Polycrystalline CrTe$_{1-x}$Se$_x$ samples were prepared using the conventional solid-state reaction technique and characterized by x-ray diffraction, temperature- and field- dependent magnetization for possible use in magnetocaloric cooling. Rietveld refinement revealed two phases in all prepared samples; a minor monoclinic phase that decreases with Se concentration until it vanishes near 10% of Se, and a major hexagonal one. At high temperature, CrTe$_{1-x}$Se$_x$ is paramagnetic, with ferromagnetic phase transition occurs at T$_c$ ~332, 320, 318, 310, 299, and 295 K for x= 0.00, 0.02, 0.04, 0.06, 0.08, and 0.10, respectively. The magnetocaloric effect analysis (at H=5T) revealed a maximum magnetic entropy change of about 8.3, 7.9, 8.2, 9.1, 9.2, and 8.5 (J/kg.K) with a relative cooling power (RCP) value of about 555, 568, 547, 638, 694, and 668 (J/kg) around T$_c$ for x= 0.00, 0.02, 0.04, 0.06, 0.08, and 0.10, respectively. Critical behavior analysis showed that the magnetic isotherms measured near T$_c$ follow 3D Mean field critical exponents and a second order phase transition. A rigorous iteration estimated the critical exponents based on modified Arrott and Kouvel-fisher plots analysis, giving $\beta$ ~ 0.44, 0.51, 0.46, 0.49, 0.42, 0.49 and $\gamma$ ~ 1.02, 1.00, 0.99, 1.08, 1.07, 0.96, and 1.01 for x= 0.00, 0.02, 0.04, 0.06, 0.08, and 0.10, respectively.
1- Introduction

Transition metals (M) Pnictogens/Chalcogens (X) MX materials divers magnetic and electrical properties with potential practical applications in spintronic and magnetocaloric cooling among many other applications [1-2]. Such materials produce binary compounds in the form of MX with wide solubility range in Pnictogens/Chalcogens substitution. These binary compounds commonly have nickel arsenide (NiAs) crystalline structure or an intimately related one [3-4].

Recently, the Cr-based systems showed interesting Van der Waals ferromagnetic properties and revived wide research interest in reduced dimensional magnetic systems. For instance, Cr-monochalcogenides CrTe has hexagonal NiAs-type structure, reveals metallic behavior which is ferromagnet with a Curie temperature $T_c \sim 320$ to $340$ K [5-9], and noncollinear magnetic state at $T_c \sim 170$ K [2]. The discrepancy in the $T_c$ is due to the non-stoichiometric effect inherent in this material [8-12]. Moreover, stoichiometric bulk CrTe does not exist in the pure hexagonal phase at room temperature [2, 8-9, 13-14]. On the other hand, in the binary CrSe, the exchange interaction is antiferromagnetic with $T_N \sim 300$ K [2, 6, 13-15] with an effective spin magnetic moment of 4.9 $\mu_B$ [2]. The change of magnetic properties due to the replacement of tellurium by selenium in CrTe, which has NiAs structure, was investigated previously [3, 6]. The experimental magnetic phase diagram for the CrTe$_{1-x}$Se$_x$ system has also been investigated [2, 11].

In the current study, we investigate the structural, and magnetocaloric effect for the CrTe$_{1-x}$Se$_x$ ($0.00 \leq x \leq 0.20$) system at room temperature. We found that CrTe$_{1-x}$Se$_x$ system has a giant room temperature magnetocaloric effect compared to the pure gadolinium Gd, which is the prototype of magnetic refrigerators. We also investigate the critical behavior near ferromagnetic to paramagnetic phase transition and found that all investigated samples are three dimensional and follow the Mean Field theory.

2- Experimental Techniques

Polycrystalline CrTe$_{1-x}$Se$_x$ samples were synthesized using the conventional solid-state reaction. Stoichiometric ratios of the high purity (4-5N) elements (Cr, Te and Se) were mixed thoroughly
in agate mortal then pressed into pellets. The pellets were sealed in evacuated quartz tubes filled partially with high purity Argon gas. The pellets were annealed at 800 °C for 12 hours, then repowered, pressed, sealed, and reannealed at 1000 °C for another 24 hours. The samples were grinded, pressed into pellets and reannealed at 1000 °C. Crystal structure analysis is done using Powder x-ray diffraction (XRD) patterns were obtained using Bruker D2-Phaser diffractometer. We used FULLPROF software to analyze the diffraction patterns. Quantum design (PPMS) has been used to obtain the magnetization isotherms.

3- Results and Discussions

A. Structural analysis

Fig. 1 shows the XRD patterns fit using Rietveld refinement for CrTe$_{1-x}$Se$_x$ (0.0 ≤ x ≤ 0.1) samples. The results confirm two Cr-Te minority phases in all samples, monoclinic phase with Cr$_3$Te$_4$ and hexagonal phase with Cr:Te ratio of 1:1. The presence of the monoclinic phase structure at low Se-concentration (x ≤ 0.04) has been reported in other work [16].

The hexagonal CrTe phase shows a preferred orientation signal along the z-axis, which is commonly seen in the hexagonal phase. The closed packed structure of the hexagonal CrTe phase gives an average Cr-Te bond length of 2.767 Å, the monoclinic deformed version of the hexagonal structure that appears to have different stoichiometry with a relaxed structure shows slightly increased average Cr-Te bond length of 2.775 Å. As Se concentration increases; the monoclinic phase decreases and essentially vanishes for x~10%. Table 2 shows the refined lattice constants, unit cell volume, and weight ratio of the hexagonal phase at appears in the prepared samples at different Selenium concentrations. CrTe$_{0.90}$Se$_{0.10}$ which has the highest prepared concentration of Selenium almost appears as a single hexagonal phase, with a trace amount of monoclinic phase weight of about 5%.
Figure 1: XRD patterns (in black) with Rietveld refinements (in colors) for \( \text{CrTe}_{1-x}\text{Se}_x \) \( (x = 0.00 \) to 0.10) sintered at 1000 °C.

Table 1: The ICDD reference numbers with Wyckoff positions for the monoclinic and hexagonal phases appeared in the samples.

| [04-002-8473] \text{Cr}_3\text{Te}_4 Monoclinic C2/m (12) | Atom | Site | \( \frac{1}{a} \) | \( \frac{1}{b} \) | \( \frac{1}{c} \) |
|----------------------------------------------------------|------|------|----------------|----------------|----------------|
|                                                          | Te   | 4i   | 0.1240         | 0.0000         | 0.4440         |
|                                                          | Te   | 4i   | 0.3635         | 0.0000         | 0.0085         |
|                                                          | Cr   | 4i   | 0.2630         | 0.0000         | 0.2750         |
|                                                          | Cr   | 2a   | 0.0000         | 0.0000         | 0.0000         |
Table 2: Lattice constants and weight fraction of the hexagonal phase (P6_3/mmc) that obtained by XRD analysis of the CrTe_{1-x}Se_x samples.

| sample x | a=b (Å)   | c (Å)   | V (Å³) |
|----------|-----------|---------|--------|
| 0.00     | 3.9649    | 6.1830  | 84.18  |
| 0.02     | 3.9668    | 6.2004  | 84.49  |
| 0.04     | 3.9643    | 6.2010  | 84.40  |
| 0.06     | 3.9594    | 6.2019  | 84.20  |
| 0.08     | 3.9594    | 6.2019  | 84.40  |
| 0.10     | 3.9561    | 6.2058  | 84.11  |

B. Magnetic Properties

Fig. 2 (a) shows the temperature dependences of magnetization \(M(T)\) for CrTe_{1-x}Se_x \((0.00 \leq x \leq 0.10)\) samples in the range of temperature 5-350 K under an applied magnetic field of 0.05 T. The magnetization curves \(M(T)\) show that all the samples have a ferromagnetic to paramagnetic (FM-PM) phase transition near room temperature; \(T_c\) decreased from 332 K \((x=0.0 \text{ Se})\) to 295 K \((x=0.1 \text{ Se})\). Moreover, the magnetic moment remarkably increases as the Se-concentration increases. The change in magnetic transition might be caused by the strong in-plane exchange interaction \([17]\).

The inflection point in the M(T) curves (the maximum slope \(\left|\frac{dM}{dT}\right|_{max}\)) has been used to obtain \(T_c\). \(T_c\) values are given in Table 3. Similar behavior was observed in the three-dimensional CrTe_{1-x}Sb_x \([8]\). It is worth mentioning that a wide variation in \(T_c\) values reported for the stoichiometric CrTe alloy. This is mainly due to difficulties in preparing pure stoichiometric alloy. Moreover, the preparation conditions may also affect the transition. The \(T_c\) of the unsubstituted sample (CrTe) reported here is 7 K higher than the previously published in \([8]\) and \([9]\); however, it is in line with the earlier published work \([10-12]\). The variations of the inverse DC-susceptibility with temperature are shown in Fig 2(b). In the paramagnetic region of FM-PM transition and at much
higher temperatures than $T_c$; the magnetic susceptibility ($\chi$) follows the Curie-Weiss law, $\chi = C(T - \theta_c)^{-1}$, where $C$ and $\theta_c$ are the Curie constant and the Curie temperature respectively. The linear extrapolation of the inverse susceptibility versus $T$ gives the $\theta_c$. The obtained $T_c$ and $\theta_c$ values are given in Table 3. The values of $\theta_c$ are commonly higher than the $T_c$ values obtained from the inflection points of the $M(T)$ curve suggesting more complex spin configuration than normal FM-PM spin configuration. Similar results in CrSbSe$_3$ and in CrTe$_{1-x}$Sb$_x$ has recently been reported in [18, 8].

![Figure 2: (a) Variations of the magnetization ($H= 0.05T$) with temperature for CrTe$_{1-x}$Se$_x$. (b) The temperature-dependent inverse susceptibility for different samples measured at 0.05 $T$.](image)

| Se content (x) | $T_c$ (K) | $\theta_c$ (K) |
|----------------|-----------|----------------|
| 0.00           | 332.(0)   | 335.(3)        |
| 0.02           | 320.(3)   | 326.(6)        |
| 0.04           | 318.(0)   | 329.(0)        |
| 0.06           | 310.(0)   | 318.(1)        |
| 0.08           | 299.(0)   | 308.(3)        |
| 0.10           | 295.(1)   | 300.(0)        |
Fig. 3(a) shows the isothermal magnetization curves for a selected sample (CrTe\textsubscript{0.90}Se\textsubscript{0.10}) at various temperatures, with \( \Delta T=4 \text{K} \). Below \( T_c \), the sample is in its ferromagnetic state, with rapidly increasing magnetization (\( H\approx 0.3 \text{T} \)), reaching saturation near 1T. On the other hand, upon increasing temperature, the magnetization decreases, and the state moves toward the paramagnetic (PM) phase. Just above \( T_c \), in the PM region, the magnetization is essentially linear in the field range 0 - 5T.

Fig. 3(b) shows the isothermals curves for selected CrTe\textsubscript{1-x}Se\textsubscript{x} samples at room temperature (300 K). In the high field region, the saturated magnetization is gradually reduced along with slightly increasing high field susceptibility (slope) with increasing Se concentration. These changes are an indication of lowering the FM- exchange interaction resulted from Se-substitutions.

The change in magnetic entropy (\( \Delta S_M \)) is the magnetization isotherms (Fig. 3a) along with thermodynamic Maxwell’s relations, the entropy change can be expressed as [19]:

\[
\Delta S_M \left( \frac{T_1+T_2}{2} \right) = \frac{1}{T_1-T_2} \left[ \int_0^{H_{max}} M(T_2, H) dH - \int_0^{H_{max}} M(T_1, H) dH \right]
\]

(1)

Which is approximated at an average field and temperature as:

\[
\Delta S_M(T, H) = \sum_i \frac{M_{i+1}(T_{i+1}, H) - M_i(T_i, H)}{T_{i+1}-T_i} \Delta H
\]

(2)

where \( M_i \) and \( M_{i+1} \) are the magnetization values measured in a field \( H \), at temperature \( T_i \) and \( T_{i+1} \), respectively.
Figure 3: Variations of the magnetization with magnetic field of: (a) CrTe$_{0.90}$Se$_{0.10}$ sample for $\Delta T=4K$ intervals. (b) Selected CrTe$_{1-x}$Se$_x$ samples at similar temperature ($T=300$ K).

Fig. 4 shows the variation of $[-\Delta S(H,T)]$ as a function of temperature in the magnetic field range 0-5T for the studied samples. The change in magnetic entropy shows a peak $\Delta S_M$ near the Tc for all magnetic fields, which indicates that heat, is released when the magnetic field is adiabatically changed [20]. The change in magnetic entropy varies with Se-concentration reaching maximum value of 9.2 J/kg.K for CrTe$_{0.92}$Se$_{0.08}$. In the FM region ($i.e$ $T<$Tc) the behavior shows oscillation that decreases with temperature and completely vanished in the PM region ($T>$Tc). This behavior has been observed previously in several magnetocaloric materials; as far as we know; no conclusive cause has addressed. It is interesting to observe that the sample with no Se (CrTe) shows minimal oscillations. Moreover; for a given sample; these oscillations seem identical at all investigated fields [21].

Figure 4 also reveals that the maximum magnetic entropy $|\Delta S(H,T)|$ increases with increasing the applied magnetic field $H$ for all samples.
Figure 4: Temperature dependence of $|\Delta S(H,T)|$ of $\text{CrTe}_{1-x}\text{Se}_x$ at different cycling field.

The relative cooling power RCP is another important factor which is used to evaluate the cooling efficiency of a magnetic refrigerator; it is defined as [22]:

$$RCP = |\Delta S_M^{\text{max}}| \times \Delta T_{FWHM}$$

(3)

Where, $\Delta S_M^{\text{max}}$ is the maximum change of magnetic entropy, and $\Delta T_{FWHM}$ is basically the operation temperature. The calculated RCP values for all $\text{CrTe}_{1-x}\text{Se}_x$ sample at different cycling magnetic fields are shown in Fig. 5. The RCP values closely follow a quadratic behavior with increasing magnetic field; however, for $x=0.1$ the fit is almost linear behavior.
Figure 5: Variation of the Relative cooling power (RCP) with the applied magnetic field (H) for the studied samples.

To facilitate comparison with the cooling power of other materials, we present the change in magnetic entropy as a function of temperature at $\Delta H = 5$T for all investigated samples in Fig. 6. The figure reveals that $|\Delta S(H,T)|$ reaches maximum value ($\sim 9.2$ J/kg.K) for $x=0.8$. The maximum values for all studied samples are presented in Table 5 along with RCP values for our samples and the prototype magnetocaloric materials pure Gd and other materials obtained at $\Delta H= 5$ Tesla [23-26].
Figure 6: Temperature dependence of $|\Delta S(H,T)|$ of CrTe$_{1-x}$Se$_x$ at maximum cycling field of 5T.

Table 3: Maximum entropy change and RCP value for CrTe$_{1-x}$Se$_x$ samples and different other materials for comparison at field of 5T.

| Material     | Tc (K) | $|\Delta S_{\text{max}}|$ (±0.3) (J/kg.K) | FWHM (±0.5) (K) | RCP (±0.8) (J/kg) | Ref.   |
|--------------|--------|------------------------------------------|-----------------|-------------------|--------|
| Gd           | 294    | 10.2                                     |                 | 410               | [24]   |
| Gd$_5$Ge$_2$Si$_2$ | 275    | ~18.5                                    |                 | 425               | [25]   |
| MnFeP$_{0.45}$As$_{0.5}$ | 300    | 18                                       |                 | 485               | [26]   |
| CrTe         | 332    | 8.3                                      | 66.5            | 555.3             | This Work |
| CrTe$_{0.98}$Se$_{0.02}$ | 326    | 7.9                                      | 71.9            | 568.0             | This Work |
| CrTe$_{0.96}$Se$_{0.04}$ | 318    | 8.2                                      | 66.8            | 546.9             | This Work |
| CrTe$_{0.94}$Se$_{0.06}$ | 310    | 9.1                                      | 70.1            | 638.1             | This Work |
| CrTe$_{0.92}$Se$_{0.08}$ | 299    | 9.2                                      | 75.5            | 694.2             | This Work |
| CrTe$_{0.90}$Se$_{0.10}$ | 295    | 8.5                                      | 78.6            | 668.1             | This Work |
The critical behavior: In the following section we investigate the critical behavior near FM-PM phase transition for all samples; CrTe$_{1-x}$Se$_x$. The modified Arrott-plots of the magnetization (MAP) along with Kouvel-Fischer ($K$-$F$) plots greatly refines the critical exponents near the phase transition [27-28]. The $K$-$F$ analysis is based on obtaining a linear behavior of the certain functions of the inverse the magnetic susceptibility ($\chi_0^{-1}$) and the spontaneous magnetization ($M_s$) with temperature; see equations 8 and 9. Moreover, their slopes determine the critical exponents [28].

The $K$-$F$ relations can be obtained from:

\[ M_s(T) = M_0(-\epsilon)^\beta, \quad \text{below } T_c \]  
\[ \chi_0^{-1} = (h_0/m_0)\epsilon^\gamma, \quad \text{above } T_c \]  
\[ M = DH^{1/\delta}, \quad \text{at } T_c \]

Where $\beta$, $\gamma$, and $\delta$ are the critical exponents; $\epsilon$ is the reduced temperature; $D$, $M_0$ and $h_0/m_0$ are the critical amplitudes and $M$ is the critical isotherm $M(H)$ at $T_c$ [29]. The critical exponents $\beta, \gamma$ take different values in different magnetic models.

According to the modified Arrott plot analysis is based on Arrott-Noakes equation of state; namely:

\[ (H/M)^{1/\gamma} = (T - T_c)/A + (M/B)^{1/\beta} \]

where, $A$ and $B$ are constants [30].

The commonly used magnetic models are the mean-field model ($\beta = 0.5; \gamma = 1$), the tricritical mean-field ($\beta = 0.25; \gamma = 1$), 3D-Heisenberg ($\beta = 0.365; \gamma = 1.336$) and the 3D-Ising ($\beta = 0.325; \gamma = 1.24$) [30]. For the correct set of critical exponents, the magnetic isotherms at high fields are expected to be parallel.
For instance, $M^{1/\beta}$ vs. $(H/M)^{1/\gamma}$ for CrTe$_{0.92}$Se$_{0.08}$ sample using different magnetic models is shown in Fig. 9. According to Banerjee [31]; the positive initial slopes of all curves in Fig. 7 indicate a second-order phase transition. Similar behavior is observed in all studied samples (Not shown). To determine which model that closely represent the magnetic isotherms, we use the relative slope method (RS). The method is based in obtaining the slope of the magnetic isotherms (various T) (Fig. 7) divided by the slope at Tc [32, 33]. The variation of the RS with temperature for various samples are presented in Fig. 8. We notice that the RS curve obtained from the mean-field model MFT ($\beta = 0.5; \gamma = 1$) is the closest to the horizontal line at RS = 1 above and below Tc indicating that the mean field model closely represents CrTe$_{0.92}$Se$_{0.08}$ magnetic state [34]. Similar analysis has been applied for all investigated CrTe$_{1-x}$Se$_x$ samples. We found that all samples closely follow the mean field model representation.

**Figure 7:** Modified Arrott-plots for CrTe$_{0.92}$Se$_{0.08}$ sample: (a) Mean-Field. (b) 3D-Ising. (c) Tricritical mean field and (d) 3D-Heisenberg model.
Once we determined that the mean field closely represents the magnetic isotherms, we use the modified Arrott plots (like in Fig. 7 (a)) to extract the spontaneous magnetization $M_s(T)$ and the inverse of the magnetic susceptibility $\chi_0^{-1}(T)$ for all investigated samples. At each temperature, the curves at high fields are fitted to Eq. 7 and extended to the $M^{1/\beta}$ and $(H/M)^{1/\gamma}$ axes. The intercept points represent the $M_s(T)$ and $\chi_0^{-1}$; these values are used in K-F analysis. For instance, the variations of $M_s(T)$ and $\chi_0^{-1}(T)$ with temperature for $CrTe_{0.90}Sb_{0.10}$ sample are presented in Fig. 9(a), and then fitted to Eqs. 4 and 5, respectively, in order to evaluate the critical exponents $\beta$ and $\gamma$ along

Figure 8: Variations of the relative slope (RS) with temperature for selected $CrTe_{1-x}Se_x$ samples.
with the transition temperature $T_c$. The obtained critical exponents are: $\beta = 0.47 \pm 0.01$, and $\gamma = 1.04 \pm 0.01$. The values of the critical exponents are close to that in the mean-field model with $T_c \sim 300$K. On the other hand, the Kouvel-Fisher (KF) plots representations of the spontaneous magnetization and the susceptibility can be used to refine the critical exponent values. According to the (KF) model we have:

$$\frac{M_s(T)}{dM_s(T)/dT} = \frac{T-T_c}{\beta}$$  \hspace{1cm} (8)$$

$$\frac{\chi_0^{-1}(T)}{d\chi_0^{-1}(T)/dT} = \frac{T-T_c}{\gamma}$$  \hspace{1cm} (9)$$

Both equations are linear in temperature $(T-T_c)$ with slopes equal to $1/\beta$ and $1/\gamma$. Fig. 9(b) shows the K-F plot for the $CrTe_{0.90}Se_{0.10}$ sample as an example. The obtained critical exponents for $x=0.10$ sample are $\beta = 0.49 \pm 0.01$, and $\gamma = 1.01 \pm 0.01$; these values are very close to the mean-field theory values with $T_c \sim 298$K. The MAP and F-K analysis have been used to calculate the critical exponents for all investigated samples. The results are presented in Table. 6. We notice that the values of both $\beta$ and $\gamma$ are very close to that in the mean-field theory with $\beta=0.5$ and $\gamma=1$.

Recently; that we found similar critical behavior in $CrTe_{1-x}Sb_x$ system; the critical exponents values are close to the standard mean field model [9].
Figure 9: **a:** Variations of $M_s$ and $\chi_0^{-1}$ with temperature. **b:** Kouvel-Fisher plots for CrTe$_{0.90}$Se$_{0.10}$

**Table 4:** Critical exponents along with $T_c$ for CrTe$_{1-x}$Se$_x$ ($0.0 \leq x \leq 0.1$) samples

| Sample       | Model | $T_c$(K) | $\beta$    | $\gamma$    | $\delta$ |
|--------------|-------|----------|------------|-------------|----------|
| CrTe         | MAP   | 340.3(7) | 0.51±0.01  | 0.98±0.01   | 2.92     |
|              | K-F   | 335.3(8) | 0.44±0.03  | 1.02±0.06   | 3.32     |
| CrTe$_{0.98}$Se$_{0.02}$ | MAP   | 329.1(1) | 0.52±0.02  | 1.00±0.01   | 2.92     |
|              | K-F   | 329.1(1) | 0.51±0.02  | 0.98±0.05   | 2.92     |
| CrTe$_{0.96}$Se$_{0.04}$ | MAP   | 329.1(1) | 0.51±0.10  | 0.99±0.01   | 2.94     |
|              | K-F   | 329.3(4) | 0.46±0.02  | 0.97±0.01   | 3.12     |
| CrTe$_{0.94}$Se$_{0.06}$ | MAP   | 317.1(0) | 0.47±0.01  | 1.08±0.08   | 3.30     |
|              | K-F   | 317.9(0) | 0.49±0.01  | 0.94±0.01   | 2.92     |
| CrTe$_{0.92}$Se$_{0.08}$ | MAP   | 310.0(0) | 0.51±0.04  | 1.07±0.02   | 3.01     |
|              | K-F   | 308.2(0) | 0.42±0.02  | 0.96±0.07   | 3.21     |
| CrTe$_{0.90}$Se$_{0.10}$ | MAP   | 298.2(0) | 0.47±0.01  | 1.04±0.01   | 3.21     |
|              | K-F   | 298.1(0) | 0.49±0.01  | 1.01±0.01   | 3.06     |
The values of third critical exponent ($\delta$) can be calculated using the Widom scaling relation: $\delta = 1 + \frac{\gamma}{\beta}$, using the obtained $\beta$ and $\gamma$ values [35]. The values are listed in Table 6. Experimentally, $\delta$ can be obtained using the magnetic isotherm at the critical temperature. The magnetic isotherm at the critical temperature is expected to reveal a linear behavior in a log-log representation; see Eq. (6). The results are plotted in Fig. 10 with a slope = $1/\delta$ at high field. The linear fit for the x=0.08 sample yields $\delta = 3.26 \pm 0.42$. The result is consistent with the one obtained from Widom’s relation ($\delta = 3.21$) as shown in Table 6.

![Figure 2](image.png)

*Figure 2: Critical magnetization isotherm at $T=T_c$ for CrTe$_{0.92}$Se$_{0.08}$ in log-log scale.*

As an additional test for the suitability of the mean field model to describe the magnetic state in CrTe$_{1-x}$Se$_x$ alloys, we can apply the universality behavior of $M/|\varepsilon|^\beta$ vs. $H/|\varepsilon|^{(\beta+\gamma)}$. Close to the transition temperature $T_c$, the normalized equation of state can be expressed as:

$$m = f_\pm(h)$$  \hfill (10)
Where, \( f_\pm \) are functions above (+) and below (-) \( T_c \); \( m \equiv |\epsilon|^{-\beta} M(H, \epsilon) \) is the normalized magnetization and \( h \equiv H|\epsilon|^{-(\beta+\gamma)} \) is the normalized field.

For the correct values of the critical exponents of \( \beta, \gamma \) and \( \delta \), Eq. (10) implies two universal branches above and below \( T_c \) presented as \( M/|\epsilon|^{\beta} \) vs. \( H/|\epsilon|^{(\beta+\gamma)} \) [34]. Both curves merge asymptotically at \( T= T_c \). The critical exponents obtained from Kouvel-Fisher analysis have been used to represent the normalized magnetization isotherm \( (m) \) versus the normalized field \( (h) \) for all investigated samples. The scaled data for are presented in Fig. 11 as two branches of the magnetization above and below \( T_c \). At high fields both branches are converging towards each other at \( T_c \). The log-log scale vividly reveals the merge of the data giving further support for the reliability of the critical exponents’ values within the mean field model.

**Figure 3:** Universal scaling behavior above and below \( T_c \) for the studied \( \text{CrTe}_{1-x}\text{Se}_x \) samples.
REFERENCES

[1] S. Polesya, G. Kuhn, D. Benea, S. Mankovsky, H. Ebert, Electronic Structure and Magnetic Properties of Chromium Chalcogenides and Pnictides with NiAs Structure, Zeitschrift Für Anorganische Und Allgemeine Chemie. 639 (2013) 2826-2835. doi:10.1002/zaac.201300314.

[2] S. Polesya, S. Mankovsky, D. Benea, H. Ebert, W. Bensch, Finite-temperature magnetism of CrTe and CrSe, Journal of Physics: Condensed Matter. 22 (2010) 156002. doi:10.1088/0953-8984/22/15/156002.

[3] F. Lotgering, E. Gorter, Solid solutions between ferromagnetic and antiferromagnetic compounds with NiAs structure, Journal of Physics and Chemistry of Solids. 3 (1957) 238-249. doi:10.1016/0022-3697(57)90028-8.

[4] M. Venkatraman, J. Neumann, The Cr-Sb (Chromium-Antimony) system, Journal of Phase Equilibria. 11 (1990). doi:10.1007/bf02898255.

[5] H. Haraldsen, E. Kowalski, Magnetoochemische Untersuchungen. XVII. Das magnetische Verhalten der Chalkogenide des zweiwertigen Chroms, Zeitschrift FuR Anorganische Und Allgemeine Chemie. 224 (1935) 329-336. doi:10.1002/zaac.19352240314.

[6] I. Tsubokawa, The Magnetic Properties of Chromium-Tellurium-Selenium System, Journal of The Physical Society of Japan. 11 (1956) 662-665. doi:10.1143/jpsj.11.662.

[7] H. Nagasaki, I. Wakabayashi, S. Minomura, The pressure dependence of the lattice parameters of CrTe and CrSb, Journal of Physics and Chemistry Of Solids. 30 (1969) 2405-2408. doi:10.1016/0022-3697(69)90064-x.

[8] M. Hamad, E. Martinez-Teren, Y. Maswadeh, R. Hamad, E. Al-Nahari, A. El-Gendy et al., Room temperature magnetocaloric effect in CrTe1-xSbx alloys, Journal of Magnetism and Magnetic Materials. 514 (2020) 167171. doi:10.1016/j.jmmm.2020.167171.

[9] M. Kh. Hamad, Y. Maswadeh, E. Martinez-Teren, A. El-Gendy, K. Ziq, Structural, magnetic, and critical behavior of CrTe1-xSbx alloys, The European Physical Journal Plus. 136 (2021) 516. doi:10.1140/epjp/s13360-021-01534-5.
[10] M. Akram, F. Nazar, Magnetic properties of CrTe, Cr23Te24, Cr7Te8, Cr5Te6, and Cr3Te4 compounds, Journal of Materials Science. 18 (1983) 423-429. doi:10.1007/bf00560631.

[11] A. Andresen, E. Zeppezauer, T. Boive, B. Nordström, C. Brändén, The Magnetic Structure of Cr2Te3, Cr3Te4, and Cr5Te6., Acta Chemica Scandinavica. 24 (1970) 3495-3509. doi:10.3891/acta.chem.scand.24-3495.

[12] T. Hamasaki, T. Hashimoto, Y. Yamaguchi, H. Watanabe, Neutron diffraction study of Cr2Te3 single crystal, Solid State Communications. 16 (1975) 895-897. doi:10.1016/0038-1098(75)90888-1.

[13] G. Makovetskii, G. Shakhlievich, Magnetic properties of the CrSxTe1−x (x = 0−0.2) solid solutions, Kristall Und Technik. 14 (1979) 97-105. doi:10.1002/crat.19790140113.

[14] A. Andresen, E. Zeppezauer, T. Boive, B. Nordström, C. Brändén, The Magnetic Structure of Cr2Te3, Cr3Te4, and Cr5Te6., Acta Chemica Scandinavica. 24 (1970) 3495-3509. doi:10.3891/acta.chem.scand.24-3495.

[15] J. Goodenough, Magnetism and the Chemical Bond, Interscience, New York, 1963.

[16] G. Street, E. Sawatzky, K. Lee, Magnetic properties of vapor grown crystals of hexagonal chromium telluride, Journal of Physics and Chemistry of Solids. 34 (1973) 1453-1455. doi:10.1016/s0022-3697(73)80048-4.

[17] H. Asano, J. Hayakawa, M. Matsui, Magnetotransport in perovskite series Lan−nxCa1+nxMnnO3n+1ferromagnets, Physical Review B. 57 (1998) 1052-1056. doi:10.1103/physrevb.57.1052.

[18] T. Kong, K. Stolze, D. Ni, S. Kushwaha, R. Cava, Anisotropic magnetic properties of the ferromagnetic semiconductor CrSbSe3, Physical Review Materials. 2 (2018). doi:10.1103/physrevmaterials.2.014410

[19] Z.M. Wang, G. Ni, Q.Y. Xu, H. Sang, Y.W. Du, J. Appl. Phys. 90 (11) (2001) 5689–5691.

[20] M.H. Phan, N.A. Frey, M. Angst, J. de Groot, B.C. Sales, D.G. Mandrus, H. Srikant, Solid State Commun. 150 (2010) 341.
[21] de Haas W.J., and van Alphen P.M., Proc. Netherlands Roy. Acad. Sci. 33, 1106(1930).

[22] K. Gschneidner Jr, V. Pecharsky and A. Tsokol, Reports on Progress in Physics 68, (2005).

[23] P. Novak, M. Marysko, M.M. Savosta, A.N. Ulyanov, Phys. Rev. B (1999) 6655–6661.

[24] M.H. Phan, S.C. Yu, J. Magn. Magn. Mater. 308 (2007) 325.

[25] O. Tegus, E. Bruck, K.H.J. Buschow, F.R. de Boer, Nature 415 (2002) 150.

[26] A. Arrott, Criterion for Ferromagnetism from Observations of Magnetic Isotherms, Physical Review. 108 (1957) 1394-1396. doi:10.1103/physrev.108.1394.

[27] J. Kouvel, M. Fisher, Detailed Magnetic Behavior of Nickel Near its Curie Point, Physical Review. 136 (1964) A1626-A1632. doi:10.1103/physrev.136.a1626.

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

[29] J. Kouvel, M. Fisher, Detailed Magnetic Behavior of Nickel Near its Curie Point, Physical Review. 136 (1964) A1626-A1632. doi:10.1103/physrev.136.a1626.

[30] A. Arrott, J. Noakes, Approximate Equation of State For Nickel Near its Critical Temperature, Physical Review Letters. 19 (1967) 786-789. doi:10.1103/physrevlett.19.786.

[31] B. Banerjee, On a generalised approach to first and second order magnetic transitions, Physics Letters. 12 (1964) 16-17. doi:10.1016/0031-9163(64)91158-8.

[32] M. Hamad, K. Ziq, Critical behavior of CrTe1-xSbx ferromagnet, AIP Advances. 8 (2018) 101416. doi:10.1063/1.5042550.

[33] M. Hamad, Y. Maswadeh, K. Ziq, Effects of Ni substitutions on the critical behaviors in Nd0.6Sr0.4Mn1-xNixO3 manganite, Journal of Magnetism and Magnetic Materials. 491 (2019) 165609. doi:10.1016/j.jmmm.2019.165609.

[34] J. Fan, L. Ling, B. Hong, L. Zhang, L. Pi, Y. Zhang, Critical properties of the perovskite manganiteLa0.1Nd0.6Sr0.3MnO3, Physical Review B. 81 (2010). doi:10.1103/physrevb.81.144426.
[35] B. Widom, Degree of the Critical Isotherm, The Journal of Chemical Physics. 41 (1964) 1633-1634. doi:10.1063/1.1726135.