Suppressed magnetic scattering sets conditions for the emergence of 40 T high-field superconductivity in UTe$_2$

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Abstract

The potential spin-triplet heavy-fermion superconductor UTe$_2$ exhibits signatures of multiple distinct superconducting phases. For field aligned along the $b$ axis a metamagnetic transition occurs at $\mu_0 H_m \approx 35$ T. It is associated with a spin reorientation inducing magnetic fluctuations that may be beneficial for the field-enhanced superconductivity surviving up to $H_m$. Once the field is tilted away from the $b$ towards the $c$ axis, a re-entrant superconducting phase emerges just above $H_m(\theta)$. However, under pressure this phase detaches from $H_m$. In order to better understand this remarkably field-resistant phase we investigate magnetic torque and electrical magnetotransport in pulsed magnetic fields. The observed zero-Hall signal evidences the superconducting nature of this distinct high-field phase. We determine its record-breaking upper critical field of $\mu_0 H_{c2} \approx 75$ T. Furthermore, we provide evidence for a strong angle-dependent reduction of magnetic scattering, likely accompanied by changes in the electronic band structure induced by the tilted field.

INTRODUCTION

The discovery of superconductivity (SC) in the heavy-fermion metal UTe$_2$ with a relatively high critical temperature $T_c$ of 1.6 K triggered much excitement as it is a potential candidate for topological spin-triplet superconductivity [1, 2]. This unconventional superconducting state is expected to arise as a consequence of magnetic fluctuations. It is characterized by a particularly strong stability against external magnetic fields. A key characteristic of UTe$_2$ is its anisotropic upper critical field $H_{c2}$, exceeding the paramagnetic limit along all field orientations [1, 3]. These findings resemble those reported for ferromagnetic superconductors such as UCoGe and URhGe [4, 5]. Profound experimental evidence in UTe$_2$ has recently been provided by NMR, STM and polar Kerr effect studies [6–9]. In its complex phase diagram, multiple phases with potentially different SC order parameters emerge that exhibit field- and pressure-induced enhancement and re-entrance behavior at very large fields applied in specific crystallographic directions [10–17]. This diversity renders UTe$_2$ a unique platform to study multiple unconventional superconducting phases and their interrelations.

SC in UTe$_2$ can survive magnetic fields close to the metamagnetic transition at approximately $H_m = 35$ T for $H||b$ [3, 17]. This suggests that magnetism, i.e., enhanced magnetic fluctuations, in the vicinity of the metamagnetic transition may play a key role in the establishment of SC in UTe$_2$. Moreover, Ran et al. [10] demonstrated that the compound
is able to reestablish superconductivity even at higher fields, just above the metamagnetic transition at \( \sim 40 \text{T} \) for field oriented at \( \theta \approx 30^\circ \) away from \( b \) towards the \( c \) axis. This new high-field superconducting phase (from here on abbreviated as hfSC) appears to extend to fields beyond 60 T, with a yet-to-be-determined \( H_{c2} \). Nevertheless, a value larger than 60 T is comparatively high considering the low critical temperature in zero field [10, 15].

Although, ferromagnetic fluctuations are proposed to exist in UTe\(_2\) [18], to date there is no unambiguous evidence for their existence. Instead, direct inelastic neutron-scattering studies report the presence of low-dimensional antiferromagnetic fluctuations with an incommensurate \( q \) vector [19–21].

Little is known about the mechanisms of the high-field superconducting phases: neither is it clear how exactly SC is suppressed for \( H \parallel b \) once \( H_m \) is approached; nor why SC can reestablish for field orientations near \( \approx 30^\circ \) within the \((b,c)\) plane above \( H_m \). Naturally, the suggested Fermi-surface change, detected by the sign change in the Hall coefficient and thermoelectric power at \( H_m \) [22] can play a role. Other quantities, as for example the \( T^2 \) term of the temperature-dependent resistivity or the specific heat exhibit a discontinuity at \( H_m \), likely connected to either a Fermi-surface instability or to a change of the magnetic fluctuations [15, 17, 23]. However, most of these quantities, such as the magnetization jump, remain unaffected by an orientation change of 30° within the \((b,c)\) plane [23–25]. Presently, the only quantity that differs is the sign of the specific-heat jump at \( H_m \), negative for \( H \parallel b \) [17, 23], but predicted to become positive at 30°. The field-reinforced SC observed for field along the hard \( b \) axis [1, 3] is associated with an enhancement of magnetic fluctuations in the vicinity of the metamagnetic transition [3, 10, 17, 24–26].

In contrast, recent pressure-dependent investigations have revealed that the hfSC phase is not necessarily tied to \( H_m \): at large enough pressures, the superconducting pocket in the polarized phase appears at fields clearly larger than \( H_m \) [27].

The nature of the superconducting ground state, the identification of the different field or pressure-induced superconducting phases, and their relation to topological superconductivity are still under debate, notably from a theoretical point of view [28–30]. Moreover, recent specific-heat measurements [31, 32] contradict the proposal of multicomponent ambient SC [8, 9]. Understanding the mechanisms responsible for the emergence of the hfSC and its relation to the low-field superconductivity (lfSC) is one of the key questions for current research in the field.
Here, we present studies of magnetic torque, magnetoresistance, and Hall effect in pulsed magnetic fields up to 70 T for micron-sized samples. They are tailored from single crystals of UTe$_2$ by focused-ion-beam (FIB) micro-fabrication. This enables us to perform extremely precise measurements. We trace the metamagnetic and superconducting transitions in the $(b,c)$ plane. We confirm the emergence of hfSC around $\theta = 30^\circ$ at fields above 40 T. We extrapolate the maximum upper critical field to $\mu_0 H_{c2} \approx 75$ T and determine its variation with angle [31, 33]. Furthermore, we show that the high-field Hall coefficient, consisting of the orbital and a significant anomalous component, experiences a drastic suppression as the field orientation approaches the hfSC region around 30°. It even changes sign before it recovers at larger angles, which indicates strong changed in the electronic properties and magnetic scattering for the observed angular range. The comparison of the angle dependence of both Hall effect and $H_{c2}$ at high fields to the low-field regime highlights the outstanding character of the hfSC phase in the $T - H$ phase diagram of UTe$_2$.

**RESULTS AND DISCUSSION**

We investigate several micron-sized samples produced from one oriented single crystal with a superconducting $T_c$ of 1.6 K. The micromachining was performed by means of Ga or Xe FIB systems (for details see the methods section). This FIB approach enables precise geometries suitable for microcantilever-torque experiments on magnetic materials with strong torque responses as well as high-precision electrical-transport measurements on metallic (i.e., highly conductive) materials with current running along any desired direction (see images in Fig. 1a and b). In this work, we will present results obtained for three transport devices shaped in the standard Hall-bar geometry. A preliminary characterization of the resistivity is presented in Fig. 1c. The critical temperature of 1.6 K is not altered by the fabrication in comparison to the bulk sample and the overall temperature dependence is reproduced.

**Magnetic torque around the metamagnetic transition**

We investigated the isothermal magnetic torque of UTe$_2$ by means of microcantilever torque-magnetometry (see Fig. 1a) in pulsed fields up to 70 T for various angles. This technique probes the magnetic anisotropy and complements magnetization measurements
As a consequence of the step-like increase of magnetization and the change in anisotropy of UTe$_2$ at $H_m$ [24, 35], its the response in magnetic torque will be strong.

Thanks to the sample preparation by FIB the volume of the sample is small enough to prevent the microcantilever from Figure 1d presents torque data recorded at 1.5 K. An additional data set for $T = 0.7$ K, can be found in the Supplementary Information Fig. S1. First of all, the up and down sweeps coincide almost perfectly. This confirms a stable temperature throughout the magnetic pulse and, hence, no apparent effect from potential eddy-current heating. The tilt angle $\theta$ was varied between $H||b$, i.e., $\theta = 0^\circ$, and the $c$ direction. The metamagnetic high-field transition shows up as a step-like feature at fields above 35 T. Furthermore, no additional feature that may indicate the presence of diamagnetism associated with SC occur for the accessed temperatures and field orientations.

**High-field superconductivity and its electrical transport signature**

We conducted resistivity and Hall-effect measurements in fields up to 70 T. Isothermal resistivity curves recorded for Hall-bar device #1 (see Fig. 1b) at 0.7 K and 1.3 K, with field oriented along the $b$ axis, are presented in Fig. 1e and f, respectively. The in-plane resistivity $\rho_a$ exhibits a step-like change at the metamagnetic transition that sets in at $\mu_0H \approx 35$ T for $H||b$. This feature is consistent with the metamagnetic jump at $H_m$ in magnetic torque. We provide additional data recorded for device #3 at various temperatures ranging between 1.4 and 77 K for the fixed field orientation $H||b$ in Supplementary Fig. S1b. Upon decreasing temperature, the metamagnetic transition evolves from a broad second-order into a sharp first-order type transition. Such an evolution resembles behavior observed in other uranium-based metal with long range magnetic order [36]. We reproduced the overall temperature and field dependence reported previously for UTe$_2$ [10, 26].

First, we focus on the data recorded for orientations close to $H||b$: In the 6° curve the normal state is reached above 12 T until the resistivity starts dropping again above 20 T, see Fig. 1e. This negative slope just before the strong step at $H_M$ is related to the re-entrant behavior of the lfSC phase reported already previously [3, 37]. Depending on the sample quality and perfect orientation UTe$_2$ may maintain SC all the way up close to the metamagnetic transition field $H_M$. Apparently, the re-entrant signature is suppressed in the 1.3 K data, shown in Fig. 1f. As we increase $\theta$ to 20° and above, the magnetoresistance in the
FIG. 1. **Magnetic torque and magnetotransport of UTe2.** (a) Picture of the piezoresistive microcantilever with a lamella-shaped sample attached to it. (b) False-color SEM image of the FIB structured Hall-bar device #1 with a thickness of 2 µm and $I \parallel a$. The $b$ axis points along the normal of the substrate. (c) Resistivity vs. temperature for device #1 in comparison to the bulk sample. (d) Magnetic torque vs. field for various angles recorded for a thin sample (90 × 15) µm at a temperature of 1.5 ± 0.1 K. The tilt angle, $\theta$, denotes the field orientation in the $(b, c)$ plane, where $0^\circ$ corresponds to $H \parallel b$. The curves were shifted by a constant offset for better visibility. (e,f) Pulsed-field resistance data recorded at (e) $T = 0.7$ K and (f) 1.35 K, respectively, for various tilt angles.
normal state below $H_M$ remains unchanged. Above $H_M$, it gradually evolves from a positive upturn into a negative dependence. Similarly, to what we observed by magnetic torque the metamagnetic transition shifts towards higher fields. However, in the case of resistivity the strong step-like feature is quenched by the onset of zero resistance associated with an additional re-entrant phase that sets in once $\theta$ reaches beyond 20°. At 0.7 K, the resistivity curve for the highest tilt angles $\theta = 35^\circ$ tested, still exhibits SC that extends up to 69 T. In comparison, for the same angle but at 1.3 K, the resistance reaches the normal state again already at fields below 60 T. At 1.3 K, no trace of hfSC was discernible for angles from 45° onward, see Fig. 1f. At 45°, the step-like resistance change followed by a negative slope is observed again. For $\theta = 50^\circ$, $H_M$ is pushed above the field range accessed in this experiment. Hence, the low-field normal-state resistance increases monotonically to the highest field.

In Fig. 2a we present a data set of the resistance recorded for various temperatures between 0.7 K and 1.4 K at the fixed orientation $\theta = 35^\circ$. We mark the points used for the determination of the temperature dependence of the critical fields of the lfSC and the hfSC phases. At the lowest temperature reached in our experiment, $T = 0.7$ K, the superconducting phase survives magnetic fields close to 70 T. Its onset is directly pinned to the metamagnetic transition.
$H_{c2}$ in the field-induced re-entrant hfSc phase

Figure 3a shows a schematic phase diagram comprised of a contour presentation of the data from Fig. 1f and the transition fields $H_M$ and $H_c$ determined from our torque and resistance results.

Figure 3b shows the superconducting upper critical field for device #1 determined in DC (gray) and pulsed (red) magnetic fields oriented parallel to the b axis (squares) and tilted 30° (circles) towards the c axis within the (b,c) plane. Figure 3c shows similar data for device #2 for fields applied at different angles within the (b,c) plane, measured all in pulsed fields.

For spin-singlet superconductors, $H_{c2}$ has an upper limit fixed by Pauli paramagnetism [38, 39]. The limiting field, $H_{Pauli}$, for a singlet superconductor at 0 K can be approximated by $\mu_0 H_{Pauli} \approx \sqrt{2\Delta/(g\mu_B)} = 1.86[T/K] \cdot T_c$, valid in the BCS weak-coupling limit without any spin-orbit coupling and $g = 2$. In the case of UTe$_2$, this would roughly lead to 3 T, much smaller than the measured critical fields (reaching close to or beyond 10 T in all directions). A combination of spin-triplet superconductivity and strong spin-orbit coupling is probably responsible for this violation of the paramagnetic limit in all field directions [40].

The evolution of $H_{c2}$ with temperature in the lfSC phase for field tilted approximately 35° towards the c axis follows the standard (close to parabolic) temperature dependence of an upper critical field in the pure orbital limit. Fits of the data were done in the strong-coupling regime appropriate for UTe$_2$ [31], using a moderate value of the strong coupling constant of $\lambda = 1$ (solid lines in Fig. 3b and c). In the Ginzburg-Landau weak-coupling regime, the slope of $H_{c2}$ at $T_c$ is given by [33]:

$$\frac{dH_{c2}}{dT} \approx 9\Phi_0 \left( \frac{k_B T_c}{\hbar \langle v_F \rangle} \right)^2 \frac{1}{T_c}.$$  

Once $\lambda$ and $T_c$ are fixed, the only parameter left is the average Fermi velocity perpendicular to the applied field $\langle v_F \rangle$. In the best fits we find it to vary between 6700 m/s and 7100 m/s for angles between 25° and 35° in the (b,c) plane.

Let us now turn to the critical fields of the hfSC phase, above $H_m$. The points shown in Fig. 3d were determined in the hfSC phase for two devices again at various tilt angles. In our pulsed-field setup we were limited to temperatures above 0.7 K. A prerequisite to a profound analysis of $H_{c2}$ in this phase is a theoretical model explaining the mechanisms for re-entrant SC above $H_m$. Indeed, in the likely case of a connection between the hfSC
FIG. 3. **High-field phase diagram of UTe$_2$**. (a) Contour plot created from data presented in Fig. 1f. White squares and circles mark the metamagnetic transition field measured by pulsed-field torque magnetometry presented in Fig. 1d. Cyan diamonds indicate the superconducting transition fields in the 0.7 K data set presented in 1e. The black dashed line indicates the approximate extension of the SC region at 0.7 K. (b),(c) Temperature dependence of the superconducting critical field of the lfSC phase, determined for device #1 and #2, respectively, in pulsed and steady fields. (d) Critical fields of the hfSC and lfSC phase determined in pulsed field. Solid lines are fits of $H_{c2}$ in the pure orbital limit, using a strong coupling parameter $\lambda = 1$. 

and magnetic fluctuations that develop upon approaching $H_m$, we can expect a reduction of the pairing strength once the external magnetic field becomes much larger than $H_m$. Such a behavior would be the symmetric of that observed for the field-reinforced SC for
$H \parallel b$ below $H_m$ [17] where the coupling strength increases on approaching $H_m$). However, to date a well-defined theoretical scenario for the field dependence of the pairing strength in the hfSc phase is lacking. Therefore, in order to determine minimal constraints from the data, we analyze them without any field dependence of the pairing strength. We use again the same strong coupling model as in the lfSc phase [33], and describe the critical temperature by the expression: $T_c/\Omega = f(\lambda, \mu^*)$. It is determined by a characteristic energy $\Omega$ (the equivalent of the Debye temperature in the weak-coupling BCS theory), the strong coupling parameter $\lambda$, and a screened Coulomb repulsion parameter $\mu^*$. Under field, the only additional parameters are the above mentioned Fermi velocity $\langle v_F \rangle$ controlling the orbital limit, and the gyromagnetic factor $g$ controlling the paramagnetic limit, here assumed to be zero.

We demonstrate in Fig. 3d that reasonable fits to the data can be achieved under the assumption of a much larger $T_c$ (extrapolated to zero temperature) for the hfSc phase. Remarkably, we can use the same averaged Fermi-velocity as control parameter of the orbital limit for the lfSc and hfSc phases at the same angle. Consequently, we assume here that the Fermi surface changes between the lfSc and hfSc phases (as measured by $H_{c2}$) cannot be dramatic. We use similar values of the coupling constant, ranging from $\lambda = 1$ at 25° to $\lambda = 1.07$ at 35°, with a more than twofold enhanced characteristic energy (now of order 40 K) that controls $T_c$ together with $\lambda$ [3]. The latter increase accounts for the enhancement of $T_c$ ($\mu_0 H = 0$ T). The necessary value corresponds to the typical energy scales observed in neutron scattering measurements for the magnetic fluctuations [19, 20]. From this analysis we conclude that the existence of this hfSc phase still requires the absence of a paramagnetic limit and large effective masses similar to the lfSc phase (same average Fermi velocity). This together with the enhanced (zero-field) critical temperature, is sufficient to explain that superconductivity can survive at these record high fields. Our approach reproduces the overall temperature dependence of $H_{c2}$ reasonably well and yields $\mu_0 H_{c2}^{\text{max}} \approx 75$ T ($\pm 1$ T) between 30 and 35°. The obtained $T_c$ values, extrapolated to zero field, range between 3.2 and 3.6 K. The maximum critical-field value sets a record-breaking mark for SC emerging in a heavy-fermion compound to date. The existence of heavy quasiparticles at fields above 40 T means that renormalization of the effective masses by the Kondo effect is still effective above $H_m$. From this analysis, it is still not possible to discuss the origin of the hfSc phase: for example, we have assumed that the strong coupling parameter $\lambda$ had values similar to
those observed in the lfSc phase. This implies that the required increase of the ”zero-field” $T_c$ in the hfSc phase originates from an increase of the characteristic energy $\Omega$, suggesting a different pairing mechanism. However, the increase of $T_c$ could also have been triggered by a field increase of the strong coupling parameter $\lambda$, keeping similar values for $\Omega$ than in the lfSc phase. In such a case, no ”evidence” would be left for a different pairing mechanism.

**Strong suppression of the anomalous Hall in the vicinity of the hfSc phase**

In Figures 4a-c, we present Hall-resistivity data recorded in pulsed magnetic fields for devices #1 and #2. The magnitude of the Hall effect is comprised of the ordinary component linked to the density of states and an anomalous component associated to scattering as a consequence of spin-orbit coupling [41]. In the case of heavy-fermion conductors the major scattering mechanism is of extrinsic origin associated with skew scattering from local and itinerant $f$ electrons [42, 43]. An analysis of the electrical-transport coefficient obtained in steady fields up to 35 T by Niu et al. show that coherent skew scattering of the conduction electrons is the dominant contribution to Hall below about 20 K for $H||b$ [22]. At 4.2 K and at a tilt angle of $\theta = 35^\circ$, a step-like discontinuity at $H_m$ occurs followed by a negative slope in the high-field regime. This behavior seems similar to the Hall signal for $H||b$, reported previously by Niu et al. [22]. We provide additional Hall data recorded at temperatures between 1.4 and 77 K for device #3 in the Supplementary Information (see Fig. S1c). As we decrease temperature, $\rho_{xy}$ acquires a weak negative slope below $H_m$. Once the hfSC sets in for temperatures below $T_c$, the Hall resistivity exhibits zero signal. We present additional high-resolution data recorded with $I = 500 \mu A$ in the Supplementary Information (see Fig. S3b).

Previous pulsed-field studies of resistivity and magnetization have already reported a zero-resistance state including a drop in the magnetization indicating the hfSC phase [10]. Nevertheless, a low non-zero resistivity in combination with a drop in magnetization may indicate a very metallic state, but may not be unambiguous proof for the presence of SC. Here, measurements of Hall resistivity can be of great help: They are sensitive to the nature and density of charge carriers near the Fermi level involved in the transport. This has been well demonstrated in layered delafossite compounds, where a super-low-resistive ground state was observed with a resistivity at 4.2 K below 0.01 $\mu \Omega \text{cm}$ (very hard to detect for bulk
FIG. 4. High-field Hall effect of UTe$_2$. (a), (b) Hall resistivity of device #1 with an applied current of $I = 200 \, \mu A$ recorded (a) at fixed field orientation, $\theta = 35^\circ$, for various temperatures and (b) at fixed temperature, $T = 0.7 \, K$, for various angles. Inset in (a): zoom into the region below 50 T. (c) Hall resistivity recorded for device #2 with $I = 100 \, \mu A$ at fixed temperature and different angles. Thin solid lines are linear fits to the high-field part above 65 T. (d) Angular dependence of the high-field slope of the normal-state Hall resistivity, $d\rho_{xy}/dH$, above 65 T of devices #1 and #2. The blue dashed line is a guide to the eye that highlights the observed strong suppression and even sign change of $d\rho_{xy}/dH$ around $\theta \approx 30^\circ$. The red dashed line follows $\cos \theta$.

deVICES) [44–46]. In this particular case a large mean free path reduces scattering resulting in a hardly detectable resistivity response. Nevertheless, the Hall resistivity and magnetic quantum oscillations exhibit clear signatures of a well-established Fermi surface. Therefore, the clear vanishing of the Hall resistance observed in the hfSC phase for UTe$_2$ (see also in
Fig. S3b), provides further proof of the gaping out of charge carriers in the hfSC phase.

We further recorded the angular evolution of Hall resistivity for the two devices at fixed temperature shown in Fig. 4b and c. The high-field slope of the Hall signal rapidly drops upon increase of $\theta$ and even becomes negative near $30^\circ$. This dramatic angular suppression is best seen in Fig. 4d. Therein, we plot the slope, $d\rho_{xy}/dH$ in the field range between 65 and 69 T against the tilt angle. For angles above approximately $40^\circ$, $d\rho_{xy}/dH$ turns positive again and seems to reach close to what would be expected from a conventional angle dependence of the orbital and anomalous Hall effect, namely scaling with $\cos\theta$.

This steep descent in the angle dependence of $d\rho_{xy}/dH$ for only slight tilts away from $H||b$ is a strong indication for a very narrow angular range within which an enhanced anomalous component contributes to the Hall signal. As the presence of antiferromagnetic fluctuations along the $b$ axis was revealed already [15, 47], it is tempting to suggest that the emergence of hfSC at tilted field orientation may be correlated with the change in the influence of the. Previous magnetization measurements observe no significant change of the magnetization around $H_m$ near $30^\circ$ tilt in the $(b,c)$ plane [35]. This study shows that at least for $H||[011]$ (corresponding to $\theta \approx 25^\circ$) the overall metamagnetic enhancement at $H_m$ of the magnetization persists for such a field alignment. Therefore, we would expect the anomalous Hall component, which is directly proportional to $M$, to remain as strong as for $\theta = 0^\circ$. However, without detailed magnetization data for our samples in such high fields (which is challenging due to the small volume), it is difficult to estimate the relative weight of each Hall component, see the analysis done by Niu et al. for bulk samples at $\theta = 0^\circ$ [22]. For $H||b$, a step-like change in the orbital Hall coefficient signals a Fermi-surface reconstruction around $H_m$ (Fig. 4b). Hence, resolving the Fermi surface for the angular range near the hfSC phase may shed further light on the electronic changes. Recent dHvA experiments and GGA+U calculations revealed the Fermi-surface topology of UTe$_2$ [18]. It is comprised of two kinds of cylindrical Fermi surfaces. A so-called “Yamaji magic angle”, was observed for the electron-like Fermi surface at field oriented around $30^\circ$ away from $b$ towards $c$. This coincides with the angle where hfSC emerges, which demonstrates the special character of the hfSC angular region. In order to learn more about the angle-dependent changes, additional experiments sensitive to thermodynamic properties are highly desirable.
CONCLUSION

In summary, our study features insights on the enigmatic high-field properties of the putative spin-triplet superconductor UTe$_2$. We demonstrate by torque magnetometry how the magnetic anisotropy can be affected by varying the magnetic field orientation within the $(b,c)$ plane. Upon varying the angle away from the hard-magnetic $b$ direction, the metamagnetic transition field, $H_m$, shifts to higher fields. At angles of around $30^\circ$, a distinct superconducting phase can be induced just above $H_m$ for very high magnetic fields larger than 40 T. We provide further evidence for the superconducting nature of this high-field phase and determined its upper critical field to $\mu_0 H_{c2} \approx 75$ T. This value is amongst the highest reported for heavy-fermion superconductors. We still have no explanation for the mechanism leading to this field re-entrant phase above $H_m$. But the important point is that it requires a new mechanism, which would lead to a ”zero field” critical temperature twice larger than for the lfSC phase, and with similar heavy quasiparticle masses. This resembles the ”higher-Tc” superconducting phase observed for pressures around 1 GPa [11–14].

Furthermore, we show that the high-field Hall resistivity experiences a drastic suppression depending on the field direction just before hfSC emerges. The strong angular dependence of the Hall resistivity in the high-field spin-polarized state indicates that the electronic band structure and/or magnetic fluctuations in UTe$_2$ strongly depend on the field direction. While the exact origin remains hidden, it becomes clear that the anomalous part linked to skew scattering from $f$ electrons is significantly suppressed. This suppression of magnetic scattering and the likely reconstruction of the electronic band structure due to a field-orientation-induced transition may be the enabling component for the stabilization of the hfSC phase at such unprecedented magnetic field values. Solving the riddle of how Cooper pairs, built by heavy quasiparticles, can survive in extreme magnetic fields will help advance our fundamental understanding of unconventional superconductors.

METHODS

**Crystal growth:** The UTe$_2$ single crystals were prepared as described in Ref. [2].

**Microcantilever torque magnetometry:** For magnetic-torque experiments cuboid we cut samples with dimensions $(100 \times 20 \times 3) \mu$m$^3$ from a single crystal using focused-ion-beam...
(FIB) assisted etching. We used a Wheatstone-bridge-balanced piezo-resistive cantilever (eigenfrequency $\sim 300$ kHz) [34]. The sample was attached by Apiezon (N) grease. The setup was mounted on a rotator, such that the angle between field and cantilever could be varied, and installed in a $^3$He cryostat. Pulsed magnetic fields of up to 70 T were applied. An example picture of the microcantilever including a sample attached to it is presented in Fig. 1a.

**FIB-microfabrication of transport devices:** Device #1, shown in Fig. 1b, was fabricated in the following steps: First, a slice $(150 \times 20 \times 2) \mu m^3$ was separated out of the crystal using FIB and transferred \textit{ex situ} onto a sapphire chip. Next, an approximately 150 nm thick layer of gold was sputter deposited covering a rectangular area around and including the sample slice. In a next step, carbon-rich platinum was deposited in a FIB system at the two ends and at six side points around the sample slice (see Fig. 1b). The platinum fixations establish a galvanic connection between the gold layer on the chip and the top surface of the sample. Next, the gold layer was partially etched away from the central top surface of the sample by ions. Then, a focused ion beam was applied to cut trenches into the gold layer and the sample in order to create well-defined terminals. Resistances of a few ohms were achieved. In the end, a droplet of transparent unfilled Stycast hardened in vacuum was used to protect the structured device from air. We fabricated three different devices for this study with the following width, thickness, and length $(w \times d \times l)$ between the contacts: device #1 $(10 \times 2.7 \times 75) \mu m^3$; device #2 $(4 \times 2.9 \times 58) \mu m^3$; device #3 $(7.1 \times 4.5 \times 48.5) \mu m^3$.

**Magnetotransport measurements:** We performed steady-field characterization measurements in an Oxford dilution refrigerator equipped with an 18 T superconducting magnet. We measured the resistance with a standard a.c. four-point lock-in technique. We conducted pulsed high-field experiments at the Dresden High Magnetic Field Laboratory in a 60 T and 70 T pulsed-magnet system with a pulse duration of 50 ms and 150 ms equipped with either $^4$He and $^3$He cryostat inserts.

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AUTHOR CONTRIBUTIONS

TH, KS, MK, and MK were involved in the preparation of the devices by FIB micro-fabrication. TH, KS, AM, TF, and MK performed the pulsed-field experiments. TF and TH performed high-field torque magnetometry. JH, JS, and TH performed low-field characterizations. GL, DA, and GK prepared the high-quality samples. JPB, TH, and KS analyzed the critical field data. All authors took part in discussing the results and writing the manuscript.

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SUPPLEMENTARY INFORMATION

In Fig. S1 we present an additional set of magnetic-torque data for the sample shown in Fig. 1a, recorded at 0.7 K.

FIG. S1. Magnetic torque recorded at 0.7 K for various angles in the \((b,c)\) plane. \(\theta = 0^\circ\) corresponds to \(H||b\).
In Fig. S2 we present results obtained for the micro-fabricated device #3. Figure S2a shows an SEM image of device #3. The measured $\rho_a(H)$ and $\rho_{xy}(H)$ reproduce results previously reported for bulk samples to temperatures of up to 77 K [26]. The measurements for this device were carried out in a pulsed-magnet system with a shorter pulse duration ($\sim 25\text{ ms}$). This is why there is a significant hysteresis between the up- (dotted) and the down-sweep (solid) curves. This device, however, did not survive transfers in air to additional experiments. The air sensitivity of UTe$_2$ may be responsible for the fast deterioration of the contacts. Consequently, devices labeled with #1 and #2 were sealed by enclosing them with epoxy, for further details see the Methods section.

FIG. S2. (a) SEM image of Hall-bar device #3. (b) Magnetoresistivity and (c) Hall resistivity of device #3 recorded in a 60 T short-pulse (25 ms) magnet at various temperatures. These results match nicely with data published previously for bulk samples [26], confirming that FIB treatment does not alter the transport properties.
Figure S3 provides an additional set of Hall-effect data recorded for device #1 with high current of 500 µA at two fixed angular orientations, θ = 0° and 30°. Thanks to the high absolute signal the weak negative slope at fields below $H_m$ is well resolved. A resolvable hysteresis appears between the up and down sweeps, likely related to heating caused by the large current. Nevertheless, the hfSC phase is clearly resolved in Fig. S3b. This effect is absent for the data presented in the main text in Figs. 2 and 3, where we applied lower currents.

FIG. S3. High-resolution Hall resistivity of UTe$_2$ recorded for device #1 at fixed angles of θ = 0° and 30° with applied current of 500 µA in a 70 T pulse magnet.
In Fig. S4 we provide data recorded for device #2 at various angles and temperatures. The critical-field values presented in Fig. 3c and d were extracted from this data set.

![Magnetoresistivity of UTe$_2$](image)

**FIG. S4.** Magnetoresistivity of UTe$_2$ recorded for device #2 at four fixed angles with applied current of 100 µA in a 70 T pulsed magnet. Up and down seeps are marked by dotted and solid lines, respectively.