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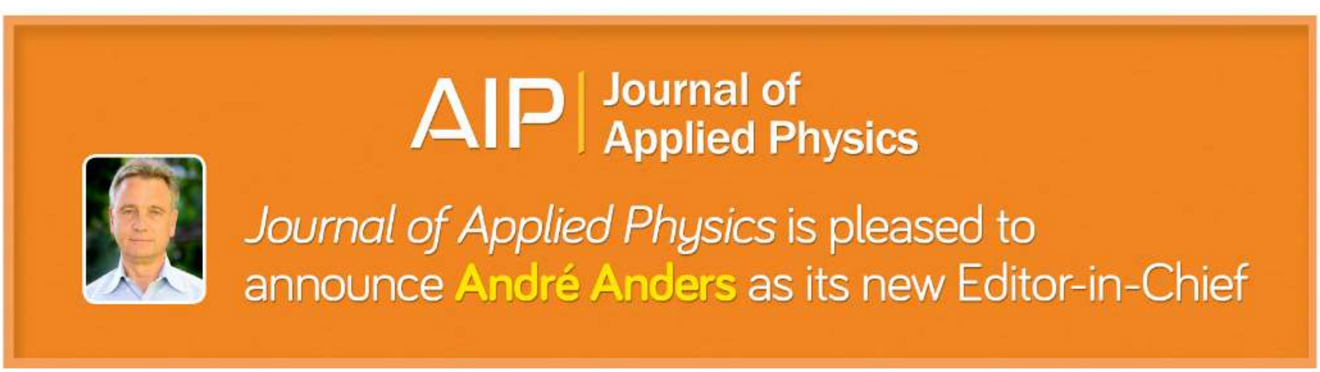

# Study of the magnetic behavior of single-crystalline $Nd_{0.5}Sr_{0.5}MnO_3$

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Zero-field-cooled and field-cooled magnetization data in single-crystalline $Nd_{0.5}Sr_{0.5}MnO_3$ revealed the existence of thermodynamic irreversibility below Curie temperature ($T_C$), indicating the presence of frustration of spins. The imaginary part of ac susceptibility ($\chi''$) indicates a prominent cusp below $T_C$, which shifts to higher temperatures with increasing frequency. Magnetization, ac susceptibility, resistivity, and specific-heat measurements were used to find three critical exponents $\alpha=0.12(1)$, $\beta=0.5(0)$, and $\gamma=1.02(2)$. The values of the critical exponents are all between mean-field values and three-dimensional Heisenberg model values. © *2006 American Institute of Physics*. [DOI: 10.1063/1.2168435]

## I. INTRODUCTION

The colossal magneto resistive (CMR) manganites are characterized by a complex phase diagram due to several competing ordering mechanisms governing different degrees of freedom.[1] Hence a careful study of the magnetic ordering and phase transition has been undertaken in single crystal of NSMO-0.5 through dynamic ac magnetic-susceptibility measurements as well as measurements of critical exponents for magnetization, magnetic susceptibility, specific heat, and electrical resistivity.

## II. EXPERIMENTAL DETAILS

Single crystals of $Nd_{0.5}Sr_{0.5}MnO_3$ were grown in an infrared image furnace by the floating zone technique[2] and characterized by x-ray-diffraction, resistivity, and magnetization measurements.[3] ac susceptibility was measured as a function of temperature using a Quantum Design Physical Property Measurement System (PPMS). Field-cooled (FC) and zero-field-cooled (ZFC) magnetizations were measured using a Magnetic Property Measurement System superconducting quantum interference device (SQUID) magnetometer (Quantum Design). Resistivity measurements were made using a standard linear four-probe technique in a Janis closed cycle refrigerator. Specific heat was measured using a NETZSCH differential scanning calorimeter (DSC 200PC "Phox") by the ratio method.

## III. RESULTS

Figure 1(a) shows the temperature dependence of the FC and ZFC magnetizations. A charge ordering transition occurs below the Néel temperature $T_N=138$ K and a ferromagnetic-paramagnetic transition occurs at $T_C=240$ K in zero field. The plot shows a small but significant difference between ZFC and FC which indicates the existence of thermodynamic

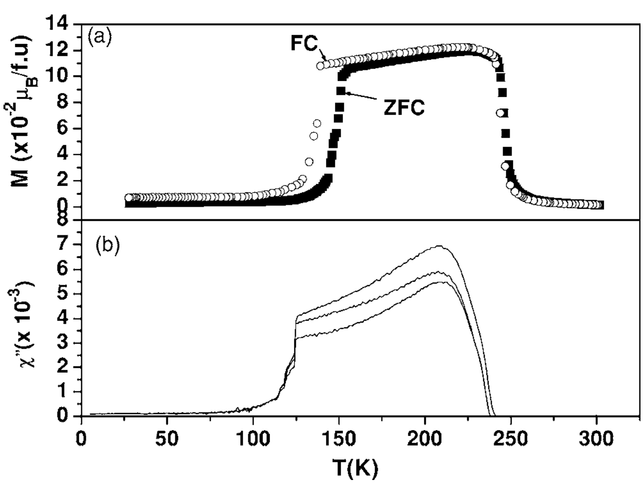


FIG. 1. Temperature dependence of (a) ZFC and FC magnetizations and (b) imaginary part of the ac susceptibilities at 333, 667, and 1333 Hz.

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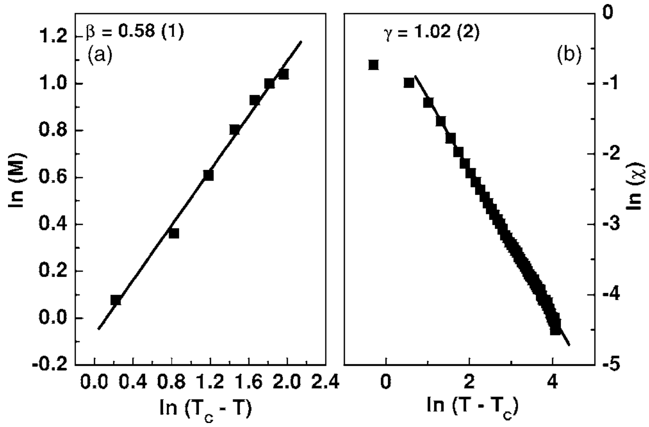


FIG. 2. Critical exponents from power-law behaviour of (a) $M$ and (b) $\chi$.

irreversibility below $T_C$. This may be due to spin-glass-like behavior[4] and motivated (5 Oe, rms) low-frequency (133 to 6667 Hz) ac magnetic-susceptibility measurements in the temperature range of 4.2 to 300 K. $\chi'$ showed a distinct change of slope at 239 and 125 K in an applied field of 5 Oe. $\chi''$ shows a dip at a temperature of 239 K and there is a steep decrease at 129 K. As the temperature is decreased, unlike the real part, $\chi''$ shows a cusp at 234 K and at 333 Hz. $\chi''$ measured at three different frequencies is shown in Fig. 1(b). The real part is slightly affected by the change in frequency, while the imaginary part exhibits an easily measurable shift in the cusp temperature $T_f$. $T_f$ is shifted to higher temperatures as the frequency is increased.

### Critical behavior

Critical exponents $\beta$ and $\gamma$ obtained from magnetization and susceptibility are shown in Fig. 2. Low-field ac susceptibility measurements in the critical region were also used to perform a Kouvel-Fischer (KF) analysis.[5] The results are shown in Fig. 3.

The spin disorder resistivity $\Delta\rho_{sp}$ has the same functional dependence as that of the magnetization, $M$.[6] From the data shown in Fig. 4, we obtained a value of 0.5 for $\beta$. Fisher and Langer showed that the short-range spin fluctuations near $T_C$ increase the carrier scattering rate and cause $d\rho/dt \sim |t|^{-\alpha}$ to scale in the same as specific heat.[7] Figure 5 shows

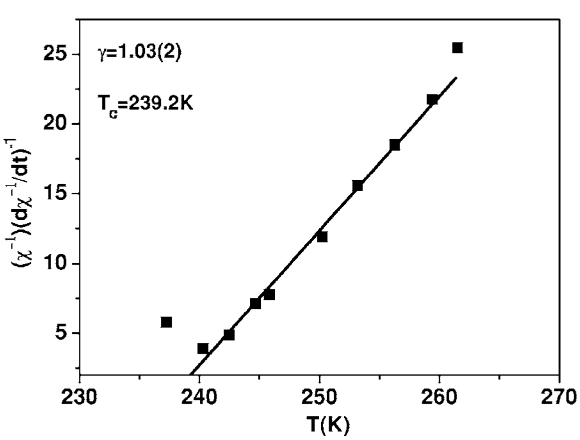


FIG. 3. Kouvel-Fischer plot of the real part of the first-order susceptibility.

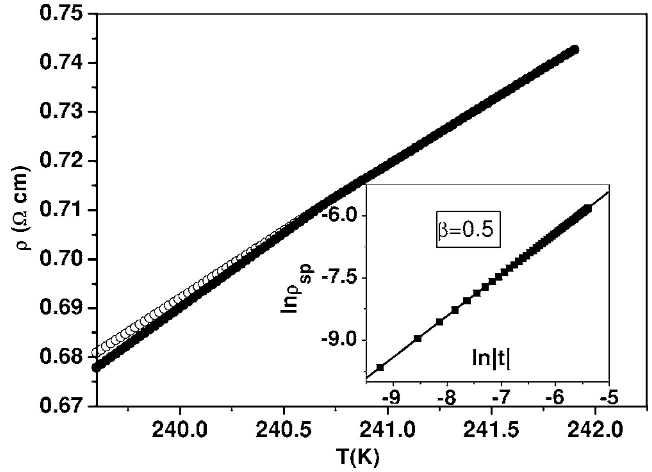


FIG. 4. Extrapolation of zero-field resistivity. Inset: critical behavior of $\Delta\rho_{sp}$ with respect to the reduced temperature $t=(T-T_C)/T_C$.

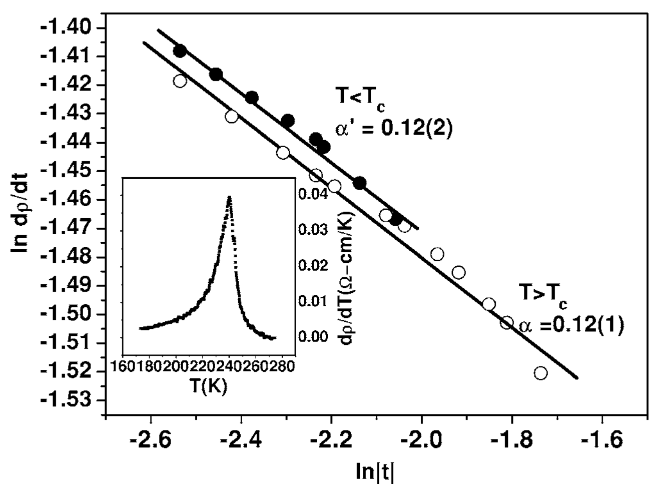


FIG. 5. $\ln|t|$ vs $\ln(d\rho/dt)$. Inset: $d\rho/dt$ vs $T$.

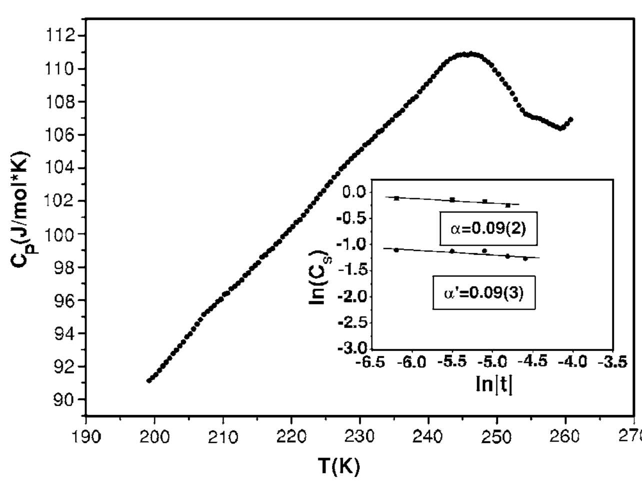


FIG. 6. Temperature dependence of specific heat. Inset: $\ln|C_S|$ vs $\ln|t|$, where ($C_s=C_p-C_{\text{polynomial fit}}$).

TABLE I. Comparison of measured critical exponents with different theoretical models.

| | | $\alpha$ | $\beta$ | $\gamma$ |
|---|---|---|---|---|
| NSMO-0.5 | This work | $\alpha'=0.12(2)$[a] | 0.58(1)[b] | 1.02(2)[b] |
| | | $\alpha=0.12(1)$[a] | 0.5(0)[a] | 1.03(2)[c] |
| | | $\alpha'=0.09(3)$[d] | | |
| | | $\alpha=0.09(2)$[d] | | |
| Mean field | | 0 | 0.5 | 1.0 |
| 3D Heisenberg | | 0.11 | 0.365 | 1.336 |

[a]Resistivity.
[b]Magnetization.
[c]K-F formalism.
[d]Specific heat.

a ln-ln plot of $d\rho/dt$ vs $|t|$ with the inset showing a peak in the resistivity at $T_C$. Above and below $T_C$, $\alpha$ has a value of 0.12(1). The value of $\alpha$ is usually observed from specific-heat measurements. In Fig. 6, the variation of $C_P(T)$ near $T_C$ which is composed of a smooth background plus a singular part $C_S$ due to magnetic phase transition is shown. The value of $\alpha$, which is shown in the inset of Fig. 6, is nearly the same as that obtained from the resistivity data. In Table I, the values of $\alpha$, $\beta$, and $\gamma$ are collected together along with the expected values for different universality classes for comparison.

## IV. DISCUSSIONS

Zang *et al.*,[8,9] suggest that the low-energy excitations of the double exchange model are different from those of the Heisenberg ferromagnet. They studied the double exchange model using mean-field approximation and their conclusions are supported by Sarkar *et al.*[8–10] The $\mu^+$ SR results on the dynamic critical behavior show deviation from the Heisenberg model which is ascribed to a crossover from exchange to dipolar critical regime.[11] Polaron formation is also expected to modify the nature of the magnetic phase transition. These are reflected in the values of critical exponents reported for $La_{1-x}Sr_xMnO_3$ compounds.[12] Single-crystal neutron diffraction data of Rosenkranz *et al.*[13] are in agreement with the three-dimensional (3D) Heisenberg model in NSMO-0.5 single crystal. The present study suggests a possible crossover from mean field to 3D Heisenberg model. A more detailed analysis of these results is in progress.

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