

Intertwining bulk and surface: The case of UTe_2 András L. Szabó^{1,*} and Aline Ramires^{2,‡}¹*Institute for Theoretical Physics, ETH Zurich, 8093 Zurich, Switzerland*²*Laboratory for Theoretical and Computational Physics, PSI Center for Scientific Computing, Theory, and Data, Paul Scherrer Institute, 5232 Villigen PSI, Switzerland*

(Received 22 April 2025; accepted 28 December 2025; published 11 February 2026)

UTe_2 has been the focus of numerous experimental and theoretical studies in recent years, as it is recognized as one of the few odd-parity bulk superconductors. Its surface has also been probed, revealing charge density wave (CDW), pair density wave, and time-reversal symmetry breaking (TRSB). Here, we propose that the interplay between bulk and surface order parameters in UTe_2 may be crucial in explaining its unusual surface properties. Through a phenomenological analysis, assuming a dominant CDW, we can account for three distinctive experimental signatures: (1) the apparent suppression of CDW order at the upper critical field of the bulk superconducting state; (2) the magnetic-field-induced imbalance of the Fourier peaks associated with the CDW; and (3) the onset of TRSB with bulk superconductivity and its field trainability. Furthermore, we propose specific experiments to validate our conjecture, which we believe could be promptly achieved.

DOI: [10.1103/nbq1-5p1d](https://doi.org/10.1103/nbq1-5p1d)

Introduction. Modulated orders in the charge, spin, and superconducting sectors are ubiquitous in strongly correlated systems and are associated with a plethora of nontrivial phenomena such as intertwined and vestigial orders [1,2]. Focusing on the superconducting state, modulated orders are known as pair-density waves (PDWs) [3]. When PDWs are the primary orders, they can induce multiple secondary orders with a remarkable interplay of topological defects [4–6]. PDWs can also emerge as secondary or induced orders, in which case their symmetries can reveal signatures of the underlying primary orders that could otherwise be hard to detect.

PDWs have been primarily characterized by scanning tunneling microscopy (STM), an intrinsically surface-sensitive technique. STM experiments originally reported PDWs in high-temperature cuprate superconductors [7–9]. Most recently, NbSe_2 , a transition-metal dichalcogenide [10], and CsV_3Sb_5 , a hexagonal kagome material [11] have been reported to host exotic PDWs. Most notable is the case of UTe_2 , for which STM experiments have reported a PDW [12] and an unusual magnetic-field-dependent charge density wave (CDW) that seems to be suppressed at the bulk superconducting upper critical field H_{c2} [13,14]. While superconductivity is a well-established bulk phase in this material, x-ray and

thermodynamic measurements failed to identify signatures of CDW in the bulk [15–17].

A growing body of experimental evidence indicates that UTe_2 is an odd-parity spin-triplet bulk superconductor [18–20]. While muon spin relaxation/rotation measurements indicate an absence of time-reversal symmetry breaking (TRSB) in the bulk [21,22], signatures of field-trainable polar Kerr effect are consistent with TRSB on the surface [23–25]. A TRSB superconducting order parameter generally requires a multicomponent order parameter. However, the low, orthorhombic symmetry of UTe_2 does not host higher-dimensional irreducible representations (irreps) supporting multicomponent order parameters. In this light, theoretical works have proposed a variety of accidental degeneracies or coexistence of symmetry-distinct homogeneous superconducting order parameters to account for the unusual phenomenology of UTe_2 from the bulk perspective [26,27].

Initial theory accounting for the surface modulated orders proposed a dominant PDW and a vestigial CDW [13]. Here, we take an alternative approach: We assume the CDW to be a primary order on the surface, which intertwines with the bulk homogeneous single-component superconducting order parameter to give rise to a multicomponent surface PDW. Using a phenomenological Landau theory, we address the suppression of CDW order as a function of magnetic field, unravel the origin of the increased imbalance of the Fourier peaks capturing modulated orders in STM experiments in the presence of external magnetic fields, and propose a scenario for TRSB superconductivity based on the surface PDW.

Symmetry considerations. UTe_2 is a three-dimensional heavy-fermion system crystallizing in space group I/mmm (No. 71), with a body-centered orthorhombic structure [28]. STM experiments have probed the easy-cleave $(0\bar{1}1)$ surface, characterized by wallpaper group cm , which includes a mirror operation M_y , with normal along the y direction (a axis in the bulk) [see Fig. 1(a)]. The primitive lattice vectors

*Present address: Max Planck Institute for Solid State Research, D-70569 Stuttgart, Germany.

†Contact author: a.szabo@kfz.mpg.de

‡Present address: Institute of Solid State Physics, TU Wien, 1040 Vienna, Austria.

§Contact author: aline.ramires@tuwien.ac.at

Published by the American Physical Society under the terms of the Creative Commons Attribution 4.0 International license. Further distribution of this work must maintain attribution to the author(s) and the published article's title, journal citation, and DOI.

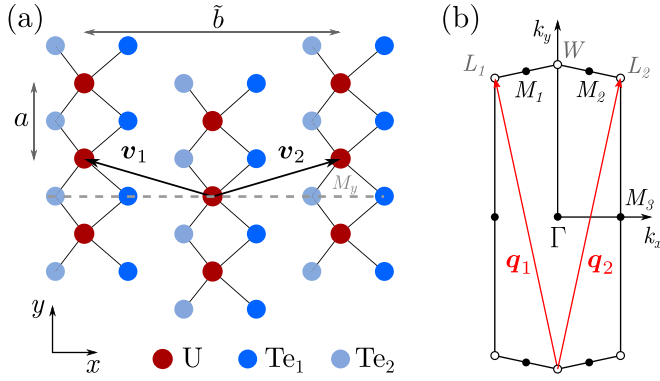


FIG. 1. (a) Easy-cleave surface of UTe_2 , where $\tilde{b} = \sqrt{b^2 + c^2}$, with a , b , and c the bulk lattice constants. The basis vectors $\mathbf{v}_1$ and $\mathbf{v}_2$ are indicated by the black arrows. The dashed gray line indicates the M_y mirror plane. (b) Surface BZ highlighting high-symmetry points (filled circles) and other relevant points (open circles). The reciprocal lattice vectors $\mathbf{q}_1$ and $\mathbf{q}_2$ are indicated by the red arrows.

$\mathbf{v}_{1,2} = (\mp\tilde{b}/2, a/2)$, where a and $\tilde{b}$ are the surface lattice parameters, span a centered rectangular lattice, resulting in an elongated hexagonal Brillouin zone (BZ), with three high-symmetry points, $M_{1,2,3}$ [see Fig. 1(b)]. In addition to the high-symmetry points, we also label the vertices of the BZ as W and $L_{1,2}$ following the notation in Aishwarya and coworkers [13,29].

The CDW order observed at the UTe_2 surface has been associated with incommensurate wave vectors $\mathbf{Q}_{i=0,1,2}$ near the W and $L_{1,2}$ points of the BZ, respectively. Note that some of these wave vectors are related by reciprocal lattice vectors (RLVs) $\mathbf{q}_{1,2} = 2\pi(\mp 1/\tilde{b}, 1/a)$, as $\pm\mathbf{Q}_{1,2} = \mp\mathbf{Q}_0 \pm \mathbf{q}_{1,2}$. The observed modulated orders, therefore, correspond to multiple “harmonics” of a two-component order parameter, related by RLVs. For the discussions associated with global symmetries, it suffices to focus only on two independent wave vectors, which we choose to be $\mathbf{Q}_0$ and $-\mathbf{Q}_0 = M_y\mathbf{Q}_0$, associated with the two-component CDW order parameter $\Delta_0 = (\Delta_{+\mathbf{Q}_0}, \Delta_{-\mathbf{Q}_0})$, leading to a spatial charge distribution following $\Delta(\mathbf{r}) = \Delta_{+\mathbf{Q}_0}e^{i\mathbf{Q}_0\cdot\mathbf{r}} + \Delta_{-\mathbf{Q}_0}e^{-i\mathbf{Q}_0\cdot\mathbf{r}}$.

Landau theory. We start the phenomenological description of the surface with the CDW order, which has the highest onset temperature with $T_{c,\Delta} \approx 12\text{ K}$ [14]. Choosing $\pm\mathbf{Q}_0$ as the representative harmonics, in addition to the CDW order parameter Δ_0 , a modulated current order parameter $\Delta'_0 = (\Delta'_{+\mathbf{Q}_0}, \Delta'_{-\mathbf{Q}_0})$ is induced in the presence of a magnetic field. Here, Δ_0 and Δ'_0 are, respectively, even and odd under time-reversal symmetry (TRS), such that $\Delta_{+\mathbf{Q}_0}^* = \Delta_{-\mathbf{Q}_0}$ and $\Delta_{+\mathbf{Q}_0}'^* = -\Delta_{-\mathbf{Q}_0}'$. In addition to being odd under TRS, magnetic field contained in the mirror plane $\mathbf{B}_{\parallel M} = (B_x, 0, B_z)$ is odd, while field perpendicular to the mirror $\mathbf{B}_{\perp M} = (0, B_y, 0)$ is even under M_y . For the sake of simplicity, we set $B_x = 0$ from here on. The Landau free energy in the charge-current sector up to fourth order reads

$$F_\Delta = \frac{\alpha}{2}|\Delta_0|^2 + \frac{\beta}{4}|\Delta_0|^4 + \frac{\alpha'}{2}|\Delta'_0|^2 + \frac{\beta'}{4}|\Delta'_0|^4 + \lambda B_y \Delta_0^\dagger \Delta'_0 + \eta B_z \Delta_0^\dagger \sigma_3 \Delta'_0 + B_z^2 \left(\frac{\zeta}{2}|\Delta_0|^2 + \frac{\zeta'}{2}|\Delta'_0|^2 \right), \quad (1)$$

where $\alpha^{(\prime)} = \alpha^{(\prime)}(T - T_{c,\Delta^{(\prime)}})$, with $T_{c,\Delta^{(\prime)}}$ the critical temperature of the pure charge (current) density wave. σ_i are Pauli matrices, and we assume the phenomenological coefficients $\alpha^{(\prime)}, \beta^{(\prime)}, \zeta^{(\prime)}, \lambda, \eta > 0$. We also assume there is no spontaneous transition to a phase with $|\Delta'_0| \neq 0$ in absence of magnetic field, such that $\alpha' > 0$.

In the superconducting sector, we assume a single-component homogeneous bulk order parameter $\Psi_b = |\Psi_b|e^{i\phi_b}$, which may be even or odd under M_y , and write its free energy as

$$F_\Psi = \alpha_b|\Psi_b|^2 + \beta_b|\Psi_b|^4 + \zeta_b B^2|\Psi_b|^2, \quad (2)$$

where $\beta_b > 0$, $\alpha_b = a_b(T - T_{c,\Psi})$, with $a_b > 0$. Here, $T_{c,\Psi} \approx 1.5\text{ K}$ is the bulk superconducting critical temperature, about one order of magnitude smaller than $T_{c,\Delta}$, and $\zeta_b > 0$ captures the general suppression of the bulk superconducting state in the presence of an external magnetic field. The free energy also includes terms that couple both sectors discussed above, which read

$$F_{\Delta\Psi} = \tilde{\alpha}|\Psi_0|^2 + \tilde{\beta}_1|\Psi_0|^4 + \tilde{\beta}_2|\Psi_0^\dagger \sigma_3 \Psi_0|^2 + \rho B_z \Psi_0^\dagger \sigma_3 \Psi_0 + \frac{|\Psi_b|^2}{2}(\gamma|\Delta_0|^2 + \gamma'|\Delta'_0|^2) + \kappa(\Psi_b^* \Delta_0^\dagger \sigma_i \Psi_0 \pm \text{c.c.}). \quad (3)$$

Here, the $\gamma^{(\prime)}$ terms are simple biquadratic couplings of the CDW (current) and bulk superconducting orders, whereas the κ term describes the induction of a two-component PDW order parameter $\Psi_0 = (\Psi_{+\mathbf{Q}_0}, \Psi_{-\mathbf{Q}_0})$ with $\tilde{\alpha} > 0$, as we assume the PDW is not a stable phase in isolation. The ρ term captures the only linear coupling to magnetic field, and we keep terms up to fourth order in the PDW order parameters with $\tilde{\beta}_1 > 0$ and $\tilde{\beta}_1 + \tilde{\beta}_2 > 0$ for stability. The $\pm$ signs in the last line correspond to Ψ_b being even ($i = 0$) or odd ($i = 3$) under M_y .

Magnetic-field-dependent CDW. The Fourier peaks associated with the CDW at the surface of UTe_2 were reported to be rapidly suppressed under magnetic fields close to H_{c2} [13]. As the STM measurements probe a (real) amplitude modulation, the Fourier decomposition always yields equal weights for $\pm\mathbf{Q}_i$. To relate our results to measurable Fourier intensities, we introduce the gap magnitude $G_i^2 = \sum_{\tau=\pm} (|\Delta_{\tau\mathbf{Q}_i}|^2 + |\Delta'_{\tau\mathbf{Q}_i}|^2)$ resulting from the presence of modulated charge and (field-induced) current orders with ordering vector $\pm\mathbf{Q}_i$. Focusing on the harmonics at $\pm\mathbf{Q}_0$, we argue that the simplest explanation for the apparent suppression of CDW is that Δ_0 and Ψ_b are strongly and *attractively* coupled, corresponding to a large negative γ coefficient. In this scenario, the CDW survives up to magnetic fields larger than the bulk upper critical field, but the onset of bulk superconductivity leads to a boost of $|\Delta_0|$. Conversely, this feature can be interpreted as an apparent suppression of $|\Delta_0|$ at H_{c2} , which we explicitly show by numerically minimizing the free energy and plotting the resulting G_0 as a function B_z [see Fig. 2(a)]. Across this work, we measure the free energy in units of α^2/β , all order parameters and external fields in units of $\sqrt{|\alpha|/\beta}$, and use dimensionless phenomenological coefficients (specific values are given in the corresponding figure caption). Note that the Fourier components at $\pm\mathbf{Q}_{1,2}$ couple to the magnetic field

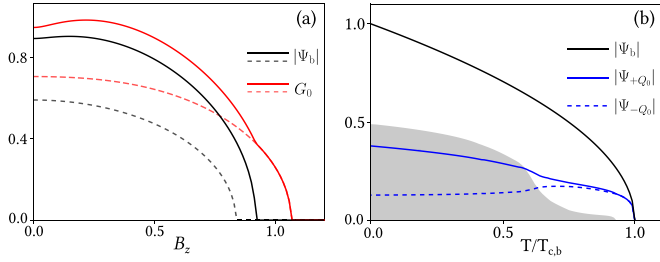


FIG. 2. (a) Evolution of bulk superconducting order, $|\Psi_b|$, and combined CDW and field-induced current order, G_0 , as a function of B_z . Dashed and solid lines correspond to $\gamma = \gamma' = 0$ (decoupled) and $\gamma/\beta = \gamma'/\beta = -1$ (attractively coupled), respectively. We used $\alpha'/|\alpha| = \beta'/\beta = \beta_b/\beta = \zeta'/\beta = \zeta_b/\beta = 1$ and $-\alpha_b/|\alpha| = \eta/\sqrt{|\alpha|\beta} = 0.5$. (b) TRSB via the imbalance of PDW components, $|\Psi_{\pm Q_0}|$. We quantify TRSB by $(|\Psi_{+Q_0}| - |\Psi_{-Q_0}|)/(|\Psi_{+Q_0}| + |\Psi_{-Q_0}|)$, shown as the shaded area. We used $|\Delta_0|/\sqrt{|\alpha|\beta} = -\alpha_b/|\alpha| = \beta_b/\beta = 1$, $\tilde{\alpha}/|\alpha| = \kappa/\sqrt{|\alpha|\beta} = 0.1$, $\tilde{\beta}_1/\beta = 1.3$, and $\tilde{\beta}_2/\beta = -1$.

via the same type of biquadratic term, describing a similar interplay, which we omit for the sake of simplicity.

TRSB superconductivity. In contrast to the single-component nature of the bulk superconducting order parameter, the intrinsic two-component nature of the PDW order parameter Ψ_0 could naturally lead to TRSB in the superconducting state. Crucially, in this case TRSB is constrained to the surface of UTe_2 , while in the bulk TRS is preserved, which could reconcile the observed field-trainable Kerr effect [23–25] with the apparent absence of TRSB in the bulk, probed by muons [21,22]. The spatial dependence of the PDW order parameter can be written as $\Psi_{\text{PDW}}(\mathbf{r}) = \Psi_{+Q_0}e^{i\mathbf{Q}_0 \cdot \mathbf{r}} + \Psi_{-Q_0}e^{-i\mathbf{Q}_0 \cdot \mathbf{r}}$. Parametrizing the two components in terms of an overall magnitude $|\Psi_0|$, an angle θ controlling their relative magnitude, and angles $\phi_{\pm}$ capturing their phases as $\Psi_{+Q_0} = |\Psi_0| \cos \theta e^{i\phi_+}$ and $\Psi_{-Q_0} = |\Psi_0| \sin \theta e^{i\phi_-}$ ($0 \leq \theta \leq \frac{\pi}{2}$), we can write explicitly

$$\Psi_{\text{PDW}}(\mathbf{r}) = |\Psi_0|e^{i\frac{(\phi_+ + \phi_-)}{2}} \left[\cos \theta e^{i\mathbf{Q}_0 \cdot (\mathbf{r} + \frac{(\phi_+ - \phi_-)}{2|\mathbf{Q}_0|} \hat{\mathbf{Q}}_0)} + \sin \theta e^{-i\mathbf{Q}_0 \cdot (\mathbf{r} + \frac{(\phi_+ - \phi_-)}{2|\mathbf{Q}_0|} \hat{\mathbf{Q}}_0)} \right], \quad (4)$$

where $\hat{\mathbf{Q}}_0 = \mathbf{Q}_0/|\mathbf{Q}_0|$. In the absence of other orders, $(\phi_+ \pm \phi_-)/2$ could be removed by suitable choice of $\text{U}(1)$ gauge and origin. However, for an induced PDW, both degrees of freedom are defined with respect to the primary CDW and bulk superconducting orders. If we assume the choice of origin at a maximum of the CDW, and gauge out the phase of the bulk superconducting state, then $(\phi_+ - \phi_-)/2$ captures a phase shift in real space between the CDW and PDW patterns, and $(\phi_+ + \phi_-)/2$ corresponds to a nontrivial $\text{U}(1)$ phase relative to Ψ_b . Given these observations, Eq. (4) highlights that the PDW can break TRS either by a nontrivial $(\phi_+ + \phi_-)/2$, or due to an imbalance between the two components, namely, $\theta \neq \pi/4$.

Minimizing the total free energy $F = F_{\Delta} + F_{\Psi} + F_{\Delta\Psi}$ in the presence of both CDW and bulk superconductivity, we find that the PDW onsets as $|\Psi_0| \approx \kappa |\Psi_b| |\Delta_0| / \tilde{\alpha}$ (see the Supplemental Material [30]). While $\tilde{\beta}_2 > 0$ favors $\theta = \pi/4$, for negative $\tilde{\beta}_2$, a solution with $\theta \neq \pi/4$ is possible, which be-

comes energetically favorable for $\tilde{\beta}_2 < -\tilde{\alpha}^3/(8\kappa^2|\Psi_b|^2|\Delta_0|^2)$ [30], breaking TRS. To demonstrate this numerically, we minimize the free energy $F_{\Psi} + F_{\Delta\Psi}$ for zero magnetic field and with a CDW background $|\Delta_0|$ taken to be constant in temperature for $T/T_{c,\Psi} \leq 1$. We choose parameters satisfying the condition above at a finite T [see Fig. 2(b)]. Here, the two components $|\Psi_{\pm Q_0}|$ onset with equal magnitudes at $T_{c,\Psi}$, such that TRS is preserved; however, they deviate at a slightly lower temperature, leading to TRSB on the surface. Notice that the sign of the deviation, or equivalently the sign of $\theta - \pi/4$, is field trainable via the ρ term in Eq. (3), potentially explaining the field-trainable polar Kerr effect reported in Wei *et al.* [24]. Considering now the phases $\phi_{\pm}$, for Ψ_b even under M_y and $\kappa > 0$ ($\kappa < 0$), the PDW emerges with a π -(zero)-phase shift with respect to the CDW pattern in direct space. Conversely, for Ψ_b odd under M_y the two orders manifest with a $\pm\pi/2$ phase shift. For more details, see the Supplemental Material [30]. Note that among the odd-parity irreps of D_{2h} , $B_{1,2u}$ are even, while A_u and B_{3u} are odd under M_y , consistent with $0, \pi$, and $\pm\pi/2$ phase shift in direct space, respectively, the former in agreement with experimental results [12].

Imbalanced Fourier peaks. Finally, we address the observations related to the Fourier peaks of the CDW around the points $\pm L_{1,2}$ above the superconducting ordering temperature. To this end, we invoke “higher harmonics” of the CDW order parameter with momenta related by RLVs, $\pm \mathbf{Q}_{1,2} = \mp \mathbf{Q}_0 \pm \mathbf{q}_{1,2}$. As $M_y \mathbf{Q}_{1,2} = -\mathbf{Q}_{2,1}$, we organize the corresponding order parameter harmonics into “left” and “right” groups, reminiscent of their location in reciprocal space [see Fig. 1(b)]. We define $\Delta_L = (\Delta_{+Q_1}, \Delta_{-Q_2})$ and $\Delta_R = (\Delta_{+Q_2}, \Delta_{-Q_1})$, with the same symmetry properties as Δ_0 . The intrinsic contribution of order parameters with modulating momenta $\mathbf{Q}_{1,2}$ to the same two-component order parameter accounts for the strong cross-correlation between amplitude maps corresponding to Fourier peaks in the vicinity of $L_{1,2}$ reported in LaFleur *et al.* [14].

Accounting for these higher harmonics of the CDW, we can address the dependence of the corresponding Fourier peak amplitudes in the presence of magnetic field. In particular, $\pm \mathbf{Q}_1$ and $\pm \mathbf{Q}_2$ were reported to be suppressed at unequal rates as magnetic field is increased [13,31]. Previously, the asymmetry was attributed to the symmetry-breaking nature of the perpendicular field B_z , which is odd under M_y , the symmetry that relates $\mathbf{Q}_{1,2}$ to $-\mathbf{Q}_{2,1}$. However, any field $\mathbf{B}_{\parallel M}$ contained in the mirror plane preserves the combination of M_y and TRS, which relates $\mathbf{Q}_1$ and $\mathbf{Q}_2$, and protects their equal weight.

To address the origin of Fourier peaks imbalance, we write the free energy for the higher harmonics of the order parameters $\Delta_{L,R}^{(\prime)}$ as $F_{L,R} = F_{L,R}^0 + F_{L,R}^{B_z} + F_{L,R}^{B_y}$, with

$$F_{L,R}^0 = \sum_{i=L,R} \left(\frac{\alpha_{LR}}{2} |\Delta_i|^2 + \frac{\alpha'_{LR}}{2} |\Delta'_i|^2 + \frac{\beta_{LR}}{4} |\Delta_i|^4 \right) + (\eta_{LR} \Delta_R^{\dagger} \Delta_L - \eta'_{LR} \Delta_R^{\dagger} \Delta'_L + \text{H.c.}), \quad (5)$$

where $\eta_{LR}^{(\prime)} = (\eta_+^{(\prime)} - i\eta_-^{(\prime)})/2$ and we take $\alpha_{LR} < 0$, assuming $T < T_{c,\Delta}$ and $\eta_{LR}^{(\prime)} > 0$. We only include the simplest fourth-order term for stability, with $\beta_{LR} > 0$. As before, $\alpha'_{LR} > 0$, such that currents are only induced in the presence of a

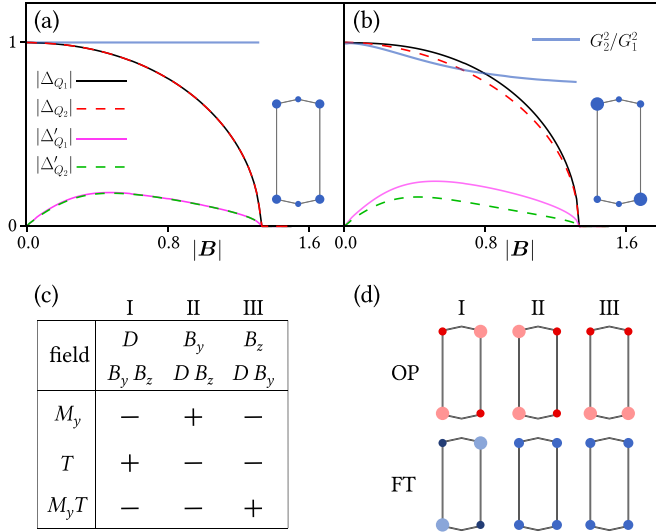


FIG. 3. (a), (b) Magnetic field evolution of charge and current order parameter amplitudes, and asymmetry of Fourier peaks, captured by the ratio G_2^2/G_1^2 (schematic in inset). We used $-\alpha_{LR}/|\alpha| = \alpha'_{LR}/|\alpha| = \beta_{LR}/\beta = \zeta/\beta = \zeta'/\beta = 1$, $\eta_{\pm}^{(i)}/|\alpha| = 0.5$, $v_{1,2}/\sqrt{|\alpha|\beta} = 0.2$, and normalized the order parameters with their zero-field amplitudes. In panels (a) and (b), $(\cos \chi \cdot \lambda_{L,R})/\sqrt{|\alpha|\beta} = 0$ and 0.1 , respectively. (c) Summary of the symmetry properties of external symmetry breaking fields and their bilinears. (d) Schematic representation of the order parameter (OP) and Fourier transform (FT) peak imbalance or lack thereof for each case identified in panel (c).

magnetic field. The evolution of $\Delta_{L,R}$ for finite B_z is captured by $F_{LR}^{B_z} = F_L^{B_z} + F_R^{B_z}$ with

$$F_{i=L,R}^{B_z} = B_z^2 \left(\frac{\zeta_{LR}}{2} |\Delta_i|^2 + \frac{\zeta'_{LR}}{2} |\Delta'_i|^2 \right) + B_z v_i \Delta_i^\dagger \sigma_3 \Delta'_i, \quad (6)$$

where $v_{L,R} = v_1 \pm i v_2$, and we assume $\zeta_{LR}^{(i)}, v_{1,2} > 0$. We minimize F_{LR} for a range of B_z [see Fig. 3(a)] and find $|\Delta_{Q_1}| = |\Delta_{Q_2}|$ and $|\Delta'_{Q_1}| = |\Delta'_{Q_2}|$, such that the gap amplitudes $G_{1,2}^2$ remain symmetric, $G_1^2/G_2^2 = 1$. A finite B_z , therefore, does not account for the Fourier peak asymmetry. This can be understood as B_z breaks both M_y and TRS, but preserves their product, which connects vectors $\mathbf{Q}_1$ and $\mathbf{Q}_2$.

To determine the origin of the Fourier peak asymmetry, we summarize the distinct types symmetry-breaking fields in Figs. 3(c)–3(d). B_z , which is odd under both M_y and TRS, is indicated as type III. In contrast, type I breaks only M_y and can be associated with spatial inhomogeneities whose distribution is not mirror symmetric on a finite field of view. Here, we account for this effect by a field D . Finally, type II breaks only TRS, associated with a magnetic-field component $B_y = B \sin \chi \neq 0$ perpendicular to the mirror plane (χ is the angle between the magnetic field and the mirror plane). For the asymmetry between peaks at $\mathbf{Q}_{1,2}$ to manifest, an effective field that breaks $M_y T$ symmetry is required. This can be achieved by either a single type I field (such as D), or the simultaneous presence of a type II and a type III field (such as B_z and B_y).

As an illustrative example, we focus on the case with the magnetic field tilted away from the mirror plane, where the field component B_y enters the free energy via

$$F_{LR}^{B_y} = B_y [\lambda_L \Delta_L^\dagger \Delta'_L - \lambda_R \Delta_R^\dagger \Delta'_R], \quad (7)$$

where $\lambda_{L,R} = \lambda_1 \pm i \lambda_2$. Minimizing F_{LR} with $B_y, B_z \neq 0$, we find a field-induced splitting of $|\Delta_{\pm Q_{1,2}}|$, leading to a deviation of G_2^2/G_1^2 from one as a function of field [see Fig. 3(b)].

Discussion and outlook. In this Letter, we employed a symmetry-based phenomenological analysis to account for salient experimental observations on the surface of UTe_2 . We now summarize our results and propose targeted experiments to validate our proposal. First, we proposed an attractive coupling between the surface CDW and bulk superconducting orders as the origin of the apparent suppression of the CDW at the superconducting upper critical field. Such coupling between two phases positively renormalizes the nominal critical field and temperature of the subdominant order parameter. If the CDW is restricted to the surface, we expect superconductivity on the surface to be more robust than in the bulk. Comparing $T_{c,\psi}$ on the surface with that in the bulk could therefore be a test for this scenario.

We also propose a mechanism for TRSB superconductivity, based on the multicomponent nature of the induced PDW on the surface. If the presence of the CDW is surface dependent, our scenario can be tested by checking whether CDW and TRSB are simultaneously present on a given cleave plane. According to our proposal, surfaces without charge order (and, therefore, induced PDW) should not give rise to TRSB superconductivity. This could be verified by STM and polar Kerr effect experiments.

Finally, our symmetry analysis shows that the asymmetric field evolution of the Fourier peaks at $\mathbf{Q}_{1,2}$ cannot be simply attributed to the presence of magnetic field perpendicular to the surface. Rather, it relies on further symmetry breaking effects or on a tilt of the magnetic field out of the mirror plane. This scenario could be tested, for example, by sweeping the angle χ , upon which the asymmetry should be minimal for $\chi = 0$. Furthermore, we also expect weaker asymmetry if the Fourier transform is performed on a field of view with less inhomogeneities.

Altogether, our analysis provides a comprehensive account of the symmetries associated with order parameters emerging on the surface of UTe_2 and puts forward a scenario with intertwined orders emerging on the surface and in the bulk. While UTe_2 is still under intense experimental investigation [32–36], the tests we propose to prove this scenario could further our understanding of the surface physics of this material and have the potential to shed light on the outstanding puzzle surrounding the nature and origin of the TRSB in this fascinating compound.

Acknowledgments. A.L.S. is grateful for financial support from the Swiss National Science Foundation (SNSF) through Division II (No. 184739). A.R. also acknowledges financial support from the SNSF through an Ambizione Grant No. 186043.

Data availability. No data were created or analyzed in this study.

- [1] E. Fradkin, S. A. Kivelson, and J. M. Tranquada, *Colloquium: Theory of intertwined orders in high temperature superconductors*, *Rev. Mod. Phys.* **87**, 457 (2015).
- [2] R. M. Fernandes, P. P. Orth, and J. Schmalian, Intertwined vestigial order in quantum materials: Nematicity and beyond, *Annu. Rev. Condens. Matter Phys.* **10**, 133 (2019).
- [3] D. F. Agterberg, J. S. Davis, S. D. Edkins, E. Fradkin, D. J. Van Harlingen, S. A. Kivelson, P. A. Lee, L. Radzihovsky, J. M. Tranquada, and Y. Wang, The physics of pair-density waves: Cuprate superconductors and beyond, *Annu. Rev. Condens. Matter Phys.* **11**, 231 (2020).
- [4] D. F. Agterberg and H. Tsunetsugu, Dislocations and vortices in pair-density-wave superconductors, *Nat. Phys.* **4**, 639 (2008).
- [5] E. Berg, E. Fradkin, and S. A. Kivelson, Charge-4e superconductivity from pair-density-wave order in certain high-temperature superconductors, *Nat. Phys.* **5**, 830 (2009).
- [6] E. Berg, E. Fradkin, S. A. Kivelson, and J. M. Tranquada, Striped superconductors: How spin, charge and superconducting orders intertwine in the cuprates, *New J. Phys.* **11**, 115004 (2009).
- [7] M. H. Hamidian, S. D. Edkins, S. H. Joo, A. Kostin, H. Eisaki, S. Uchida, M. J. Lawler, E.-A. Kim, A. P. Mackenzie, K. Fujita, J. Lee, and J. C. S. Davis, Detection of a Cooper-pair density wave in $\text{Bi}_2\text{Sr}_2\text{CaCu}_2\text{O}_{8+x}$, *Nature (London)* **532**, 343 (2016).
- [8] W. Ruan, X. Li, C. Hu, Z. Hao, H. Li, P. Cai, X. Zhou, D.-H. Lee, and Y. Wang, Visualization of the periodic modulation of Cooper pairing in a cuprate superconductor, *Nat. Phys.* **14**, 1178 (2018).
- [9] S. D. Edkins, A. Kostin, K. Fujita, A. P. Mackenzie, H. Eisaki, S. Uchida, S. Sachdev, M. J. Lawler, E.-A. Kim, J. C. Séamus Davis, and M. H. Hamidian, Magnetic field-induced pair density wave state in the cuprate vortex halo, *Science* **364**, 976 (2019).
- [10] X. Liu, Y. X. Chong, R. Sharma, and J. C. S. Davis, Discovery of a Cooper-pair density wave state in a transition-metal dichalcogenide, *Science* **372**, 1447 (2021).
- [11] H. Chen *et al.*, Roton pair density wave in a strong-coupling kagome superconductor, *Nature (London)* **599**, 222 (2021).
- [12] Q. Gu, J. P. Carroll, S. Wang, S. Ran, C. Broyles, H. Siddiquee, N. P. Butch, S. R. Saha, J. Paglione, J. C. S. Davis, and X. Liu, Detection of a pair density wave state in UTe_2 , *Nature (London)* **618**, 921 (2023).
- [13] A. Aishwarya, J. May-Mann, A. Raghavan, L. Nie, M. Romanelli, S. Ran, S. R. Saha, J. Paglione, N. P. Butch, E. Fradkin, and V. Madhavan, Magnetic-field-sensitive charge density waves in the superconductor UTe_2 , *Nature (London)* **618**, 928 (2023).
- [14] A. LaFleur, H. Li, C. E. Frank, M. Xu, S. Cheng, Z. Wang, N. P. Butch, and I. Zeljkovic, Inhomogeneous high temperature melting and decoupling of charge density waves in spin-triplet superconductor UTe_2 , *Nat. Commun.* **15**, 4456 (2024).
- [15] C. S. Kengle, J. Vonka, S. Francoual, J. Chang, P. Abbamonte, M. Janoschek, P. Rosa, and W. Simeth, Absence of bulk charge density wave order in the normal state of UTe_2 , *Nat. Commun.* **15**, 9713 (2024).
- [16] F. Theuss, A. Shragai, G. Grissonnanche, L. Peralta, G. de la F. Simarro, I. M. Hayes, S. R. Saha, Y. S. Eo, A. Suarez, A. C. Salinas, G. Pokharel, S. D. Wilson, N. P. Butch, J. Paglione, and B. J. Ramshaw, Absence of a bulk thermodynamic phase transition to a density wave phase in UTe_2 , *Phys. Rev. B* **110**, 144507 (2024).
- [17] C. S. Kengle, D. Chaudhuri, X. Guo, T. A. Johnson, S. Bettler, W. Simeth, M. J. Krogstad, Z. Islam, S. Ran, S. R. Saha, J. Paglione, N. P. Butch, E. Fradkin, V. Madhavan, and P. Abbamonte, Absence of a bulk signature of a charge density wave in hard x-ray measurements of UTe_2 , *Phys. Rev. B* **110**, 145101 (2024).
- [18] S. Ran, C. Eckberg, Q.-P. Ding, Y. Furukawa, T. Metz, S. R. Saha, I.-L. Liu, M. Zic, H. Kim, J. Paglione, and N. P. Butch, Nearly ferromagnetic spin-triplet superconductivity, *Science* **365**, 684 (2019).
- [19] D. Aoki, A. Nakamura, F. Honda, D. Li, Y. Homma, Y. Shimizu, Y. J. Sato, G. Knebel, J.-P. Brison, A. Pourret, D. Braithwaite, G. Lapertot, Q. Niu, M. Vališka, H. Harima, and J. Flouquet, Unconventional superconductivity in heavy fermion UTe_2 , *J. Phys. Soc. Jpn.* **88**, 043702 (2019).
- [20] G. Nakamine, S. Kitagawa, K. Ishida, Y. Tokunaga, H. Sakai, S. Kambe, A. Nakamura, Y. Shimizu, Y. Homma, D. Li, F. Honda, and D. Aoki, Superconducting properties of heavy fermion UTe_2 revealed by ^{125}Te -nuclear magnetic resonance, *J. Phys. Soc. Jpn.* **88**, 113703 (2019).
- [21] S. Sundar, S. Gheidi, K. Akintola, A. M. Côté, S. R. Dunsiger, S. Ran, N. P. Butch, S. R. Saha, J. Paglione, and J. E. Sonier, Coexistence of ferromagnetic fluctuations and superconductivity in the actinide superconductor UTe_2 , *Phys. Rev. B* **100**, 140502(R) (2019).
- [22] N. Azari, M. Yakovlev, N. Rye, S. R. Dunsiger, S. Sundar, M. M. Bordelon, S. M. Thomas, J. D. Thompson, P. F. S. Rosa, and J. E. Sonier, Absence of spontaneous magnetic fields due to time-reversal symmetry breaking in bulk superconducting UTe_2 , *Phys. Rev. Lett.* **131**, 226504 (2023).
- [23] I. M. Hayes, D. S. Wei, T. Metz, J. Zhang, Y. S. Eo, S. Ran, S. R. Saha, J. Collini, N. P. Butch, D. F. Agterberg, A. Kapitulnik, and J. Paglione, Multicomponent superconducting order parameter in UTe_2 , *Science* **373**, 797 (2021).
- [24] D. S. Wei, D. Saykin, O. Y. Miller, S. Ran, S. R. Saha, D. F. Agterberg, J. Schmalian, N. P. Butch, J. Paglione, and A. Kapitulnik, Interplay between magnetism and superconductivity in UTe_2 , *Phys. Rev. B* **105**, 024521 (2022).
- [25] M. O. Ajeesh, M. Bordelon, C. Girod, S. Mishra, F. Ronning, E. D. Bauer, B. Maiorov, J. D. Thompson, P. F. S. Rosa, and S. M. Thomas, Fate of time-reversal symmetry breaking in UTe_2 , *Phys. Rev. X* **13**, 041019 (2023).
- [26] D. Aoki, J.-P. Brison, J. Flouquet, K. Ishida, G. Knebel, Y. Tokunaga, and Y. Yanase, Unconventional superconductivity in UTe_2 , *J. Phys.: Condens. Matter* **34**, 243002 (2022).
- [27] F. Theuss, A. Shragai, G. Grissonnanche, I. M. Hayes, S. R. Saha, Y. S. Eo, A. Suarez, T. Shishidou, N. P. Butch, J. Paglione, and B. J. Ramshaw, Single-component superconductivity in UTe_2 at ambient pressure, *Nat. Phys.* **20**, 1124 (2024).
- [28] V. Hutanu, H. Deng, S. Ran, W. T. Fuhrman, H. Thoma, and N. P. Butch, Low-temperature crystal structure of the unconventional spin-triplet superconductor UTe_2 from single-crystal neutron diffraction, *Acta Crystallogr. B* **76**, 137 (2020).
- [29] W. Setyawan and S. Curtarolo, High-throughput electronic band structure calculations: Challenges and tools, *Comput. Mater. Sci.* **49**, 299 (2010).

- [30] See Supplemental Material at <http://link.aps.org/supplemental/10.1103/nbq1-5p1d> for the properties of isolated and induced pair-density wave order.
- [31] A. Aishwarya, J. May-Mann, A. Almoalem, S. Ran, S. R. Saha, J. Paglione, N. P. Butch, E. Fradkin, and V. Madhavan, Melting of the charge density wave by generation of pairs of topological defects in UTe_2 , *Nat. Phys.* **20**, 964 (2024).
- [32] S. Wang, K. Zhussupbekov, J. P. Carroll, B. Hu, X. Liu, E. Pangburn, A. Crépieux, C. Pepin, C. Broyles, S. Ran, N. P. Butch, S. Saha, J. Paglione, C. Bena, J. C. S. Davis, and Q. Gu, Imaging odd-parity quasiparticle interference in the superconductive surface state of UTe_2 , *Nat. Phys.* **21**, 1555 (2025).
- [33] Q. Gu, S. Wang, J. P. Carroll, K. Zhussupbekov, C. Broyles, S. Ran, N. P. Butch, J. A. Horn, S. Saha, J. Paglione, X. Liu, J. C. S. Davis, and D.-H. Lee, Pair wave function symmetry in UTe_2 from zero-energy surface state visualization, *Science* **388**, 938 (2025).
- [34] A. Crépieux, E. Pangburn, S. Wang, K. Zhussupbekov, J. P. Carroll, B. Hu, Q. Gu, J. C. S. Davis, C. Pépin, and C. Bena, Quasiparticle interference and spectral function of the UTe_2 superconductive surface band, *Phys. Rev. B* **112**, 214509 (2025).
- [35] H. Christiansen, M. Geier, B. M. Andersen, and A. Kreisel, Nodal superconducting gap structure and topological surface states of UTe_2 , *Phys. Rev. B* **112**, 054510 (2025).
- [36] P. G. Talavera, M. Águeda Velasco, M. Shimizu, B. Wu, G. Knebel, M. A. Patino, G. Lapertot, J. Flouquet, J. P. Brison, D. Aoki, Y. Yanase, E. Herrera, I. Guillamón, and H. Suderow, Surface charge density wave in UTe_2 , [arXiv:2504.12505](https://arxiv.org/abs/2504.12505).