Magnetic-field-sensitive charge density waves in the superconductor UTe$_2$

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The intense interest in triplet superconductivity partly stems from theoretical predictions of exotic excitations such as non-Abelian Majorana modes, chiral supercurrents and half-quantum vortices$^{1–3}$. However, fundamentally new and unexpected states may emerge when triplet superconductivity appears in a strongly correlated system. Here we use scanning tunnelling microscopy to reveal an unusual charge-density-wave (CDW) order in the heavy-fermion triplet superconductor UTe$_2$ (refs. 5–8). Our high-resolution maps reveal a multi-component incommensurate CDW whose intensity gets weaker with increasing field, with the CDW eventually disappearing at the superconducting critical field $H_{c2}$. To understand the phenomenology of this unusual CDW, we construct a Ginzburg–Landau theory for a uniform triplet superconductor coexisting with three triplet pair-density-wave states. This theory gives rise to daughter CDWs that would be sensitive to magnetic field owing to their origin in a pair-density-wave state and provides a possible explanation for our data. Our discovery of a CDW state that is sensitive to magnetic fields and strongly intertwined with superconductivity provides important information for understanding the order parameters of UTe$_2$.

In the ongoing search for new phases of matter, the heavy-fermion superconductor uranium ditelluride (UTe$_2$), which combines strong correlations and triplet superconductivity$^{2,3}$ with possible non-trivial topology$^{9–11}$, is an extremely promising system. UTe$_2$ is paramagnetic, exhibiting no magnetic ordering down to the lowest temperatures$^{12}$, and superconducts below the critical temperature ($T_c$) of about 2 K (refs. 5,8). The unusually high upper critical field ($H_{c2}$)$^5$, multiple field-reentrant superconducting phases$^7$, minimal change in the Knight shift$^5,12$ and exceptionally large Sommerfeld coefficient below $T_c$ (ref. 10) show that the superconducting state may have broken time-reversal symmetry. Theoretical studies suggest that UTe$_2$ might be a topologically non-trivial Weyl superconductor$^{13,14}$ and harbour a chiral triplet state with Majorana arcs$^{15,16}$. These phenomena combined with indications of non-trivial topology make UTe$_2$ an exciting and unique platform for the realization of fundamentally new states.

In this work, we use scanning tunnelling microscopy and scanning tunnelling spectroscopy to study single crystals of UTe$_2$ below $T_c$. UTe$_2$ crystallizes into a body-centred orthorhombic structure with two uranium atoms per unit cell$^{17}$. The unit cell consists of bi-trigonal prisms of U and Te in which a U–U dimer is surrounded by two inequivalent Te atoms (based on U–Te bond lengths) labelled Te1 and Te2 in Fig. 1a (dark and light blue colours). The chains of bi-trigonal prisms run parallel to the $a$ direction and are offset by $c/2$ in the $c$ direction (Fig. 1b), in which $c$ is the height of the unit cell. The lattice may also be visualized as slabs of bi-trigonal prisms oriented along the $<011>$ direction (Fig. 1b). The UTe$_2$ samples in this study were cleaved at temperatures of about 90 K and immediately inserted into the head of the scanning tunnelling microscope (see Methods and Extended Data Fig. 1 for details). Previous studies$^9$ have shown that $<011>$ is the easy-cleave plane and the atoms readily visible in the topography are the Te1 and Te2 atoms, which appear as chains (Fig. 1c,d). A fast Fourier transform (FFT) of the topography is shown in Fig. 1g, in which the Te Bragg peaks are shown by cyan dashed arrows. We denote the Te Bragg peaks as $q_{\alpha}=(\pm q_{\alpha x}, q_{\alpha y})$, in which $q_{\alpha x}$ and $q_{\alpha y}$ represent coordinates in the $x$ and $y$ directions in the FFT as labelled. Note that the $x$ and $y$ directions used here are for ease of notation and do not indicate the crystallographic directions. To complete the picture, we identify the $<011>$ projection plane of the three-dimensional orthorhombic Brillouin zone (BZ) in momentum space as shown in Fig. 1e. Constructing the BZ for the surface from the primitive lattice vectors gives rise to an elongated, hexagonal BZ as shown in Fig. 1g. The centre of this BZ is labelled as S and the vertices are labelled as L$_1$, L$_2$ and W by convention$^{38}$.

Incommensurate CDWs in the superconducting state

As is evident from Fig. 1g, apart from the Te Bragg peaks, there are three additional peaks (outlined by two squares and a triangle), near the L$_1$, L$_2$ and W points of the BZ in the FFT. To understand the origin of these

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maps as a function of $q$. We note that all three CDWs are incommensurate with the underlying lattice. This indicates that the observed modulations arise from a multi-component CDW order in this material. We have verified the existence of these CDWs across 11 different samples and tips from three different growth batches.

To distinguish between signals from quasiparticle interference and CDWs, we study the energy dependence of the $q$ vectors associated with the peaks in the FFT. To do this, we obtain linecuts of the FFTs of the LDOS maps in the three important momentum space directions, $S$–$L_1$, $S$–$L_2$, and $S$–$W$ (henceforth labelled as line 1, 2, and 3, respectively) and plot this as a function of energy. This information is presented as an intensity map in Fig. 2g–i. Contrary to energy-dispersive features such as quasiparticle interference, we find that the magnitude of the three $q$ vectors shows no energy dependence. This indicates that the observed modulations arise from a multi-component CDW order in this material.

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The observation of a CDW in a superconductor immediately leads to the question of its relationship with superconductivity. In most instances when a CDW is found in the superconducting phase, it is an independent order parameter, which could coexist and/or compete with superconductivity. In a more interesting scenario, a CDW is a direct consequence of a periodically modulated superconducting order parameter or a pair-density-wave (PDW) phase. A PDW is a new phase of matter for which the superconducting order parameter shows periodic spatial oscillations. A unidirectional PDW state can coexist with a uniform superconductor. In this scenario, a PDW with wavevector \( Q \) is expected to generate a CDW at both \( Q \) and \( 2Q \) (ref. 22). In a scenario with three CDWs, we would invoke PDWs with three primary ordering wavevectors \( Q_i (i = 1, 2, 3) \), which coexist with the uniform superconducting state. The associated CDWs should then show the same primary ordering wavevectors as well as their linear combinations (‘higher harmonics’) playing the role of the above-mentioned 2Q component. PDWs have been proposed to exist in superconductors with an in-plane field, but zero-field PDWs require strong interactions. Experimental data showing evidence for this exotic state have been limited to cuprates and more recently to kagome superconductors.

**Magnetic field response of the CDWs**

To investigate the relationship between the CDWs and superconductivity, we study the effect of magnetic fields on the CDW. As the magnetic field is perpendicular to the (011) cleave plane and to the \( a \) axis, it makes an angle of 23.7° with the \( b \) axis (Fig. 3a). Extremely high magnetic fields (about 40 T) oriented along this direction give rise to the mysterious Lazarus superconducting phase or the field-polarized superconducting...
Remarkably, at our much smaller fields, we see a peculiar response of the CDWs to the magnetic field. Figure 3b,c shows FFTs at 0 T and 10.5 T. The data in Fig. 3 (at 10.5 T) were obtained on the same area as the 0 T data shown in Fig. 2 and obtained at −10 meV ($T = 300 \text{ mK}$, tunnelling setpoint: $V = 50 \text{ mV}, I = 250 \text{ pA}$). The colour scale has been kept identical for b,c. d–f, Linecuts of the Fourier transforms of the LDOS maps at a single energy (−10 meV), along the three different CDW directions and of (indicated by the dashed arrows in e) for the FFT at 0 T and 10.5 T, respectively.

The CDWs are marked by the orange and red squares and purple triangle. Although all of the CDW peaks are substantially suppressed, the CDW along line 2 as shown in e shows a much stronger suppression in comparison to d. This reveals a putative breaking of the mirror symmetry in the presence of a magnetic field. g–i, Linecuts of FFTs at 10.5 T at different energies along the three directions indicated by the dashed arrows in c, plotted as an intensity map. One can visually see that the Fourier amplitude at in h is highly suppressed compared to the 0 T data in Fig. 2h.

Notably, the suppression of the CDW with field is further enhanced when the magnetic field is tilted slightly with respect to the [011] direction. We can generate such a tilt in the sample while mounting the sample on the sample holder. Although these angles at present cannot be tuned controllably, they can provide valuable insights for a crystal such as UTe$_2$, whose superconducting properties are highly sensitive to magnetic field orientation. Figure 4 shows magnetic-field-dependent measurements obtained on one such fortuitous sample with a 11° tilt. Figure 4b–d shows a series of FFTs of topographies obtained at selected magnetic fields, and Fig. 4f–h shows FFT linecuts obtained along the three different momentum space directions. The intensities of the CDW peaks are once again suppressed with magnetic field, with the CDWs eventually disappearing at around 10 T. This is captured in Fig. 4e, which plots the intensity of the different CDW peaks normalized to the Te Bragg peak as a function of field. We find that the CDW order parameter is concomitantly suppressed with superconductivity. This phenomenology was confirmed with other tip–sample combinations (see Extended Data Fig. 10).
the 11°-tilted field is consistent with the lower $H_{c2}$ value when the field is applied in this direction.

Ginzburg–Landau theory

Conventionally, a CDW order is a periodic modulation of the local charge density, and as such is not expected to couple substantially to an external magnetic field except in unconventional cases such as in the kagome system, for which there are preliminary indications of an exotic chiral CDW state (presumably carrying local orbital currents) that reverses chirality in field. This leaves us with two unexplained phenomena: the suppression of the CDWs with magnetic field; and the asymmetric behaviour of the two mirror-symmetry-related CDWs with field. To provide a possible explanation for our data, we construct a Ginzburg–Landau theory that considers a triplet superconductor suggested by the symmetries of UTe$_2$. We construct a model for multi-component triplet PDW order that coexists with a uniform triplet superconductor order. In this scenario, the multi-component CDW occurs as a ‘daughter’ order of the superconducting orders:

$$\rho_{q_{\text{CDW}}} \propto \Delta_{q_{\text{CDW}}} \cdot \Delta_0 + \Delta_0 \cdot \Delta_{-q_{\text{CDW}}} + h.c.,$$

in which $\Delta_{q_{\text{CDW}}}$ is the PDW order parameter with wavevector $\pm q_{\text{CDW}}$, and $\Delta_0$ is the uniform triplet superconductivity order parameter.

A Ginzburg–Landau theory analysis of these orders leads to the following conclusions: above the upper critical field of the superconducting orders, the PDW and uniform superconducting orders are suppressed, as are the daughter CDWs; owing to the triplet nature of the superconducting order parameter, the critical magnetic field is direction dependent; and as $\Delta_{q_{\text{CDW}}}$ and $\Delta_{-q_{\text{CDW}}}$ are related by mirror symmetry, one of the two corresponding mirror-related CDWs may be more suppressed than the other when mirror symmetry is broken by an external magnetic field. A coexisting triplet PDW order is therefore a possible explanation for the unusual magnetic field response of the CDWs as seen in our experiments.

Discussion

It is important to consider whether there might be other explanations for our data. There are in fact very few alternative explanations for a CDW that is sensitive to magnetic fields. Two other possibilities are that the CDW is a daughter order of a spin density wave, or that the CDW itself has a finite angular momentum, similar to what has been observed in kagome superconductors. Although both of these scenarios might explain the dependence of the CDW on a magnetic field, they each have limitations. First, no static magnetic order has been observed in UTe$_2$ by other experimental probes, which makes the spin density wave explanation unlikely. Second, the fact that the critical field for the CDW...
Suppression is close to the critical field of the superconductor is difficult to explain with either the spin density wave or the finite angular momentum CDW possibility. In a nutshell, although our data are most consistent with the existence of a triplet PDW state in UTe₂, additional theory as well as experimental tests are important to unequivocally establish this scenario. We note here that as scanning tunnelling microscopy probes the surface, the natural question is whether these orders are also observed in the bulk. This calls for bulk measurements such as low-temperature X-ray scattering measurements.

There are two further points to mention. Our preliminary temperature-dependent measurements indicate that the CDW (as seen in the FFT) survives to 4 K and disappears somewhere between 4 K and 10 K (Extended Data Fig. 11). This is not inconsistent with the PDW scenario, as the PDW can melt to a CDW phase, which can survive at higher temperatures. A more detailed discussion of this question is presented in the Methods. The other question concerns the identification of the observed peaks with the primary ordering peaks (1Q) or their linear combinations (2Q). The peaks we observe may represent the primary 1Q peaks as we do not see any peaks at smaller q vectors in the FFT. Consistent with this, all linear combinations of the primary peaks and Bragg peaks are also observed in our data (see Extended Data Fig. 4).

To conclude, we report the observation of multi-component, incommensurate CDW order coexisting with superconductivity in UTe₂. Strikingly, we observe that the CDWs are strongly affected by an external magnetic field and vanish at the Hc₂ of the superconducting order. This last observation clearly implies that the CDW and superconducting order parameters are not merely coexisting but are in fact strongly coupled. This, combined with the established presence of a uniform triplet order, may indicate that the superconducting state of UTe₂ has a triplet PDW component, which necessitates strong interactions.

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In this section, we consider a Ginzburg–Landau theory of three triplet PDWs coexisting with uniform triplet superconductivity in a material with \( D_{\text{xy}} \) symmetry (the same symmetry as UT\(_2\)). As we shall show, this theory leads to daughter CDWs that are suppressed in a magnetic field. Furthermore, when the triplet superconducting orders have finite angular momentum, the suppression is anisotropic, and uneven for different CDWs. This theory is applicable to the situation in which the superconducting, PDW and CDW orders are bulk orders of UT\(_2\), as well as the situation in which they are surface orders.

Ginzburg–Landau theory

In this section, we consider a Ginzburg–Landau theory of three triplet PDWs coexisting with uniform triplet superconductivity in a material with \( D_{\text{xy}} \) symmetry. Here we shall consider both case in which the PDW and CDW are bulk orders and the case in which they are surface orders. Our Ginzburg–Landau-based analysis applies equally well to both situations. In both cases, our theory predicts the existence of ‘daughter’ CDWs that are suppressed in an external magnetic field.

Snelling tunnelling microscopy experiments

Single crystals of UT\(_2\) were used. The growth and characterization are mentioned in detail elsewhere\(^1\). Samples were cleaved in situ at about 90 K and in an ultrahigh-vacuum chamber. After cleaving, the samples were directly transferred to the scanning tunnelling microscope (STM) head. STM measurements were carried out using a Unisoku STM at an instrument temperature of 300 mK (unless otherwise specified) using chemically etched and annealed tungsten tips. The temperature values reported were measured in the \(^3\)He pot; the actual sample temperature could be slightly higher. \( dI/dV \) spectra were collected using a standard lock-in technique at a frequency of 913 Hz.

Ginzburg–Landau description of the triplet PDWs

In this section we consider a Ginzburg–Landau description of triplet PDWs coexisting with a uniform triplet superconductor in a material with the same symmetries as UT\(_2\). Here we shall consider both the case in which the PDW and CDW are bulk orders and the case in which they are surface orders. Our Ginzburg–Landau-based analysis applies equally well to both situations. In both cases, our theory predicts the existence of ‘daughter’ CDWs that are suppressed in an external magnetic field.

The triplet PDW

Before considering the full Ginzburg–Landau theory, it will be useful to give an overview of the triplet PDW state. In real space, we expand the local triplet Cooper pair amplitude as

\[
\langle c_{\sigma}(r) c_{\sigma}(r') \rangle = i [r_i \tau_{j\alpha}, [\Delta_0(r-r') + \sum Q \Delta_Q(r-r') e^{iQ(r-r')/2}]],
\]

in which \( \tau_i \) (with \( i = x,y, z \)) are the two 2 \( \times \) 2 Pauli matrices, \( r \) and \( r' \) label the coordinates of the two electrons that form the Cooper pair, and the possible ordering wavevectors (and their harmonics) are given by \( Q \). Here \( \Delta_0 \) is the uniform triplet superconductor, and \( \Delta_Q \) is the triplet PDW with wavevector \( Q \). Equation (1) is applicable to both two-dimensional and three-dimensional systems. In the context of UT\(_2\), \( \Delta_0 \) and \( \Delta_Q \) describe surface orders if \( r, r' \) and \( Q \) label positions and momentum on the surface of UT\(_2\). Similarly, \( \Delta_0 \) and \( \Delta_Q \) correspond to bulk orders if \( r, r' \) and \( Q \) label bulk positions and momentum.

Owing to the fermion anti-commutation relationships, \( \Delta_0 \) and \( \Delta_Q \) must be odd functions of \( r - r' \). In momentum space, the above equation becomes

\[
\langle c_{\sigma}(q+2\mathbf{k}) c_{\sigma}(q-2\mathbf{k}) \rangle = i [\tau_i \tau_{j\alpha}, [\Delta_0(k\delta^2(q) + \sum Q \Delta_Q(k\delta^2(q-Q))]],
\]

in which \( k \) is the relative momentum of the two electrons, \( q \) is the total momentum of the Cooper pairs, and \( \delta \) is the Dirac delta function. The vectors \( \Delta_0 \) and \( \Delta_Q \) are both odd functions of \( k \). In the limit in which \( Q \to 0 \), \( \Delta_Q \) is equivalent to the uniform triplet superconductor \( \Delta_0 \). The PDW state has the same periodic modulation of a Larkin–Ovchinnikov superconducting state\(^2\) but in the absence of an external magnetic field (that is, without explicit breaking of time reversal invariance), and the period of the PDW is thus not tuned by an external magnetic field (for a review see ref. 25).

In a real material, \( \Delta_0 \) and \( \Delta_Q \) should form parity-odd irreducible representations (irreps) of the crystal space group. If we take \( \Delta_0 \) and \( \Delta_Q \) to be bulk orders of UT\(_2\), then they should form irreps of \( D_{\text{xy}} \) (the space group of UT\(_2\)). \( D_{\text{xy}} \) is characterized by three mirror symmetries, \( M_x, M_y \), and \( M_z \), (it is also possible to equivalently characterize \( D_{\text{xy}} \) in terms of three \( C_2 \) rotations). There are four parity-odd irreps of \( D_{\text{xy}} \) (ref. 43), which are referred to as \( A_u, B_u, B_x \) and \( B_y \). Their transformation properties of the triplet PDW, \( \Delta_Q \), under \( M_i \) are

\[
M_i : \Delta_Q \rightarrow M_{iQ} \quad \text{for} \quad \Delta_Q \in B_u, B_x,
\]

\[
M_i : \Delta_Q \rightarrow -M_{iQ} \quad \text{for} \quad \Delta_Q \in A_u, B_y,
\]

in which \( M_{iQ} \) is the \( M_i \) mirror-transformed wavevector \( Q \). The transformation properties under \( M_i \) are

\[
M_i : \Delta_Q \rightarrow \Delta_{M_{iQ}} \quad \text{for} \quad \Delta_Q \in B_u, B_x,
\]

\[
M_i : \Delta_Q \rightarrow -\Delta_{M_{iQ}} \quad \text{for} \quad \Delta_Q \in A_u, B_y.
\]

The transformation properties under \( \Delta_0 \) are

\[
\Delta_0 : \Delta_Q \rightarrow \Delta_{\Delta_{0Q}} \quad \text{for} \quad \Delta_Q \in B_u, B_x,
\]

\[
\Delta_0 : \Delta_Q \rightarrow -\Delta_{\Delta_{0Q}} \quad \text{for} \quad \Delta_Q \in A_u, B_y.
\]

The transformation properties of the uniform component, \( \Delta_0 \), are related to those above by taking \( Q = M_{iQ} \). If \( M_{iQ} \) are surface orders of UT\(_2\), their transformation properties can be understood by projecting the bulk irreps onto the surface.

Ginzburg–Landau theory

In this section, we consider a Ginzburg–Landau theory of three triplet PDWs coexisting with uniform triplet superconductivity in a material with \( D_{\text{xy}} \) symmetry. Here we shall show that this theory leads to daughter CDWs that are suppressed in a magnetic field. Furthermore, when the triplet superconducting orders have finite angular momentum, the suppression is anisotropic, and uneven for different CDWs. This theory is applicable to the situation in which the superconducting, PDW and CDW orders are bulk orders of UT\(_2\), as well as the situation in which they are surface orders.

As \( M_i \) mirror symmetry is the only symmetry preserved by the cleave surface, we will primarily consider the transformation properties of the order parameters under \( M_i \). On the cleave surface, mirror symmetry acts as \( M_i : q_{\text{CDW}} \rightarrow -q_{\text{CDW}} \) and \( M_i : q_{\text{CDW}} \rightarrow -q_{\text{CDW}} \). Therefore, \( M_i : Q_1 \rightarrow -Q_2 \) and \( M_i : Q_3 \rightarrow -Q_3 \) regardless of whether we are considering surface orders or bulk orders.

The Landau free-energy density for \( \Delta_0 \) and \( \Delta_{iQ} \) is given by

\[
\mathcal{F} = \mathcal{F}_2 + \mathcal{F}_3,
\]

\[
\mathcal{F}_2 = m_0 |\Delta_0|^2 + \sum Q m(Q(|\Delta_Q|^2 + |\Delta_{-Q}|^2)),
\]

\[
\mathcal{F}_3 = \lambda_{00} |\Delta_0|^4 + \sum Q \lambda_{0Q} (|\Delta_Q|^4 + |\Delta_{-Q}|^4 + |\Delta_Q|^2 |\Delta_{-Q}|^2 + |\Delta_{-Q}|^2 |\Delta_Q|^2) + \sum_Q \lambda_{iQ} (|\Delta_Q|^4 + |\Delta_{-Q}|^4 + |\Delta_Q|^2 |\Delta_{-Q}|^2 + |\Delta_{-Q}|^2 |\Delta_Q|^2)
\]

(6)

Here \( \lambda_{ij} = \lambda_{ji} \). Owing to mirror symmetry, \( m_i = m_2 \), \( \lambda_{00} = \lambda_{02} \), \( \lambda_i = \lambda_{-i} \), and \( \lambda_{ij} = \lambda_{ji} \). For stability, \( \lambda_{00} > 0 \). To favour coexistence of the superconducting order parameters, \( \lambda_{ij} < 0 \) for all \( i, j \neq 0 \) for \( i \neq j \) and \( \lambda_{ij} < 0 \) for all \( i \) and \( j \). In this section, we are interested only in the values of the order parameters in different phases, and not, for example, in the details of the phase transitions that connect different phases. As a
result, equation (6) can describe either bulk orders (if the $Q_i$ are bulk wavevectors) or surface orders (if the $Q_i$ are surface wavevectors).

In the ordered phase, for which $\Delta_{q_0}$ and $\Delta_{q_0}\cdot Q_i$ all have expectation values ($m_i$, $m_i < 0$), there will be daughter CDW orders

$$\rho_{q_0} \propto \Delta_{q_0} \cdot \Delta_{q_0} + \Delta_{q_0} \cdot \Delta_{q_0}^*,$$

$$\rho_{q_0, Q_i} \propto \Delta_{q_0} \cdot \Delta_{q_0}^* + a_{q_0} \rho_{q_0} \rho_{Q_i},$$

$$\rho_{Q_i, q_0} \propto \Delta_{q_0} \cdot \Delta_{q_0}^* + b_{q_0} \rho_{q_0} \rho_{Q_i}.$$ (7)

in which $a_{q_0}$ and $b_{q_0}$ are constants, and the CDW order parameters $\rho_{q_0}$ are a complex scalar field that satisfies $\rho_{q_0}^* = \rho_{q_0}^{-1}$. If we are considering bulk orders, then on the cleave surface, the CDW operators project onto surface CDW operators $\rho_{q_0} \rightarrow \rho_{q_0, \text{surf}}$ and $\rho_{q_0, Q_i} \rightarrow \rho_{q_0, \text{surf}} \cdot \rho_{Q_i, \text{surf}}$. If we are considering surface orders, then $Q_i = q_i, \text{surf}$ and $Q_i = q_i, \text{surf} \pm q_i, \text{FW}^\prime$ in equation (7).

In this Landau theory, the daughter orders arise from the following terms

$$\mathcal{F}_{\text{CDW}} = \sum_i m_{i, \text{surf}}^2 \rho_{i, \text{surf}}^2 + \sum_j m_{j, \text{surf}}^2 \rho_{j, \text{surf}}^2 + \sum_j m_{j, \text{surf}}^2 \rho_{j, \text{surf}}^2 + \sum_j \rho_{j, \text{surf}} \rho_{j, \text{surf}}^* \rho_{j, \text{surf}} \rho_{j, \text{surf}}^* + \sum_j \rho_{j, \text{surf}} \rho_{j, \text{surf}}^* \rho_{j, \text{surf}} \rho_{j, \text{surf}}^* + \lambda_{ij} \rho_{i, \text{surf}} \rho_{j, \text{surf}} \rho_{j, \text{surf}} \rho_{i, \text{surf}} + \text{h.c.},$$ (8)

in which $m_{i, \text{surf}}$, $m_{j, \text{surf}}$, $m_{j, \text{surf}}$ are positive. For brevity, we have omitted the quartic terms from $\mathcal{F}_{\text{CDW}}$, although such terms are allowed by symmetry. We should note that if one considers the case of a system with CDW and uniform superconducting coexistent orders, then a modulated (PDW) component would be induced by the first of the cubic terms. Thus, the Landau theory does not distinguish these two scenarios. This will be discussed in more detail towards the end of this section.

We now add an external magnetic field $H$ to the Landau theory. If we include a gradient term in the free-energy expansion, the magnetic field minimally couples to the superconducting orders as

$$\mathcal{F}_{\text{Max}} = -e_v \mathbf{H} \cdot (\Delta_0 \times \Delta_0) - \sum_j e_{j} \mathbf{H} \cdot (\Delta_{j, \text{surf}} \times \Delta_{j, \text{surf}}) - \sum_j e_{j} \mathbf{H} \cdot (\Delta_{j, \text{surf}} \times \Delta_{j, \text{surf}})^*.$$ (9)

Here $e_v$, $e_j > 0$ and the field symmetry requires that $e_1 = e_2$. For time-reversal-invariant systems, the angular momenta all vanish. However, if time-reversal symmetry is broken, the angular momentum can be non-vanishing, $(\Delta_0 \times \Delta_0)^* \neq 0$. As $e_v$, $e_j > 0$, it is energetically favourable for the angular momentum to align with the magnetic field. Here, non-vanishing angular momentum also requires the order parameters to be sums of different irreps (for bulk orders) or sums of different surface-projected irreps (for surface orders). When the superconducting order parameters are combinations of different irreps, each irrep should correspond to a distinct term in the Ginzburg–Landau theory. Nevertheless, for simplicity, we have assumed that the Ginzburg–Landau theory can be written in terms of the superconducting orders $\Delta_0$ and $\Delta_{j, \text{surf}}$ instead of the distinct irreps. This simplification does not reflect the fact that different irreps will, in general, transition at different temperatures. However, as we are interested in physics that is far away from any transitions, this additional feature does not change the qualitative features of our analysis.

Owing to the minimal coupling between the superconducting orders and $\mathcal{A}$, the superconducting orders are suppressed in an external magnetic field, and above an upper critical field the superconducting orders (and by extension the daughter CDW orders) will vanish. The Ginzburg–Landau theory therefore correctly predicts the suppression of the CDW orders in an external magnetic field. Owing to the coupling between the angular momentum and magnetic field, the upper critical field will be higher when the magnetic field is aligned with the angular momentum of a superconducting order and lower when they are anti-aligned.

In this case, for $H_x > 0$ or $H_z < 0$, the $\Delta_{q_0}$ PDW will be more suppressed than the $\Delta_{q_0}$ PDW or vice versa. Which of the two is more suppressed depends on the sign and magnitude of $H_x$ and $H_z$. This agrees with the observed mirror-symmetry breaking.

We note that the Ginzburg–Landau theory predicts existence of both $\rho_{q_0}$ and $\rho_{q_0, Q_i}$ daughter CDWs. Both types of CDW are observed in UT e2, in which $\rho_{q_0}$ CDWs are primary orders and the PDWs occur as daughter orders. To do this, let us first assume that the PDWs are not primary orders (that is, the PDW masses $m_i$ are positive). We also need to include the following quartic CDW terms

$$\mathcal{F}_{\text{PDW}} = \sum_j \lambda_{j, \text{PDW}} |\rho_{j, \text{surf}}|^4 + \ldots.$$ (10)

in which the $\rho_{j, \text{surf}}$ CDWs would be the dominant charge orders, as $\rho_{j, \text{surf}}$ is linear in the PDW order parameters, whereas $\rho_{q_0, Q_i}$ is quadratic in PDWs. The Ginzburg–Landau theory presented here can also be adapted to describe the situation in which the uniform superconductivity and CDWs are primary orders and the PDWs occur as daughter orders. To do this, we first assume that the CDWs are not primary orders (that is, the PDW masses $m_i$ are positive). We also need to include the following quartic CDW terms

$$\mathcal{F}_{\text{PDW}} = \sum_j \lambda_{j, \text{PDW}} |\rho_{j, \text{surf}}|^4 + \ldots.$$ (11)

In this case, the $\rho_{j, \text{surf}}$ CDWs would be the dominant charge orders, as $\rho_{j, \text{surf}}$ is linear in the PDW order parameters, whereas $\rho_{q_0, Q_i}$ is quadratic in PDWs.

The Ginzburg–Landau theory presented here can also be adapted to describe the situation in which the uniform superconductivity and CDWs are primary orders and the PDWs occur as daughter orders. To do this, let us first assume that the PDWs are not primary orders (that is, the PDW masses $m_i$ are positive). We also need to include the following quartic CDW terms

$$\mathcal{F}_{\text{PDW}} = \sum_j \lambda_{j, \text{PDW}} |\rho_{j, \text{surf}}|^4 + \ldots.$$ (12)

in which the... indicates various bi-quadratic terms between different CDW orders and the superconducting and PDW orders. We take the bi-quadratic terms to be tuned such that they favour coexistence of the uniform superconductivity and CDW orders. When $m_i^2 > 0$ and $\lambda_{j, \text{PDW}} > 0$, the CDW order parameter $\rho_{j, \text{surf}}$ acquires a non-vanishing expectation value. If the uniform superconductivity $\Delta_\sigma$ coexists with the CDWs, the PDW order parameters $\Delta_{j, \text{surf}}$ will acquire expectation values because of the tri-linear terms in equation (8). This leads to the correct intertwined orders. However, this scenario does not explain why the CDWs are suppressed in an external magnetic field, as the charge-neutral CDW order parameters do not minimally couple to $A_\sigma$.

Melting the PDWs and uniform superconductivity

Finally, we briefly discuss the potential role of vortices in the destruction of the PDWs and the uniform superconductivity. Let us consider the situation in which the PDWs and the uniform superconductivity share the same vortices. These vortices proliferate, the expectation values of the PDWs and the uniform superconductivity all vanish.

In large phase wind that has a multiple of $2\pi$ around the vortices. Here all of the PDWs and the uniform superconductivity share the same vortices. When these vortices proliferate, the expectation values of the PDWs and the uniform superconductivity all vanish.
However, the vortex proliferation does not cause the expectation values of the CDWs to vanish, as \( \rho_{\text{CDW}} \) does not depend on the vortex phase \( \theta_v \) (see equation (7)). As such, proliferation of the vortex in equation (13) leads to a phase in which the daughter CDW orders persist in the absence of the parent PDW and uniform superconducting orders. It is not clear at this stage whether this vortex proliferation accurately describes the destruction of superconductivity at \( T_c \) and the observation of CDWs at 4 K. However, our arguments do indicate that the observation of CDWs at 4 K is not inconsistent with the PDW scenario we have presented in this work.

Data availability
All of the data for the main figures have been uploaded to the Illinois Databank (https://doi.org/10.13012/B2IDB-1713879_V1).

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Author contributions A.A. and V.M. conceived the experiments. The single crystals were provided by S.R., S.R.S., J.P. and N.P.B. M.R. carried out the Laue characterization of the single crystals. A.A. and A.R. obtained the STM data. A.A. and V.M. carried out the analysis and J.M.-M., L.N. and E.F. provided the theoretical input on the interpretation of the data. A.A., V.M., J.M.-M. and E.F. wrote the paper with input from all authors.

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Extended Data Fig. 1 | Laue diffraction from the (011) aligned crystal. Laue diffraction of a single UTe₂ crystal which was used for the STM study is shown. A few specific \((hkl)\) surfaces are marked.

- Measured Laue diffraction pattern
- Simulated Laue diffraction pattern - \((0\bar{1}1)\) crystal plane
Extended Data Fig. 2 | LDOS at 300 mK. LDOS maps obtained at several energies above and below $E_F$. 
Extended Data Fig. 3 | FFT of LDOS at 300 mK. FFTs of LDOS maps obtained at several energies above and below $E_F$. 

FFT amplitude (a.u.)
Extended Data Fig. 4 | Inverse FFT of the CDW peaks, FFT showing primary and secondary CDW peaks and low energy dI/dV spectra. a, Topography obtained on the (011) surface (same area as that shown in Fig. 1c of the manuscript. Inset shows the corresponding FFT with the CDW peaks circled in orange. b, Inverse FFT obtained from the circled CDW peaks (in orange) allowing real space visualization of the CDW modulations. c, FFT at the $E_F$, where the primary and secondary CDWs are shown using red circles and blue circles respectively. d, Linecut of the dI/dV spectra (shown in grey) and the average dI/dV spectrum (shown in red) obtained along the Te-chains. Apart from the Fano lineshape associated with the Kondo resonance, the individual spectra and the average dI/dV spectrum show an additional low energy feature (slope change around $-1\,\text{meV}$ to $+2\,\text{meV}$) shown by the blue shaded region.
Extended Data Fig. 5 | LDOS in presence of a 10.5 T magnetic field. LDOS maps obtained at several energies in a perpendicular magnetic field.
Extended Data Fig. 6 | FFT of LDOS in presence of a 10.5 T magnetic field. FFTs of LDOS maps obtained at several energies in a perpendicular magnetic field.
Extended Data Fig. 7 | Partial suppression and mirror symmetry breaking of the CDWs in the integrated FFT signal. 

**a-b.** Comparison of FFTs of integrated signal obtained from integrating LDOS maps below $E_F$ for a 0 T field and 10.5 T field. The FFT of the integrated signal also shows similar behavior as the FFT of individual energy slices.

**c-e.** Linecuts obtained along 3 different directions for the 3 CDWs illustrating the mirror symmetry breaking. 

**d** is clearly more suppressed than **c.**
Extended Data Fig. 8 | Second and third sample-tip combinations for perpendicular magnetic field showing reproducibility of the partial suppression and mirror symmetry breaking of the CDW at 10.5 T.

**a**–**b**, Second dataset obtained with a different tip-sample combination showing the partial suppression and mirror symmetry breaking of the CDW in a perpendicular magnetic field. The FFTs shown have the same intensity scale. **c**–**g**, Series of FFT of topographies as a function of increasing magnetic field perpendicular to the [011] surface with a third sample-tip combination. (V = 20 mV, I = 100 pA) The intensity scale of all FFTs has been kept constant. The critical field for the mirror-symmetry breaking in $q_{CDW}^1$ and $q_{CDW}^2$ is close to 10 T.
Extended Data Fig. 9 | FFTs showing the suppression of the CDWs at positive bias in a 11-degree tilted magnetic field. a–c, Series of FFT of topographies obtained as a function of increasing magnetic field at 11 degrees with respect to the [011] direction with a different tip. (V = 40 mV, I = 120 pA). The intensity scale of all FFTs has been kept constant. The surface tilt is measured using the tilt correction function in the Nanonis module. d–f, Fourier transform linecuts obtained along 3 different directions of the CDWs as a function of magnetic field, showing clear suppression of the peak amplitudes above 9 T.
Extended Data Fig. 10 | Additional dataset with a different tip showing reproducibility of the suppression of the CDWs in a 11-degree tilted magnetic field. a–f. Additional dataset showing a series of FFT of topographies obtained as a function of increasing magnetic field at 11 degrees with respect to the [011] direction with a different tip. (V = 50 mV, I = 150 pA). The intensity scale of all FFTs has been kept constant. The surface tilt is measured using the tilt correction function in the Nanonis module.
Extended Data Fig. 11 | Melting of the CDWs as a function of temperature. a–c, FFTs of LDOS maps obtained as a function of temperature. The CDWs persist till 4 K and have disappeared by 10 K.