Scaling behaviour of magnetic entropy change in bilayered manganites by two-variable polynomials fitting to magnetization *

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Based on the two-variable polynomial model of magnetization, magnetic entropy change of bilayered manganites with 327-structure and its scaling behaviour with respect to applied magnetic fields are investigated. It’s found that the Curie temperature, which is defined as the point at which the partial derivative of magnetization with respect to temperature reaches its maximum, is different from the temperature of peak magnetic entropy change. Thus a mean-field model can not apply to this kind of manganites. In contrast to what has been found in manganites with the 113-structure, the scaling behaviour at the Curie temperature in manganites with 327-structure is much different from that at the temperature of peak magnetic entropy. It’s also found that the temperature dependence of the scaling exponent under weak fields is distinct from that under strong fields. This difference is attributed to an crossover from one-step transition under weak fields to two-step transition under strong fields.

Keywords: scaling exponent, magnetic entropy, bilayered manganite

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1 Introduction

For magnetic materials, both physical properties coupled with the magnetic degree of freedom and associated microscopic coupling mechanism can be revealed from magnetization data. Following are some examples: First of all, the magnetic transition points, and the type of effective exchange couplings under molecular field approximation (ferromagnetic, antiferromagnetic, or ferrimagnetic type), can be determined from the temperature dependence of inverse susceptibility. The second example is to identify the order of magnetic transitions according to the Banerjee criterion, subsequently qualitatively assess the strength of spin-lattice couplings, and eventually provide valuable information for the construction and test of different microscopic models. The third one mentioned here is to estimate the grain distribution of polycrystalline, especially nanocrystalline, samples through investigating the ratio of spontaneous magnetization at finite temperature with respect to that at zero point. By comparing the resultant distribution with that obtained from X-ray diffraction (XRD), one can give clues to optimizing the chemical doping and also controlling the preparation process. The fourth one is for first-order transition materials.

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By measuring its first-order reversal curve (FORC), the contribution to magnetization from irreversible rotations can be quantitatively analysed, and therefore information about magnetocrystal anisotropy and associated lattice symmetry is provided. The fifth but not the last one is to calculate magnetic entropy change from magnetization data and assess its potential value as a new magnetocaloric material.

In spite so much information is revealed by magnetization data, the analysis results quite depend on the particular model and approximation that are employed. This paper aims at studying the the scaling properties of magnetic entropy change $\Delta S_H$ based on series approximation of magnetization. The magnetic entropy change at temperature $T$ and maximum applied field $H$ is estimated as

$$\Delta S_H = \int_0^H \left( \frac{\partial M}{\partial T} \right)_{H'} dH'.$$

(1)

Its scaling exponent with respect to applied magnetic field $n$ is defined as

$$n = \frac{\partial \ln |\Delta S_H|}{\partial \ln H} = \frac{H}{\Delta S_H} \left( \frac{\partial M}{\partial T} \right)_{H'} .$$

(2)

(3)

In deriving expressions (2) and (3), the magnetic entropy at $H = 0$ with fixed $T$ is assumed to be a constant number. and the Maxwell relation $(\frac{\partial S_H}{\partial H})_T = (\frac{\partial M}{\partial T})_H$ is used.

To calculate exponent $n$, the model most often used is the approximated version of molecular field theory at $M$ much smaller than its saturated value. Under this approximation, the equation of state can be expressed as

$$H/M = a(T - T_C) + bM^2$$

(4)

and exponent $n$ can be easily obtained as

$$n(T) = \frac{2M^2}{3M^2 - M_s^2} \theta(T \leq T_C) + \frac{2H/M}{H/M + 2bM^2} \theta(T > T_C)$$

(5)

where, spontaneous magnetization $M_s$ equals $[a(T_C - T)/b]^{1/2}$ at temperatures lower than $T_C$; $\theta(A) = 1, 0$ correspond to logical expression $A$ being true and false, respectively. Note that $n = 1, \frac{2}{3}, 2$ in cases with $T \ll T_C$ ($M$ approximately equal to $M_s$), $T \to T_C$ ($M_s$ approaching zero) and $T \gg T_C$ ($M^2$ being a small quantity), respectively[4]. The above approximation applies to materials with weak short-range correlations.

When short-range correlations becomes important, the molecular field model (4) fails to give correct results in the vicinity of critical point $T_C$. In this case one can employ the semi-empirical Arrott-Noakes equation of state[5]

$$\left( \frac{H}{M} \right)^{1/\gamma} = a(T - T_C) + bM^{1/\beta},$$

(6)

with $a, b, T_C, \beta$ and $\gamma$ are parameters to be determined. Near to the critical point, $\beta$ and $\gamma$ correspond to critical exponents defined as $M_s \propto (T_C - T)^{1/\beta}$ and

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\((\frac{\partial M}{\partial T})_{H \to 0} \propto (T - T_C)^\gamma\), respectively. It’s considered that the Arrott-Noakes equation is particularly suitable to deal with magnetization data in the vicinity of the critical point. From equation (6), it’s easy to obtain following relations at \(T_C\)

\[
\left(\frac{\partial M}{\partial T}\right)_H = -\frac{a}{b} \frac{\beta \gamma}{\beta + \gamma} M^{1+\frac{1}{\beta}} H^{\frac{A-1}{\beta+\gamma}},
\]

and

\[
\Delta S_H = -\frac{a}{b^{1+\gamma}} \frac{\beta \gamma}{2 \beta + \gamma - 1} M^{2+\frac{2-1}{\beta+\gamma}} H^{\frac{2\beta+\gamma-1}{\beta+\gamma}}.
\]

Substituting (8) into (2), exponent \(n\) can be obtained as\(^{[6,7]}\)

\[
n(T_C) = 1 + \frac{\beta - 1}{\beta + \gamma}.
\]

The amazing thing is that, by substituting (7), (8) into (3), exponent \(n\) is again obtained. By assigning \(\gamma = 1\) and \(\beta = 1/2\), equation (9) reduces to the molecular field result 2/3. It’s also noted that the scaling exponents of \(\Delta S_H\) with respect to magnetic fields equals that of \((\frac{\partial M}{\partial T})_H\).

To determine \(n\) at \(T_C\), one can perform fitting to the field dependence of peak magnetic entropy \(\Delta S_{Hpk}(H)\). This method does not strictly distinguish \(T_C\) from the temperature of peak magnetic entropy, \(T_{pk}\). For estimating exponent \(n\) within the whole measuring temperatures, it’s usually to utilize the definition in (3). This paper not only uses above two methods but also apply (7) to estimating \(n\) from magnetization data.

The paper is organized as follows: Section 2 provides the model and formula used in this work; In Section 3 the numerical results and associated discussions can be found. Conclusions are put into Section 4.

2 Model and method

2.1 Series estimation of magnetization without symmetry restriction

Before doing the series estimation, make size transformations as follow: Applied magnetic field \(H\), temperature \(T\) and magnetization \(M\) are given as

\[
H = f_H(x) = H_{\text{min}} + x(H_{\text{max}} - H_{\text{min}}),
\]

\[
T = f_T(y) = T_{\text{min}} + y(T_{\text{max}} - T_{\text{min}}),
\]

\[
M = f_M(z) = M_{\text{min}} + z(M_{\text{max}} - M_{\text{min}}),
\]

where, dimensionless variants \(x, y, z \in [0, 1]\) represent reduced magnetic field, temperature and magnetization. For brevity, the \(\mu_0\) before \(H\) is omitted and the applied fields are measured in Tesla.

Giving up the symmetry restriction connecting magnetization and applied fields, the reduced magnetization \(z\) can be represented as a series in \(x\) and \(y\)

\[
z = \sum_{t=0}^{s} c_t h_t(x, y)
\]
where \( h_t(x, y) = 1, x, y, x^2, xy, y^2, x^3, \cdots \) and \( S \) denotes the maximum index in above series expression. To determine coefficients \( c_t \), a straight method is two-variable orthogonal polynomial fitting to experimental data.

### 2.2 Estimation of coefficients \( c_t \)

Expression (10) can be estimated by rewriting it in normalized orthogonal polynomials \( P_s(x, y) \) as

\[
\hat{z}(x, y) = \sum_{t=0}^{S} b_t P_t(x, y),
\]

where, \( P_t(x, y) \) is the \( t \)-th orthogonal polynomial and \( b_t \) the corresponding coefficient with subscripts \( t \geq 0 \).

By applying the Gram-Schmidt orthogonalization process to linearly independent functions \( h_t(x, y) \), the orthogonal polynomial \( P_s(x, y) \) can be recursively generated as

\[
P_s(x, y) = a_{ss} h_s(x, y) + \sum_{t=0}^{s-1} a_{st} P_t(x, y).
\]

Coefficients \( a_{ss} \) and \( a_{st} \) are given by summing over \( N \) experimentally recorded values, \((x_i, y_i, z_i)\), as

\[
a_{ss} = -\left[ \sum_{i=1}^{N} P_0(x_i, y_i) h_s(x_i, y_i) \right]^{-1},
\]

\[
a_{st} = -a_{ss} \sum_{i=1}^{N} P_t(x_i, y_i) h_s(x_i, y_i).
\]

By minimizing the fitting error with a regularization term, characterized by parameter \( \lambda \), as

\[
\sigma_1 = \frac{1}{N} \sum_{i=1}^{N} [\hat{z}(x_i, y_i) - z_i]^2 + \lambda \left[ \nabla^2 \hat{z}(x_i, y_i) \right]^2,
\]

coefficient \( b_t \) is determined as

\[
b_t = \frac{-\lambda R_t Q_t + \sum_{i=1}^{N} z_i P_t(x_i, y_i)}{1 + \lambda (Q_t)^2},
\]

where,

\[
R_t = \sum_{r=0}^{t-1} b_r Q_r,
\]

\[
Q_t = \sum_{i=1}^{N} \nabla^2 P_t(x_i, y_i),
\]

with \( t \geq 0 \). After \( a_{st} \) and \( b_s \) being determined, the values of coefficient \( c_t \) can be readily computed from them.
2.3 Spontaneous magnetization, partial derivative of magnetization with respect to temperature, and magnetic entropy change

By expressing subscript $t$ as  
\[ t(m,j) = \frac{1}{2}m(m+1) + j \]  
with $m \geq 0$ and $0 \leq j \leq m$, reduced magnetization $z$ in \[\text{(10)}\] can be expressed as  
\[ z = \sum_{p=0}^{p_s} z_p x^p \]  
where  
\[ z_p = \sum_{j=0}^{j_p} c_{t(j+p,j)} y^j, \]  
and $p_s$ and $j_p$ are maximum indices of $p$ and $j$, respectively.

2.3.1 Spontaneous magnetization

Spontaneous magnetization at reduced temperature $y$ is expresses as  
\[ M_0 = f_M(z_0) \]  
with  
\[ z_0 = \sum_{j=0}^{j_0} c_{t(j,j)} y^j. \]  
Other coefficients before the powers like $x^j$ with $1 \leq j \leq j_p$ can be similarly obtain.

2.3.2 Partial derivative of magnetization with respect to temperature

At fixed magnetic field $H$, the partial derivative of $M$ with respect to $T$ can be estimated as  
\[ \frac{\partial M}{\partial T} = A_1 \frac{\partial z(x,y)}{\partial y} = A_1 \sum_{t=0}^{S} c_t \frac{\partial h_t(x,y)}{\partial y}, \]  
with  
\[ A_1 = (M_{\text{max}} - M_{\text{min}})/(T_{\text{max}} - T_{\text{min}}). \]  
Representing $t$ as in \[\text{(16)}\], the summation over $t$ in \[\text{(21)}\] can be rewritten as  
\[ \sum_{t=0}^{S} c_{t(m,j)} \frac{\partial h_t(m,j)(x,y)}{\partial y} = \frac{1}{x} \sum_{k=1}^{k_w} c_k(y)x^k \]  
where,  
\[ c_k(y) = \sum_{j=1}^{j_k} c_{t(k+j-1,j)} \cdot j \cdot y^{j-1}, \]
\[ j_k = \left\lfloor \sqrt{2S + 2k + \frac{1}{4}} - k - \frac{1}{2} \right\rfloor, \quad (25) \]

and

\[ k_S = \left\lfloor \sqrt{2S - \frac{7}{4}} - \frac{1}{2} \right\rfloor, \quad (26) \]

with \( \lfloor \cdot \rfloor \) denoting the rounding down operation. In above derivations, index replacement \( m = k + j - 1 \) has been used.

### 2.3.3 Magnetic entropy change

The magnetic entropy change is calculated according to expression (1)

\[ \Delta S_H = A_2 \int_0^x \frac{\partial z(x', y)}{\partial y} \, dx'. \quad (27) \]

In above equation, the integral can be computed as

\[ \int_0^x \frac{\partial z(x', y)}{\partial y} \, dx' = \sum_{t=0}^S c_t \int_0^x \frac{\partial h_t(x', y)}{\partial y} \, dx'. \]

Thus the magnetic entropy change can be estimated as

\[ \Delta S_M = A_2 \sum_{t=0}^S c_t \int_0^x \frac{\partial h_t(x', y)}{\partial y} \, dx', \quad (28) \]

where the leading factor \( A_2 \) is expressed as

\[ A_2 = (M_{\text{max}} - M_{\text{min}})(H_{\text{max}} - H_{\text{min}})/(T_{\text{max}} - T_{\text{min}}). \]

At fixed reduced temperature \( y \), equations (28) can be rewritten as

\[ \sum_{t=0}^S c_{t(m,j)} \int_0^x \frac{\partial h_t(x', y)}{\partial y} \, dx' = \sum_{k=1}^{k_S} k \epsilon_k(y) x^k \quad (29) \]

By comparing equation (23) and (29), it’s easy to see that \( T_C \) determined from the maximum magnitude of partial derivative \( \left| \left( \frac{\partial M}{\partial T} \right)_H \right|_{\text{max}} \) generally differs from \( T_{pk} \) that is identified from the peak value of magnetic entropy change \( |\Delta S_{H}^{pk}| \); and the difference increases with the applied field. Actually, inspections of the recursive relations (36) and (37) give the following relation

\[ \int_0^x \frac{\partial h_t(m,j)(x', y)}{\partial y} \, dx' = \frac{x}{m - j + 1} \frac{\partial h_t(m,j)(x, y)}{\partial y}. \quad (30) \]

### 2.4 Scaling exponent of magnetic entropy change with respect to applied magnetic fields

We next calculate exponent \( n \). Substituting (21) and (28) into (3), exponent \( n \) can be expressed as

\[ n = \frac{A_1 f_H(x)}{A_2 x} \frac{\sum_{t=0}^S c_t \frac{\partial h_t(x, y)}{\partial y}}{\sum_{t=0}^S c_t \int_0^x \frac{\partial h_t(x', y)}{\partial y} \, dx'}. \quad (31) \]
By fixing $H_{\text{min}} = 0$, the leading factor in (31) equal to 1, we now reach the expression of exponent $n$ as

$$n = \frac{\epsilon_1(y) + \epsilon_2(y) + \epsilon_3(y) + \cdots + \epsilon_{k_0}(y)}{\epsilon_1(y) + \frac{1}{2} \epsilon_2(y) + \frac{1}{3} \epsilon_3(y) + \cdots + \frac{1}{k_0} \epsilon_{k_0}(y)}.$$  

(32)

Note that $n$ depends on the reduced temperature at fixed reduced field. For the exponent $n$ in (5), it’s obvious that at weak magnetic fields, i.e., much smaller than saturation field and $x$ being small quantity, the exponent $n \approx 1$. At $T$ much higher than $T_C$, the $k = 1$ term should be abandoned for the vanishing spontaneous magnetization, and exponent $n$ approaches 2 at weak magnetic fields. It’s noted that in the range of $T \ll T_C$ or $T \gg T_C$, exponent $n$ is not dependent on $y$, i.e., reduced temperature. When the applied field increases up to the saturation field, i.e., $x \to 1$, exponent $n$ is expressed as

$$n = \frac{\epsilon_1(y) + \epsilon_2(y) + \epsilon_3(y) + \cdots + \epsilon_{k_0}(y)}{\epsilon_1(y) + \frac{1}{2} \epsilon_2(y) + \frac{1}{3} \epsilon_3(y) + \cdots + \frac{1}{k_0} \epsilon_{k_0}(y)}.$$  

(33)

2.5 Exponent $n$ at $T_C$ and $T_{pk}$

When exponent $n$ at the transition point is considered, the situation becomes complicated as $T_C$ generally differs from $T_{pk}$. $T_C$ is determined in this work as the temperature where the maximum value of the partial derivative of magnetization with respect to temperature, $\left| \frac{\partial M}{\partial T} \right|_H$, occurs. Exponent $n$ at $T_C$ can be determined as

$$\left| \frac{\partial M}{\partial T} \right|_H \bigg|_{\text{max}} \propto H^{n-1}.$$  

(34)

$T_{pk}$ is the temperature at which the peak value of magnetic entropy change, $\Delta S_{pk}$, appears. Exponent $n$ as $T_{pk}$ is determined as

$$\left| \Delta S_{pk}^H \right| \propto H^n.$$  

(35)

It needs stressing that both (34) and (35) are derived from the Arrott-Noakes equation (6), with assumption that parameters $a$, $b$, $T_C$, $\beta$ and $\gamma$ do not depend on temperatures or applied fields. Another point needs noticing is that exponent $n$ at $T_C$ and $T_{pk}$ are usually considered to the same.

2.6 Useful recursive relations

2.6.1 $h(i) = \frac{\partial h_i(x,y)}{\partial y}$ used to determine partial derivative of magnetization with respect to temperature

$$h(0) = 0; \quad h(1) = 0; \quad h(2) = 1; \quad s = 1;$$

For $m \geq 2$

$$h(s + j) = \begin{cases} 0, & j = 0; \\ x \cdot h(s + j - m), & 1 \leq j \leq m - 1; \\ \frac{m}{m-1} \cdot y \cdot h(s-1), & j = m; \\ m = m + 1. \end{cases}$$  

(36)
2.6.2 \( h(i) \leftarrow \int_0^x \frac{\partial h(x',y)}{\partial y} \, dx' \) used to compute magnetic entropy change

\[
h(0) = 0; \quad h(1) = 0; \quad h(2) = x; \quad s = 1;
\]
For \( m \geq 2 \)
\[
\{ s = s + m; \}
\]
\[
h(s + j) = \begin{cases} 
\frac{m-j}{m-j+1} \cdot x \cdot h(s + j - m), & 1 \leq j \leq m - 1; \\
\frac{m}{m-1} \cdot y \cdot h(s - 1), & j = m; 
\end{cases}
\]
\[
m = m + 1. \} \quad (37)
\]

3 Results and discussions

Here, we apply above method to deal with the magnetization data of polycrystalline samples \( \text{La}_{1.2}\text{Sr}_{1.8}\text{Mn}_2\text{O}_7 \) obtained with Physical Property Measurement System (PPMS) of Quantum Design Company. More details can be found in reference \[8\]. Following calculations use the whole data (3789) as the training group. The regularization parameter \( \lambda = e^{-24} \approx 0.3775 \times 10^{-10} \), is selected out by comprehensive considerations about the overfitting degree \( \gamma \) (with sampling factor equal to 3) and magnetic entropy change \( |\Delta S_H| \). With 96 orthogonal polynomials \( (S = 95) \), the fitting error reached is \( 3.34540 \times 10^{-4} \). For comparison, the fitting error with \( S = 0 \) is \( 0.78397 \times 10^{-1} \).

Fig. 1 summarizes the temperature dependence of magnetic entropy change under applied magnetic fields \( 0.25T \leq H \leq 5.00T \). Calculations are according to the recursive relations defined in \( (28) \). To find out the present value of \( \lambda \), we have also created magnetization data on the uniform mesh from the fitted expression \( (17) \); and compared the value of \( |\Delta S_H| \), estimated according to equation \( (28) \), with that calculated according to finite difference

\[
\Delta S_H \left( \frac{H_{j_{\max}} + T_i + T_{i+1}}{2} \right) = -\sum_{j=1}^{j_{\max}-1} \frac{M(H_{j+1}+T_{i+1}) - M(H_{j+1}+T_i)}{T_{i+1} - T_i} (H_{j+1} - H_j). \quad (38)
\]

At the value of \( \lambda \) given above, no obvious fluctuations appear in the vicinity of \( T_{pk} \), which manifests that overfitting is not significant.

Fig. 2 displays the temperature dependence of spontaneous magnetization. Note that in contrast to the 113-structure, spontaneous magnetization in bilayered manganites does not approaches zero at the Curie temperature \( T_C \) at vanishing magnetic fields, which is considered to be the temperature at which spontaneous magnetization reaches the minimum. The fact that the minimum is not equal to zero at \( T_C \), might be attributed to the finite magnetization in the Mn-O two-layers above \( T_C \). Therefore, a two-step magnetization process takes place in the bilayered manganites. Since experimental recorded data are fewer in this temperature range, the fitting error at \( T \geq 135K \) is obviously larger than the global error, and therefore we cannot identify the temperature, at which the spontaneous magnetization equals zero, to be the real phase transition point.

Fig. 3 compares the magnetic-field dependence of Curie temperature \( (T_C) \) with that of the temperature of peak magnetic entropy change \( (T_{pk}) \). It’s noted
that $T_C$ is bigger than $T_{pk}$ in bilayered manganites. This result is in contract to that found in reference,[7] the latter announces that $T_{pk}$ is equal to $T_C$ while using the mean field model, and larger than $T_C$ with the Heisenberg model. It's also noted that with increasing field intensity, the difference $T_C - T_{pk}$ increases up to the maximum and then lowers down to negative value at about $\mu_0 H = 5$ T. The strange field-dependence of $T_C$ might suggest spin dimerization occurs within the Mn-O two-layers, as similar field-dependences are usually found in spin-dimerized insulators. However, it needs to stress that the electronic itinating properties and magnetic frustrations in the bilayered manganite might mask the step-by-step magnetization that is found in other spin-dimerized two-layered compounds. Hence, the perfect step structure of magnetization can not be observed in two-layered manganite.

Shown in Fig. 4 are the magnetic field dependences of magnetic entropy change $\Delta S_H$, the partial derivatives of magnetization with respect to temperature $\left| \left( \frac{\partial M}{\partial T} \right)_H \right|$, and $|H \left( \frac{\partial M}{\partial T} \right)_H|$, at $T_C$ and $T_{pk}$. The magnetic entropy $\Delta S_H$ is measured in $\text{J} \cdot \text{Kg}^{-1} \cdot \text{K}^{-1}$ and magnetization $M$ in $\text{A} \cdot \text{m}^2 \cdot \text{kg}^{-1}$. We try to determine the scaling exponents $n$ at $T_C$ and $T_{pk}$ according to $H \left( \frac{\partial M}{\partial T} \right)_H |_{\text{max}} \propto H^n$ and $\left| \Delta S^\text{pk}_H \right| \propto H^n$. It's noted that two distinct dependences of $|H \left( \frac{\partial M}{\partial T} \right)_H|$ on the applied field at $H \leq 1.75$T and $H \geq 1.75$T. We find that $n(T_C) = 1$ with $H \leq 1.75$T and $n(T_C) \approx 0$ with $H \geq 1.75$T can explain the obtained results. Hence, the crossover between two different scaling laws happens at bout $H = 1.75$T. For the magnetic entropy change, however, we can not find a proper numerical value of $n(T_{pk})$ to unify the estimated results in the whole range of measurement. In contrast, a nonlinear dependence is found like

$$\ln |\Delta S^\text{pk}_H| = 0.19 + 0.99 \ln H - 0.16 \ln^2 H.$$  \hspace{1cm} (39)

It needs emphasizing that under weak fields, exponent $n$ equal to 1 is a direct consequence of the non-vanishing spontaneous magnetization at $T_C$ or $T_{pk}$, which is the typical characteristic of bilayered compounds. Comparing panel (a) with (c), it is noted that the value of exponent $n$ estimated according to (3) is unreasonably large at $T_C$, and that $T_{pk}$ seems more reliable.

Shown in Fig. 5 is the temperature dependence of the scaling exponent of magnetic entropy change with respect to applied magnetic field. It is noticed that two different transitions seem present under strong magnetic fields. It may be explained by one transition in the vicinity of the transition point occurs under weak magnetic fields, and a magnetic structure rearrangement and therefore two-step process happens under strong fields.

4 Conclusions

In conclusion, we apply an two-variable polynomial fit to the magnetization of bilayered manganites, in order to investigate its magnetic entropy change and the associated scaling behaviour with respect to applied magnetic fields. It’s found that the Curie temperature is different from the temperature of peak magnetic entropy change. The difference between these two temperatures are dependent on applied magnetic fields. Therefore a mean-field theory does not apply to bilayered manganites. The field dependence of the Curie temperature might imply weak dimerization occurs in the bilayered manganite. In contrast to
Figure 1: The temperature dependence of magnetic entropy change under applied magnetic fields $0.25T \leq H \leq 5.00T$.

Figure 2: The temperature dependence of spontaneous magnetization.
what has been found in manganites with the 113 structure, the scaling behaviour at the Curie temperature in bilayered manganites is much different from that at the peak temperature. Hence it requires distinguishing the actual transition point from the peak temperature while discussing the scaling law of magnetic entropy change. It’s also found that the temperature dependence of the scaling exponent at peak temperatures under weak fields is distinct from that under strong fields. This difference is attributed to an crossover from one-step transition under weak fields to two-step transition under strong fields. To further test the validity of the method provided in this paper, other kinds of magnetic materials will be analysed in the future.

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Figure 4: The magnetic field dependence of magnetic entropy change $\Delta S_H$, the partial derivatives of magnetization with respect to temperature $\left| \frac{\partial M}{\partial T} \right|_H$, and $|H \frac{\partial M}{\partial T}|_H$, at $T_C$ and $T_{pk}$. $T_C$ is defined as the temperature at which $\left| \frac{\partial M}{\partial T} \right|_H$ reaches its maximum, and $T_{pk}$ the temperature at which $|\Delta S_H|$ reaches its peak value. The magnetic field is measured in Tesla, $\Delta S_H$ in J·Kg$^{-1}$·K$^{-1}$ and magnetization $M$ in A·m$^2$·kg$^{-1}$.

Figure 5: The temperature dependence of the scaling exponent of magnetic entropy change with respect to applied magnetic field.
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