

Anisotropic field-induced changes in the superconducting order parameter of UTe_2 Sangyun Lee ^{1,2,*}, Andrew J. Woods ^{1,3,*}, P. F. S. Rosa ¹, S. M. Thomas ¹, E. D. Bauer ¹,
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UTe_2 is a newly discovered unconventional superconductor, where electron Cooper pairs combine into a spin-triplet ground state. We study the specific heat $C(H,T)$ of a high-quality UTe_2 single crystal, with a single anomaly at a high superconducting transition temperature $T_c = 2.1$ K and a low residual Sommerfeld coefficient γ_0 . Applying magnetic fields up to 12 T along the crystallographic axes a , b , and c , we observe highly anisotropic behavior in $\gamma_0(H)$. Below 4 T, $\gamma_0(H) \approx \gamma_0 + \lambda i \sqrt{H}$ ($i = a, b, c$), which is expected for an unconventional superconductor with nodes on the Fermi surface away from the direction of the magnetic field. At 4 T (a and b axes) and 5.5 T (c axis), distinctive changes in the behavior of $\gamma_0(H)$ suggest that a stable low-field ground state begins to evolve above 4 T. The data analysis indicates that the nodes are located near the a – b plane, with possible order parameters $d_{B2u} + i\epsilon d_{B1u}$ or $d_{B2u} + i\epsilon d_{Au}$. Our findings support B_{2u} as the primary superconducting order parameter in UTe_2 .

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Introduction. The experimental search for odd-parity superconductivity has intensified in recent years due to the potential for this state to host Majorana modes, which could be used to realize fault-tolerant quantum computers [1–4]. A Cooper pair in an odd-parity superconductor has spin 1 and odd orbital parity, which can be robust against applied magnetic field compared to its even-parity counterpart. In the recently discovered superconductor UTe_2 , the upper critical fields (H_{c2}) surpass the Pauli limit for weakly coupled superconductors without spin-orbit coupling (see, e.g., Ref. [5]), and a reentrant superconducting state is observed for the field applied along the b axis of this orthorhombic system [6].

A prototypical odd-parity superfluid ground state was discovered experimentally and described theoretically in superfluid ^3He [7,8]. A number of solid-state compounds were suggested to host odd-parity superconducting ground states [9,10]. A fruitful avenue to odd-parity superconductivity may be found in uranium-based ferromagnetic (FM) compounds, wherein superconductivity is realized near a FM quantum critical point [11]. Several U-based superconductivities, such as UGe_2 , UCoGe , and URhGe , appear to fit this scenario well, with superconductivity developing within the FM-ordered state [12–16]. We note, however, that odd-parity supercon-

ductivity may also emerge close to an antiferromagnetic instability, as in the case of UPt_3 [17].

Based on several investigations, it was proposed that UTe_2 is an end member of the family of FM superconductors without a FM ground state [18]. The muon spin relaxation (μSR) and neutron scattering studies of UTe_2 showed evidence of magnetic fluctuations, although no long-range magnetic order has been observed down to 25 mK, implying magnetic fluctuations still play a role for SC in UTe_2 [20–25].

Nuclear magnetic resonance (NMR) measurements revealed a small decrease in Knight shift below T_c for $H \parallel b$, which is smaller than that expected for a spin-singlet state [26–28]. Combined with the observation that H_{c2} greatly exceeds the Pauli limit [29–31], these results indicate that UTe_2 is a prime candidate for an odd-parity superconductor. Initial studies of the specific heat, thermal conductivity, and effective penetration depth on lower T_c samples indicated nodal superconductivity with either line or point nodes in the a – b plane [32–34].

In low magnetic fields, polar Kerr rotation revealed multicomponent superconductivity in UTe_2 , suggesting time-reversal symmetry breaking (TRSB) [35]. However, higher-quality samples with $T_c = 2.1$ K showed a single specific heat anomaly [36–38], weakening support for multicomponent superconductivity. Recent measurements, including the Kerr effect and NMR, suggested a single-component order parameter [39–41]. In contrast, experiments on the superfluid density probed by penetration depth measurements suggested a multicomponent superconducting state even in the highest-quality salt-flux-grown samples [42]. Variations in findings may result from sample differences and experimental conditions. The question of whether the superconducting order

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parameter in UTe_2 is single- or multicomponent as well as the symmetry of the SC order parameter, and its nodal structure, therefore, remains unsettled.

There are general constraints on the possible order parameters arising from the symmetry of the crystal structure. UTe_2 crystallizes in a body-centered orthorhombic crystal structure within space group $Immm$ (D_{2h}^{25}). The order parameter at a second-order phase transition must belong to an irreducible representation (IR) of the total symmetry group. Therefore, the possible superconducting phases are classified by the crystalline point group symmetry [18]. The basis functions of IRs listed in Table I of Ref. [18] (and Table S1 of the Supplemental Material [19]) for D_{2h}^{25} are one-dimensional. As a result, if the superconducting order parameter is multicomponent, there is no symmetry argument that guarantees degeneracy between the two superconducting transition temperatures. In contrast, if the superconducting order parameter is single component and odd-parity, then the superconducting state of UTe_2 may host point nodes at different high-symmetry points depending on the irreducible representation. A B_{1u} order parameter would display nodes along the c -axis, whereas B_{2u} and B_{3u} would contain nodes along b and a , respectively. Identifying signatures of point or line node(s) in the SC order parameter of UTe_2 is an important issue and can narrow down the set of possible ground states in UTe_2 , as an odd-parity state can either have nodes or be fully gapped according to Blount's theorem [43,44].

Here, we focus on the orbital structure of the order parameter revealed by specific heat measurements in a magnetic field up to 12 T applied along the three principal crystal axes. We obtain the residual Sommerfeld coefficient as a function of field $\gamma_0(H)$ by extrapolating the electronic component of C/T to $T = 0$ K for a given field. Our data show an anisotropic evolution of $\gamma_0(H)$ that indicates that the gap nodes are located close to the a - b plane and remain static in low field (up to roughly 4 T). As the field is increased above 4 T our results offer strong evidence that the nodes' positions begin to evolve, at least for the field applied along the a and b axes, with the nodes on the Fermi surface moving away from the direction of the magnetic field.

Results and discussion. We measure the specific heat C/T of UTe_2 in various magnetic fields ($H \parallel a$, $H \parallel b$, and $H \parallel c$) using a single crystal. UTe_2 displays a T_c of 2.1 K, allowing for precise $T_c(H)$ determination (see Figs. S1 and S2 in the Supplemental Material [19]). The superconducting H - T phase diagram for $H \parallel b$ is consistent with previous findings [45–51], with slightly higher $T_c(H)$. H_{c2} shows a linear dependence on the field for $H \parallel a$ and $H \parallel c$.

To provide additional information on the gap structure of UTe_2 , we fit the experimental data by using various gap models, including fully gapped (e.g., s -wave or A_u p -wave), with lines of nodes (e.g., d -wave), and with the single nodes' (e.g., p -wave) order parameters. The specific heat C/T is expected to follow different expressions for each gap type: $C_{\text{fit}}(T)/T = \gamma_0 + \beta T^{-1} \exp(-\Delta/k_B T) + \delta/T^3$ for s -wave, $C_{\text{fit}}(T)/T = \gamma_0 + \beta T + \delta/T^3$ for d -wave, and $C_{\text{fit}}(T)/T = \gamma_0 + \beta T^2 + \delta/T^3$ for p -wave. Figure 1(a) illustrates fits corresponding to these gap structures, revealing the poor quality of the exponential and T -linear fits to our experimental results. In contrast, the T -square fit, expected for the order parameters

with point nodes (e.g., B_{2u} p -wave) closely matches the experimental data, particularly evident in the inset of Fig. 1(a) where the T -square behavior ($n \approx 2$) is well pronounced up to 80% of T_c .

Furthermore, numerical simulations of the p -wave gap structure [$\Delta(\theta, \varphi) = \Delta_0 \sin \theta$] reproduce the temperature-dependent specific heat observed experimentally. Based on our specific heat analysis, UTe_2 exhibits a p -wave superconducting gap structure with point nodes. We, therefore, employ a T^2 fit to analyze our specific heat results in the remainder of the article.

We turn to the low-temperature specific heat of UTe_2 as a function of temperature in various fields for three different field orientations [Figs. 1(b)–1(d)]. The residual Sommerfeld coefficient $\gamma_0(H)$ for different fields was determined from fits of the data to $C_{\text{fit}}(T)/T = \gamma_0(H) + \beta T^2 + \delta/T^3$, where the βT^2 term is expected for an unconventional superconductor with point nodes in the order parameter, and δ/T^3 is the high-temperature tail approximation of a Schottky anomaly from a nuclear contribution.

Figures 1(b)–1(d) show the extracted anisotropic field dependence of the residual Sommerfeld coefficient [$\gamma_0(H)$] for a field applied along the b , a , and c axes, respectively. $\gamma_0(H)$ behaves *qualitatively* differently for the three field orientations. However, there are some features that are common for all directions of the magnetic field. We can identify two regimes—the low-field and high-field regimes, with a boundary at H_g^i , where the superscript i stands for the a , b , or c axis, the directions of the applied magnetic field. There are clear kinks in $\gamma_0(H)$ at $H_g^b \approx 4$ T, and $H_g^a \approx 4$ T, for the field along the b and a axes, respectively, and a more subtle inflection point for $H \parallel c$, with $H_g^c \approx 5.5$ T. These characteristics are independent of the fitting procedure used [see Figs. S3 to S5 in the Supplemental Material [19]].

We examine the low-field region first. For all field directions $\gamma_0(H)$ is sublinear for $H < H_g^i$. The sublinear behavior of the residual Sommerfeld coefficient in unconventional superconductors is commonly attributed to the presence of the nodes in the order parameter [52–55] and dubbed a Volovik effect. The enhanced specific heat in the magnetic field is due to the Doppler shift $\vec{k} \cdot \vec{v}_s$ of the energy of a nodal quasiparticle with momentum $\vec{k}$ in the presence of a supercurrent with velocity $\vec{v}_s$ associated with magnetic vortices. The energy of the quasiparticles with momentum along the supercurrent is reduced, and the energy of the quasiparticles with opposite momentum is enhanced. This splitting leads to the enhanced density of states around the nodes of the order parameter. An analytical calculation results in a logarithmic field dependence of $\gamma_0(H) \propto H \log(\lambda_L/H)$, where λ_L is a constant [52]. The increase in specific heat was also investigated numerically for states with both lines of nodes and point nodes in the order parameter and for a number of representative directions of the magnetic field [53]. The resulting specific heat was given functionally as $\gamma_0(H) \propto \lambda_P H^\alpha$. The exponent α was determined to be 0.35 and 0.45 for polar states (nodes along the equator, a - b plane) with the field parallel and perpendicular to the c -axis, respectively. For point nodes, $\alpha \approx 0.64$ when the magnetic field is perpendicular to the momentum of the point nodes and $\alpha \approx 1$ when the field is along the nodal direction [53]. In a situation with multiple nodes in the order parameter,

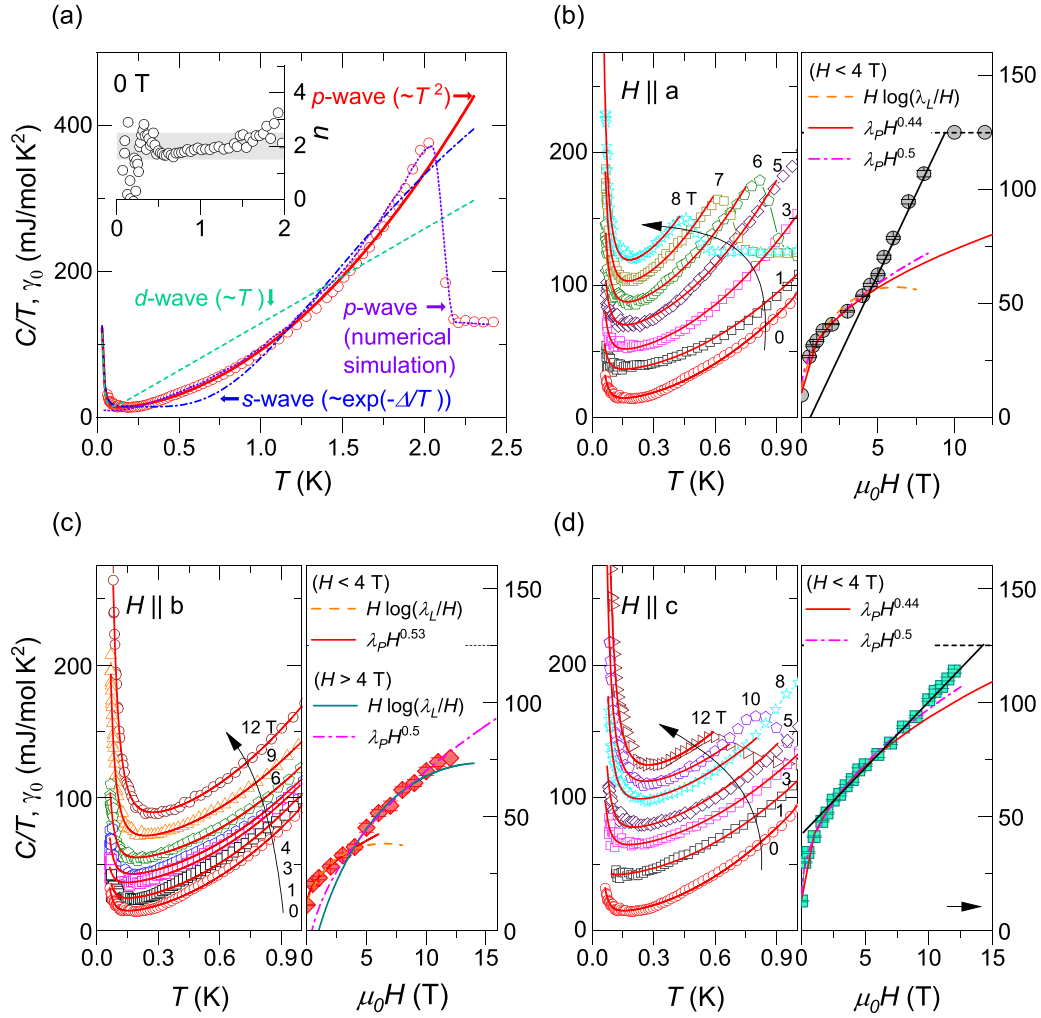


FIG. 1. (a) C/T at 0 T is plotted with four different fittings suggested by difference gap structures: s -wave (dot-dashed line), d -wave (dashed line), and p -wave (solid and dot lines). Inset shows extracted temperature-dependent exponent n by $\partial\{\ln[C(T)/T - \gamma_0]/\partial(\ln(T))\}$, where $C(T)/T = \gamma_0 + \beta T^n$. C/T below 1 K for three field orientations: (b) $H \parallel a$; (c) $H \parallel b$; (d) $H \parallel c$. In the left panels (b)–(d) C/T is fitted with $C(T)/T = \gamma_0 + \beta T^2 + \delta/T^3$. Right panels (b)–(d) show residual C/T (0 K) = γ_0 versus magnetic field, with the power law $\lambda_P H^\alpha$ and logarithmic $H \log(\lambda_L/H)$ fits for two regimes: $H < H_g^i$ and $H > H_g^i$, where i is a , b , and c .

nodes that lead to sublinear field dependence would dominate the response at low field. In general, therefore, the sublinear behavior is expected in the presence of nodes in the superconducting order parameter. The evolution of $\gamma_0(H)$ with field, therefore, provides a powerful tool for investigating the nodal structure of unconventional superconductors (see, e.g., Ref [55]).

The field dependence of γ_0 for $H < H_g^i$ for all i is well described by $\gamma_0(H) = \gamma_0^0 + \lambda_P H^\alpha$ with α close to 0.5, as expected for the order parameter with nodes. Here γ_0^0 is the residual Sommerfeld coefficient at zero field. Power-law fits as well as logarithmic fits are shown in Figs. 1(b)–1(d). The coefficient λ_P of the H^α term (the contribution of a particular node to specific heat) depends on the angle between the applied field and the direction of that node. The Doppler shift (and the resulting contribution of the node to the density of states) is greatest when the field is perpendicular to the direction of the node, as the supercurrent $\vec{v}_s$, perpendicular to magnetic field, can then align (anti)parallel with the mo-

mentum of the quasiparticles in the node. The coefficients λ_P obtained from the fits and shown in Figs. 1(b)–1(d) are 12.1, 22.4, and 28.6 (mJ/mol K² T $^\alpha$) for $H \parallel b$, $H \parallel a$, and $H \parallel c$, respectively. The nodes in the low-field regime are, therefore, closest to the b direction and furthest away from the c direction. Importantly, the fact that for $H < H_g^{a,b,c}$ the data are well described by single power-law fits also indicates that the nodes are static for $H < H_g^i$.

At $H_g^{a,b}$ we observe a sharp upward kink in the data. The power-law fit to the data for $H > H_g^b$ [magenta curve in Fig. 1(c)] results in a negative zero-field intercept (residual zero-field γ_0^0). A negative zero-field intercept is unphysical, therefore, the data for $H > H_g^b$ cannot be described by an order parameter with static nodes as a function of field. Rather, the coefficient λ_P acquires field dependence above H_g^b . The observed increase above the extrapolated fit to the data in the low-field regime can be due to the gradual evolution of the position of the nodes with field for $H > H_g^b$. Specifically, the movement of the nodes away from the direction of the

magnetic field, becoming more perpendicular to it, will lead to an increase in the contribution of the nodes to the specific heat via the Volovik effect.

A similar behavior is observed for $H \parallel a$ [Fig. 1(b)]. There is a sharp upward kink at $H_g^a \approx 4$ T. The data curve up quickly to reach the normal value at H_{c2} , which is the lowest when $H \parallel a$. The proximity of H_{c2} to H_g^a may influence the precise functional field dependence of γ_0 above H_g^a . The sharp kink of $\gamma_0(H)$ at H_g^a , however, indicates that the nodes in the order parameter begin to move at H_g^a , similar to the case for $H \parallel b$. The increase of γ_0 again suggests that the nodes move away from the direction of the magnetic field toward the b - c plane, perpendicular to $H \parallel a$.

When $H_g^c \approx 5.5$ T, our data begin to deviate from the $\sqrt{H}$ dependence in the low-field region via a mild inflection. Coupled with the expected increase of γ_0 towards its normal state value at H_{c2} , the subtle change at H_g^c indicates that the movement of the nodes for this field direction is much smaller (if any) than for the other two. This is consistent with the observation that the coefficient λ_P of the H^α term for $H < H_g^i$ is greatest for $H \parallel c$, indicating that the nodes are already located close to the a - b plane in the low-field regime.

To summarize, our results in Fig. 1 strongly indicate that the nodes of the superconducting order parameter in UTe₂ are located close to or within the a - b plane and remain static in the low-field regime $H < H_g^{a,b,c}$. Importantly, the nodes are substantially closer to the b axis than to the a axis. In the high-field regime, the nodes begin to move away from the direction of the magnetic field. This effect is pronounced for both $H \parallel a$ and $H \parallel b$, indicating that the nodes remain largely within the a - b plane.

On theoretical grounds, a single-component irreducible representation (IR) order parameter is insufficient to explain even the data in the low-field region. A single node, in this case, must lie along one of the principal crystallographic axes (although see note [56]). However, $\gamma_0(H)$ is expected to be linear for the magnetic field applied along that axis, which is not observed experimentally. Recent penetration depth measurements in magnetic field [42] were also interpreted as evidence for the presence of multiple nodes in the superconducting order parameter of UTe₂. However, in contrast to our results, the nodes were postulated to be close to both the b - and c -axes. The authors of Ref. [42] suggested a multicomponent d -vector $\mathbf{d}_{B3u+iA_u} = \mathbf{d}_{B3u} + i\mathbf{d}_{A_u} = (c_1k_xk_yk_z, c_2k_z, c_3k_y) + i(c_4k_x, c_5k_y, c_6k_z)$, where c_i are the coefficients of d -vectors [42]. The coefficients c_i in multicomponent d -vectors can be tuned by the application of the magnetic field, thereby changing the locations of the point nodes. The multiband nature of the Fermi surface in UTe₂ may effect the magnetic-field response of the superconducting order parameter. Further experimental and theoretical investigations are called for, as previously suggested [26,57–59].

The possible combinations of the two IRs are displayed in Fig. S6 of the Supplemental Material [19] (Fig. A1 in Ref. [60]). We can rule out many of these combinations based on the findings that (1) $\lambda_1^c > \lambda_1^a > \lambda_1^b$, (2) that the nodes move away from the applied magnetic field above H_g^i , and (3) that nodes lie in the a - b plane. These conditions allow us

to eliminate the possibilities in Fig. S6 in the Supplemental Material [19] (Figs. A1(a), A1(d), A1(f), A1(i), A1(j), A1(k), and A1(l) in Ref. [60]). Next, we make two additional assumptions that (1) in the low field the superconducting order has a primary/dominant order parameter and the secondary order parameter is much weaker (smaller magnitude), and (2) the evolution of the relative amplitudes does not move the nodes through the k_z -axis (consult Table II in Ref. [42], also reproduced in the Supplemental Material, Table S2 [19]). There are then only two possible combinations: $\mathbf{d}_{B1u} + i\mathbf{d}_{B2u}$ with $|\mathbf{d}_{B2u}| \gg |\mathbf{d}_{B1u}|$, and $\mathbf{d}_{B2u} + i\mathbf{d}_{A_u}$ with $|\mathbf{d}_{B2u}| \gg |\mathbf{d}_{A_u}|$ for the low-field state, see Fig. S6 in the Supplemental Material [19] and Ref. [58]. In both cases, the evolution of the relative magnitudes of the order parameter components keeps the nodes close to within the a - b plane (Table S2 in the Supplemental Material [19] and Ref. [42]). Figure 2(b) shows the evolution of the point nodes for $\mathbf{d}_{B1u} + i\mathbf{d}_{B2u}$ with $|\mathbf{d}_{B2u}| \gg |\mathbf{d}_{B1u}|$ toward $|\mathbf{d}_{B2u}| \approx |\mathbf{d}_{B1u}|$ ($|c_3| \gg |c_5|$ to $|c_3| \approx |c_5|$, see the node positions and pairing symmetry section in the Supplemental Material [19]). The nodes remain in the a - b plane and move away from the b -axis. Figure 2(c) shows the second combination, with two pairs of nodes, where the pair of nodes that lie within the a - b plane move away from the b -axis towards the a -axis. For the $B_{2u} + i\epsilon A_u$ order parameter, the movement of the nodes must conspire to be consistent with the data in the following way: the nodes that lie in the b - c plane must move very slowly with increasing field (or perhaps even remain static), while the nodes within the a - b plane must move away from the b -axis ($|c_1| \gg |c_6|$ and $|c_3| \gg |c_4|$ to $|c_1| \approx |c_6|$ and $|c_3| > |c_4|$). For the $B_{2u} + i\epsilon B_{1u}$ order parameter, the two pairs of nodes remain within the a - b plane and are consistent with observations as long as the increasing splitting between the nodes leaves them closer to the b -axis. On this basis, we conclude that B_{2u} is the primary superconducting order parameter in UTe₂, which is also suggested by the recent pulsed-echo measurement [40]. Previous studies on UTe₂ proposed various gap structures based on experimental results obtained on samples with different values of T_c . Superconductivity of UTe₂ appears to be singularly sensitive to the crystallographic quality/properties of the sample, i.e., extrinsic factors, such as impurities and dislocations. Our single-crystal measurements with the highest T_c demonstrate that applying an external magnetic field also affects the positions of nodes in UTe₂. Taken together, our results suggest that discrepancies between the available experimental investigations arise from the sensitivity of the superconducting order parameter in UTe₂ to both extrinsic effects (sample crystal quality) and to the experimental conditions, such as application of the magnetic field and pressure. We propose that the secondary order parameter in UTe₂ is induced by impurities or crystal imperfections, highlighting the inherent exquisite sensitivity of the superconductivity in UTe₂ to variations in crystal growth methods and conditions [61,62]. Furthermore, magnetic-field-induced variations, especially of the secondary order parameter of UTe₂, should be carefully considered when classifying p -wave superconductors. We suggest that crystal imperfections (impurities and defects) and the presence or absence of the magnetic field are key factors underlying the diverse superconducting order parameters in UTe₂ inferred

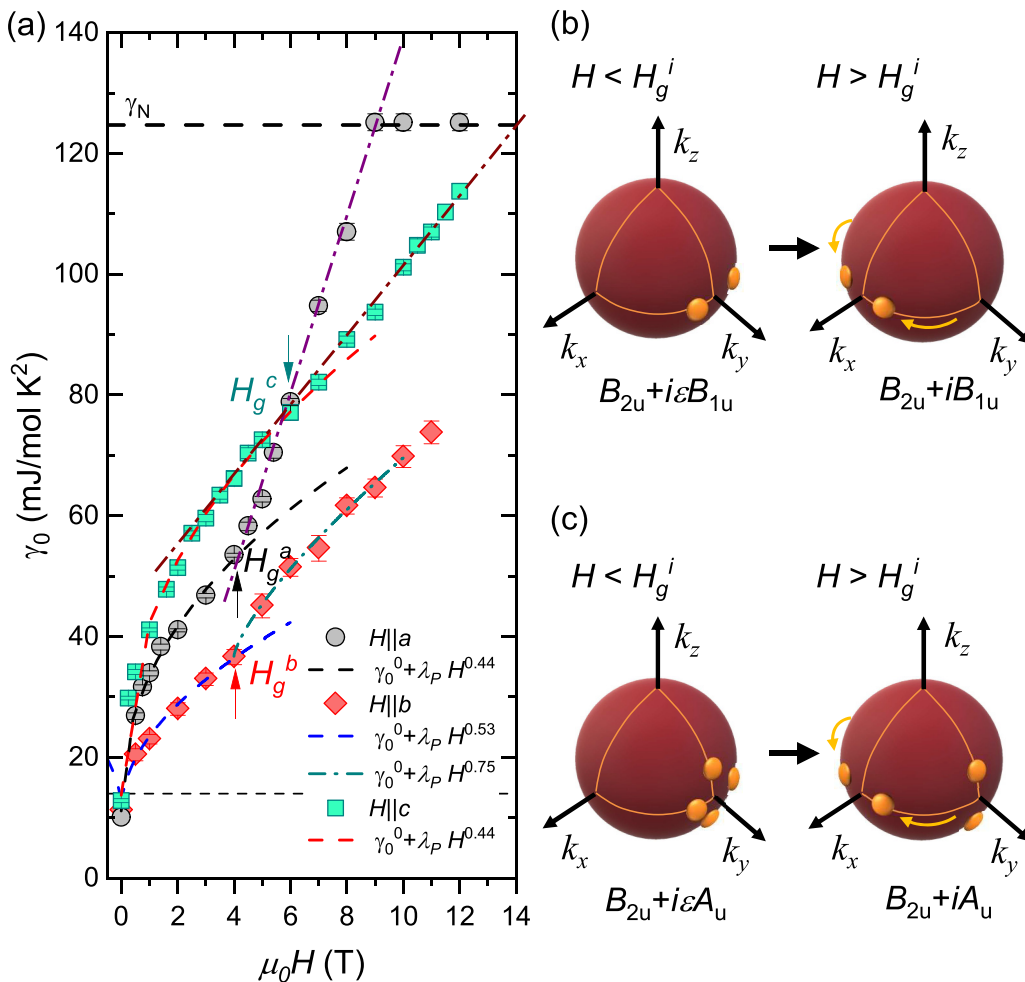


FIG. 2. (a) When magnetic field is applied along $H \parallel a$, $H \parallel b$, and $H \parallel c$, residual $C/T = \gamma_0$ versus the magnetic field with H^a fit for $H > H_g^i$ and $H < H_g^i$, respectively. (b), (c) Schematics of $B_{2u} + i\epsilon B_{1u}$ and $B_{2u} + i\epsilon A_u$ in magnetic field, where ϵ is a small constant. The possible locations of the point nodes are marked by the orange spots on a spherical Fermi surface. Left panels of (b), (c) represent potential point nodes when $H < H_g^i$, and right panels represent them when $H > H_g^i$, respectively.

in various studies. The corollary is that controlled doping and applied magnetic field are powerful control parameters in tuning the superconducting state of UTe₂.

Conclusion. To summarize, we report the low-temperature specific heat of UTe₂ in a magnetic field up to 12 T applied along the a , b , and c axes. Two regimes with distinct responses to the magnetic field are observed. Below the direction-dependent field $H_g^{a,b,c}$, the residual Sommerfeld coefficient γ_0 displays sublinear field dependence $\gamma_0 = \gamma_0^0 + \lambda_P H^\alpha$ for all three directions, which points to the presence of static point nodes in the superconducting order parameter. The lowest coefficient λ_P is observed for $H \parallel b$, which indicates that the nodes are the closest to the b -axis for $H < H_g^b$. Above H_g^a and H_g^b , for $H \parallel a$ and $H \parallel b$, respectively, $\gamma_0(H)$ gradually grows above the fits to the data in the low-field region, with a more subtle change at H_g^c for $H \parallel c$. Together with the observation that the largest coefficient λ_P occurs for the c -axis field, the evolution of $\gamma_0(H)$ indicates that the nodes in UTe₂ are (1) located close to the a - b plane (and closest to b) in the low-field region and (2) begin to move away from the direction of the applied magnetic field with increasing field

for $H > H_g^{a,b,c}$, more evidently for $H \parallel a, b$. There are two two-component order parameters that can describe our observations: $B_{2u} + i\epsilon A_u$ with four pairs of nodes and $B_{2u} + i\epsilon B_{1u}$ with two pairs of nodes. ϵ is constant (and small) for $H < H_g^i$, and begins to grow with increasing field for $H > H_g^i$. Based on the discussion above, we suggest that the $B_{2u} + i\epsilon B_{1u}$ is the more likely candidate for the order parameter in UTe₂. We emphasize, however, that in either $B_{2u} + i\epsilon B_{1u}$ or $B_{2u} + i\epsilon A_u$ scenarios, our measurements indicate that B_{2u} is the primary superconducting order parameter in UTe₂. The subdominant order parameter can be stabilized in several ways, including magnetic field (see the Supplemental Material [19]), disorder, and sublattice degrees of freedom.

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