Critical behavior in monoclinic Cr_3Te_4

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High-quality monoclinic Cr_3Te_4 crystals are synthesized by the chemical vapor transport method and confirmed by synchrotron powder x-ray diffraction. Critical behaviors of Cr_3Te_4 are studied by bulk isothermal magnetization measurements around its paramagnetic to ferromagnetic phase transition. From these data, we evaluate the modified Arrott plot, the Kouvel-Fisher plot, and critical isotherms, and estimate critical exponent values of $\beta \sim 0.3827$, $\gamma \sim 1.2119$, and $\delta \sim 4.16$, and the Curie temperature $T_C \approx 321$ K. After the scaling, the isothermal magnetization curves below and above the critical temperatures collapse into two independent universal branches which signifies the reliability of our critical exponent estimation. The estimated critical exponent values of Cr_3Te_4 do not match well with theoretically calculated values of any three-dimensional models.

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I. INTRODUCTION

Magnetic materials are interesting for fundamental studies and have many applications. A macroscopic magnetic system consists of many atoms with complex interactions between them. Although these systems can be very complex, they also exhibit some remarkable simplifications. A second-order magnetic system undergoes a continuous magnetic phase transition with a correlation length that diverges at the phase transition. Consequently, thermodynamic properties of these systems in the vicinity of the magnetic phase transition are largely independent of microscopic details and the underlying interactions of its constituents. Instead, they may fall into one of a small number of different classes characterized by global features, such as system dimensionality, symmetries, etc. This phenomenon is called universality, which finds a simple explanation within the framework of renormalization group theory. Near a second-order magnetic phase transition, thermodynamic quantities such as heat capacity, magnetic susceptibility, magnetization, etc., exhibit power-law dependencies on parameters as a function of the distance away from the phase transition (e.g., T–T_C, the departure of the measurement temperature T from the phase transition temperature T_C). The extracted powers are known as critical exponents, and their magnitude can shed light on the nature of the phase transition. We investigate here the critical behaviors of monoclinic Cr_3Te_4 around its paramagnetic to ferromagnetic phase transition temperature.

In recent years, chromium telluride compounds have drawn significant interest due to their diverse magnetic properties [1–11]. The Cr-Te binary phase diagram has several stable binary phases [9,11–13]. They have been found to have several magnetic binary phases with transition temperatures ranging from 180 K up to 321 K [7]. Reported stable binary phases include hexagonal CrTe [14], hexagonal $CrTe_2$ [15–17], trigonal Cr_2Te_3 [18–20], monoclinic Cr_3Te_4 [7,21,22], layered Cr_4Te_5 [23], hexagonal $Cr_{1-x}Te$ ($x < 0.1$) [7], and trigonal and monoclinic phases of Cr_5Te_8 [24–26]. Recent theoretical studies have predicted some layered, room-temperature magnetic Cr_xTe_y phases [2,12]. However, the material of interest for this paper is monoclinic Cr_3Te_4. This is an interesting material because it may be useful for room-temperature magnetocaloric applications.

There are alternating stacks of Cr-full and Cr-deficient layers along the c axis in these compounds. Cr content plays a crucial role in determining their structural and magnetic properties. Interestingly, some research groups studied these Cr-Te compounds in the 1960s and 1970s, but these studies mostly focused on material synthesis, followed by bulk magnetic, heat capacity, and electrical transport studies, and some density functional theory (DFT) calculations [7,8,21,27–30]. However, in recent times there has been a renewed interest in this class of binary phases. A recent theoretical calculation predicted two-dimensional (2D) layered room-temperature ferromagnetic Cr_xTe_y phases [2,12]. Recently, there was also a report of an anomalous Hall effect in trigonal Cr_5Te_8 [31]. A recent analysis of critical exponents of Cr_4Te_5 revealed the three-dimensional Heisenberg-like spin coupling inside this material [23].

The monoclinic Cr_3Te_4 phase was studied in the 1960s and 1970s [7,8,21]. Powder neutron diffraction pattern at 4.2 K shows the presence of both ferromagnetic and antiferromagnetic peaks [28]. However, this study does not have many

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details about the temperature dependence of these peaks. Magnetic measurements show the presence of two magnetic phase transitions: ∼100 and 320 K, which was corroborated by heat capacity [32] and transport studies [7]. Moreover, band structure calculation [13], reflectivity spectra [33], and magneto-optical effect [34] studies are reported on Cr_3Te_4. However, these studies did not address the nature of magnetic phase transition in this material; we will address that here.

To evaluate possible applications of this material, it is necessary to investigate the nature of its magnetic phase transition. In this work, we focus on understanding the nature of magnetic phase transition in Cr_3Te_4 crystals. First, we analyze its crystal structure by synchrotron powder x-ray diffraction. Then we investigate the critical behavior of Cr_3Te_4 by using a modified Arrott plot, a Kouvel-Fisher plot, and critical isothermal analysis. Previously, critical behavior analysis has been reported on other Cr-Te binary phases such as $Cr_{0.62}Te$ [26], $CrTe_2$ [15], Cr_4Te_5 [23], Cr_5Te_8 [24,25], etc. However, this is an analysis of critical exponents reported on Cr_3Te_4. Using the estimated critical exponents, we estimate the length scale of magnetic exchange interaction. Moreover, this may be a useful material for magnetocaloric applications which use entropy change at the magnetic phase transition to transfer heat. The magnetocaloric effect is also related to the critical behaviors at magnetic phase transition [25,35–38]. The relative power cooling (RCP) and magnetic entropy change are two important parameters to characterize the usefulness of magnetocaloric materials. Both RCP and magnetic entropy changes at the transition have power-law dependencies on the applied magnetic field where these exponents are also functions of critical exponents [39–42]. Therefore, this study will be helpful in understanding the usefulness of this material for practical applications.

II. SAMPLE SYNTHESIS AND PHASE ANALYSIS

Cr_3Te_4 crystals were synthesized by chemical vapor transport (CVT) using Cr and Te elements, with I_2 as the transport agent. These CVT syntheses were performed in a Thermo Scientific Lindberg Blue M three-zone furnace equipped with UP150 model program controllers. Cr (Alfa Aesar, powder, −100 + 325 mesh, 99.99% metals basis) and Te (Thermo Scientific, shot, 2–5 mm diameter, 99.9999% metals basis) were used as received without further purification. Between 35 and 50 mg of solid I_2 was used as the vapor transport agent. Stoichiometric amounts of Cr and Te plus the transport agent were placed inside a fused quartz tube and sealed under vacuum. The sealed tube was, at minimum, long enough to equal the distance between the centers of two zones of a three-zone furnace. This tube was then placed inside the three-zone furnace. All three zones were heated at a rate of 100 °C per hour, with the charge zone reaching 1050 °C and the crystallization zone reaching 820 °C. This temperature gradient was held for 7 days; then the furnace was cooled at a rate of 100 °C per hour to room temperature. Synthesized crystals of Cr_3Te_4 are silvery metallic in color and are generally between 1 and 5 mm in dimensions.

Room-temperature x-ray powder diffraction measurements were carried out at the Pair Distribution Function (PDF) beamline 28-ID-1 of the National Synchrotron Light Source-II. Cr_3Te_4 crystals were ground to get the powder sample. Data were collected in capillary transmission geometry using a PerkinElmer amorphous silicon detector placed 1000 mm downstream from the sample. The setup utilized a 74.5 keV ($\lambda = 0.1665$ Å) x-ray beam. Two-dimensional diffraction data were radially integrated to obtain intensity vs Q data using the PYFAI software package [43]. The Rietveld refinement was carried out using the GSAS-II software package [44]. Figure 1(a) shows the powder x-ray diffraction pattern of the Cr_3Te_4 sample, and the corresponding Rietveld fit. The inset of Fig. 1 shows the refined crystal structure of monoclinic Cr_3Te_4 generated using CrysX-3D Viewer [45]. The powder diffraction pattern was fitted with the symmetry space group *H-M* "*C* 1 2/*m* 1". The refined unit cell parameters are $a = 13.977(11)$, $b = 3.930(0)$, $c = 6.862(3)$, $\beta = 118.281(11)^\circ$. Refined fractional coordinates, occupancy of Cr and Te, and the isotropic thermal displacement parameters (Uiso) are given in Table I. The corresponding crystallographic information file (cif) is included as Supplemental Material [46]. All parameters related to this refinement are included in Table II. The Laue diffraction is used to determine the crystallographic axes of the Cr_3Te_4 crystal using the crystal structural parameters obtained from the refinement, as shown in Fig. 1(b).

TABLE I. Results of the Rietveld refinement.

Element	x	y	z	Occupancy	U_{iso} (Å^2)
Cr^{2+}	0.0000	0.0000	0.0000	0.904(4)	0.0102(9)
Cr^{3+}	0.2558(2)	0.0000	0.2732(3)	1.000	0.0080(4)
Te	0.3677(1)	0.0000	0.0305(1)	1.000	0.0069(2)
Te	0.1188(1)	0.0000	0.4531(1)	1.000	0.0078(2)

III. MAGNETIC STUDIES AND ANALYSIS OF CRITICAL EXPONENTS

A Quantum Design Physical Property Measurement System (PPMS) 9 T Dynacool model was used for all these magnetic studies. A Cr_3Te_4 crystal of 18.5 mg mass was

TABLE II. Various parameters related to the Rietveld refinement.

Number of function calls	Five
Number of observations	3080
Number of parameters	30
wR	3.32%
χ^2	276.515
Reduced χ^2	0.09
Goodness of fit (GOF)	0.30
RF	1.26%
RF^2 (on 543 reflections)	2.75%
Durbin-Watson statistics	0.091
Bragg intensity sum	1.67×10^5
PWDR histogram weight factor	1.000
R	2.5%
R-bkg	2.53%
wR-bkg	3.32%
wR-min	11.08%

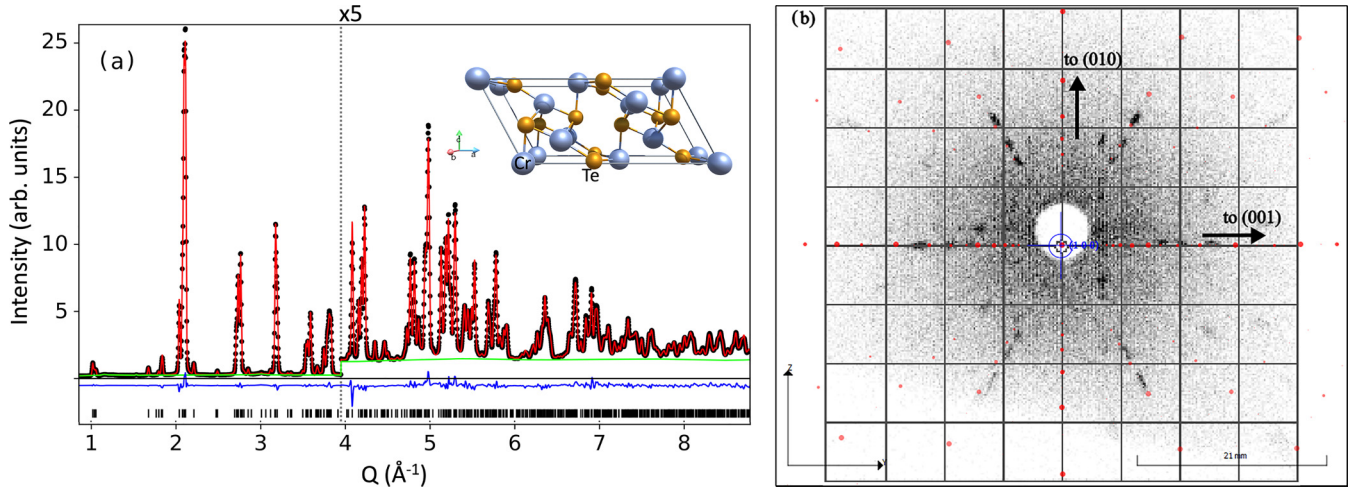

FIG. 1. (a) Rietveld fit to room-temperature powder diffraction data. Black dots and the red line represent measured and calculated intensities, respectively. The green line represents the polynomial fit to the background that was subtracted in the Rietveld refinement. A residue plot (blue), and calculated Bragg reflection tick marks are shown below. The observed and calculated intensities, and the fit residue above $Q = 3.9$ Å^{-1} are multiplied by 5 for clarity. The inset shows Cr_3Te_4 crystal structure in three-dimensional form, plotted using VESTA software after the refinement. (b) Laue diffraction image of the Cr_3Te_4 crystal. The sample is oriented along the crystallographic (100) axis. Arrows show the direction to the other crystallographic axes, as simulated by the QLAUE software.

used for all magnetic studies reported here. We studied four samples for the consistency check. Figure 2 shows the temperature-dependent zero-field-cooled (ZFC) and field-cooled (FC) magnetization (M) studies of the Cr_3Te_4 crystal at 1000 Oe magnetic field (H) applied along the *ab* plane and *c* axis. For the ZFC study, the sample was rapidly cooled down to 2 K in zero field; then a 1000 Oe field was applied and the sample ZFC magnetic moment was measured with increasing temperature (T) up to 400 K. For the FC study, the sample was cooled down to 2 K in the presence of the same field. The temperature-dependent magnetization studies show two phase transitions: one at about 320 K and another below 100 K. While the high-temperature phase transition

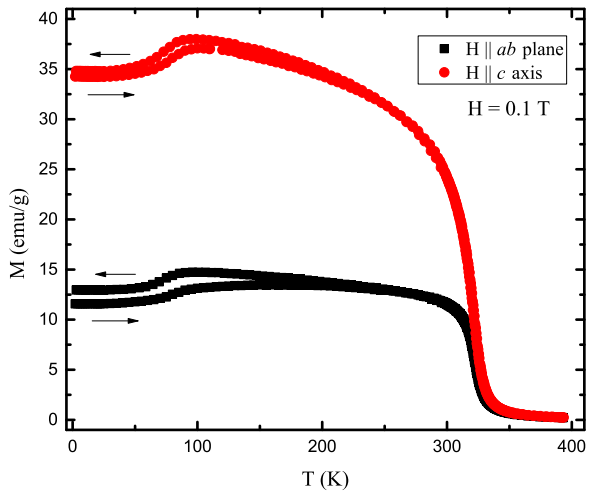

FIG. 2. Temperature (T) dependence of field-cooled and zero-field-cooled magnetizations (M) measured along the *c* axis and *ab* plane of the Cr_3Te_4 crystal. This figure indicates the presence of two magnetic phase transitions in Cr_3Te_4: a high-temperature transition around 320 K and another transition below 100 K.

appears to be from a paramagnetic to a ferromagnetic phase, the low-temperature (below 100 K) phase transition seems to have some antiferromagnetic component. This agrees well with a previous powder neutron diffraction study [8]. This type of transition is also reported in Cr_4Te_5 [23] and Cr_5Te_8 [25,47], which is ascribed to the presence of a canted antiferromagnetic structure.

Figure 3 plots field dependence of magnetization for the Cr_3Te_4 crystal along the (a) *c* axis and (b) *ab* plane for four different temperatures. For temperatures above 100 K, magnetization curves along the *c* axis change rapidly with changing field within an about ±1000 Oe field range, and then change slowly with changing magnetic field outside this field range. However, field-dependent magnetization curves along the *ab* plane make this transition around a ±1 T field. This is an indication that above 100 K the magnetic easy axis is along the *c* axis of Cr_3Te_4, but the 2 K magnetization curves for field along both directions make this transition around a ±1 T field. Previous powder neutron diffraction studies [8] have reported a rotation of magnetic easy axis direction below ∼100 K temperature, which could explain our 2 K field-dependent magnetization data. Moreover, a closer inspection of the 2 K magnetization curves for field show that magnetizations do not saturate even at ±9 T magnetic field. Furthermore, we estimate an effective magnetic moment of ∼ 2.65 μ_B per Cr atom at a 9 T field at 2 K, which agrees well with other studies [5,29].

The isothermal magnetizations around the high-temperature paramagnetic-ferromagnetic phase transition region are used to study the critical behaviors of Cr_3Te_4. We measured magnetizations from a 0–9 T field for a constant temperature. Through the analysis of the isothermal magnetizations, we will be able to determine the critical exponents associated with this phase transition [48,49]. These isothermal magnetizations were done for a temperature range from 290 to 350 K with an increment of 2 K. Figure 4 is

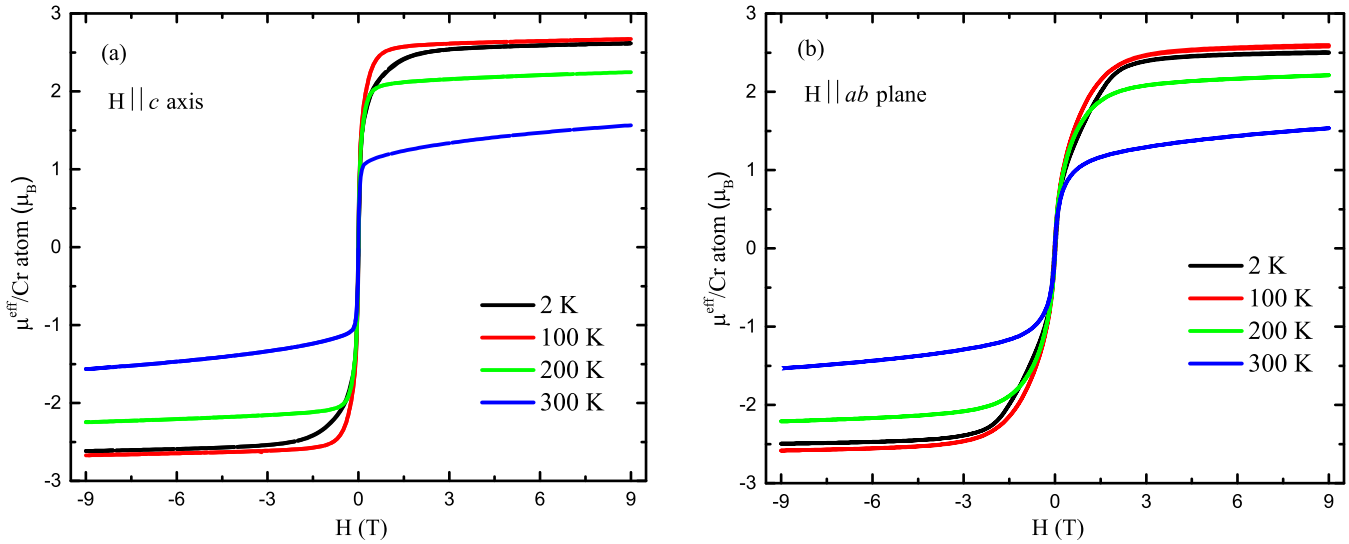

FIG. 3. Temperature-dependent magnetization curves for field of the Cr_3Te_4 crystal performed along the (a) c axis and (b) ab plane.

a plot of isothermal magnetizations along the c axis. The Arrott-Noakes equation of state [49] is given as

$$(H/M)^{1/\gamma} = a\varepsilon + bM^{1/\beta}, \tag{1}$$

where $\varepsilon = (T - T_C)/T_C$ is the reduced temperature; T_C is the Curie temperature; and a, b are two constants. For appropriate β and γ values, the isothermal magnetization at $T = T_C$ will be a straight line passing through the origin. For the mean-field theory $\beta = 0.5$ and $\gamma = 1$ which gives rise to the (conventional) Arrott plot [50]. Figure 5 shows the Arrott plot (M^2 vs H/M) for Cr_3Te_4. It is known that the Arrott plot is a conventional method to determine the Curie temperature. In the high magnetic field region, the linear nature of the curves will signify the mean-field-type interaction. In the Arrott plot (Fig. 5), all the curves show nonlinear behavior with a downward curvature in the high-field region indicating a non-mean-field-like behavior. In addition to that, the concave (downward) nature of the curves strongly suggests a second-order magnetic phase transition, in accordance with Banerjee's criterion [51]. This deviation from the mean-field theory is expected because the mean-field theory neglects the effects of spin fluctuations and correlation which are generally present in real magnetic materials.

Besides the mean-field model, there are other three-dimensional (3D) models with theoretically calculated β and γ values. To find out if the Cr_3Te_4 phase transition can be described by any of these 3D models, we plotted the modified Arrott plots using known β and γ values of these models (Fig. 6). These known 3D models are (a) the tricritical mean-field model ($\beta = 0.25$, $\gamma = 1.0$), (b) the 3D Ising model ($\beta = 0.325$, $\gamma = 1.24$), (c) the 3D XY model ($\beta = 0.345$, $\gamma = 1.316$), and (d) the 3D Heisenberg model ($\beta = 0.365$, $\gamma = 1.386$) [51,52]. Using γ and β values from these models, we failed to generate parallel straight lines (in the high-field

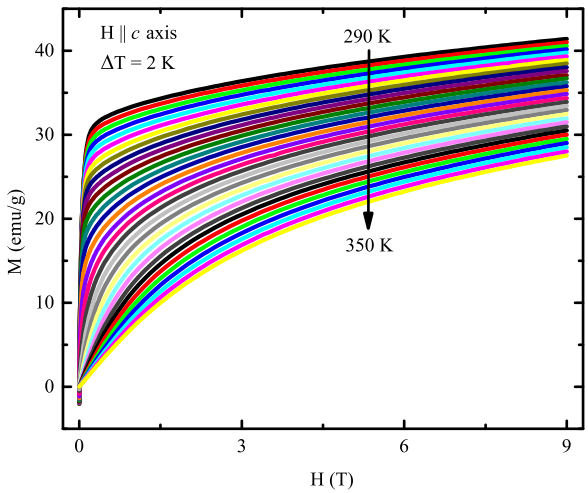

FIG. 4. The isothermal magnetization measured along the c axis at 2 K intervals around the high-temperature magnetic phase transition for the Cr_3Te_4 sample.

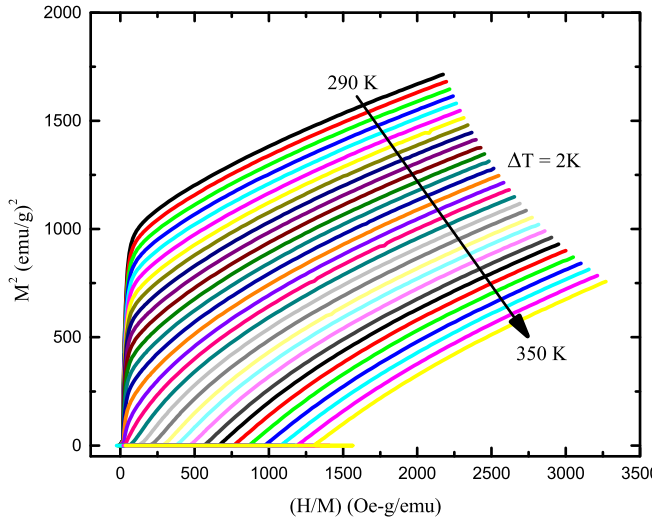

FIG. 5. The Arrott plot of isothermal magnetizations along the c axis of the Cr_3Te_4 crystal shows clear deviation from the mean-field model description of Cr_3Te_4 magnetic phase transition.

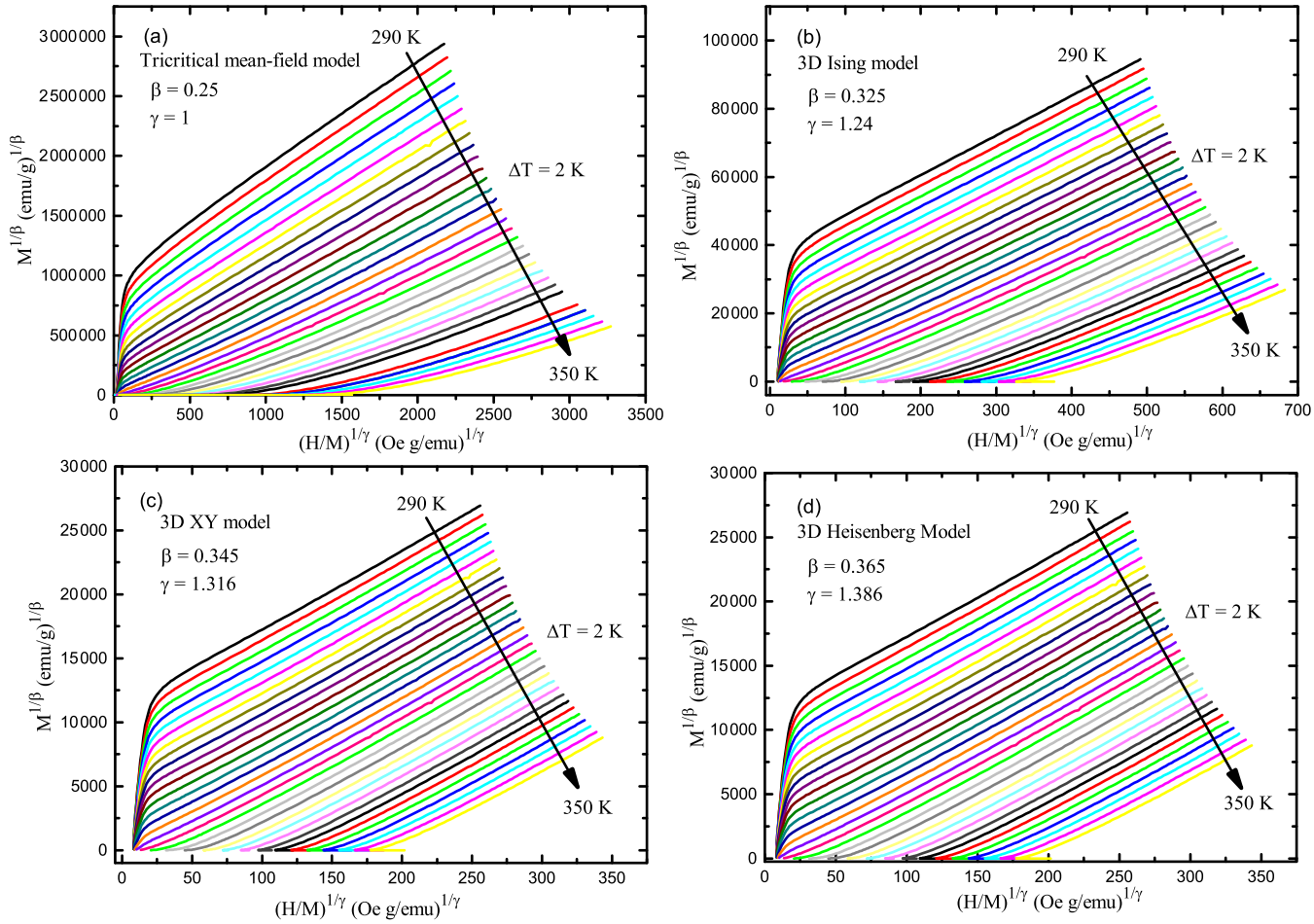

FIG. 6. Modified Arrott plots of isothermal magnetizations plotted using known β and γ values from four models: (a) tricritical mean-field model, (b) 3D Ising model, (c) 3D *XY* model, and (d) 3D Heisenberg model. In the high-field limits, isothermal magnetizations of these plots are not parallel to each other, indicating that any of these four models may not be most effective in describing the critical behaviors at Cr_3Te_4 magnetic phase transition.

region) suggesting that *none* of these 3D models is best suited to describe the magnetic phase transition in this material.

It is well known that the critical behavior of a second-order phase transition can be explained by a series of interrelated critical exponents. Near a second-order magnetic phase transition, the correlation length ξ diverges as

$$\xi = \xi_0 |(T - T_C)/T_C|^{-\nu}, \tag{2}$$

where ν is a critical exponent. This leads to the universal scaling laws for the spontaneous magnetization M_s and the inverse initial magnetic susceptibility χ_0^{-1}. The set of critical exponents β, γ, and δ is determined by the temperature dependencies of spontaneous magnetization $M_S(T)$ below T_C, inverse initial magnetic susceptibility $\chi_0^{-1}(T)$ above T_C, and measured field-dependent magnetization $M(H)$ at T_C, respectively. The corresponding mathematical expressions are the following:

$$M_s(T) = M_0(T)(-\varepsilon)^{\beta}, \quad \varepsilon < 0, \quad T < T_C, \tag{3}$$

$$\chi_0^{-1}(T) = (h_0/m_0)(\varepsilon)^{\gamma}, \quad \varepsilon > 0, \quad T > T_C\,, \tag{4}$$

$$M = DH^{\frac{1}{\delta}}, \quad \varepsilon = 0, \quad T = T_C, \tag{5}$$

where $\varepsilon = (T - T_C)/T_C$ is called the reduced temperature, and M_0, h_0/m_0, and D are called critical amplitudes [53].

Moreover, the magnetic equation of state is a relationship among the variables $M(H, \varepsilon)$, H, and T. Using the scaling hypothesis, the magnetic equation of state can be expressed as

$$M(H, \varepsilon) = \varepsilon^{\beta} f_{\pm}(H/\varepsilon^{\beta+\gamma}), \tag{6}$$

where f_+ for $T > T_C$ and f_- for $T < T_C$, are two regular functions. In terms of renormalized magnetization $m \equiv \varepsilon^{-\beta} M(H, \varepsilon)$ and renormalized field $h \equiv \varepsilon^{-(\beta+\gamma)} H$, Eq. (6) can be written as

$$m = f_{\pm}(h), \tag{7}$$

which signifies that for correct values of critical exponents (β, γ, and δ) and Curie temperature (T_C), scaled m and h will overlap on two universal curves: one above T_C and another below T_C. This is an important verification criterion for our analysis of critical exponents [53].

Because the conventional Arrott plot (Fig. 5) did not generate parallel straight lines in the high-field region, we need to estimate critical exponent values for the Cr_3Te_4 magnetic phase transition. We used an iterative method to find the β,

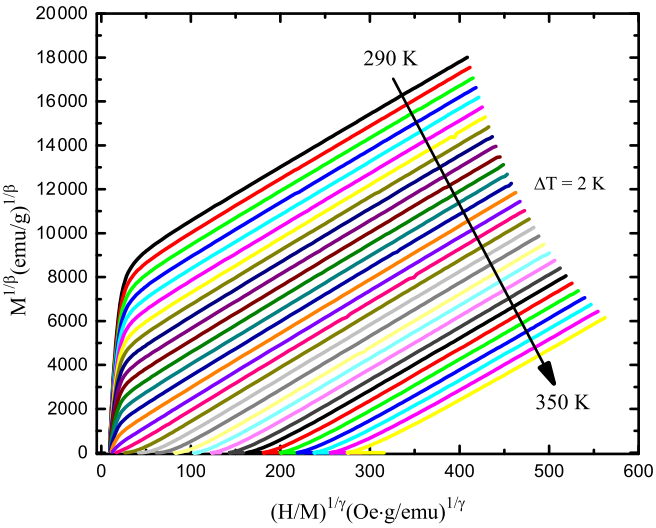

FIG. 7. The modified Arrott plot of the isothermal magnetizations around the magnetic phase transition temperature plotted with the optimum fitted values of $\beta = 0.3814$ and $\gamma = 1.2215$.

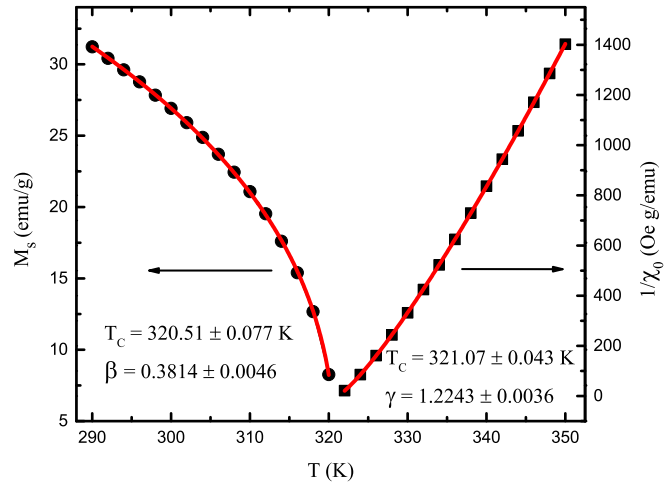

FIG. 8. Temperature-dependent spontaneous magnetization (M_S) and inverse initial susceptibility (χ_0^{-1}) are plotted around the magnetic phase transition. M_S and χ_0^{-1} are extracted by extrapolating the modified Arrott plot at high-field regions. Estimated β, γ, and T_C values are shown in the figure.

γ, and T_C values for Cr_3Te_4 as described by Pramanik and Banerjee [54]. Starting with the (conventional) Arrott plot, we estimate spontaneous magnetization (M_S) for temperatures below T_C and the inverse of initial magnetic susceptibility (χ_0^{-1}) for temperatures above T_C by extrapolating the linear portion of the curves (in the high magnetic field region) to the y axis and x axis, respectively. After plotting these estimated $M_S(T)$ and $\chi_0^{-1}(T)$ values for different temperatures, we determine a new set of β and γ values by fitting these data with Eqs. (3) and (4), respectively. Using these new sets of values of β, γ, and T_C, we plot a modified Arrott plot (MAP) and repeat the above-mentioned steps until β, γ, and T_C reach respective stationary values. The estimated stationary values of critical exponents are $\beta = 0.3814(\pm 0.0046)$ and $\gamma = 1.2243 \pm 0.0036$. The final modified Arrott plots generated with these β and γ values are shown in Fig. 7. A set of parallel straight lines in the high-field region demonstrates the validity of our β and γ estimation. The corresponding plots of $M_S(T)$ and $\chi_0^{-1}(T)$ are shown in Fig. 8. By fitting these data sets to Eqs. (3) and (4), we estimate $T_C = 320.51 \pm 0.077$ and 321.07 ± 0.043 K, respectively. The estimated critical exponent values by this iterative method are independent of their starting values which implies that the estimated critical exponents are reliable and correct.

Alternatively, the critical exponents β and γ can be determined by the Kouvel-Fisher (KF) method [55]. According to Kouvel and Fisher, the following relations hold for a second-order magnetic phase transition:

$$\frac{M_s(T)}{\frac{dM_s(T)}{dT}} = \frac{T - T_C}{\beta}, \tag{8}$$

$$\frac{1/\chi_0(T)}{\frac{d(1/\chi_0)(T)}{dT}} = \frac{T - T_C}{\gamma}. \tag{9}$$

By analyzing the final modified Arrott plot's $M_S(T)$ data using Eq. (8) and $\chi_0^{-1}(T)$ data using Eq. (9), we get $\beta = 0.3827 \pm 0.0035$ with $T_C = 320.97 \pm 0.051$ K and $\gamma = 1.2119 \pm 0.0063$ with $T_C = 321.17 \pm 0.071$ K, respectively (Fig. 9). The estimated β, γ, and T_C values from the Kouvel-Fisher method are consistent with those estimated from the final modified Arrott plot (MAP). This is another verification of reliability of our estimated critical exponents. Moreover, according to Eq. (5), the isothermal magnetization $M(H)$ at T_C should be a straight line with a slope of $1/\delta$ in the logarithmic scale. From the measured $M(H)$ curve at T_C, we estimate $\delta = 4.140 \pm 0.002$ (Fig. 10). Additionally, we can calculate the δ value using the Widom scaling law [56]: $\delta = 1 + \frac{\gamma}{\beta}$. Using the estimated β and γ values from the final modified Arrott plot and the Kouvel-Fisher plot, we calculate $\delta = 4.21$ and 4.16, respectively. These δ values agree well with one obtained from critical isotherm analysis. Therefore, three critical exponents, β, γ, δ, and Curie temperature T_C estimated in this

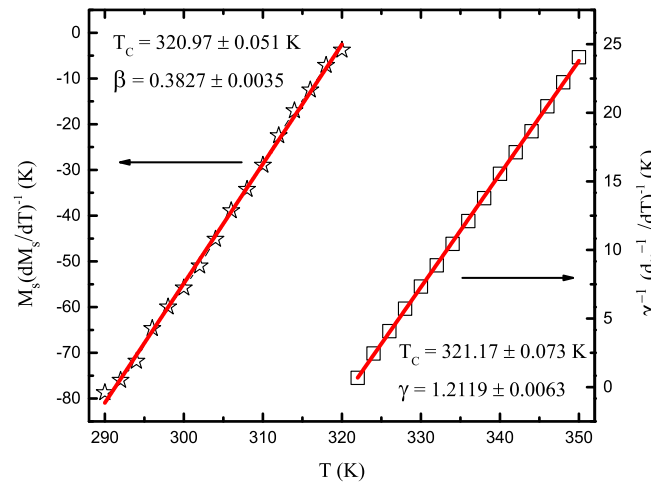

FIG. 9. The Kouvel-Fisher plot shows the temperature dependencies of $M_s(T)/[dM_s(T)/dT]^{-1}$ (star symbol) and $\chi_0^{-1}(T)[d\chi_0^{-1}(T)/dT]$ (squares) for the Cr_3Te_4 sample. The best estimated β, γ, and T_C values are indicated in the figure.

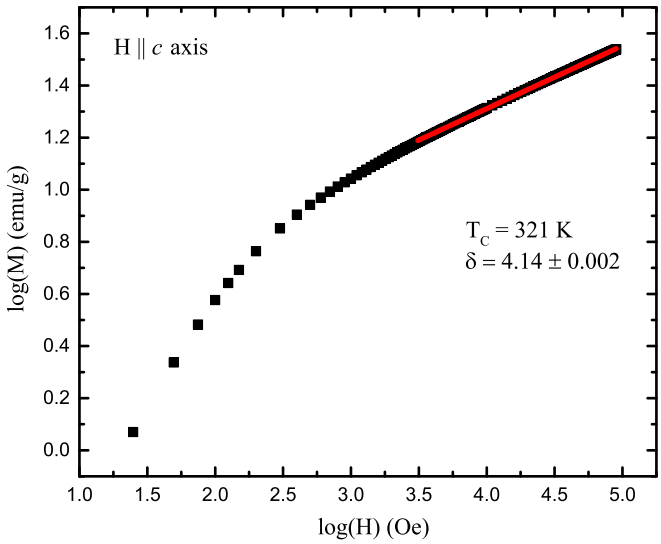

FIG. 10. The isothermal magnetization at $T_C = 321$ K along the c axis of the Cr_3Te_4 crystal gives an estimated $\delta = 4.14$.

study are self-consistent and accurate within our experimental limitations.

The reliability of the estimated critical exponents and Curie temperature has been further verified by scaling analysis. In Fig. 11(a), we plot the scaled magnetization (m) as a function of scaled magnetic field (h) in a linear scale. All the data collapse onto two separate branches below and above T_C, which is consistent with the scaling Eq. (7). This has also been verified in the plot of m^2 vs h/m in Fig. 11(b), where all data collapse onto two different branches like the previous one, indicating the proper values of estimated critical exponents. The scaling equation of state has another form:

$$\frac{H}{M^{\delta}} = k\left(\frac{\varepsilon}{H^{1/\beta}}\right), \tag{10}$$

where $k(x)$ is the scaling function. According to Eq. (10), all the experimental data will fall into a single universal curve when they are scaled accurately. This is shown in Fig. 11(c), a plot of $MH^{-1/\delta}$ vs $\varepsilon H^{-1/(\beta\delta)}$ where all isothermal magnetization data collapse into a single universal curve and T_C is at the zero point of the horizontal axis. This is another confirmation of the reliability of our estimated critical exponents.

For a comparison, our estimated critical exponents and those calculated from different theoretical models are summarized in Table III. According to the estimated critical exponents, Cr_3Te_4 cannot be categorized in any single universality class. The value of exponent β lies between the 3D Heisenberg model and mean-field model values. However, the β value of Cr_3Te_4 is much closer to the value of the 3D Heisenberg model, which implies the existence of long-range ordered exchange interaction. Moreover, the γ value lies between the 3D Ising model and mean-field model values, which points to the presence of strong uniaxial magnetic anisotropy in Cr_3Te_4 as shown in Figs. 2 and 3. The presence of multiple interactions in this system may well explain this discrepancy of critical exponent values between our estimation and known theoretical models, which are based on simple magnetic interaction between spins.

We also can estimate the effective magnetic moment per Cr atom in the paramagnetic phase of Cr_3Te_4 by analyzing the temperature-dependent magnetic susceptibility and inverse initial magnetic susceptibility data (Fig. 12). Temperature-dependent magnetic susceptibilities are calculated from the temperature-dependent magnetization data, as shown in Fig. 2. Also, we can calculate temperature-dependent initial magnetic susceptibility by analyzing the isothermal magnetizations above T_C (Fig. 8). By fitting these data to the Curie-Weiss law, we get the effective magnetic moment per Cr atom in the paramagnetic phase and Curie-Weiss temperature. Our estimated magnetic moments per Cr atom in the paramagnetic phase are $3.624 \pm 0.007\,\mu_B$, $3.541 \pm 0.005\,\mu_B$, and $3.994 \pm 0.009\,\mu_B$ for the $H \parallel c$ axis, $H \parallel ab$ plane, and χ_0^{-1} plots, respectively. These values agree with other studies [5,43]. For a comparison, the theoretical values of the expected magnetic moment of Cr^{2+} and Cr^{3+} ions are $2.83\,\mu_B$ and $3.87\,\mu_B$, respectively. Moreover, our estimated empirical Curie-Weiss temperatures are $+328.24 \pm$

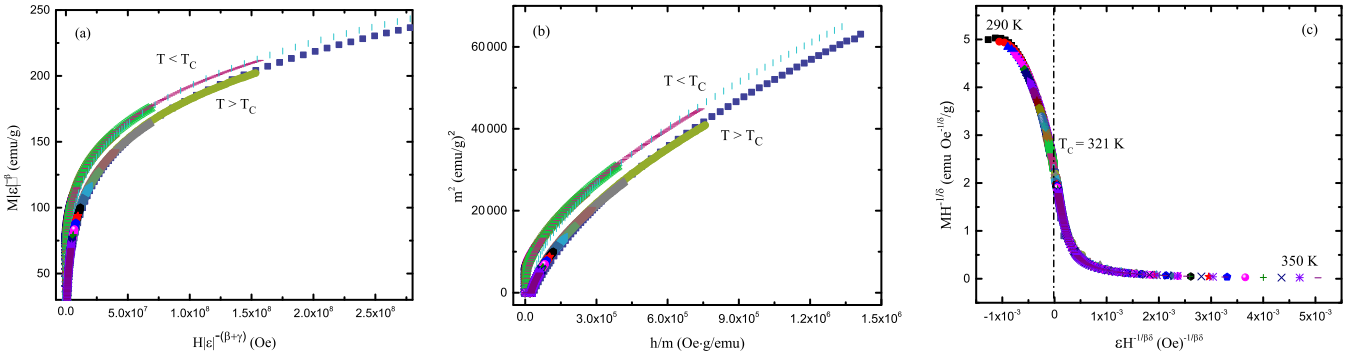

FIG. 11. Verification of reliability of our analysis of critical exponents: (a) A plot of normalized magnetization ($m = M|\varepsilon|^{-\beta}$) as a function of normalized field ($h = H|\varepsilon|^{-(\beta+\gamma)}$) of isothermal magnetizations scale into two groups: one below and another above the T_C. This plot shows the accuracy of our critical exponent analysis. (b) The normalized magnetization (m^2) as a function of normalized inverse magnetic susceptibility (h/m) for different temperatures also scales into two groups validating our analysis of critical exponents. (c) All temperature-dependent isothermal magnetization $M(H)$ data map onto one curve when they are plotted as $MH^{-1/\delta}$ vs $\varepsilon H^{-1/\beta\gamma}$. These three figures show the reliability of our analysis of critical exponents.

TABLE III. This table summarizes estimated critical exponent values of Cr_3Te_4 (this work), five models, and other known Cr-Te binary phases, calculated by Widom scaling law: $\delta = 1 + \gamma/\beta$.

Composition	Technique	β	γ	δ
Cr_3Te_4 (this work)	Modified Arrott plot	0.3814 ± 0.0046	1.2243 ± 0.0036	4.21
Cr_3Te_4 (this work)	Kouvel-Fisher method	0.3827 ± 0.0035	1.2119 ± 0.0063	4.16
Cr_3Te_4 (this work)	Isothermal magnetization at $T_C = 321$ K			4.140 ± 0.002
Theory [50]	Mean-field model	0.5	1	3
Theory [60]	3D Ising model	0.325	1.24	4.80
Theory [60]	3D Heisenberg model	0.365	1.386	4.82
Theory [59]	3D *XY* model	0.345	1.361	4.81
Theory [60]	Tricritical mean-field model	0.25	1	5
Cr_4Te_5 [23]	Kouvel-Fisher method	0.387	1.287	4.32
Cr_5Te_8 [24]	Kouvel-Fisher method	0.321	1.27	4.9
$Cr_{0.62}Te$ [26]	Kouvel-Fisher method	0.315	1.81	6.75
Cr_5Te_6 [61]	Kouvel-Fisher method	0.406	1.199	3.95

0.33, $+325.68 \pm 0.16$, and $+327.65 \pm 0.25$ K for the $H \parallel c$ axis, $H \parallel ab$ plane, and χ_0^{-1} plots, respectively. These empirical Curie-Weiss temperatures are slightly higher than the Curie temperature estimated by the analysis of critical exponents.

Additionally, it is important to analyze the nature of the magnetic interaction range in Cr_3Te_4. It is known that the universality class of magnetic phase transition depends on the range of the exchange interaction $J(r)$. According to the renormalization group theory, the interaction decays with distance r as the following,

$$J(r) \approx r^{-(d+\sigma)}, \tag{11}$$

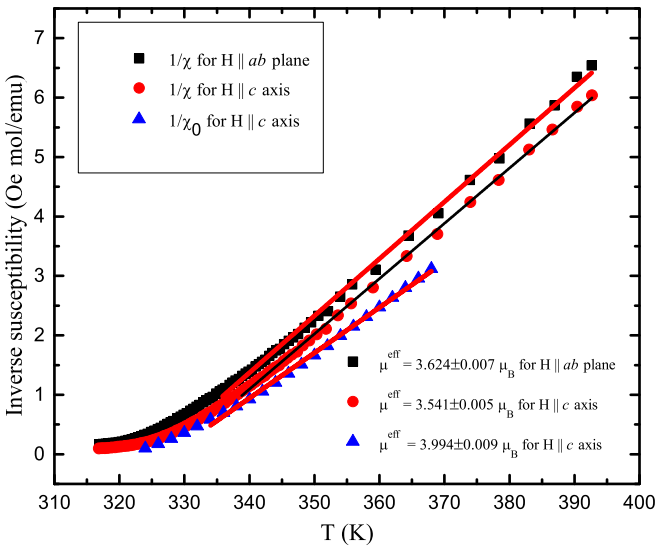

FIG. 12. Temperature-dependent inverse magnetic susceptibility along the c axis, ab plane, and inverse initial magnetic susceptibility plots of Cr_3Te_4 sample gives effective magnetic moment of $3.624(\pm 0.007)\,\mu_B$, $3.541(\pm 0.005)\,\mu_B$, and $3.994\,(\pm 0.009)\,\mu_B$ per Cr atom, respectively.

where σ is a positive constant and d is the system dimensionality. Moreover, the susceptibility critical exponent γ can be expressed as

$$\gamma = 1 + \frac{4}{d}\left(\frac{n+2}{n+8}\right)\Delta\sigma + \frac{8(n+2)(n-4)}{d^2(n+8)^2} \times \left[1 + \frac{2G\left(\frac{d}{2}\right)(7n+20)}{(n-4)(n+8)}\right]\Delta\sigma^2, \tag{12}$$

where $\Delta\sigma = (\sigma - \frac{d}{2})$, $G(\frac{d}{2}) = 3 - \frac{1}{4}(\frac{d}{2})^2$, and n is the spin dimensionality [57,58]. Our estimated critical exponents do not exactly match any theoretical model, so we will use various combinations of d and n to estimate σ using Eq. (12). Moreover, to check the consistency of our assumption, we will calculate these critical exponents using the following equations in succession: $\nu = \gamma/\sigma$, $\alpha = 2 - \nu d$, $\beta = (2 - \alpha - \gamma)/2$, and $\delta = 1 + \gamma/\beta$. Here ν and α are the critical exponents of correlation length and heat capacity, respectively. Our estimated critical exponents are close to 3D Heisenberg model values (Table III), so it is natural to use $d = 3$ and $n = 3$ first, which gives us $\sigma = 1.78$ using Eq. (12). Furthermore, the self-consistency check gives us $\beta = 0.4046$, $\gamma = 1.1856$, and $\delta = 3.91$, which are in good agreement with our estimated critical exponent values (Table III). All other combinations of d and n (such as 3:2, 3:1, 2:3, etc.) fail this self-consistency check. For a Heisenberg-type system in a 3D isotropic magnet, $\sigma > 2$ and $J(r)$ decreases faster than r^{-5}. When $\sigma \leqslant \frac{3}{2}$, the mean-field model more accurately describes the system, and $J(r)$ decreases slower than $r^{-4.5}$. In the present case, it is found that the magnetic exchange distance decays as $(r) \approx r^{-4.78}$, which lies between that of the 3D Heisenberg model and mean-field model.

IV. CONCLUSION

In summary, we have grown Cr_3Te_4 crystals by the chemical vapor transport (CVT) method. We studied the crystal structure of Cr_3Te_4 by x-ray diffraction (XRD) methods. We made a comprehensive study of its critical behavior at its paramagnetic-ferromagnetic phase transition at ~321 K,

which can be described as a second-order magnetic phase transition. By analyzing the isothermal magnetizations around the magnetic phase transition temperature, we estimated critical exponents $\beta \approx 0.3827$, $\gamma \approx 1.2119$, $\delta \approx 4.14$, and the Curie temperature $T_C \approx 321$ K by the modified Arrott plot and Kouvel-Fisher method. Next, we use the scaling analysis to check the reliability of our critical value estimations. Our estimated Cr_3Te_4 critical exponents do not match with theoretically calculated values of any known 3D models. Moreover, we estimate the magnetic exchange distance in Cr_3Te_4 which decays as $r^{-4.78}$. Our study shows that Cr_3Te_4 has a large uniaxial magnetic anisotropy which may be useful for alternative spintronic applications. Furthermore, our analysis of critical exponents will be useful to understand its magnetocaloric effects.

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