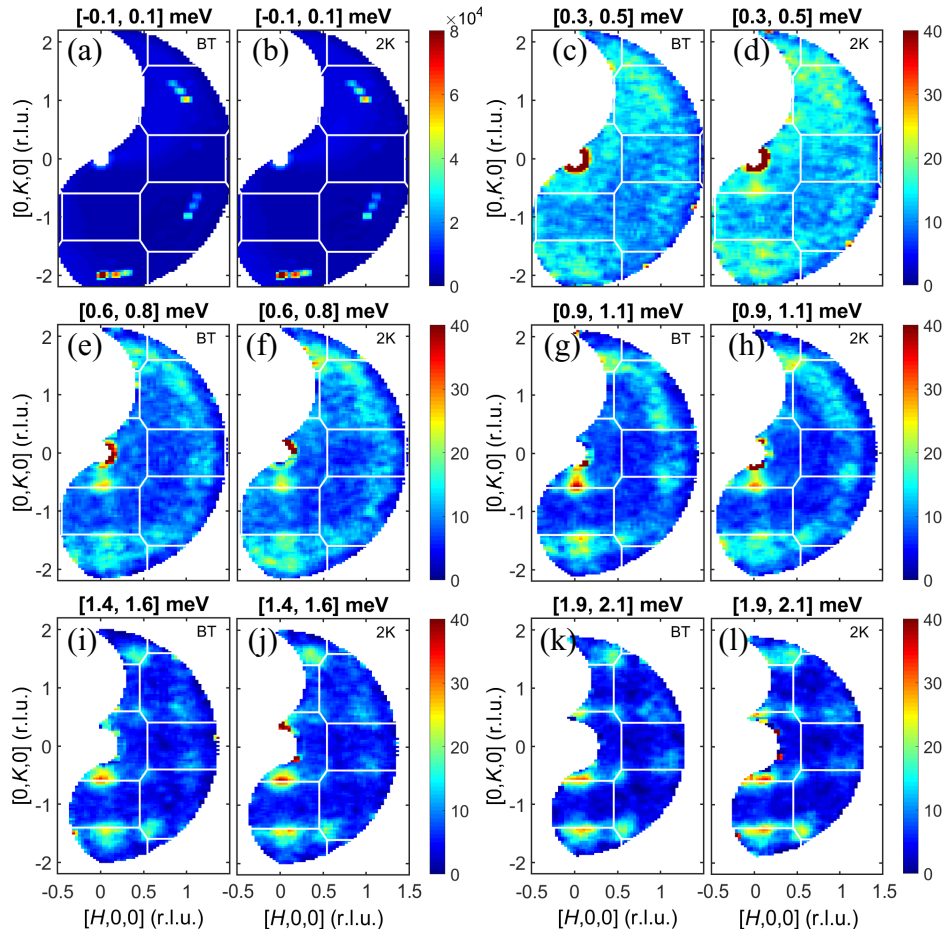


Extended Data Fig. 2 | Summary of temperature-dependent heat capacity C/T for single-crystal specimens of UTe_2 . **a**, Comparison of C/T versus T for two representative crystals of UTe_2 . One crystal shows a single superconducting phase transition whereas the other shows two features. Several other crystals were measured, which all show similar behavior. **b**, The electronic component of the heat capacity C_e/T , which was obtained by

subtracting the low temperature phonon heat capacity βT^2 , which was obtained by fitting the data for $T > T_c$ using the expression $C/T = \gamma + \beta T^2$. The normal state electronic coefficient of the heat capacity γ is indicated by the horizontal dotted blue line. An equal entropy construction is also indicated by dotted blue lines to determine T_c and the ideal size of the heat-capacity jump $\Delta C/T_c$.

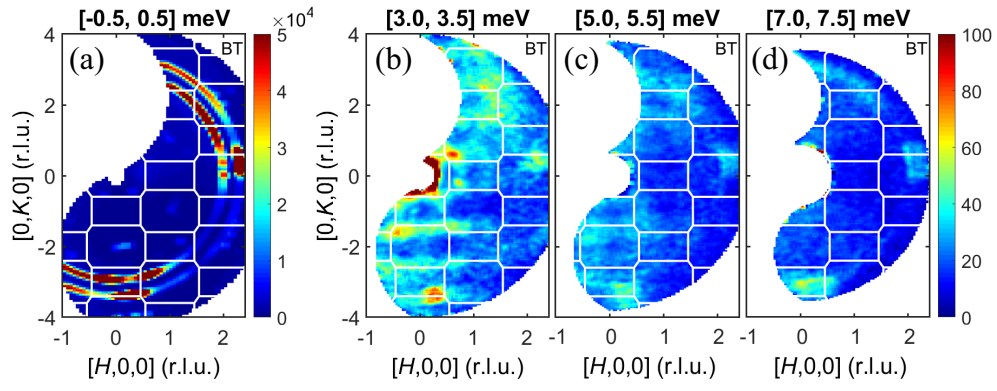


Extended Data Fig. 3 | X-ray Laue pattern of the [0, 0, 1] plane of UTe_2 .
Pattern is shown for one of the samples used in the experiment.



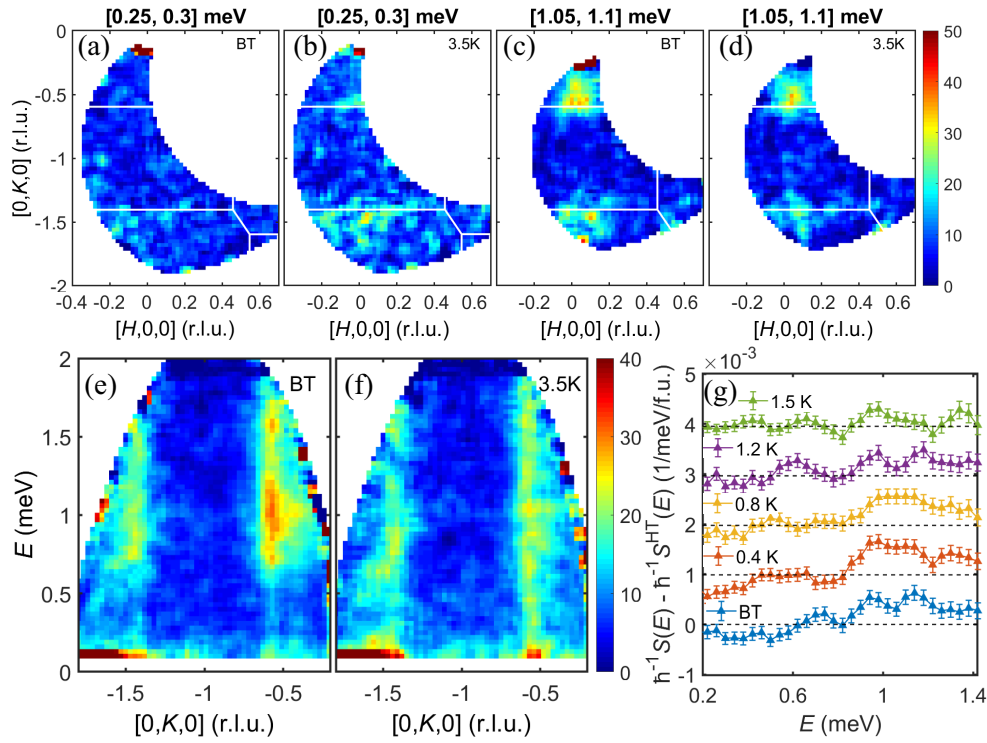
Extended Data Fig. 4 | Unsymmetrized raw data in the $[H, K, 0]$ plane with $E_i = 3.32$ meV. a–l, Constant-energy cuts of the unsymmetrized $S(\mathbf{Q}, E)$ with $E_i = 3.32$ meV at (a) 0.0 ± 0.1 meV and BT, (b) 0.0 ± 0.1 meV and 2K, (c) 0.4 ± 0.1 meV and BT, (d) 0.4 ± 0.1 meV and 2K, (e) 0.7 ± 0.1 meV and BT, (f) 0.7 ± 0.1 meV and 2K, (g) 1.0 ± 0.1 meV and BT, (h) 1.0 ± 0.1 meV and 2K,

(i) 1.5 ± 0.1 meV and BT, (j) 1.5 ± 0.1 meV and 2K, (k) 2.0 ± 0.1 meV and BT, (l) 2.0 ± 0.1 meV and 2K. The bin size is 0.035 r.l.u. along both H and K . The integration range is ± 0.2 r.l.u. in L , and ± 0.1 meV in E . The unit of the colour bars in Extended Data Figs. 4, 5, 6 is the same as that of Fig. 2b.



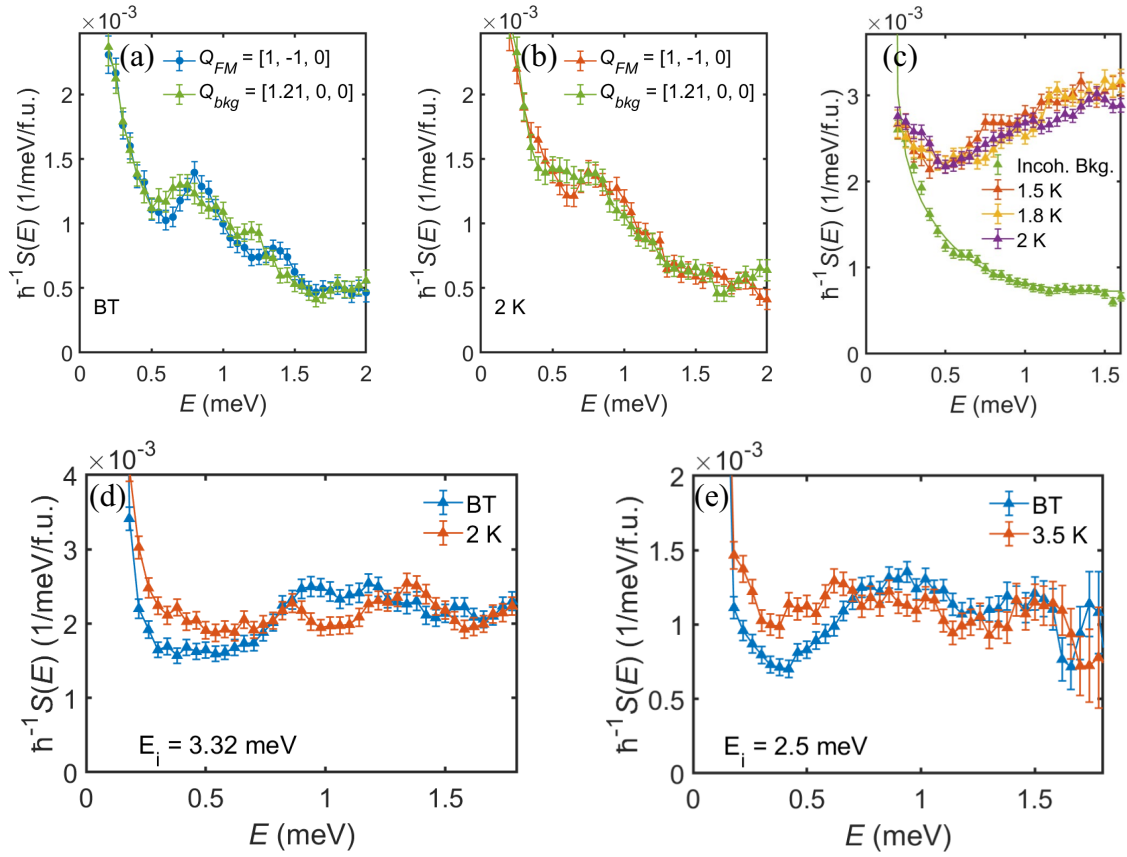
Extended Data Fig. 5 | Unsymmetrized raw data in the $[H, K, 0]$ plane with $E_i = 12$ meV. a–d, Constant energy cuts of the unsymmetrized $S(\mathbf{Q}, E)$ with $E_i = 12$ meV and BT at (a) 0.0 ± 0.5 meV, (b) 3.25 ± 0.25 meV, (c) 5.25 ± 0.25 meV,

(d) 7.25 ± 0.25 meV. The bin size is 0.04 r.l.u. along both H and K . The integration range is ± 0.2 r.l.u. in L , and ± 0.25 meV in E . The rings of scattering in **a** are from the nuclear (1, 1, 1) and (2, 0, 0) Bragg peaks of the Cu sample holder.



Extended Data Fig. 6 | Unsymmetrized raw data, E - Q plots and one-dimensional energy cuts with $E_i = 2.5$ meV. **a–d**, Constant energy cuts of the unsymmetrized $S(\mathbf{Q}, E)$ with $E_i = 2.5$ meV at (a) 0.25 to 0.3 meV and BT, (b) 0.25 to 0.3 meV and 3.5 K, (c) 1.05 to 1.1 meV and BT, (d) 1.05 to 1.1 meV and 3.5 K. The bin size is 0.02 r.l.u. along H and 0.03 r.l.u. along K . The integration range is ± 0.3 r.l.u. in L . **e, f**, E - Q plots of the scattering function $S(\mathbf{Q}, E)$ with $E_i = 2.5$ meV at BT (e) and 3.5 K (f), respectively. The integration range is ± 0.08 r.l.u. in H and ± 0.3 r.l.u. in L , the bin size along K is 0.03 r.l.u., and the E step is 0.03 meV. **g**, One-dimensional cuts of the scattering function $S(\mathbf{Q})$ with high

temperature data ($S^{HT}(\mathbf{Q})$) subtracted. The cuts are taken at Y1 along E taken at BT (blue), 0.4 K (red), 0.8 K (yellow), 1.2 K (purple), and 1.5 K (green) with $E_i = 2.5$ meV. The high-temperature data are taken at 3.5 K. At low energy the excitation at Y1 is not fully covered with this E_i , which causes the gap feature between 0.2 to 0.7 meV to be hard to observe in the subtracted one-dimensional data. Different temperature data in **g** are artificially shifted, with the dashed black line representing the base line for each temperature. The integration ranges in **g** are: ± 0.08 r.l.u. in H , ± 0.15 r.l.u. in K , and ± 0.3 r.l.u. in L . The bin size in E is 0.04 meV.



Extended Data Fig. 7 | Temperature dependence of the excitations at different Q positions. **a, b**, One-dimensional cuts of $S(E)$ with $E_i = 3.32$ meV at Bragg peak $(1, -1, 0)$ along E at BT and 2 K, respectively. Incoherent background scattering integrated at Q_{bkg} is plotted in green triangles. There are no FM spin fluctuation signals observed above the background. The broad peak around $E = 0.7$ meV is powder ring of scattering not associated with UTe_2 (see Extended Data Fig. 4e, g). **(c)** One-dimensional cuts of $S(E)$ with $E_i = 3.32$ meV at Y1 along

E at 1.5, 1.8, and 2 K. There is no significant change in the quasielastic energy range for temperature close to and above T_c . **d, e**, One-dimensional cuts of $S(E)$ with $E_i = 3.32$ meV (**d**) and 2.5 meV (**e**), respectively. The subtle increase of $S(E)$ above T_c near 1.4 meV with $E_i = 3.32$ meV is just above one standard deviation, and is not observed with $E_i = 2.5$ meV. The integration ranges of the one-dimensional data in **d, e** are: ± 0.1 r.l.u. in H , ± 0.15 r.l.u. in K , and ± 0.3 r.l.u. in L . The bin size in E is 0.04 meV.