Physical properties of the layered f-electron van der Waals magnet Ce$_2$Te$_5$

Yu Liu, M. M. Bordelon, A. Weiland, P. F. S. Rosa, S. M. Thomas, J. D. Thompson, F. Ronning, and E. D. Bauer

MPA-Q, Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA

(Dated: October 17, 2022)

We report a detailed study of the magnetic, transport, and thermodynamic properties of Ce$_2$Te$_5$ single crystals, a layered f-electron van der Waals magnet. Four consecutive transitions at $\sim 5.2$, $2.1$, $0.9$, and $0.4$ K were observed in the ac-plane electrical resistivity $\rho(T)$, which were further confirmed in specific heat $C_p(T)$ measurements. Analysis of the magnetic susceptibility $\chi(T)$, the magnetic-field variation of $\rho(T)$, and the increase of the first transition temperature ($T_1 \sim 5.2$ K) with applied magnetic field indicates ferromagnetic order, while the decrease of the other transitions with field suggests different states with dominant antiferromagnetic interactions below $T_2 \sim 2.1$ K, $T_3 \sim 0.9$ K, and $T_4 = 0.4$ K. Critical behavior analysis around $T_c$ that gives critical exponents $\beta = 0.31(2)$, $\gamma = 0.99(2)$, $\delta = 4.46(1)$, $T_c = 5.32(1)$ K indicates that Ce$_2$Te$_5$ shows a three-dimensional magnetic critical behavior. Moreover, the Hall resistivity $\rho_{xy}$ indicates that Ce$_2$Te$_5$ is a multi-band system with a relatively high electron mobility $\sim 2900$ cm$^2$ V$^{-1}$ s$^{-1}$ near $T_c$, providing further opportunities for future device applications.

INTRODUCTION

Layered van der Waals (vdW) materials have attracted widespread attention due to the exotic quantum states they exhibit, such as correlated insulating, ferromagnetic, and superconducting states in “twisted” bilayer graphene $[1,2]$, or quantum criticality in twisted transition metal dichalcogenides $[3]$. The discovery of intrinsic long-range magnetic order in monolayer CrI$_3$ and bilayer CrGeTe$_3$ has opened up new avenues of research into magnetism in the two-dimensional (2D) limit $[3,4]$ as well as integration of 2D magnetic layers for control of magnetism by gating or other electrical means in devices $[5,6,7]$. Accordingly, several other 3d-electron vdW magnets, such as FePS$_3$, Fe$_3$GeTe$_2$, VSe$_2$, V$_{13}$Cr$_{23}Te_6$, and MnSe$_2$, have been extensively investigated $[8,9,10,11]$. In contrast, very few f-electron vdW magnets have been studied (e.g., CeSi$_2$ $[21]$, EuCe$_2$ $[22,23]$, and GdTe$_3$ $[24]$). Many f-electron materials exhibit significant hybridization between the f-electrons and conduction electrons, leading to highly correlated quantum states with narrow f-bands near the Fermi level; thus, 2D f-electron vdW materials may be highly tunable with modest amounts of pressure, uniaxial strain, or magnetic field, making them promising candidates for discovering and exploring unusual quantum states.

The family of rare-earth telluride RTe$_x$ ($R =$ rare-earth element: $x = 2, 2.5$, and $3$) adopts a layered crystal structure, consisting of square planar Te layers and corrugated RTe slabs. The RTe slabs are semiconducting and responsible for magnetism, while the Te layers form 2D conducting bands; thus RTe$_x$ exhibits highly anisotropic transport and magnetic properties $[26,27]$. Among this series, CeTe$_2$ and CeTe$_3$ crystallize in the layered Cu$_2$Sb$_2$-type tetragonal (space group: $P4/nmm$) structure and NdTe$_3$-type weakly orthorhombic (space group: $Cmcm$) structure, respectively, with localized Ce$^{3+}$ magnetic moments. CeTe$_2$ contains a single layer of Te and undergoes an antiferromagnetic (AFM) transition at $T_N = 4.3$ K $[32,33]$. At 2 K, a metamagnetic transition to a field-induced ferromagnetic (FM) state with an easy $c$ axis occurs at a small magnetic field of 0.06 T. The resistivity shows a sharp peak at $T_p = 6$ K well above $T_N$ with a large negative magnetoresistance (MR) $[34,35]$ arising from magnetic-polaron and/or short-range FM ordering. Neutron diffraction measurements indicate a down-up-down AFM configuration along the $c$ axis with FM Ce double layers above and below the Te layer in CeTe$_2$ $[36,37]$. CeTe$_3$ contains double layers of Te connected via weak vdW force; it exhibits two AFM transitions at $T_{N1} = 3.1$ K and $T_{N2} = 1.3$ K with non-parallel easy axes that are perpendicular to the layer stacking direction, i.e., strongly easy-plane character $[38,39]$.

Layered Ce$_2$Te$_5$ can be considered as a combination of CeTe$_2$ and CeTe$_3$ (Fig. 1), consisting of alternating single and double Te layers stacked along the $b$ axis of the orthorhombic unit cell and separated by CeTe slabs $[40]$. Ce$_2$Te$_5$ crystallizes in a weakly orthorhombic structure, similar to CeTe$_3$, with two Ce sites either adjacent to the double layers of Te (Ce1) or to the monolayer of Te (Ce2). Chen et al. reported three magnetic transitions at 5.1, 2.3, and 0.9 K in Ce$_2$Te$_5$ single crystals $[41]$. In this study we report the physical properties of single crystals of Ce$_2$Te$_5$, including magnetic susceptibility, magnetization, specific heat, and longitudinal and Hall resistivity measurements. An additional magnetic transition at $\sim 0.4$ K was observed, where the resistivity features a weak kink and the specific heat exhibits a peak. When magnetic field is applied along the $b$ axis, the resistivity shows that the first transition $T_1 \sim 5.2$ K broadens and shifts to higher temperatures, consistent with FM ordering; however, the second and third transitions at $T_2 = 2.1$ K and $T_3 = 0.9$ K move to lower temperatures. The critical exponents obtained around $T_c$ indicates that Ce$_2$Te$_5$ shows a three-dimensional magnetic critical behavior. Furthermore, the Hall effect suggests that Ce$_2$Te$_5$
is a multi-band system with a relatively high electron mobility around $T_c$.

**METHODS**

**Experimental details**

Single crystals of Ce$_2$Te$_5$ with typical dimensions of $3 \times 3 \times 0.1$ mm$^3$ were grown by a RbCl/LiCl flux [48]. The crystallographic structure of Ce$_2$Te$_5$ was verified at room temperature by a Bruker D8 Venture single-crystal X-ray diffractometer equipped with Mo radiation. X-ray diffraction analysis shows that Ce$_2$Te$_5$ crystallizes in the orthorhombic space group $Cmcm$ orthorhombic space group.

The magnetization was measured in a Quantum Design Magnetic Property Measurement System (MPMS) from 2 to 350 K up to magnetic fields $\mu_0 H = 6$ T and $\mu_0$ is magnetic permeability in vacuum. For critical analysis, the reported internal magnetic field ($\mu_0 H_{int}$) has been corrected, $\mu_0 H_{int} = \mu_0 H - NM$, where $\mu_0 H$ is the applied magnetic field, $M$ is the measured magnetization, and $N \sim 0.95$ is the demagnetization factor. The specific heat was measured using a Quantum Design Physical Property Measurement System (PPMS) from 0.35 to 20 K that utilizes a quasi-adiabatic thermal relaxation technique. The longitudinal and Hall resistivity were measured in a PPMS using standard four-probe configurations with the current flowing in the $ac$-plane and the magnetic field applied along the $b$-axis. The Hall resistivity $\rho_{xy}(\mu_0 H)$ was calculated by the difference of transverse resistivity measured at positive and negative fields, i.e., $\rho_{xy}(\mu_0 H) = (\rho_{+} - \rho_{-})/2$, so as to effectively eliminate the longitudinal resistivity contribution due to voltage probe misalignment.

**Scaling analysis**

A second-order phase transition around the Curie temperature $T_c$ is characterized by a set of interrelated critical exponents $\beta$, $\gamma$, $\delta$ and a magnetic equation of state [49]. The critical exponents $\beta$ and $\gamma$ are associated with the spontaneous magnetization $M_s$ and the inverse initial susceptibility $\chi_{ini}^{-1}$, below and above $T_c$, respectively, while $\delta$ is the critical isotherm exponent. The definitions of $\beta$, $\gamma$, $\delta$ from magnetization measurement are given below:

$$M_s(T) = M_0(-\varepsilon)^\beta, \varepsilon < 0, T < T_c, \quad (1)$$

$$\chi_{ini}^{-1}(T) = (\mu_0 h_0/m_0)\varepsilon^\gamma, \varepsilon > 0, T > T_c, \quad (2)$$

$$M = D(\mu_0 H_{int})^{1/4}, T = T_c, \quad (3)$$

where $\varepsilon = (T - T_c)/T_c$ is the reduced temperature, and $M_0$, $\mu_0 h_0/m_0$ and $D$ are critical amplitudes [50].

The magnetic equation of state in the critical region ($\varepsilon \leq 0.1$) can be expressed as

$$M(\mu_0 H_{int}, \varepsilon) = \varepsilon^\beta f_+(\mu_0 H_{int}/\varepsilon^{\beta+\gamma}), \quad (4)$$

where $f_-$ for $T < T_c$ and $f_+$ for $T > T_c$, respectively, are regular functions. Eq.(4) can be further written in terms of scaled magnetization $m \equiv \varepsilon^{-\beta}M(\mu_0 H_{int}, \varepsilon)$ and scaled field $\mu_0 h \equiv \varepsilon^{-(\beta+\gamma)}\mu_0 H_{int}$ as

$$m = f_+(\mu_0 h). \quad (5)$$

This suggests that for true scaling relations and the right choice of $\beta$, $\gamma$, $\delta$ values, the scaled $m$ and $\mu_0 h$ will fall on universal curves above $T_c$ and below $T_c$, respectively.

**RESULTS AND DISCUSSION**

Figure 2(a) shows the temperature dependence of magnetic susceptibility $\chi(T)$ measured in $\mu_0 H = 0.1$ T applied parallel and perpendicular to the $b$-axis. A rapid upturn in $\chi(T)$ at low temperature is observed for both field directions, indicating a FM transition. In this field, the zero-field-cooled (ZFC) and field-cooled (FC) data overlap well for each orientation. The temperature dependence of inverse susceptibility $1/\chi(T)$ is plotted in Fig. 2(b). A linear fit from 200 to 300 K to a Curie-Weiss form, $\chi = C/(T - \theta)$, where $C$ is the Curie constant and $\theta$ is the paramagnetic Curie-Weiss temperature, gives $\theta = 9.6$ K for $H \parallel b$ and -18.0 K for $H \perp b$, respectively. The positive value of $\theta$ for $H \parallel b$ is consistent with a dominant FM interaction, while the negative $\theta$ for $H \perp b$ suggests a dominant AFM interaction. The derived effective moment $\mu_{eff} = 2.56 \mu_B$/Ce for $H \parallel b$.
FIG. 2. (Color online). Temperature dependence of (a) magnetic susceptibility $\chi(T)$, defined as $M/\mu_0 H$, and (b) inverse magnetic susceptibility $1/\chi(T)$ of Ce$_2$Te$_5$ measured in magnetic field of $\mu_0 H = 0.1$ T applied parallel and perpendicular to the $b$-axis in zero-field-cooled (ZFC) and field-cooled (FC) modes. The solid lines are linear fits to the data. (c) The low temperature $\chi(T)$ measured in a low magnetic field of $\mu_0 H = 1$ mT. (d) Field dependence of magnetization $M(\mu_0 H)$ of Ce$_2$Te$_5$ measured at $T = 2$ K.

and $2.52 \mu_B$/Ce for $H \perp b$, respectively, are very close to Hund’s value for Ce$^{3+}$ of 2.54 $\mu_B$. It should be noted that the high-temperature anisotropy and deviation from Curie-Weiss behavior with decreasing temperature may be attributed to a crystalline electric field (CEF) effect as explained below. Figure 2(c) shows the low-temperature $\chi(T)$ measured in a small field of $\mu_0 H = 1$ mT. In the ordered state, $\chi(T)$ for $H \parallel b$ is 20 times larger than that of $H \perp b$, indicating a large magnetic anisotropy. The bifurcation of ZFC and FC curves below $T_c \approx 5.2$ K is likely due to a FM domain effect. Figure 2(d) displays the isothermal magnetization measured at 2 K. The magnetization $M(H \parallel b)$ rapidly saturates to $\sim 0.5 \mu_B$/Ce at 40 mT, whereas $M(H \perp b)$ gradually increases. It is interesting that $M(H \perp b)$ increases up to a higher value than $M(H \parallel b)$ above 2.5 T [Fig. 2(d)], in line with the previous results [18], indicating that the magnetic order is more complex than simple ferromagnetism in Ce$_2$Te$_5$. A similar feature was also observed in bulk CeI$_3$ [12]. As shown in the inset of Fig. 2(d), a clear hysteresis loop with coercive field $\mu_0 H_c \approx 20$ mT is observed for $H \parallel b$, indicating soft ferromagnetism with an easy $b$ axis.

As shown in Fig. 3, the anisotropic magnetic susceptibilities can be modeled with a CEF Hamiltonian for Ce$^{3+}$ of total angular momentum $J = 5/2$. In Ce$_2$Te$_5$, due to $a$ and $c$ being accidentally degenerate in the orthorhombic Cmcm crystal structure, the local Ce point group has $C_{4v}$ symmetry with the four-fold rotational axis along the crystallographic $b$-axis. The resultant CEF Hamiltonian contains three CEF parameters $B_{n}^m$ with corresponding Steven’s operators $\hat{O}_m$ [$51$] as

$$H_{CEF} = B_{0}^{0} \hat{O}_{2}^{0} + B_{1}^{0} \hat{O}_{1}^{0} + B_{2}^{0} \hat{O}_{1}^{0},$$  

which produces three Kramers doublets. In the $C_{4v}$ point group and $J, m_j$ basis, these doublets are labeled $\Gamma_B$, with $m_j = \pm 1/2$ components or $\Gamma^\ast_{B}$ with mixed $m_j = \pm 5/2$ and $\pm 3/2$ components. Magnetic susceptibility of the CEF Hamiltonian was calculated using Mantid Plot [52] with an additional temperature independent $\chi_0$ term and effective mean-field exchange interactions $\Theta_\perp$ and $\Theta_\parallel$. An effective susceptibility was calculated as $\chi_{\text{eff}} = \chi_{\text{CEF}}/(1 - \Theta_\text{CEF})$ and compared to the observed $\chi_{\text{obs}} = \chi - \chi_0$, where $\chi_0$ is a temperature-independent contribution. The overall fit was determined by minimizing $X^2 = (\chi_{\text{calc}} - \chi_{\text{obs}})^2/\chi_{\text{calc}}$ with a final $X^2 = 15.8$ and extracted parameters $B_{0}^{0} = -0.39003 \text{ meV}$, $B_{1}^{0} = 0.06595 \text{ meV}$, $B_{2}^{0} = -0.21987 \text{ meV}$, $\chi_0 = -0.000195 \text{ emu mol}^{-1}$, $\Theta_\perp = 24.74 \text{ K}$, and $\Theta_\parallel = 18.81 \text{ K}$. The ground state doublet is $\Gamma_{B}^{0} = 0.396(\pm 5/2) + 0.918(\pm 3/2)$, the first excited state doublet $\Gamma_{B}^{2} = 0.918(\pm 5/2) + 0.396(\pm 3/2)$ is at $16.23 \text{ meV}$, and the second excited state doublet $\Gamma_{B}^{4} = |\pm 1/2\rangle$ is at $24.67 \text{ meV}$. The ground state doublet has projected $g$ factors $g_\perp = 1.393$ and $g_\parallel = 1.497$, respectively. Taking $J_\text{eff} = 1/2$ for the ground state doublet, the expected saturated moment $g_J \mu_B$ is $0.697 \mu_B$/Ce for $H \perp b$ and $0.749 \mu_B$/Ce for $H \parallel b$, in reasonable agreement with the magnetization at 2 K and 6 T $M_{H \parallel b} = 0.87 \mu_B$/Ce and $M_{H \parallel b} = 0.76 \mu_B$/Ce.

In order to understand the nature of the FM transition in Ce$_2$Te$_5$, one approach is to study in detail the critical exponents around $T_c$. Magnetization isotherms along the easy $b$-axis were measured from 4.6 to 6 K at intervals of 0.1 K. An Arrrott plot of $M^2$ vs $\mu_0 H_{\text{int}}/M$ at various
temperatures is displayed in Fig. 4(a). In the mean field description of the magnetization near $T_c$, curves in the Arrott plot should be a series of parallel straight lines with the one passing through the origin indicating the $T_c$. It is clear that mean field critical exponents do not work for Ce$_2$Te$_5$, as illustrated by a set of curved lines shown in Fig. 4(a). According to the Arrott-Noaks equation of state $(\mu H_{int}/M)^{1/\gamma} = a\varepsilon + bM^{1/\beta}$, $a$ and $b$ are constants, a modified Arrott plot should be used to obtain the critical exponents. $\beta$ and $\gamma$ can be obtained self consistently. After selecting $\beta$ and $\gamma$, the linear extrapolation from the high field region to the intercepts with the axes $M^{1/\beta}$ and $(\mu H_{int}/M)^{1/\gamma}$ yields the values of $M_c(T)$ and $\chi^{-1}_{\text{int}}(T)$. A new set of $\beta$ and $\gamma$ can be obtained by fitting data following Eqs. (1) and (2), which can be used to reconstruct a new modified Arrott plot. This procedure is then repeated until the values of $\beta$ and $\gamma$ are stable.

Figure 4(b) presents the final $M_c(T)$ and $\chi^{-1}_{\text{int}}(T)$ with the fitted curves. Critical exponents $\beta = 0.30(2)$, $\gamma = 0.99(5)$, and $T_c = 5.32(1)$ K are obtained. Figure 4(c) exhibits the field dependence of magnetization of Ce$_2$Te$_5$ at $T_c = 5.3$ K in a log$_{10}M$-log$_{10}(\mu H_{int})$ plot, yielding $\delta = 4.46(1)$ from Eq. (3). In comparison to the theoretical prediction based on the Widom relation $\delta = 1 + \frac{\gamma}{\beta}$ (7), the derived $\delta = 4.3(1)$ is close to that obtained in Fig. 4(c). In addition, critical exponents can also be determined according to the Kouvel-Fisher (KF) method:

$$\frac{M_c(T)}{dT} = \frac{T - T_c}{\beta}$$

$$\frac{\chi^{-1}_{\text{int}}(T)}{dT} = \frac{T - T_c}{\gamma}$$

$M_c(T)/[dT(T)/dT]$ and $\chi^{-1}_{\text{int}}(T)/[d\chi^{-1}_{\text{int}}(T)/dT]$ are linear functions of temperature with slopes of $1/\beta$ and $1/\gamma$, respectively. As shown in Fig. 4(d), the linear fits give $\beta = 0.31(2)$, $\gamma = 0.99(2)$, and $T_c = 5.32(1)$ K, which are consistent with those generated by the modified Arrott plot.

Following Eq. (5), the scaled $m$ vs scaled $\mu H$ is plotted in Fig. 5(a). All the data reasonably well collapse into two separate branches: one below $T_c$ and another above $T_c$. The scaling equation of state also takes another form:

$$\frac{\mu H_{int}}{M^{1/\beta}} = k [\frac{\varepsilon}{(\mu H_{int})^{1/\beta}}]$$

(10)

where $k(x)$ is the scaling function. Figure 5(b) shows $M(\mu H_{int})^{1/\beta}$ vs $\varepsilon(\mu H_{int})^{-1/\beta}$ for Ce$_2$Te$_5$, where the experimental data collapse reasonably onto a single curve, and $T_c$ locates at the zero point of the horizontal axis. The well-scaled curves confirm reliability of the obtained critical exponents. Figure 5(c) presents the derived magnetic entropy change $-\Delta S_M = \int_0^{\mu H} [\partial M(T, \mu H)/\partial T] d(\mu H)$, which shows a
broad peak centered near $T_c$. The peak value monotonically increases with increasing field, reaches 4.7(1) $\Omega$ cm$^{-1}$ K$^{-1}$ in 6 T. The field dependence of $-\Delta S_{M}^{\text{max}}$ follows a power law $-\Delta S_{M}^{\text{max}} \propto (\mu_0 H)^n$ with $n = 1 + (\beta - 1)/(\beta + \gamma)$ [61]. Fitting of $-\Delta S_{M}^{\text{max}}$ gives $n = 0.49(1)$, which is close to the calculated value of 0.46(1), further verifies the reliability of the obtained critical exponents.

Taroni et al. pointed out that the value of $\beta$ for a 2D magnet should be within a window $0.1 \leq \beta \leq 0.25$ [62]. The value of $\beta = 0.325$ obtained here indicates a clear 3D behavior in Ce$_2$Te$_5$. As we can see, the critical exponent $\beta$ of Ce$_2$Te$_5$ is close to the theoretical value ($\beta = 0.325$) of the 3D Ising model (Table I), consistent with the large anisotropy in magnetization below $T_c$ [Fig. 2(d)]. However, the value of $\gamma = 1.24$ of the 3D Ising model, which might be arising from the long-range Ruderman-Kittel-Kasuya-Yosida (RKKY) interactions.

Having delineated salient features of the FM state below $T_c$, we now turn to an investigation of electrical transport properties. Figure 6(a) shows the temperature dependence of $\rho(T)$ and (b) specific heat $C_p/T$ of Ce$_2$Te$_5$ in zero field. Inset in (b) shows the electron entropy $S_{4f}(T)$/Rln2 of Ce$_2$Te$_5$.

FIG. 6. (Color online). Temperature dependence of (a) in-plane electrical resistivity $\rho(T)$ and (b) specific heat $C_p/T$ of Ce$_2$Te$_5$ in zero field. Inset (b) shows the electron entropy $S_{4f}(T)$/Rln2 of Ce$_2$Te$_5$.
The longitudinal magnetoresistance of Ce$_2$Te$_5$ at different temperatures. Inset shows transport measurements (solid symbols from MR). PM, FM, and AFM represent paramagnetic, ferromagnetic, and antiferromagnetic phases, respectively. The nature of $T_4$ at the lowest temperature needs further investigation, and neutron scattering measurements are required to determine the CEF levels and the magnetic structure of Ce$_2$Te$_5$.

To shed light on the transport carriers in Ce$_2$Te$_5$, we further measured the field dependence of Hall resistivity $\rho_{xy}(\mu_0 H)$ of Ce$_2$Te$_5$ with current flowing in the $ac$-plane and the field applied along the $b$-axis at various temperatures, as shown in Figs. 8(a) and 8(b). The Hall coefficient $\rho_{xy}/(\mu_0 H)$ is negative at high temperatures, indicating dominant electron-like carriers. With decreasing temperature, $\rho_{xy}$ exhibits nonlinear behavior below 60 K, and the shape of $\rho_{xy}$ changes significantly below 40 K, becoming parabolic at low temperatures. These observations suggest that Ce$_2$Te$_5$ is a multi-band system, as has been observed in a related compound GdTe$_5$.

Assuming a two-band model, the Hall resistivity is expressed as

$$\rho_{xy} = \frac{\mu_0 H}{e} \left( n_e (n_e^2 - n_e \mu_e^2) + 0.5 n_h - n_e (0.5 \mu_e \mu_h \mu_0 H)^2 \right)$$

where $e$ is the elementary charge; $n_e$ and $n_h$ are the electron and hole carrier concentrations, respectively; $\mu_e$ and $\mu_h$ are the electron and hole carrier mobilities, respectively. The derived fitting parameters $n_e$, $n_h$, $\mu_e$ and $\mu_h$...
are plotted in Figs. 8(c) and 8(d), respectively, where the electron and hole carriers are almost compensated at high temperatures and become uncompensated below 60 K. The carrier concentration is of the order of $10^{20} - 10^{21}$ cm$^{-3}$ [Fig. 7(c)]. The hole mobility $\mu_h$ is $\sim 350 - 930$ cm$^2$/V·s and is weakly temperature-dependent; however, $\mu_e$ increases abruptly below 60 K and features a relatively large value of $\sim 2900$ cm$^2$/V·s near $T_c$. This high electron mobility in Ce$_2$Te$_5$, a vdW layered and magnetically ordered material, is larger than that of some other rare-earth materials such as YbMn(Bi,Sb)$_2$ and EuMnBi$_2$ [4-7], and provides further opportunities for future device applications.

CONCLUSIONS

In summary, we studied the magnetic, transport, and thermodynamic properties of the $f$-electron vdW magnet Ce$_2$Te$_5$ and summarized its magnetic phase diagram. Four magnetic transitions were observed at $T_1 = 5.2$, $T_2 = 2.1$, $T_3 = 0.9$, and $T_4 = 0.4$ K. Critical exponents in the vicinity of the FM transition are determined to be $\beta = 0.31(2)$, $\gamma = 0.99(2)$, $\delta = 4.46(1)$, $\zeta_c = 5.32(1)$ K, indicating that Ce$_2$Te$_5$ shows a three-dimensional magnetic critical behavior. A crystal electric field model of the magnetic susceptibility suggests that the ground state $\Gamma_1^7$ doublet has a dominant $3/2$ character with excited $\Gamma_3^2$ and $\Gamma_8$ states at $\sim 16$ and 25 meV, respectively. Further neutron scattering or X-ray absorption spectroscopy measurements will be needed to confirm this CEF scheme. The Hall resistivity analysis indicates that Ce$_2$Te$_5$ is a multi-band system with a relatively high electron mobility around $T_c$. Furthermore, with rapid developments in the field of 2D materials, we expect our experimental work to stimulate broad interest for exploring its magnetic and transport properties in the 2D limit.

ACKNOWLEDGEMENTS

Work at Los Alamos National Laboratory was performed under the auspices of the U.S. Department of Energy, Office of Basic Energy Sciences, Division of Materials Science and Engineering under project “Quantum Fluctuations in Narrow-Band Systems”. Y.L., M.M.B., and A.W. acknowledges the Director’s Postdoctoral Fellowship through the Laboratory Directed Research and Development program.

[1] Y. Cao, V. Fatemi, A. Demir, S. Fang, S. L. Tomarken, J. Y. Luo, J. D. Sanchez-Yamagishi, K. Watanabe, T. Taniguchi, E. Kaxiras, R. C. Ashoori, and P. Jarillo-Herrero, Correlated insulator behaviour at half-filling in magic-angle graphene superlattices, Nature 556, 80-84 (2018).
[2] Y. Cao, V. Fatemi, S. Fang, K. Watanabe, T. Taniguchi, E. Kaxiras, and P. Jarillo-Herrero, Unconventional superconductivity in magic-angle graphene superlattices, Nature 556, 80-84 (2018).
[3] M. Yankowitz, S. Chen, H. Polshyn, Y. Zhang, K. Watanabe, T. Taniguchi, D. Graf, A. F. Young, and C. R. Dean, Tuning superconductivity in twisted bilayer graphene, Science 363, 1059-1064 (2019).
[4] A. Ghiotto, E.-M. Shih, G. S. S. G. Pereira, D. A. Rhodes, B. Kim, J. Zang, A. J. Mills, K. Watanabe, T. Taniguchi, J. C. Hone, L. Wang, C. R. Dean, and A. N. Pasupathy, Quantum criticality in twisted transition metal dichalcogenides, Nature 597, 345-349 (2021).
[5] B. Huang, G. Clark, E. Navarro-Moratalla, D. R. Klein, R. Cheng, K. L. Seyler, D. Zhong, E. Schmidgall, M. A. McGuire, D. H. Cobden, W. Yao, D. Xiao, P. Jarillo-Herrero, and X. D. Xu, Layer-dependent ferromagnetism in a van der Waals crystal down to the monolayer limit, Nature 546, 270 (2017).
[6] C. Gong, L. Li, Z. L. Li, H. W. Ji, A. Stern, Y. Xia, T. Cao, W. Bao, C. Z. Wang, Y. Wang, Z. Q. Qu, R. J. Cava, S. G. Louie, J. Xia, and X. Zhang, Discovery of intrinsic ferromagnetism in two-dimensional van der Waals crystals, Nature 546, 265 (2017).
[7] K. F. Mak, J. Shan, and D. C. Ralph, Probing and controlling magnetic states in 2D layered magnetic materials, Nat. Rev. Phys. 1, 646-661 (2019).
[8] K. S. Burch, D. Mandrus, and J.-Geun Park, Magnetism in two-dimensional van der Waals materials, Nature 563, 47-52 (2018).
[9] T. Song, X. Cai, M. W.-Y. Tu, X. Zhang, B. Huang, N. P. Wilson, K. L. Seyler, L. Zhu, T. Taniguchi, K. Watanabe, M. A. McGuire, D. H. Cobden, D. Xiao, W. Yao, and X. Xu, Giant tunneling magnetoresistance in spin-filter van der Waals heterostructures, Science 360, 1214-1218 (2018).
[10] Q. H. Wang, A. B.-Pinto, M. Blei, A. H. Dismukes, A. Hamo, S. Jenkins, M. Koperski, Y. Liu, Q.-C. Sun, E. J. Telford, et al., The magnetic genome of two-dimensional van der Waals materials, ACS Nano 16, 6060 (2022).
[11] Y. Liu, L. Wu, X. Tong, J. Li, Y. Zhu, and C. Petrovic, Thickness-dependent magnetic order in CrI$_3$ single crystals, Sci. Rep. 9, 13599 (2019).
[12] Y. Liu and C. Petrovic, Three-dimensional magnetic critical behavior in CrI$_3$, Phys. Rev. B 97, 014420 (2018).
[13] Y. Liu and C. Petrovic, Critical behavior of quasi-two-dimensional semiconducting ferromagnet Cr$_2$Ge$_2$Te$_6$, Phys. Rev. B 96, 054406 (2017).
[14] J. Lee, S. Lee, J. H. Ryoo, S. Kang, T. Y. Kim, P. Kim, C. Park, J. Park, and H. Cheong, Ising-Type Magnetic Ordering in Atomically Thin FePS$_3$, Nano Lett. 16, 7433 (2016).
[15] Y. J. Deng, Y. J. Yu, Y. C. Song, J. Z. Zhang, N. Z. Wang, Z. Y. Sun, Y. F. Yi, Y. Z. Wu, S. W. Wu, J. Y. Zhu, J. Wang, X. H. Chen, and Y. B. Zhang, Gate-tunable room-temperature ferromagnetism in two-dimensional Fe$_3$Te$_5$, Nature 563, 94 (2018).
[16] M. Bonilla, S. Kolekar, Y. Ma, H. C. Diaz, V. Kalappattil, R. Das, T. Eggers, H. R. Gutierrez, M. Phan, and M. Batzill, Strong room-temperature ferromagnetism in VSe$_2$ monolayers on van der Waals substrates, Nat. Nanotechnol. 13 289 (2018).
[17] X. Zhang, Q. Lu, W. Liu, W. Niu, J. Sun, J. Cook, M. Vaninger, P. F. Miceli, D. J. Singh, S. Lian, T. Chang, X. He, J. Du, L. He, R. Zhang, G. Bin, and Y. Xu, Room-temperature intrinsic ferromagnetism in epitaxial CrTe$_2$ ultrathin film, Nat. Commun. 12, 2492 (2021).

[18] D. J. O’Hara, T. Zhu, A. H. Trout, A. S. Ahmed, Y. K. Luo, C. H. Lee, M. R. Brenner, S. Rajan, J. A. Gupta, D. W. McComb, and R. K. Kawabata, Room Temperature Intrinsic Ferromagnetism in Epitaxial Manganese Selenide Films in the Monolayer Limit, Nano Lett. 18, 3125 (2018).

[19] Y. Liu, M. Abeykoon, and C. Petrovic, Critical behavior and magnetocaloric effect in V$_3$I, Phys. Rev. Res. 2, 013013 (2020).

[20] Y. Liu, V. N. Ivanovski, and C. Petrovic, Critical behavior of the van der Waals bonded ferromagnet Fe$_3$-$\delta$GeTe$_2$, Phys. Rev. B 96, 144429 (2017).

[21] R. Okuma, C. Ritter, G. J. Nilsen, and Y. Okada, Magnetic frustration in a van der Waals metal CeS$_2$I, Phys. Rev. Mater. 5, L121401 (2021).

[22] I. S. Sokolov, D. V. Averyanov, O. E. Parfenov, I. A. Karateev, A. N. Taldnkov, A. M. Tokmachev, and V. G. Storchak, 2D ferromagnetism in europium/graphene bilayers, Mater. Horiz. 7, 1372-1378 (2020).

[23] I. S. Sokolov, D. V. Averyanov, O. E. Parfenov, A. N. Taldnkov, I. A. Karateev, A. M. Tokmachev, and V. G. Storchak, Two-dimensional ferromagnetism in Eu- intercalated few-layer graphene, J. Alloys Compd. 884, 161078 (2021).

[24] I. S. Sokolov, D. V. Averyanov, F. Wilhelm, A. Rogalev, O. E. Parfenov, A. N. Taldnkov, I. A. Karateev, A. M. Tokmachev, and V. G. Storchak, Emerging 2D magnetic states in a graphene-based monolayer of EuC$_6$, Nano Research 15, 408-413 (2022).

[25] S. Lei, J. Lin, Y. Jia, M. Gray, A. Topp, G. Farahi, S. Klemenz, T. Gao, F. Rodolakis, J. L. McChesney, C. R. Ast, A. Yazdani, K. S. Burth, S. Wu, N. P. Ong, and L. M. Schoop, High mobility in a van der Waals layered antiferromagnetic metal, Sci. Adv. 6, eaay6407 (2020).

[26] B. H. Min, J. H. Cho, H. J. Lee, C. W. Han, D. L. Kim, and Y. S. Kwon, Specific heat study in RTe$_2$ (R: La, Ce, Pr, Sm and Gd), Physica B 281&282, 118 (2000).

[27] Y. S. Kwon and B. H. Min, Anisotropic transport properties in RTe$_2$ (R: La, Ce, Pr, Sm and Gd), Physica B 281&282, 120 (2000).

[28] Y. S. Shin, C. W. Han, B. H. Min, H. J. Lee, C. H. Choi, Y. S. Kim, D. L. Kim, and Y. S. Kwon, Anisotropic magnetization in RTe$_2$ (R: Ce, Pr, Gd and Sm), Physica B 291, 225 (2000).

[29] Y. Iyeiri, T. Okumura, C. Michioka, and K. Suzuki, Magnetic properties of rare-earth metal tritellurides RTe$_2$ (R = Ce, Pr, Nd, Gd, Dy), Phys. Rev. B 67, 144417 (2003).

[30] N. Ru and I. R. Fisher, Thermodynamic and transport properties of YTe$_3$, LaTe$_3$, and CeTe$_3$, Phys. Rev. B 73, 033101 (2006).

[31] N. Ru, J. H. Chu, and I. R. Fisher, Magnetic properties of the charge density wave compounds RTe$_3$ (R = Y, La, Ce, Pr, Nd, Sm, Gd, Tb, Dy, Ho, Er, and Tm), Phys. Rev. B 78, 012410 (2008).

[32] Y. S. Wkon, T. S. Park, K. R. Lee, J. M. Kim, Y. Haga, and T. Suzuki, Transport and optical properties of CeTe$_2$, J. Magn. Magn. Mater. 140-144, 1173 (1995).

[33] B. H. Min, H. Y. Choi, and Y. S. Kwon, Physica B 312-313, 203 (2002).

[34] M. Jung, B. Min, Y. Kwon, I. Oguro, F. Iga, T. Fujita, T. Ekino, T. Kasuya, and T. Takabatake, Anisotropic transport and magnetic properties and magnetic-polaron-like behavior in CeTe$_2$-x, J. Phys. Soc. Jpn. 69, 937 (2000).

[35] M. H. Jung, K. Umeo, T. Fujita, and T. Takabatake, Competing interactions and anisotropic magnetoresistance in layered CeTe$_2$, Phys. Rev. B 62, 11609 (2000).

[36] M. H. Jung, Y. S. Kwon, and T. Suzuki, Physica B 240, 83 (1997).

[37] T. Kasuya, M. H. Jung, and T. Takabatake, J. Magn. Magn. Mater. 220, 235 (2000).

[38] B. H. Min, E. D. Moon, H. J. Im, S. O. Hong, Y. S. Kwon, D. L. Kim, and H. C. Ri, Transport properties in low carrier system CeTe$_2$, Physica B 312-313, 205 (2002).

[39] J. G. Park, I. P. Swainson, W. J. L. Buyers, M. H. Jung, and Y. S. Kwon, Physica B 241-243, 684 (1998).

[40] J. G. Park, Y. S. Kwon, W. Kockelmann, M. J. Bull, I. P. Swainson, K. A. McEwen, and W. J. L. Buyers, Neutron scattering study of CeTe$_2$, Physica B 281&282, 451 (2000).

[41] K. Stöwe, Crystal structure and magnetic properties of CeTe$_2$, J. Alloys Compd. 307, 101 (2000).

[42] Z. S. Liu, J. G. Park, Y. S. Kwon, K. A. McEwen, and M. J. Bull, Crystal-field excitations and model calculations of CeTe$_2$, J. Magn. Magn. Mater. 256, 151 (2003).

[43] J. H. Shim, S. J. Youn, M. S. Park, and B. I. Min, Electronic and magnetic structures of CeTe$_2$, J. Appl. Phys. 97, 10A918 (2005).

[44] K. Deguchi, T. Okada, G. F. Chen, S. Ban, N. Aso, and N. K. Sato, Magnetic order of rare-earth tritelluride CeTe$_3$ at low temperature, J. Phys.: Conf. Ser. 150, 042023 (2009).

[45] D. A. Zocco, J. J. Hamlin, T. A. Sayles, M. B. Maple, J. H. Chu, and I. R. Fisher, High-pressure, transport, and thermodynamic properties of CeTe$_3$, Phys. Rev. B 79, 134428 (2009).

[46] R. Okuma, D. Ueta, S. Kuniyoshi, Y. Fujisawa, B. Smith, C. H. Hsu, Y. Inagaki, W. Si, T. Kawae, H. Lin, F. C. Chuang, T. Masuda, T. Kobayashi, and Y. Okada, Fermionic order by disorder in a van der Waals antiferromagnet, Sci. Rep. 10, 15311 (2020).

[47] M. Watanabe, S. Lee, T. Asano, T. Ike, M. Tokuda, H. Taniguchi, D. Ueta, Y. Okada, K. Kobayashi, and Y. Niimi, Quantum oscillations with magnetic hysteresis observed in CeTe$_3$ thin films, Appl. Phys. Lett. 117, 072403 (2020).

[48] D. Chen, S. Zhang, H. X. Yang, J. Q. Li, and G. F. Chen, Magnetic and transport properties of a layered compound Ce$_2$Te$_5$. J. Phys.: Condens. Matter 29, 265803 (2017).

[49] H. E. Stanley, Introduction to Phase Transitions and Critical Phenomena (Oxford U. P., London and New York, 1971).

[50] M. E. Fisher, The theory of equilibrium critical phenomena, Rep. Prog. Phys. 30, 615 (1967).

[51] K. Stevens, Matrix elements and operator equivalents connected with the magnetic properties of rare earth ions, Proc. Phys. Soc. A 65, 209 (1952).

[52] O. Arnold, J.-C. Bilheux, J. M. Borreguero, A. Buts, S. I. Campbell, L. Chapon, M. Doucet, N. Draper, R. F. Leal, M. A. Gigg, V. E. Lynch, A. Markvardsen, D. J. Mikkelson, R. I. Mikkelson, R. Miller, K. Palmens, P. Parker, G. Passos, T. G. Perrin, P. F. Peterson, S. Ren, M. A. Reuter, A. T. Savici, J. W. Taylor, R. J. Taylor,
R. Tolchenov, W. Zhou, and J. Zikovsky, Mantid-data analysis and visualization package for neutron scattering and μSR experiments, Nucl. Instrum. Methods A 764, 156 (2014).

[53] A. Arrott, Criterion for ferromagnetism from observations of magnetic isotherms, Phys. Rev. B 108, 1394 (1957).

[54] S. K. Banerjee, On a generalised approach to first and second order magnetic transitions, Phys. Lett. 12, 16 (1964).

[55] A. Arrott and J. Noakes, Approximate equation of state for nickel near its critical temperature, Phys. Rev. Lett. 19, 786 (1967).

[56] A. K. Pramanik and A. Banerjee, Critical behavior at paramagnetic to ferromagnetic phase transition in Pr0.5Sr0.5MnO3: A bulk magnetization study, Phys. Rev. B 79, 214426 (2009).

[57] L. Kadanoff, Scaling laws for Ising models near Tc, Physics, 2, 263 (1966).

[58] B. Widom, Degree of the Critical Isotherm, J. Chem. Phys. 41, 1633 (1964).

[59] J. S. Kouvel and M. E. Fisher, Detailed magnetic behavior of nickel near its critical temperature, Phys. Rev. Lett. 136, A1626 (1964).

[60] J. Amaral, M. Reis, V. Amaral, T. Mendonc, J. Araujo, M. Sa, P. Tavares, J. Vieira, Magnetocaloric effect in Er- and Eu-substituted ferromagnetic La-Sr manganites, J. Magn. Magn. Mater. 290, 686 (2005).

[61] V. Franco, J. S. Blázquez, and A. Conde, Field dependence of the magnetocaloric effect in materials with a second order phase transition: A master curve for the magnetic entropy change, Appl. Phys. Lett. 89, 222512 (2006).

[62] Y. Liu and C. Petrovic, Anisotropic magnetocaloric effect in single crystals of Cr3, Phys. Rev. B 97, 174418 (2018).

[63] Y. Liu and C. Petrovic, Critical behavior and magnetocaloric effect in Mn3Si2Te6, Phys. Rev. B 98, 064423 (2018).

[64] Y. Liu and C. Petrovic, Anisotropic magnetic entropy change in Cr2X2Te6 (X = Si and Ge), Phys. Rev. Mater. 3, 014001 (2019).

[65] Y. Liu, J. Li, J. Tao, Y. Zhu, and C. Petrovic, Anisotropic magnetocaloric effect in Fe3−xGeTe2, Sci. Rep. 9, 13233 (2019).

[66] A. Taroni, S. T. Bramwell, and P. C. W. Holdsworth, Universal window for two-dimensional critical exponents, J. Phys.: Condens. Matter 20, 275233 (2008).

[67] K. Huang, Statistical Mechanics (2nd ed., Wiley, New York, 1987).

[68] M. Phan, V. Franco, N. Bingham, H. Srikanth, N. Hur, and S. Yu, Tricritical point and critical exponents of La0.7Ca0.3−xSr2MnO3 (x = 0, 0.05, 0.1, 0.2, 0.25) single crystals, J. Alloy. Compd. 508, 238 (2010).

[69] M. E. Fisher, S. K. Ma, and B. G. Nickel, Critical Exponents for Long-Range Interactions, Phys. Rev. Lett. 29, 917 (1972).

[70] S. Kaul, Static critical phenomena in ferromagnets with quenched disorder, J. Magn. Magn. Mater. 53, 5 (1985).

[71] J. C. LeGuillou, and J. Zinn-Justin, Critical exponents from field theory, Phys. Rev. B 21, 3976 (1980).

[72] S. F. Fischer, S. N. Kaul, and H. Kronmüller, Critical magnetic properties of disordered polycrystalline Cr72Fe28 and Cr76Fe30 alloys, Phys. Rev. B, 65, 064443 (2002).

[73] Y. Onuki, R. Settai, K. Sugiyama, T. Takeuchi, F. Honda, Y. Haga, E. Yamamoto, T. D. Matsuda, N. Tateiwa, D. Aoki, I. Sheikin, and H. Harima, Heavy fermions and unconventional superconductivity in high-quality single crystals of rare-earth and actinide compounds, J. Korean Phys. Soc. 63, 409 (2013).

[74] A. Wang, I. Zaliznyak, W. Ren, L. Wu, D. Graf, V. O. Garlea, J. B. Warren, E. Bozin, Y. Zhu, and C. Petrovic, Magnetotransport study of Dirac fermions in YbMnBi2 antiferromagnet, Phys. Rev. B 94, 165161 (2016).

[75] Y. Wang, S. Xu, L. Sun, and T. Xia, Quantum oscillations and coherent interlayer transport in a new topological Dirac semimetal candidate YbMnSb2, Phys. Rev. Mater. 2, 021201(R) (2018).

[76] A. F. May, M. A. McGuire, and B. C. Sales, Effect of Eu magnetism on the electronic properties of the candidate Dirac material EuMnBi2, Phys. Rev. B 90, 075109 (2014).