Anomalous c-axis Transport Response of UTe$_2$

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We study the temperature dependence of electrical resistivity for currents directed along all crystallographic axes of the spin-triplet superconductor UTe$_2$. We focus particularly on an accurate determination of the resistivity along the c-axis ($\rho_c$) by using transport geometries that allow extraction of two resistivities along with the primary axes directions. Measurement of the absolute values of resistivities in all current directions reveals a surprising degeneracy in the anticipated highly anisotropic band structure nearly isotropic transport behavior at temperatures above Kondo coherence, with $\rho_c \sim \rho_b \sim 2 \rho_a$, but with a qualitatively distinct behavior at lower temperatures. The temperature dependence of $\rho_c$ exhibits a Kondo-like maximum at much lower temperatures compared to that of $\rho_a$ and $\rho_b$, providing important insight into the underlying electronic structure necessary for building a microscopic model of UTe$_2$.

Introduction. The recently discovered superconductivity in UTe$_2$ is believed to be a strong contender for spin-triplet Cooper pairing driven by ferromagnetic spin fluctuations, as suggested by scaling of magnetization data, muon spin relaxation experiments, and an upper critical field that greatly exceeds the Pauli limit in all principle axis directions. A point node superconducting gap structure is evidenced by thermal conductivity and penetration depth studies, and the temperature dependence of the Knight shift in nuclear magnetic resonance is weak, showing evidence of the degeneracy existing in the triplet state. Many other exciting features, such as re-entrant superconductivity at high fields and multiple superconducting phases under applied pressures suggest that UTe$_2$ is a very rich system. Most recently, observations of a splitting of the transition temperature ($T_c$) at ambient pressure, together with a Kerr effect rotation indicating breaking of time-reversal symmetry in the superconducting state, point to a two-component order parameter consistent with a topological (Weyl) superconducting state, potentially explaining the observations of novel surface states in both scanning tunneling microscopy (STM) and microwave experiments.

To date, the majority of experiments have focused on elucidating the symmetry and topological class of the superconducting order parameter, or probing the landscape of proximate ground states, such as magnetism. However, the role of Kondo physics and f-electron contributions, and the construction of the normal state electronic structure in general, remains an open question. Band calculations seem to depend sensitively on the on-site Coulomb interaction strength and the role of f-electron physics. LDA calculations suggested the normal state of UTe$_2$ is a semimetal, while more recent LDA+U calculations find that a metal-to-insulator evolution can be tuned by the strength of the on-site Coulomb interaction strength ($U_{int}$), with two perpendicular Fermi surface (FS) sheets forming a quasi-2 dimensional FS emerging when $U_{int}$ is tuned to $\sim 2$ eV. Recent ARPES experiments indeed observed this quasi-2D FS in addition to a more 3d f-like pocket surrounding the Z-point at 20 K. Importantly, band calculations (DFT + DMFT) in the same study suggest the two sets of sheets comprising the quasi-2D FS derive from the U-6d and Te-5p orbitals, respectively, without the need to invoke $U_{int}$, but fail to predict the existence of the f-like Z pocket, leaving the role of 5f electrons as an important open question.

To build a microscopic model for the superconducting pairing mechanism of UTe$_2$, the normal state fermiology and the role of f-like electrons must be unambiguously understood. Careful experiments, focusing on the details, are therefore highly desirable. Given the confluence of interaction- and dimension-dependent contributions to the normal state electronic behavior in UTe$_2$, it is imperative to have a clear knowledge of the conductivity anisotropy in this system. This study provides a comprehensive measure of electrical transport in all primary crystallographic directions, focusing on the so-far elusive c-axis transport behavior in order to help elucidate the role of dimensionality and orbital contributions to the normal state electronics, and provide constraints on a microscopic theory of pairing.
behavior is observed ($T < \sim 50$ K), and low temperatures where Fermi liquid behavior is observed ($T_c (1.6$ K)$ < T < \sim 50$ K). As shown in Fig. 1 the resistivities start from a relatively high magnitude and drop rapidly below $\sim 50$ K or less, with a qualitative difference found in $\rho_c$ which drops at lower temperatures. Motivated by this pronounced qualitative difference at $T < \sim 50$ K, we also study magnetotransport in this intermediate temperature range.

High temperature ($\sim 50$ K$ < T < 300$ K). At high temperatures, the weak increase of $\rho_a$ and $\rho_b$ upon lowering the temperature ($d\rho/dT < 0$) has been previously attributed to the single-ion Kondo behavior before the coherence starts to develop [1]. We additionally note that all three resistivities in this temperature window are larger than 0.3 m$\Omega$cm. For such large values, we must also consider the possibility of the transport regime being close to localization [22]. When the Fermi surface is highly anisotropic, a lower $\rho$ value is required for violating the Ioffe-Regel criterion than the isotropic case (See SI for more details). In contrast to the $d\rho/dT < 0$ behavior in $\rho_a$ and $\rho_b$ at high temperatures, $\rho_c$ exhibits a metallic-like temperature behavior ($d\rho/dT > 0$) upon decreasing temperature from 300 K, although the resistivity magnitude is comparable to the $a$- and $b$-axis resistivities. From the perspective that the Fermi surface can be approximated by a corrugated cylinder centered around the $c$-axis, the extended state carriers are permitted to have much larger resistivity magnitudes along the $c$-axis direction (See SI for calculation) compared to the $a$ and $b$ direction. Unfortunately, the temperature dependence of all three directions is too weak to definitively determine the scattering mechanism in this temperature range (See SI for details).

Intermediate Temperature ($\sim 5$ K$ < T < \sim 50$ K). The richest qualitative anisotropy exists in the intermediate temperature range. Especially, $\rho_c$ shows the most distinct behavior. First, at $\sim 50$ K, $\rho_a$ and $\rho_b$ starts to drop rapidly while $\rho_c$ starts to increase. The behavior of $\rho_a$ and $\rho_b$ can be considered as the onset of coherence of the Kondo lattice. On the other hand, the increase in $\rho_c$ upon cooling is arrested with a peak around 14 K, below which $\rho_c$ drops. Unfortunately, the origin of this peak is difficult to identify because of its small range. Typically, the Hall effect provides information on whether the carrier density or mobility is the cause of increase in resistivity. However, the carrier information of the Hall effect is likely buried under the skew scattering contribution at this temperature range, as pointed out earlier [14]. Similar peak behavior has also been found in other Kondo lattice systems, where the upturn at temperatures above the peak can be attributed to the scattering rate following a $\propto -T^2$ behavior below $T_K$ (Kondo temperature). Another possibility is a crossover between different conducting channels. For example, the dominant transport behavior may be crossing from the corrugated FS pocket to the heavy $Z$-pocket. Within an assumption that a single transport channel dominates, the change in FS with temperature, and therefore decreasing carrier

Resistivity Results. In this work, we utilize a unique transport setup that measures two primary-direction resistivities simultaneously on a single sample (see SI for details). Figure 1 presents the resistivity results in all three primary crystal directions. We provide a detailed analysis in the SI showing that we have carefully considered the common issues of anisotropic transport such as homogeneity of the sample, misalignment between the sample geometry and the crystallographic axis, and sample-to-sample quality dependence.

Since we have determined the absolute magnitudes of resistivity in all three directions with confidence, we now comment on the quantitative anisotropy. Naively, one would expect the anisotropy to be very large since two perpendicular chains of uranium and tellurium atoms, respectively, would result in a highly anisotropic Fermi surface. Especially, the $c$-axis direction, which is perpendicular to these atomic chains, would expected to be most resistive. Recent band calculations and ARPES results support this expectation. In contrast, our measurements reveal that $\rho_c$ is comparable in magnitude to the other directions overall in the entire temperature range. Although the relative anisotropy in high-temperature magnitude is rather mild, with $\rho_a < \rho_b \approx \rho_c$, it changes to $\rho_a < \rho_b < \rho_c$ in the low temperature regime. Our findings of mild anisotropy in contrast to the anticipated highly anisotropic band structure suggest that the scattering mechanism and the possibility of multiple transport channels must be investigated further.

We further discuss resistivities in the three temperature regimes: high temperatures up to 300 K, intermediate temperatures around Kondo coherence ($\sim 5$ K$ < T < \sim 50$ K), and low temperatures where Fermi liquid behavior is observed ($T_c (1.6$ K)$ < T < \sim 5$ K). As shown in Fig. 1, the resistivities start from a relatively high magnitude and drop rapidly below $\sim 50$ K or less, with a qualitative difference found in $\rho_c$ which drops at lower temperatures. Motivated by this pronounced qualitative difference at $T < \sim 50$ K, we also study magnetotransport in this intermediate temperature range.

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density can be an alternative possible explanation. Later in magnetotransport studies, we show that this peak in \( \rho_c \) is suppressed greatly by an applied magnetic field, indicating that the typical \( \propto -T^2 \) behavior from Kondo is not likely. Also, we will show that magnetoresistance and magnetic susceptibility have distinct features at a similar temperature (\( \sim 10 \) K), which might indicate that they are originating from the same energy scale determining the \( \rho_c \) peak.

**Low Temperature** (\( T_c < T < \sim 5 \) K). At the lowest temperatures in the normal state, the resistivity along all principle axes exhibits a Fermi liquid-like \( T^2 \) dependence, as shown in Fig. [2](#). For cleaner signals, we present data from bar-shaped samples that agree with the resistivity values found in Fig. [1](#). We note that in this temperature range, the anisotropy ratio reverses, changing from \( \rho_a < \rho_c < \rho_b \) at intermediate temperatures to \( \rho_a < \rho_b < \rho_c \) at low temperatures. Interestingly, the \( T^2 \) coefficient (\( A_{FL} \)) is largest for \( \rho_c(T) \). Since the anisotropy in \( A_{FL} \) is likely attributed to anisotropy in the Fermi velocity (\( A_{FL} \propto 1/v^2_F \)) [23], such anisotropy cannot be accounted for solely by the quasi 2D-like FS becoming a Fermi liquid since it is expected to be much more highly anisotropic in the \( z \)-direction.

This raises an important question about the detailed temperature evolution of quasi-2d (hybridized two perpendicular FS sheets) and 3d (\( Z \)-pocket) Fermi surfaces, and that of their relative weights in respective transport channels. One possibility is that the FS might evolve dramatically with temperature, for instance, becoming gapped via hybridization or tuned by \( U_{\text{int}} \). It is hoped that future ARPES experiments will help shed light on this evolution.

**Magnetotransport.** Understanding the role of uranium \( f \)-electrons in \( \text{UTe}_2 \) is important for building a microscopic theory. In \( \text{UTe}_2 \), uranium atoms form chains along the \( a \)-axis and form rungs within the unit cell along the \( c \)-axis. We focus on to what extent \( \text{UTe}_2 \) transport obeys or deviates from a standard Kondo system. We study, in particular, if a current and field direction dependence exists. Since the \( a \)-axis consists of uranium atomic chains and the \( b \)-axis consist of tellurium chains, we apply magnetic fields along those two directions and measure magnetoresistance (MR) of \( \rho_a \) and \( \rho_c \) (more details including other field directions are presented in the SI). As shown in the red color plots in Figs. [3](#) (a) and (b), a negative MR is observed for \( \rho_a \) and \( \rho_c \) over the entire temperature range when the field is applied along the \( a \)-axis. Notably, the peak in \( \rho_c \) is greatly suppressed in this field direction. As shown in the blue color plots, when the field is directed along the \( b \)-axis, a positive MR is seen at temperatures below \( \sim 5 - 10 \) K. As shown in Fig. [1](#), the MR for both \( \rho_a \) and \( \rho_c \) are strikingly similar in magnitude and temperature dependence, suggesting the MR response does not depend heavily on the current direction but depends mostly on the magnetic field direction.

An important reference is the magnetization (\( \vec{M} \)) at high fields. A Curie-Weiss (CW) susceptibility behavior \( M/H = \chi_{CW} \) was observed at higher temperatures for all three field orientations [1], consistent with the behavior of a Kondo lattice system above its coherence temperature. However, at low temperatures, while \( M/bH \) saturates with a slight decrease, \( M_a/H_a \) and \( M_c/H_c \) continue to rise with a slope change around \( \sim 10 \) K [1]. This increasing \( M/H \) saturates in higher magnetic fields [24], a trend previously attributed to a scaling behavior of spin-fluctuations [1]. In Fig. [4](#) we compare MR to the deviation of susceptibility from the CW behavior by plotting the difference \( \Delta M/H = \chi_{CW} - M/H \) for both \( a \)- and \( b \)-axis directions. We do this analysis for two reasons. First, this subtraction emphasizes the subleading order temperature dependence that only shows up as a mild slope change in the raw \( M/H \) data. Second, in a standard Kondo system, \( \Delta M/H > 0 \) at low temperatures since CW behavior is expected to stop and saturate below \( \sim T_K \). Therefore, the sign of \( \Delta \chi \) indicates whether the susceptibility is obeying or deviating from a Kondo-like behavior. For \( H \parallel b \), \( \Delta M/H \) is indeed positive in Fig. [4](#), but in contrast we find \( \Delta M/H < 0 \) for \( H \parallel a \) (Fig. [4](#)), which is clearly non-Kondo-like and likely dominated by easy-axis magnetism of the uranium chains. Comparing MR and \( \Delta M/H \), we notice that there is a qualitative agreement in the temperature trend and sign for both field orientations, suggesting the scattering in transport is predominantly magnetic in nature for both current directions.

Overall, the qualitative and quantitative differences observed between basal plane and \( c \)-axis transport, as well as the crossovers in resistivity anisotropy as a function of temperature, suggest that 1) at least two differ-
different transport channels are responsible for transport in different directions, and 2) the scattering mechanism(s) involves energy scales that are quite sensitive to the temperature range under study. In addition, from magneto-transport studies, 3) the peak in \( \rho_c \) and minima in MR and \( \Delta M/H \) for \( H \parallel a \) occur at nearly the same temperature \( \sim 10 \text{ K} \), which is quite different to the Kondo coherence temperature observed in \( \rho_a \) and \( \rho_b \) in Fig. 1.

All of these observations can be explained by transport channel having a distinct \( \sim 10 \text{ K} \) energy scale that is magnetic (non-Kondo-like) in nature. Interestingly, recent nuclear magnetic resonance experiments have revealed a divergence in the spin–spin relaxation rate \( 1/T_2 \) only for \( H \parallel a \), suggesting the development of spin fluctuations below \( \sim 20 \text{ K} \), presumably due to the proximity to a (quasi) long-range ordered phase \[25\]. Given the absence of long-range magnetic order \[2\], the temperature scales in \( \rho_c \), MR and magnetic response may indicate a possible magnetic crossover scale for fluctuations that dominate the \( c \)-axis transport channel. Future studies using applied pressure and magnetic fields will make use of this foundational work to address these questions.

This work provides a definitive measure of the electrical resistivity along all three primary axes of UTe\(_2\) in the normal state. Given the expectation of strong anisotropy from electronic structure calculations, the magnitude of the \( c \)-axis resistivity is surprisingly comparable in magnitude to the \( a \)- and \( b \)-axis resistivities in the entire temperature range, but exhibits a qualitative difference in behavior at lower temperature below the onset of Kondo coherence. This study adds valuable information to our understanding of the normal state of UTe\(_2\), and will be important for understanding the electronic structure and for building a microscopic theory of superconductivity.

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