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Application of improved scaling procedure to magnetic heat capacity in $La_{0.85}Ag_{0.15}MnO_3$ manganite

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Studying critical phenomena near phase transitions is known to be an important branch of condensed matter physics. These studies can provide an important information about the nature of the various mechanisms causing transitions and their symmetry. At the same time to get this information through the measurements of heat capacity is relatively easy and much cheaper than, for example, from so expensive and difficult methods as neutron diffraction and muon spin-lattice relaxation. Moreover, scaling appears to be very fruitful to study cosmological problem [1, 2]. So scaling hexagonal manganites [2] has supported out that the expansion of the Universe during the inflationary period was rapid. Moreover, recently, the condensed matter experience [3] has also appeared to be very useful for describing dark energy and dark matter as the components of the vacuum field at or above Planck energy scale. However, despite this, articles dealt with scaling manganites has been a long time not issued. Before manganites, scaling was studied in systems when there was no hint of hysteresis. In fact, hysteresis was a feature of first-order phase transition and a taboo for studying fluctuation phenomena. However, it was found that the hysteresis observed in certain manganites with double exchange and the colossal change of the resistance and magnetoresistance is unusual: it coexists with thermodynamic fluctuations near T_C [4].

So, the futility of exploring the critical properties of manganites [5] is caused by the following circumstances: (i) Scaling in manganites realizes in a relatively narrow neighborhood of T_C in comparison with other substances, classic magnets, superconductors and etc. [6–8]. (ii) In many manganites, the strong sensitivity of T_C to a magnetic field (unusual for classic ferromagnets) complicates the scaling procedure. (iii) Hysteresis splitting T_C on Curie points for ferromagnetic-to-paramagnetic transition, T_C^{fm}, appearing at warming and paramagnetic-to-ferromagnetic one, T_C^{pm}, arising at cooling makes it impossible to carry out the classical scaling procedure.

In view of these difficulties, we have adapt the classic scaling to explore successfully new materials undergoing hysteresis and/or strong field dependence of T_C. In the Article, we have approbated our modernized scaling to one of such materials, Ag-doped lanthanum manganite. The essence of our improvements of classic scaling is the following rules: (i) In the case of hysteresis, different values of T_C apply for ferromagnetic, T_C^{fm}, and paramagnetic, T_C^{pm}, states. (ii) In the case of strong field dependence of T_C, to make successfully scaling procedure it needs to use own critical temperature, T_C^H, for each of magnetic fields.

Our study aims to partly resolve the mentioned problems and difficulties of scaling in certain manganites to open a way to more accurately predict the physical properties of manganite and strongly-correlated substances being necessary for modern nanoelectronics and spintronics.

The $La_{0.85}Ag_{0.15}MnO_3$ manganite is non-hysteric, but its T_C has strong sensitivity to a magnetic field. Therefore, we have utilized the second rule. So we take $T_C^0 = 280.80$, $T_C^{11\,\mathrm{kOe}} = 287.90$, and $T_C^{26\,\mathrm{kOe}} = 294.00$ K. Thus, the absolute invariant of the peak position, though in the reduced, in relation to a magnetic field has been reached. This representation is comfortably for analysis of a difference between the anomalous heat capacity in a nonzero field and that without a field, $C_p(t,H)-C_p(t,H=0)$, used for fitting the scaling function $f(t/H^{1/2\nu})$ with the following expression [9]:

$$[C_p(t,H) - C_p(t,H=0)]H^{\alpha/2\nu} = f(t/H^{1/2\nu}), \quad (1)$$

where α is a critical exponent of heat capacity and ν a critical exponent of correlation radius.

Exp. (1) have in the best way fitted the experimental data at $\alpha = -0.230$. At this value of α, the superscaling relation, $D\nu = 2 - \alpha$, gives the critical exponent of correlation radius $\nu = 0.7433$, provided the dimensionality of fluctuation space $D = 3$. In Fig. 1, the magnetic specific heat, $\Delta C_p = C_p(t,H) - C_p(t,H=0)$, is plotted in the scale $H^{\alpha/2\nu}[C_p(t,H) - C_p(t,H=0)]$ vs. $t/H^{1/2\nu}$ to match Exp. (1) at these values of α and ν.

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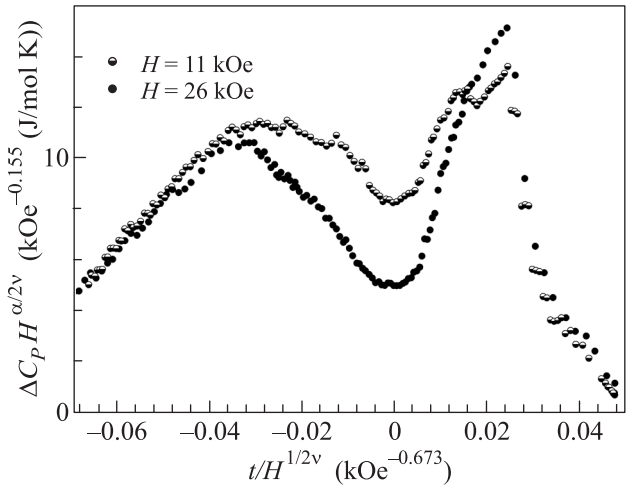

Fig. 1. Magnetic heat capacities $\Delta C_p = C_p(t,H) - -C_p(t,H=0)$ scaled in coordinates, according to Exp. (1) at the values of $\alpha = -0.23$ and $\nu = 0.7433$

The figure is seen clearly demonstrate the collapse of the data, i.e. successful superimposing the anomalous specific heats, ΔC_p, in the fields 11 and 26 kOe in the intervals of $t/H^{1/2\nu} \approx [-0.070; -0.033]\&[0.024; 0.047]$. But these values, $\alpha = -0.230$ and $\nu = 0.7433$, do not fall into any existing universality class.

This failure is supposed to indicate that the transition is a non-ordinary second-order ferromagnetic transition. It appears there is a non-linear effect of a magnetic field, being intrinsic to the system with 3*d*-transition Mn. The presence of 3*d*-transition Mn in manganites makes us involve spin-orbital interaction for interpreting many their physical properties [10]. It should be emphasized that strong magnetic field effects observed in the $La_{0.85}Ag_{0.15}MnO_3$ are features of the substances with the strong spin-orbital coupling of t_{2g}-electrons. Ordering t_{2g}-orbitals, a magnetic field also favors via the Hund's pairing of t_{2g} and e_g electrons to extra strengthening ferromagnetic exchange. At this point, it is natural to suppose a new universality class taking place in strong-correlated electron systems. We could name such universality class as Double 3D-Heisenberg.

This new universality class is consistent with the crystal, magnetic and orbital symmetries for the investigated manganite, $La_{0.85}Ag_{0.15}MnO_3$. It should be noted that double exchange is quite different qualitatively from ordinary exchange [11] (direct, indirect, RKKI, *s-d*, *s-f*...). In contrast to ordinary ferromagnetism, its inverse susceptibility can be a curved line. Moreover, as opposed to virtual indirect Kramer's superexchange, double exchange is real: one e_g-electron from a Mn^{3+}-cation transfers through intervened O^{2-}-anion into the nearest Mn^{4+}. Such real transfer under electric field leads to electric current. Double-exchange ferromagnetism can be understood rather easily on a simple semiclassical model [11]: ions polarize free electrons, which in turn polarize the ions; so that the electrons can easily travel between the Mn cations. Therefore, that the $La_{0.85}Ag_{0.15}MnO_3$ demands a new universality class to its critical behavior must not be a surprise.

Discovering Jahn-Teller, double exchange and ferroelectric interactions in manganites multiferroics, and other strong-correlated electron materials gives a complicated pattern of their interplay, including hysteresis and strong field-sensitive T_C. Therefore, although our improved scaling has been applied to the particular manganite compound, $La_{0.85}Ag_{0.15}MnO_3$, our findings are important in a broader sense. In this Letter, we have studied the scaling behavior of the heat capacity as a function of temperature and magnetic field. Taking other variables (electric field, pressure, doping level) we can yield rich scaling information to move both condensed matter and applied physics forward. Particularly, technologic issue is to spread hysteresis up to room temperatures to use bistable magnetic states within hysteresis loop in nonvolatile memory devices.

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