Pressure-induced critical suppression of high-field nematicity in CeRhIn$_5$

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CeRhIn$_5$ provides a textbook example of heavy fermion superconductivity: Pressure suppresses local-moment antiferromagnetic (AFM) order and induces superconductivity in a dome around the associated quantum critical point (QCP). Strong magnetic fields also suppress the AFM order at a field-induced QCP at $B_c \approx 50$ T. In its vicinity, a nematic phase at $B^* \approx 28$ T characterized by a large in-plane resistivity anisotropy with no apparent relation to magnetic order emerges. Here, we directly investigate the interrelation between these phenomena via magnetoresistivity measurements under high pressure by combining Focused Ion Beam microstructures, diamond-anvil pressure-cells and pulsed magnetic fields. While hydrostatic pressure suppresses magnetic order in zero field as the QCP at $p_c \approx 23$ kbar is approached, magnetism strengthens under strong magnetic fields, as evidenced by a growth of the critical field $B_c(p)$. The resulting strongly non-mean-field-like phase diagram shows AFM order present in a much larger phase space than previously expected. As pressure increases, the nematic phase shifts to higher fields, until it vanishes abruptly around 20 kbar. Our results reveal an intriguing phase diagram, much richer than the common local-moment description of CeRhIn$_5$ would suggest.

Keywords: Heavy fermion superconductor; Nematicity; Quantum criticality; Diamond anvil pressure cell; High magnetic field

The physical properties of cerium-based heavy fermion superconductors are strongly governed by the Ce $4f^1$ electrons and their influence on, and local interaction with, the itinerant charge carriers [1, 2]. Due to the small scale of the relevant energies associated with the hybridization of the $4f$-electrons with the conduction bands, small changes in the chemical composition, magnetic field, or pressure can strongly influence the quantum ground state and frequently lead to quantum critical phenomena [3–7]. Here we focus on CeRhIn$_5$, a local moment antiferromagnet characterized by a Néel temperature of $T_N = 3.85$ K [8]. The AFM order is suppressed under pressure, and superconductivity emerges in a dome located around the associated AFM quantum critical point (QCP) at $p_c \approx 23$ kbar [9]. The picture of pressure-induced quantum criticality is further supported by the observation of Non-Fermi-liquid behavior [9–11]. Recent experiments have provided evidence for a second QCP at ambient pressure and under strong magnetic fields, $B_c(p = 0) \approx 50$ T [12, 13]. The temperature-dependence of the resistivity at the field-induced QCP is well described by a similar power law, $\rho(B = 50$ T, $p = 0) \propto T^{0.31}$, compared to the behavior at the zero-field QCP, $\rho(B = 0, p = 23$ kbar) $\propto T^{0.85}$ [9, 13]. Interestingly, the critical-field value is almost completely independent of the field orientation, despite the sizable magnetic anisotropy $\chi_c/\chi_a \approx 2$ in low fields [14]. This isotropy provides a first hint about unconventional behavior of CeRhIn$_5$ in high magnetic fields.

Recently, a field-induced phase transition was reported at intermediate magnetic fields $B^* \geq 28$ T [12, 15]. Later work has uncovered a nematic nature of this high field phase, characterized by the sudden emergence of an in-plane resistivity anisotropy [13]. Magnetic probes, such as magnetization and torque, however, show hardly any features in the relevant field-temperature range [13, 14], which support the notion of an itinerant nematic phase with broken $C4$ rotational symmetry in the ($a$, $b$)-plane. This symmetry breaking is naturally expected to be reflected by a small lattice distortion [16], which has recently been verified by magnetostriction experiments confirming the thermodynamic character of the transition at $B^*$ [17].

The cooperative or competitive interrelation of the magnetic and nematic phases, and in particular their role in the Cooper pairing mechanism, remains a major outstanding question. The observation of nematicity in CeRhIn$_5$ presents a unique opportunity to investigate this interplay, as the entire phase diagram can be mapped with the two least invasive tuning parameters, pressure and magnetic field. While conceptually appealing, a comprehensive investigation of this relation meets multiple experimental challenges: Transport experiments on metallic samples in pulsed magnetic fields need to be combined with diamond-anvil pressure-cells (DACs) and $^3$He temperatures. Inspired by previous experiments in
high fields and high pressures [18–21], we here present a new approach combining Focused Ion Beam (FIB) crystal micromachining [22] and DACs [21] made from plastic for multi-terminal measurements of transport-anisotropy. To minimize heating due to eddy currents in pulsed magnetic fields, the body of the pressure cell and the 3He cryostat were made entirely from plastic (for further details see the supplement).

In the following, we will detail three main experimental observations uncovered by this study: First, the nematic onset field \( B^* \), characterized by an anisotropy jump and a 1\(^{st} \) order-like hysteretic behavior, grows with applied pressure from 28 T at ambient conditions to around 40 T for close to \( p^* \approx 20 \) kbar (see Fig. 2 left panel). At the same time the transport anisotropy, hallmark of the nematic behavior, continuously diminishes until \( p^* \), at which it vanishes completely. Second, the AFM suppression field \( B_c \) also shifts to higher fields upon pressure increase - exceeding 60 T at \( p \approx 17 \) kbar, in contrast to the zero-field suppression of the AFM order around this pressure. Third, for pressures above \( p_c \) a field induced magnetic phase emerges with an onset field \( B_{c,\text{low}} \) that increases with increasing pressure. The full data set, as well as the procedure of the extrapolation of \( B_c \) at higher pressures, is given in the supplement.

Our pulsed field measurements of the FIB fabricated samples at ambient pressure are in excellent agreement with previous measurements on chip-based crystalline devices (Fig. 1). The onset of nematic behavior at \( B^* \approx 28 \) T is signaled by a hysteretic step-like transition with a sudden strong enhancement of the in-plane resistivity anisotropy. The easy direction exhibits a drop in the resistivity, while at the same time, the orthogonal hard direction shows an increase. The easy and hard directions arise from an alignment of the nematic director by a small in-plane magnetic field [13]. In solenoid magnets, such an experimental situation is typically achieved by rotation of the sample with respect to the field axis. The limited space of the used setup, however, did not allow a rotation of the pressure cell during the experiment. To align the nematic order parameter in our pressure experiment, microdevices were cut from the parent crystal at a deliberate \( \theta = 20^\circ \) misalignment angle with respect to the layered crystal lattice (See Fig. 1b). Indeed, a pronounced in-plane resistivity anisotropy at ambient pressure in the devices fabricated onto the diamond demonstrates an effective field-alignment in agreement with previous results outside of a pressure cell [13].

Due to this special field configuration required in order to study the nematic state, however, one of the bars probes a geometric mixture of in- and out-of-plane resistivity (\( \rho_{\nu} = \rho_b \cos^2 20^\circ + \rho_a \sin^2 20^\circ \)), while the other bar senses a pure in-plane resistivity \( \rho_a \). The interlayer resistivity \( \rho_{\nu} \) of CeRhIn\(_3\) in high magnetic fields is lower than for the in-plane directions, which is consistently reflected in the lower resistivity of the deliberately tilted \( b^* \) leg (see Fig. 1c) [15]. The main features of the magneto-resistivity at ambient pressure are in good agreement with previously reported measurements outside of a pressure cell and indicate that the fabrication on the diamond has not altered the properties of the material. The high quality of the devices is further supported by the clean Shubnikov-de Haas oscillations in high fields superimposed to data in Fig. 1c. The observed frequencies agree with previous de Haas-van Alphen oscillation measurements on macroscopic crystals (see supplement) and verify an unchanged electronic state for the pressure microdevices [11].

Figure 2 shows data obtained at low temperatures for sample 2 at six different pressures of up to 37 kbar. An additional data set on a third near duplicate device of similar dimensions in a different DAC that covers pressures of up to 24 kbar supports our main results (see supplement). The resistance noise levels did not increase under pressure, and the overall data quality remains remarkable for a good metal measured in pulsed fields in a DAC.

Here, we examine the state with nematic character that
begins at $B^*$. A hallmark of the transition into the nematic state is its strong first-order nature, apparent in the extended hysteretic region, which was found to be enhanced for micron-sized devices [15]. The difference between the up-and-down sweep, $\rho_{\text{up}} - \rho_{\text{down}}$, for both current directions $a$ and $b^*$, allows us to trace the evolution of the nematic high-field phase (see Fig. 3a). The onset field $B^*(p)$ grows upon increase of pressure, and reaches $B^*(20 \text{kbar}) \approx 43 \text{T}$ (see also sample 3 in the supplement). Remarkably, the magnetoresistance changes its character significantly above 20 kbar (see Fig. 2 and S1). The hysteresis vanishes, and at higher pressure no signature of the nematic transition was observed. The field range of $B^*$ is still significantly below the maximum field, $B_{\text{max}} = 60 \text{T}$, reached in this experiment. A dashed line in Fig. 3b highlights that the evolution of $B^*$, if it continued gradually, would be easily detected within the range accessible in our experiment. Intriguingly, the nematic behavior vanishes at a pressure consistent with a line of critical points between 17 kbar and 23 kbar reported previously from heat capacity experiments in low fields [23].

We now turn to the observed evidence for an enhancement of magnetism upon pressure increase. The suppression of AFM order is visible as a sharp minimum (maximum) in the bars aligned with the $a$-direction ($b^*$-direction) at ambient pressure conditions (marked by a black dotted line in Fig. 1c and Fig. 2). This prominent feature can be associated with the field-induced suppression of the AFM measured by heat capacity [12] and magnetization [14]. Its evolution with temperature and pressure is exhibited in the supplement. The low-temperature value of $B_c$ exceeds the field range, accessible in this study, already for $p \geq 17 \text{kbar}$ (see black diamonds in Fig. 2). For stronger pressures we rely on the extrapolation of the temperature dependence - above 2 K the suppression of AFM order occurs at fields lower than 60 T (see supplement). Interestingly, we find a continuous growth of the suppression field $B_c$ extending to beyond the critical pressure $p_c$ (see Fig. 3a). The presence of an AFM critical field above $p_c \approx 23 \text{kbar}$, where no magnetic order exists in zero field, implies the existence of an onset for field-induced AFM state above $p_c$. Indeed, at pressures

FIG. 2. Magnetoresistivity curves recorded at lowest temperatures in sample 2 for six different pressures. Red and blue correspond to field pulses that overlay the up- and down-sweep data for the $I||a$- and $I||b^*$-direction, respectively. The magenta dotted line marks the zero-pressure onset field, $B^*(p = 0)$, of the nematic phase and the black dotted line the zero-pressure AFM suppression field, $B_c(p = 0)$. For 12.6 and 16.7 kbar $B_c(p)$ is marked by a diamond. The arrows highlight the feature we associate with field-induced magnetism, see supplement.

FIG. 3. (a) Difference between up- and down-field sweeps for $I||a$ (red) and $I||b^*$ (blue), respectively, in Figure 1c, and 2. The purple area highlights the area associated with the hysteresis due to the nematic high-field phase. The onset field $B^*$ is marked by squares. (b) upper panel: Critical fields $B^*$, $B_c$, and $B_{c,\text{low}}$ plotted vs. pressure for sample 2 (squares) and 3 (circles), respectively. The dashed line marks the accessible field range in this experiment. Points beyond that line were obtained by extrapolation of the evolution at higher temperatures (see supplement). (b) lower panel: Phenomenological strength of the nematic behavior, obtained as the maximal difference between each couple of curves in (a).
above $p_c$, a field-induced suppression of the resistivity can be observed (marked by arrows in Fig. 2). This feature is reminiscent of the drop in resistivity at the Néel transition in zero field, due to the suppression of spin disorder scattering at the re-entrance of the AFM state. Its onset field $B_{c,low}$ increases as well, see Fig. 3b. The emergence of unconventional superconductivity, magnetism, and nematicity in close proximity appears to be a unifying observation in cuprates, pnictides, and heavy-fermion systems [24–26]. In the FeAs superconductors, doping suppresses magnetism and nematicity alike, which leads to the emergence of superconductivity around a putative nematic critical point. This appears to be different in the case of the heavy fermion metal CeRhIn$_5$ as the nematic phase moves to higher fields upon pressure increase, instead of collapsing into the zero-field magnetic QCP at $p_c \approx 23$ kbar. Furthermore, this state with electronic nematic character weakens with increasing the pressure until it vanishes very close to $p_c$, see Fig. 3b. It is tempting to correlate the vanishing of the electronic nematic state with the abrupt change in the Fermi surface topology that has been previously observed by magnetic quantum oscillation studies at lower fields [11]. A direct relation between the low field superconducting region and high-field nematicity would require the critical pressure at which the Fermi surface changes from small to large (i.e. the pressure at which the $f$-electrons become incorporated into the Fermi sea) to be roughly independent of the field strength. Given the observed reinforcement of magnetism in strong fields and large pressures, a direct correlation between the critical pressure in zero and high field would imply nematicity to be disentangled from magnetic order.

This is a possible scenario, compatible with our experimental findings summarized in Fig. 4. At the nematic transition field $B^*$ no magnetic anomalies have been detected, neither in torque nor by magnetization experiments. Although the transition occurs within the antiferromagnetic part of the phase diagram, experimental findings disfavor a metamagnetic origin [13]. On the other hand, the observed 10-fold in-plane anisotropy suggests a significant modification of the itinerant electron system. These results pose an intriguing conundrum: While the $4f$-states are critical for the establishment of the nematic phase, their magnetic character remains unchanged across the $B^*$ transition. If the nematic response was a purely electronic phenomenon, disentangled from metamagnetism, the electronic subsystem responsible for the resistivity anomaly in high fields remains to be identified. A possible route to further insights may be found in the recent prediction of Dirac fermions present near the Fermi level in CeMIn$_5$, with $M = \text{Rh, In, Co}$ [30].

In an alternative scenario, the high-field nematic transition is unrelated to superconductivity, and the coincidence of the pressure range of the superconducting instability at zero pressure and the pressure range at which the nematic response vanishes, is coincidental. Such a picture is supported by the pressure dependence of the critical field $B_c(p)$, associated with the suppression of AFM order. While hydrostatic pressure suppresses magnetic order, here $B_c$ increases with larger pressure until it surpasses the field window accessible to this study. This strong growth is counter to the notion that pressure, in general, suppresses AFM order in favor of delocalized $4f$ states [11, 23, 31, 32]. Furthermore, we can trace the prominent feature linked to the metamagnetic transition at low fields to pressures beyond $p_c$, as we discuss in the supplement. Such a pressure-induced growth is reminiscent of the anomalous increase of $T_N$ at very low pressure, before its rapid suppression to zero at the

![FIG. 4.](image-url)
QCP. The generalized phase diagram proposed by Doniach [29] may qualitatively rationalize such a pressure anomaly. For ideal single-ion Kondo lattices, pressure initially strengthens magnetism due to a more rapid growth of Ruderman–Kittel–Kasuya–Yoshida (RKKY) interactions ($T_{\text{RKKY}} \propto J^2$) that favor magnetic order. At higher pressures, the on-site Kondo effect ($T_{\text{Kondo}} \propto \exp (-\frac{J}{t})$) starts to dominate. It eventually weakens the AFM order due to strong screening of the moments followed by the formation of a heavy fermion fluid above the QCP. In a large magnetic field one would expect the Kondo screening to be suppressed, and hence the critical magnetic field to achieve a fully field polarized state. $B_c$ should follow the pressure dependence of the RKKY scale [33], consistent with our observations.

The suppression of the Kondo screening with an applied magnetic field is also likely responsible for the field induced AFM state that is observed above $p_c$. To extend the zero-field Doniach model, the field dependence of the coupling $J$ has to be taken into account (Fig. 4b). Theoretical work on Kondo insulators suggests that a magnetic field suppresses the Kondo screening, while it enhances transverse spin fluctuations. As a result a field-induced AFM state may be established [34–37]. As the hybridization of the $f$-electrons with the conduction band strengthens, magnetic order would, in contrast to its usual suppression due to the Zeeman coupling, become stronger, too. This agrees well with our observations summarized in Figure 4a. Indeed, a reestablishment of AFM order induced by magnetic field beyond $p_c$ was suggested previously for CeRhIn$_5$ [38].

Given the propensity of theory to predict field induced AFM states emerging in Kondo lattices, it is surprising that similar behavior is not commonly observed even in systems that are close to an AFM QCP at ambient conditions [3]. A part of the answer may be found in the pronounced magnetic frustration of CeRhIn$_5$ [39], which may favor reentrant magnetism above $p_c$. Another possible origin for the field induced AFM above $p_c$ is the presence of low lying crystal-electric-field (CEF) excitations. Ab-initio calculations could help to estimate CEF contributions. Strong magnetic fields naturally change the character of the occupied $f$-orbital, and hence, modify the strength of the hybridization to the conduction electrons [17, 40]. To investigate this possibility, hard X-ray absorption spectroscopy under pressure on CeRhIn$_5$ would be useful.

Our magnetotransport studies show that superconductivity and nematicity reside in separate parts of the ($p, B, T$) phase diagram. A key question to our understanding of both the relation between superconductivity and nematicity as well as the anomalous phase diagram is to identify the fate of the Kondo breakdown in the presence of strong magnetic fields. At low fields, specific heat measurements have revealed a line of critical pressures for the suppression of AFM order between $p_{c1} = 17$ kbar and $p_c = 23$ kbar, the critical point at which quantum oscillation studies find the delocalization transition of the 4$f$ states. Does this localized-to-delocalized transition coincide with the field-induced magnetic order above $p_c$, $B_c(p)$, as sketched in Fig. 4b, or does it occur at a field-independent pressure scale of $p_c$, suggested by its coincidence with the pressure scale of the vanishing nematic order? These scenarios cannot be distinguished from the present transport study, and further theoretical and experimental efforts that contribute to complementary thermodynamic measurements will be necessary to unravel this mystery. Our initial work here, however, strongly suggests rich behavior to be uncovered in the high-field/high-pressure phase of CeRhIn$_5$. Both critical end points $p_c$ and $B_c$ must be connected by a continuous line of phase transitions, as the destruction of magnetic order is associated with a change in symmetry. We indicate this anticipated transition in Fig. 4a by a schematic dotted green line in the zero-temperature plane. This line of transitions appears to be highly complex, and thus, hints at multiple low energy scale phenomena and potentially new correlated phases at higher pressure and magnetic field. Magnetoresistance is highly sensitive to property changes in the material and the significant transformation of its overall field dependence beyond $p_c$ suggests a non-trivial behavior in high fields and pressure. Future efforts to develop complementary thermodynamic probes for a detailed investigation of this challenging region in the phase diagram will be pivotal to identify the nature of these phases.

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SUPPLEMENTARY INFORMATION

Methods

DACs and custom plastic $^3$He-fridge tails and $^4$He-cryostat tails were developed at the NHMFL DC-field facility in Tallahassee, FL (USA). The high-field experiments were performed in a multi-shot 65 T magnet system at the NHMFL pulsed-field facility in Los Alamos, NM (USA).

Experimental challenges and solutions

1. The small bore (15.5 mm) of the 65 T magnet at LANL limits the overall sample space inside of the $^3$He cryostat to about 10 mm in diameter. The plastic DAC is fit into this space and provides a high-pressure volume with less than 200 µm in diameter for the transport devices under pressure on top of the culet of the diamond; see the zoom-in images in Fig. S1. The reader can find further details about the pressure technique and focused-ion-beam (FIB) microstructuring process in the methods section (ii) below.

2. The strong forces induced by the compression of the gasket to reach high pressures above 30 kbar commonly deteriorate the leads fed into the sample space. This issue is naturally absent in FIB-deposited platinum leads. The FIB-deposition process is based on the ion-beam induced decomposition of a Pt-containing precursor gas, methylcyclopentadienyl-trimethyl platinum. The deposited material is rich in carbon, typically around 30 at.% [41]. At the same time, the high kinetic energy of the incident ions (30 keV) amorphizes a ~20 nm thick surface layer of the diamond, breaking the C-C bonds. This allows for a chemical bonding process of the carbon-rich deposit onto the diamond. This chemical bonding is at the origin of a superb mechanical adhesion of FIB-deposits on diamond, compared to other approaches of metallization based on deposition and diffusion.

3. Measuring magnetotransport in highly conductive metallic samples such as CeRhIn$_5$ ($\rho_{xx}|_{T=0K} \approx 0.5 \mu\Omega cm$) in pulsed fields is prone to self-heating effects due to strong eddy currents induced by rapidly changing magnetic field (LANL: pulse duration $t \approx 0.1$ s, with a rise time of 15 ms). This imposes limits on the achievable base temperature as well as on the thermal stability during the pulse. By use of FIB microstructuring, the shape of
devices can be designed to minimize eddy currents. Precise control over the sample geometry on the sub-µm level enables us to tune the total device resistance into the experimentally favorable range of 1 – 10 Ω. This permits high-precision measurements and signal-to-noise ratios of about 10⁻³ with a noise of about 1 µV at a measurement frequency of 450 kHz yielding 2 nV/√Hz noise figure (see Fig. S3a).

Combining these approaches allows us reliably to conduct multi-terminal magnetotransport measurements in a strongly constrained sample space under hydrostatic pressures of up to 40 kbar (see for example Fig. S5).

Diamond-anvil pressure-cell and pressure determination

Non-metallic pressure cells and gaskets have been developed for pulsed field experiments to avoid eddy current heating due to rapidly changing fields during the pulse [21]. The absence of significant heating is evidenced by the overlap of up and down sweep curves recorded at a temperature of 0.5 K, as shown in Fig. 2 of the main text and Fig. S3, minus the hysteresis which is related to the intrinsic physics of CeRhIn₅. The use of non-metallic cells and gaskets enables us to reach and sustain ³He temperatures in field of up to 60 T.

Various pressure media can be used, depending on the pressure range as well as the reactivity of that medium with the sample. For this study, we used glycerin, as it remains hydrostatic to 30 kbar at low temperature. The pressure determination is based on the detection of ruby fluorescence lines [42]. Hydrostatic conditions are monitored by measurements of the full-width-half-maximum (FWHM) of the ruby fluorescence line: FWHM < 0.3 nm for hydrostatic conditions as defined by [43]. Micron-sized ruby spheres were placed inside the DAC, close to the sample so that they experience the same pressure conditions as the sample. We determined the pressure in the cell, \( p_{DAC} \) at room and at ³He temperature via optical fibers placed against the back of the diamond. In order to have a reference for the ambient pressure an additional set of spheres was attached onto a separate optical fiber and placed outside the cell at the same temperature. The difference of the fluorescence peaks, \( P_1 \) and \( P_2 \) of the ambient and pressurized ruby spheres, respectively, was used to determine the pressure via the expression: \( p_{DAC} = \frac{(P_1 - P_2) \mu m}{0.00000000000089} \) [44]. The 532 nm excitation laser was attenuated to power of about 100 µW in order to avoid any laser-induced heating of the cell during the pressure measurements.

Focused-ion-beam (FIB) microfabrication

We fabricated transport devices from high-quality single crystals of CeRhIn₅ by the application of Ga or Xe FIB microstructuring, which enable high-resolution investigations of anisotropic high-field transport. FIB micromachining has already proven extremely powerful in various other metallic compounds. A detailed description of the fabrication process can be found elsewhere [13, 15, 22]. We conducted electrical transport measurements by a standard 4-terminal Lock-In technique. Devices were fabricated directly on the culet of the diamond anvil (see Fig. S1). In brief: Pt leads, running along the side faces of the diamond, were deposited by the use of Ga- or Xe-Ion beam currents \( I_{FIB} \) between 1 nA and 21 nA. A \((100 \times 20 \times 3) \mu m^3\) lamella-like slice of CeRhIn₅ was separated with FIB and manually transferred ex-situ onto the culet without any use of adhesives or glue. We used FIB Pt deposition to grow wedge-shaped ramps on each side of the crystal slice that provide a smooth transition from the culet surface onto the crystal. We then deposited a 100 nm thick gold (Au) layer on top in order to electrically connect the Pt leads with the crystal. With the help of FIB we thereafter patterned the Au/Pt interfaces into 6 separate terminals. In a final step, we removed the Au from the central area of the slice before we cut the lamellas into L-shaped transport devices, highlighted by purple color in Fig. S1.
Magnetic quantum oscillation analysis

Here we review the magnetic quantum oscillations (MQOs) observed in the resistivity of Sample 1, i.e. Shubnikov-de Haas oscillations at ambient pressure. Fig. S2a shows the data from Fig. 1d of the main text. The fast Fourier analysis (FFT) spectrum of the inverse background-subtracted oscillation data above 50 T is shown in Fig. S2b. Multiple distinct frequencies are evident in the spectra. Figure S2b contrasts the observed frequencies from transport devices on a diamond anvil with those published from previous low-field de Haas-van Alphen (dHvA) measurements [11]. The frequencies match well, and small deviations are expected as our measurement applies magnetic field at 20° off the c-direction. We were able to resolve SdH oscillations for sample 1 even at a pressure of 10 kbar (Compare the T = 0.5 K curves in Fig. S2a and b). From dHvA oscillation studies we know that the effective masses grow upon increase in pressure until they diverge at the QCP. Hence, it is no surprise that there are no oscillations discernable for higher pressures in our data.

FIG. S2. SdH oscillations from Fig. 1e and f of the main text obtained from Sample 1 at ambient pressure, T = 0.5 K, and a tilt angle of $\theta = 20^\circ$. Vertical red lines mark frequencies published from previous dHvA measurements at $\theta = 0^\circ$ [11].
Base temperature curves of the third sample

To ensure reproducibility of the results, the entire series of experiments was carried out on three, nearly duplicate, devices. The second and third device were cut from CeRhIn$_5$ single crystals at the same orientation as sample 1. Two samples were alternatingly measured inside of the same setup attached to two different probe sticks. The quality and reproducibility of the data from cell to cell is evidenced by the almost seamless interleaving of relevant features in the three samples and the main results reported in the main manuscript are well supported by the two extensively studied ones. We note here that there are slight differences in the absolute values that are within the experimental error bars due to a likely difference of alignment between the devices of a few degrees.

FIG. S3. (a) and (b) Magnetoresistivity curves recorded for sample 3 (with the exact same design as for sample 1 and 2) at five different pressures at lowest temperatures; Red and blue correspond to $I||a$- and $I||b^*$, respectively. The magenta and black dotted lines mark the nematic onset field $B^*$ and the AFM suppression field $B_c$, respectively. (c) Difference between up- and down-field sweeps in (a) and (c). Purple area highlights the area associated with the hysteresis due to the nematic high-field phase. The critical field $B^*$ is marked by hollow circles.
Indications for magnetism in the temperature-dependent high-field magnetoresistivity

The magnetic phase diagram, and the role of magnetic scattering in the anisotropic transport coefficients, is typically complicated in frustrated magnets and currently defies a quantitative analysis. In the following, we will analyze the main features of the magnetoresistivity. We recorded a comprehensive set of data including field sweeps for all pressures at various temperatures. Shown in Fig. 4 are resistivity curves recorded for three samples of the very same geometry and orientation: Sample 1 was measured at ambient pressure and 10 kbar; For sample 2 and 3 we started at approximately 9 kbar. In Figures S5 and S6 we show the full data set for sample 2 and 3, respectively.

We can trace a shoulder-like feature (marked by green vertical dashes) that follows the temperature dependence of the AFM suppression field, $B_c$, it experiences a shift towards lower fields upon temperature increase and is most significant for fields applied within the $ab$-plane, see Ronning et al. \cite{ronning13}.

Since the AFM suppression moves to lower fields upon temperature increase, we rely on extrapolation of $B_c(T)$ to $B_c(T = 0.5 \text{ K})$ when its value exceeds the experimental limit of 60 T. Figure 4 shows the temperature dependence of $B_c$ for the three samples at different pressures extracted from Figures S4, S5, and S6, respectively. We obtained a rough extrapolation of the low temperature values by mimicking the low pressure slopes (thin black lines in Fig. 4a). Figure 4c shows the extracted values at 2.0 K and 1.0 K in the left and right panel, respectively. Since there seems to be only a minor increase as $T$ decreases we use the 1 K data for our schematic phase diagram in Fig. 4a in the main paper to present the base temperature dependence of $B_c(p)$. Error bars indicate the uncertainty in our determination of $B_c$.

A second feature shows up for pressures larger than 23 kbar (marked by black diamond in Fig. 5e and f). Such a sudden suppression of the resistivity at $B_{c,\text{low}}$ may indicate magnetic order induced by magnetic field for pressures beyond the QCP near $p_c$ (see main text). Its temperature dependence exhibits the opposite slope as compared to $B_c(T)$, see cyan data points in Fig. 5b, agreeing with an onset behavior. Indeed, there is also a second hump-like feature below $B_c$ observable in the $T = 3.5 \text{ K}$ resistivity curve of the $p = 23.5 \text{ kbar}$ data set of sample 3 (see Fig. S6). It is likely related to $B_{c,\text{low}}$, and hence, to the onset of magnetic order for this temperature at high field.

Furthermore, at low fields and low pressures ($B \leq 20 \text{ T}$ for $p \leq 19 \text{ kbar}$) a step occurs at $B_M$ that leads to an increase of $\rho$ for both current directions (highlighted by a black arrow in Fig. 4, S4, S5, and S6). This resistive signature of a metamagnetic transition becomes more pronounced as the pressure increases. At this metamagnetic transition, the spin-spiral-like AFM order experiences a transformation into a fan-like configuration at in-plane fields of approximately $2 \text{ T}$ \cite{ronning11}. In our case the devices were set at a tilt angle of $\theta = 20^\circ$ off the $c$ direction in order to induce the strongest transport anisotropy at $B^*$. Hence, $B_M$ is enhanced to about 6 T under ambient pressure. Upon pressure increase the transition is shifting towards higher fields, as can be seen from Figures S7c. The comparison to $B^*(p)$ and $B_c(p)$ suggest a rather simultaneous growth of the three features with pressure. While the nematic behavior disappears already at $p \geq 20 \text{ kbar}$, we can trace $B_M(T)$ and $B_c(T)$ up to at least 23.5 kbar and 28.5 kbar (see Fig. 7b and c).
FIG. S4. Magnetoresistivity curves recorded at different temperatures for three different samples of exactly the same device design and orientation ($\theta = 20^\circ$). Left and right panels exhibit the two current directions, $I \parallel a$ and $I \parallel b^*$, respectively. (a) and (b) Sample 1 at ambient pressure and 10 kbar, (c) Sample 2 at 9 kbar, and (d) Sample 3 at 8.7 kbar. Note: Strong electric noise occurred for samples 2 and 3 due to strong vibrations that couple into loose wiring. These issues were significantly improved for higher pressures (see Fig. S5 and S6). Black arrows mark the shoulder-like feature associated with the metamagnetic transition.
FIG. S5. Magnetoresistivity for Sample 2 recorded for six pressures at different temperatures. Left and right panels exhibit the $I||a$- and $I||b^*$-direction, respectively. The curves are vertically offset for better visibility. Green vertical dashes mark the AFM suppression field $B_c$. Black arrows mark the sholder-like feature associated with the metamagnetic transition. Black diamonds mark a temperature dependent feature we associate with onset behavior of magnetic order.
FIG. S6. Magnetoresistivity for Sample 3 recorded for six pressures at different temperatures. Left and right panels exhibit the $I||a$- and $I||b'$-direction, respectively. Green vertical dashes mark the AFM suppression field $B_c$. Black arrows mark the shoulder-like feature associated with the metamagnetic transition.
FIG. S7. (a) Positions of the AFM suppression field $B_c$ for sample 2 (left) and 3 (right) for the $a$ axis (solid line) and $b^*$ axis (dashed line), extracted from the data set in Figures S4, S5, and S6. (b) Position of the AFM onset field $B_{c,low}$. (c) Extrapolated $B_c$ values at 2 K and 1 K plotted versus pressure for sample 2 and 3. (d) Metamagnetic transition field $B_M$ versus pressure. Note: data points at ambient pressure in (a), (c), and (d) were obtained from sample 1.