Low-temperature resistivity minimum and weak spin disorder of polycrystalline $La_{2/3}Ca_{1/3}MnO_3$ in a magnetic field

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Low-temperature transport properties were systemically studied for the optimal magnetic coupled polycrystalline $La_{2/3}Ca_{1/3}MnO_3$ system under an applied magnetic field from 0 to 8.0 T. The temperature dependence of resistivity shows a generally minimum behavior at low temperatures ($T<30$ K) under various applied fields. For the low fields of $H<1.0$ T, best fittings were made by considering both the electron-electron (e-e) interactions in terms of $T^{1/2}$ dependence and the Kondo-like spin dependent scattering in terms of $\ln T$ dependence. But for the high fields, at the low-temperature region of $T<15$ K, accompanying a disappearance of Kondo term $\ln T$, the electronic resistivity only follows $T^{1/2}$ dependence, which is a characteristic of enhanced e-e interactions in three dimension (3D) disorder system, and is also confirmed by the specific-heat measurement. It is found that the $\ln T$ dependence of resistivity under low fields could be attributed to the weak spin disorder scattering including both spin polarization and grain boundary (GB) tunneling, which are the typical characteristics of the polycrystalline sample. The suppression of resistivity upturn under low fields may result from the increase of the conduction electrons tunneling and the decrease of the resistivity by the applied magnetic field. The existence of e-e interaction should be a general characteristic and reflect the strong correlated interaction between electrons in the mixed-valent manganites.

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I. INTRODUCTION

In the past two decades, enormous effort have been exerted to understand systems with strongly correlated electrons, for example, the high-T_c superconductors in cuprate and the colossal magnetoresistance (CMR) in mix-valent manganites, because both of them have wide range of technological applications and the strong correlated characteristics.[1,2] However, despite the efforts made, the nature of the strongly correlation physics is still not clear. Especially, in the manganites, the strong coupling between the charge, spin, orbit, and the lattice freedom lead to rich phase diagrams.[3–7] Meanwhile, the multiple interactions in these materials would give more obstacles to the comprehension on the correlated electron system. It is well known that the coupling between localized spin and conduction electrons serves as a fundamental model for understanding correlated electron physics. As a consequence, the interplay between electronic and magnetic degrees of freedom has been intensely studied in manganites for all these years. For the existence of the possible quantum phase transition[8] and the intrinsic disorder[9] caused by the chemical substitution of the A site in the general chemical formula ABO_3, to make clear the underlying mechanism of the CMR manganites, more and more attention was forced on the electronic and magnetic properties of manganites at low temperatures. At low temperatures, the contribution from the electron-lattice interaction is weakening and the Coulomb correlation effect is obviously. In this way, the low-temperature transport properties of the manganites may reflect the intrinsic mechanism of the systems. Therefore, extensive studies of magnetic, structural, and transport properties on the manganites at low temperatures have been carried out,[10,11] just like the study on heavy electrons systems for the sake of superconductivity. Beside the distinct low-field magnetoresistance (LFMR) at low temperatures, many recent experiments have provide evidence for the existence of the resistivity minimum at low temperatures in the manganites, no matter the polycrystalline, the quality film, or the single crystal,[11–14] which is similar to the Kondo effect. The Kondo effect, as observed early in the dilute magnetic alloys, which arises from the exchange interaction between itinerant conduction electrons and localized spin impurities, leads to anomalous temperature dependences in various physical parameters due to the Fermi-surface effect.[15] As for the manganites, the spinless defects induce a local moment in their vicinity. Therefore, one can wonder whether these magnetic degrees of freedom play a role in the charge scattering, and induce, for instance, a Kondo-like spin-flip contribution to the resistivity. On the other hand, for the strongly correlated system, there may be another contribution arising from the renormalization of the effective e-e interactions, which can modify the density of the states at the Fermi energy and cause the increasing of the resistivity.[16] Although an extensive experimental as well as theoretic work related to the scattering of electrons from impurities in nonmagnetic metals and doped semiconductors have been performed to study the quantum correction to electrical conductivity,[17–19] the problem of quantum effects on the ferromagnetic materials at low temperatures requires further investigation. More efforts have been made trying to explain the resistivity minimum in manganites, but up to date, clear conclusions are not drawn; because of the great number of different experimental results and different interpretations were given.[10–14,20] These also challenge our understanding of the correlated electrons. In order to give some light on this project, we have carried out low-temperature resistivity, magnetotransport, and specific heat measurements for the optimal magnetic coupling $La_{2/3}Ca_{1/3}MnO_3$ polycrystal. This sample is selected in order to ensure the dopant contributions to the resistivity as few as possible. It will in-

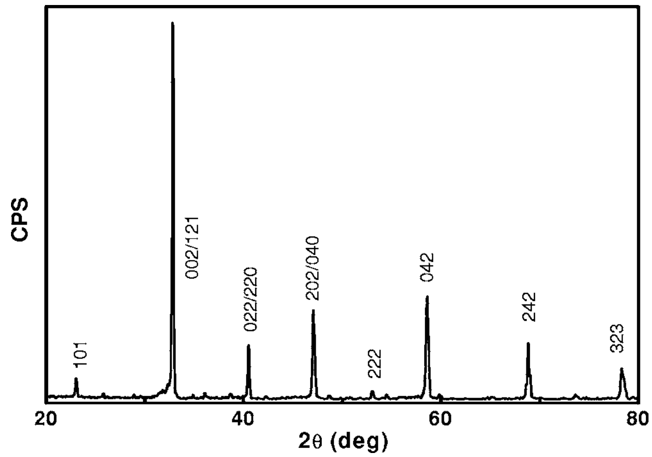

FIG. 1. XRD pattern for the experimental $La_{2/3}Ca_{1/3}MnO_3$ sample.

dicate some intrinsic physical mechanism of the manganites. In this paper, we pay our attention on the effect of applied magnetic field on the low-temperature resistivity minimum. The present results show that the low-temperature resistivity minimum behavior is strongly dependent on the applied magnetic field when the field is smaller than 1.0 T, but almost independent on it when the field is higher. The results are not consistent with the reported results that the resistivity minimum temperature T_{min} moves first to higher temperature at low applied fields and then to lower temperature for the high applied fields as in Ref. 13 and the resistivity upturn disappears at a certain field H_{cr} as in Ref. 21. At the same time, the existence of the e-e interaction under various fields reflects a general characteristic of the strong correlated interaction in the mixed-valent manganites.

II. EXPERIMENTAL

The $La_{2/3}Ca_{1/3}MnO_3$ bulk sample was prepared by the conventional solid-state reaction method. Just before all the measurements, the sample was annealed in oxygen at 1100 °C for 12 h. The structure was analyzed by scanning electron microscopy (SEM) and x-ray diffraction (XRD, 18 kWD/max-2500 model, Cu-Kα radiation). The XRD pattern is shown in Fig. 1. It can be seen that the spectra is well characterized without detectable extra peaks appearing, indicating the sample is well crystallized and in good single phase. All the measurement was performed on the same sample. The electrical transport, magnetization, and specific heat measurements were carried out using the PPMS (quantum design) in the temperature range of 1.8–400 K and the magnetic field of 0–9 T. The magnetic field is perpendicular to the measurement current. The temperature and magnetic field dependence of resistivity (ρ-T and ρ-H curves) were measured on a rectangular parallelepiped sample ($8.0 \times 2.0 \times 1.5$ mm) using the standard four-probe technique in 0 and applied fields up to 8.0 T and temperature range of 2 to 300 K. All the ρ-T curves were measured under field cooling. For the ρ-H and M-H curves, before each run, the sample was heated above their T_c and cooled to the measuring temperature under zero field, in order to ensure a prefect demagnetization of the sample. The experimental results are well repeatable.

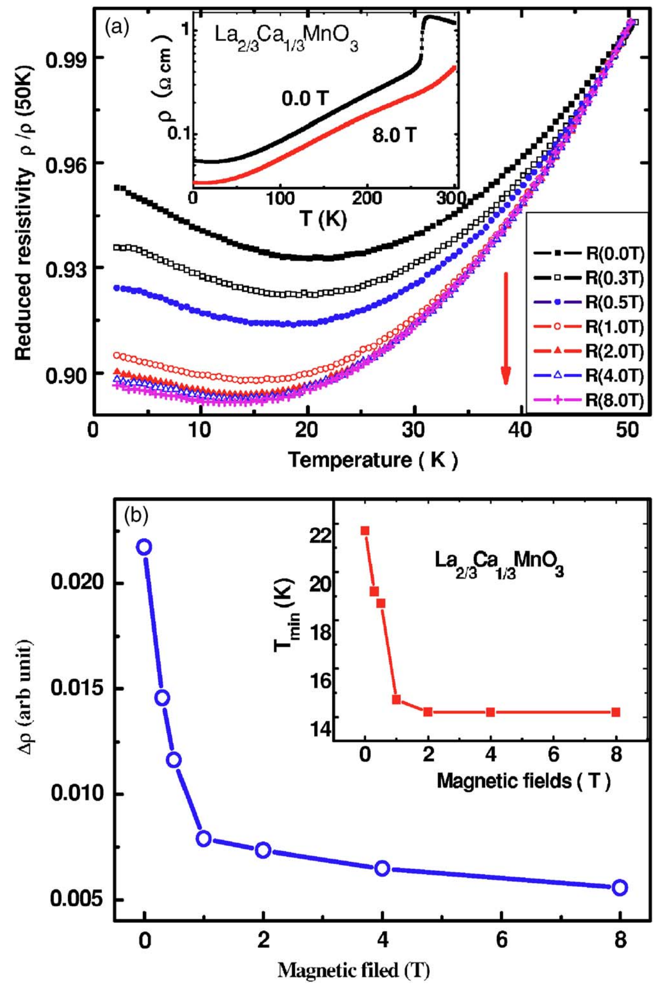

FIG. 2. (Color online) Details of the temperature dependence of resistivity under various applied fields between 0 and 8.0 T in a low temperature region of 2–50 K for the optimal doped $La_{2/3}Ca_{1/3}MnO_3$. (a) Reduced resistivity as a function of temperature. The inset is the temperature dependence of resistivity in the whole range of 2–300 K at zero field and an applied field of 8 T. (b) The depth of increased resistivity $\Delta\rho$ below T_{min} as a function of the applied field H and the inset shows the dependence of T_{min} on the applied field H.

III. RESULTS AND DISCUSSION

A. A general characteristics of resistivity minimum

Figure 2 shows the temperature dependence of resistivity and the change of corresponding characteristic parameters under various applied fields between 0 and 8.0 T in the temperature range of 2–50 K for the $La_{2/3}Ca_{1/3}MnO_3$ sample. In Fig. 2(a), a normalized resistivity is used by $\rho(T)/\rho(T=50\text{ K})$. The inset shows the resistivity in the whole temperature range of 2–300 K under 0 field and 8.0 T, respectively, which indicates the existence of the CMR effect. It can be seen that distinct resistivity minima appear below 30 K and shows strong dependence on the applied fields. It is worth noting that, the resistivity upturn below T_{min} is gradually suppressed at low fields but almost achieves saturation when the field is larger than 1 T. T_{min}, where the resistivity begins upturn with the temperature decreasing, moves monotonously toward lower temperature with the increase of applied field. In order to quantificationally show the changes and the effect of the applied magnetic field, Fig. 2(b) plots the depth $\Delta\rho$ as a function of the applied field H and the inset shows the applied field dependence of T_{min}. The depth is the representation of the degree of the upturn at low temperatures, which is written as $\Delta\rho = |\rho_{2K} - \rho_{\min}| / \rho_{\min}$. Figure 2(b) and the inset show that both curves decrease rapidly in the range of low applied field, $H < 1.0$ T, and almost achieve a low saturation value when the magnetic field is larger than 1.0 T. They indicate that the low-temperature resistivity abnormally is sensitive to magnetic field when it is lower than 1.0 T but almost independent on it when it is higher than 1.0 T. Therefore, we suppose that the resistivity minimum partly originate from spin dependent scattering which is suppressed by the external applied magnetic field. It may also enable us to contact it with the LFMR which may be cause by the GB. But these are only plausible explanations, and must be verified by additional evidence. Detailed description and account for these will be given in the following sections. Of course, there is a discrepancy of the effect of applied magnetic field between the experimental data in this paper and the result of Refs. 13 and 21. For Ref. 21, the used sample is $La_{0.5}Pb_{0.5}MnO_3$ containing 10 at. % of Ag which is different from our sample. Therefore, we cannot give more discussion. But the other work done by the same group used single crystal and ceramic $La_{0.8}Sr_{0.2}MnO_3$ (Ref. 20) also did not find the same fact, i.e., the resistivity upturn disappears at a certain field H_{cr}. For Ref. 13, the used sample is $La_{0.7}Ca_{0.3}MnO_3$ films. The polycrystalline and the film sample may have difference. Moreover, the discussion in Ref. 13 that the B and n are correlated with the depth of minima and $T_{\min}$ may be controversial.

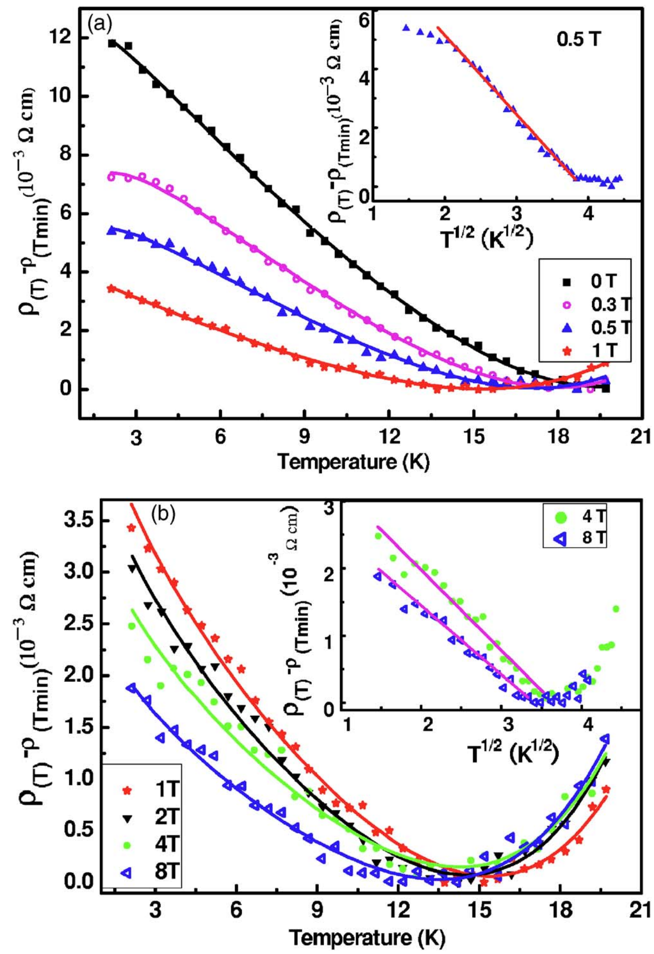

FIG. 3. (Color online) (a) Low field ($H < 1$ T) resistivity subtracted the minimum value fitted using Eq. (1), the inset is the resistivity obtained under 0.5 T simply fitted in terms of $T^{1/2}$ below 20 K for $La_{2/3}Ca_{1/3}MnO_3$ sample. (b) High field ($H > 1$ T) resistivity subtracted the minimum value fitted using Eq. (2), the inset is the resistivity obtained under 4 T and 8 T simply fitted in terms of $T^{1/2}$ below 20 K for the same sample. The solid lines are the fitting results and the symbols are the corresponding experimental data.

B. The e-e interaction and spin dependent scattering

In order to understand the origin of the observed resistivity minimum in manganites, the experimental data had been analyzed taking account of Kondo-like scattering, the e-e interaction, weak localization, intergranular tunneling of the polarized charge carriers, and so on as discussed in Refs. 10–14 and 20. Also, because the sample was prepared by solid-state reaction method, there may be oxygen deficiency which cannot be ruled out as a reason for enhanced resistivity upturn at low temperatures. Therefore, before measurement, our used sample was annealed in oxygen at 1100 °C for 12 h. Using the XRD data (shown in Fig. 1), we calculated the lattice parameters to see whether the unit cell is modified. Here, the lattice parameters obtained are $a=5.4732$ Å, $b=5.4662$ Å, $c=7.7287$ Å. Comparing with the standard card of $La_{2/3}Ca_{1/3}MnO_3$ where $a=5.451$ Å, $b=5.467$ Å, $c=7.700$ Å, a and c increases about 0.4%, and b decreases about 0.014%, indicating that the oxygen content of our sample is enough.

Based on strong correlated effect in manganites, we must first consider the contribution from the e-e interaction, which causes a $T^{1/2}$ dependence of the conductivity in a disordered system and insensitive to the applied magnetic field.[12,14,16] As show in the inset of the Fig. 3(a) and 3(b), when we tried to fit all the curves obtained from different fields simply by the term of $T^{1/2}$, it is only suitable for the data obtained under higher applied fields, $H \geqslant 2.0$ T, but for the lower field, it has distinct departure at low temperatures. The insets of Fig. 3(a) and 3(b) show some typical examples of all the curves. For the e-e interaction is not sensitive to the applied field, this may also be the reason why $\Delta\rho$ and T_{min} are saturated under the magnetic field above 1.0 T. Hence, the upturn of the resistivity under higher field can be attributed to the interference of e-e scattering from static inhomogeneities in 3D disorder system. Though this is a popular explanation, it must be verified by additional evidence, which will be discussed below. But for the lower fields, obviously, the e-e interaction alone does not sufficiently fit the resistivity upturn. Based on the sensitivity of the resistivity to the lower applied fields, except to the e-e interaction, there should exist another mechanism that can be rapidly suppressed by low fields. As mentioned above, it may be a spin dependent scattering or have some relation with the LFMR.

According to Abhay and He *et al.*,[22,23] the Kondo correlations are still present in ferromagnetic (FM) system, and in particular conditions the strong-coupling limit of Kondo effect can still be achieved. Considering our results published before,[24] a similar explanation may also be applied to these cases. Therefore, we fitted the low-temperature ($T<20$ K) resistivity data under lower fields ($H<1.0$ T) to the equation:

$$\rho(T) = \rho_0 + \rho_e T^{1/2} - \rho_s \ln T + \rho_p T^5. \quad (1)$$

In Eq. (1), the first term is residual resistivity, the second term is the contribution from the correlated e-e interactions, the third term may be caused by Kondo-like spin dependent scattering, and the fourth term is due to the *e-p* interaction. The fitted results are shown in Fig. 3(a), the symbols are the experimental data and the solid lines are the fitting results. It can be seen that the data are well fitted. But as mentioned before, for the insets of Figs. 3(a) and 3(b), the resistivity upturn under higher fields can be fitted by $T^{1/2}$, i.e., the contribution to the resistivity upturn may only come from the e-e interactions. Hence, the experimental data obtained from higher fields ($H>1.0$ T) is fitted without accounting for the spin dependent scattering, i.e., without the term of $\ln T$

$$\rho(T) = \rho_0 + \rho_e T^{1/2} + \rho_p T^5. \quad (2)$$

The fitted results are shown in Fig. 3(b), the symbols are the experimental data and the solid lines are the fitting result. It is also a surprisingly well fitting. However, when we try to fit the data obtained from lower fields using Eq. (2) good fitting was not achieved. From Fig. 2(b), it is seen that, the magnetic field about 1.0 T may be a characteristic field. Therefore, the data obtained under 1 T is fitted using both Eqs. (1) and (2). Although the fittings are only phenomenological analysis, the good agreement between the experimental data and the fitting results [Figs. 3(a) and 3(b) and the insets] also provide the possibility to understand resistivity minimum at low temperatures by taking into account both the e-e interaction and the Kondo-like spin dependent scattering. The corresponding coefficients are shown in Table I.

Because the fittings are only the results of the phenomenological analysis, the values of the coefficients (shown in Table I) do not reflect the nature of the physics. It can be seen that all the parameters can be tuned by applying the external magnetic field. The residual resistivity ρ_0 decreases with the increase of field, which is different from the usual conductors. It is well known that, in good conductors, ρ_0 should not depend on temperature T and magnetic field H. In fact, this may be related to the intrinsic properties of the system and does reflect *CMR* effect and disorder characteristics for the manganite system. As for the ρ_p, it is found that the electron-phonon (*e-p*) interaction seems not sensitive to the applied fields, because it is smaller than the other coefficients by several orders. ρ_s and ρ_e, show similar behaviors, i.e., they decrease with the increase field up to 8.0 T, like the ρ_0. It has been suggested that the resistivity minimum at low temperatures come from the competition of two contributions: one, usually, increases and the other, decreases with the increase of the temperature. It is well known that the resistivity come from the *e-p* interaction increases with the increase of temperature and the contributions from the e-e and the spin-disorder scattering decrease with the increase of temperature. Therefore, in Eq. (1), we should deal with ρ_e and ρ_s together because our fitting is only the result of the phenomenological analysis. For the contribution from the e-e interaction we will confirm it using the specific heat measurement as below. Someone may notice that the positive ρ_s value should be unexpected according to the Kondo effect, which gives more suggestions that we should consider the ρ_s and ρ_e together, i.e., taking into account the contribution from both the charge and spin of the electrons. To qualitatively separate the ρ_s and ρ_e, the data obtained from the lower fields is fitted by the following Eq. (3):

TABLE I. The fitting results of the coefficients of Eqs. (1) and (2) for all the applied fields from 0 to 8.0 T. The two rows in the middle of the table show the different data for the same field of 1.0 T from Eqs. (1) and (2).

$\rho(T)=\rho_0-\rho_e T^{1/2}+\rho_s \ln T+\rho_p T^5$				
Applied field H (T)	ρ_0	ρ_e	ρ_s	$\rho_p(^*10^{-10})$
0.0	0.02071	0.00849	0.00474	9.892
0.3	0.01442	0.00771	0.00561	11.418
0.5	0.01065	0.00542	0.00365	10.089
1.0	0.00642	0.00254	0.00101	9.283
1.0	0.00619	0.00174	N/A	7.918
2.0	0.00546	0.00157	N/A	9.2299
4.0	0.00452	0.00128	N/A	8.214
8.0	0.0034	0.00102	N/A	8.2992

$$\rho = \frac{1}{\rho_0 + \rho_e T^{1/2}} - \rho_s \ln T + \rho_p T^5. \quad (3)$$

Here, the first term is considered together, and the second term may reflect the spin dependent scattering. The fitting results are well but do not like the one by using the Eq. (1). For the ρ_s, $\rho_s=0.004\,77$ for 0 T and $\rho_s=0.002\,41$ for 0.5 T, it decreases with the increase of field sharply. We have attempted to fit the data measured under the field of 8.0 T and also use Eq. (3), a good fitting is obtained, but the ρ_s is very small, about 1% of the data obtained from 0.5 T. This may indicate that the spin dependent scattering disappeared under 8.0 T which confirms our consideration. But for Eq. (3), we cannot distinguish the residual resistivity and the contribution from the e-e interaction.

Figures 3(a) and 3(b) and the fitted values of ρ_e and ρ_s reflect a consistency between the current experiments and Kondo's theory, i.e., the present electrical transport behavior show the presence of Kondo-like transport. This means the

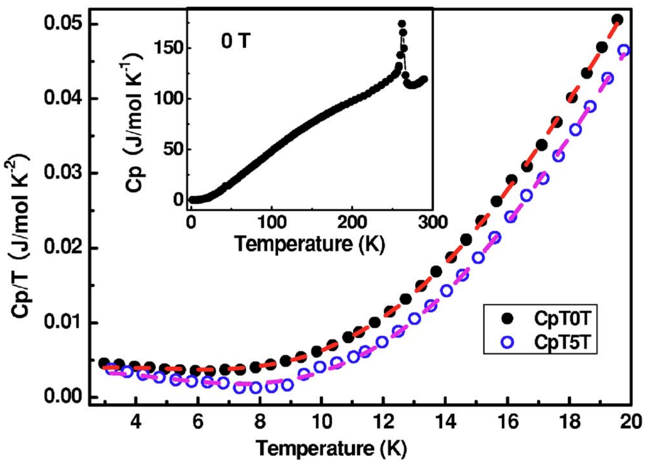

FIG. 4. (Color online) Low-temperature specific heat of the $La_{2/3}Ca_{1/3}MnO_3$ sample under a magnetic field of 5 T and zero fileld, the inset is the specific heat from the 3 K to 300 K in zero field.

possibility of the existence of new interaction between the electrons in strongly correlated manganites. It would be more important and to prove a possible existence of a new mechanism other than a simple e-e interaction in a conventional conductor. We should consider not only the Coulomb interaction between the electrons but also the spin dependent scattering.

C. The result of specific heat and e-e interaction

To make certain of our analysis above, we also performed specific heat measurement on the sample under applied field of 0.0 T and 5.0 T to obtain the electronic specific heat. Figure 4 shows the low-temperature (0–20 K) specific heat of the sample on an enlarged scale, plotted as C/T vs T. The inset is the specific heat of the sample from 3 K to 300 K without applied field. We cannot find out any abnormal changes of the specific heat at low temperatures corresponding to the resistivity abnormal. It means that the abnormal resistivity at low temperatures may be a second order phase transition. This also does not consist with the abnormal specific heat appearing in the Kondo effect. In order to get more insight into e-e interaction, we try to separate its contribution from the specific heat, the fittings are performed on each set of data using Eq. (4)

$$C = C_{elec} + C_{mag} + C_{latt} = \gamma T + \beta_{3/2}T^{3/2} + \beta_3 T^3 + \beta_5 T^5. \qquad (4)$$

Here, our measurement was performed above 3 K to avoid the hyperfine term,[25] the coefficients γ and $\beta_{3/2}$ result from the contribution of electron and ferromagnetic spin wave, respectively, β_3 and β_5 are from the lattice. Among these terms we only pay attention to the contribution from electronic specific heat, i.e., the γT term. In Fig. 4 the symbols are the experimental data and the lines are the fitting results. The best fittings are obtained with the parameters $\gamma_{0T} = 4.2$ mJ/mol K^2 for the 0 field and $\gamma_{5T} = 4.1$ mJ/mol K^2 for the field of 5 T. The linear term in the specific heat originates from the electron specific heat is related to the density of state at the Fermi surface $N(E_F)$

$$\gamma = \frac{\pi^2 k_B^2 N(E_F)}{3}. \qquad (5)$$

Using $\gamma_{0T} = 4.2$ mJ/mol K^2 yields a $N(E_F) = 3.05 \times 10^{22}/(\text{ev cm}^3)$ for 0 T which is comparable or, to some extent, consistent with the value $N(E_F) = 1.4 \times 10^{22}/(\text{ev cm}^3)$ determined from band-structure calculations for $La_{0.67}Ca_{0.33}MnO_3$.[26] It indicates that the applied field makes the $N(E_F)$ change a little, namely, the e-e interaction almost is not affected by the applied field, which also gives evidence for our aforementioned conclusion on the e-e interaction.

D. Spin polarization and grain boundary tunneling

After testifying the e-e interaction's contribution to the resistivity, in this work, our attention also focuses on the role of spin dependent scattering in the low-temperature electrical transport behavior. It is well known that the $La_{0.67}Ca_{0.33}MnO_3$ is ferromagnetic at low temperatures. In magnetic materials the ferromagnetic *s-d* exchange yields spin splitting ΔEs which is comparable or larger than the thermal energy or the Landau level splitting $\hbar\omega_c$ due to the external magnetic field. Thus, the conduction electron spins in these materials are polarized, which provides a flexible templet for the studies of spin polarized transport and tunneling.[27–29] There exists experimental evidence that the presence of grains and GB modifies drastically the type of temperature and magnetic field dependence of the resistivity $R(T,H)$ in ceramic manganites as compared to the single-crystalline samples.[30–32] Since the double exchange mechanism responsible for metallic conduction in the manganites depends sensitively on the Mn-O-Mn bond angle, structural disorder near the GB weakens the double exchange and leads to a strong increase in resistivity. Therefore, according to the aforementioned reasons that may cause the resistivity minimum, and the used sample in this paper is polycrystalline, we cannot help taking into account the contribution from GB. Namely, we need to assume that, in the discussed material, most of the grains are isolated from each other. In this model the tunneling between grains brings dominating contribution to the low-temperature conduction. The GB region acts as a barrier for spin-polarized tunneling between adjacent grains; in weak magnetic fields, the grains are aligned, leading to the observed large resistance drop. The tunneling process is generally inelastic proceeding via few Mn ions localized in the barrier.[33] In fact, the average grain size of our sample obtained by the SEM is about 5 μm, which is comparable with the experiments done by Balcells *et al.*[34] It indicates that the spin-polarized tunneling between GB barriers will affect the low-temperature resistivity of the system.

To clarify if the GB caused the $\ln T$ term under lower fields, we performed magnetic measurement on the sample. Figures 5(a) and 5(b) and the inset show the correlation between electrical transport and magnetic properties. The experimental results of the LFMR reported previously[35–41] show that the effect is very pronounced only at low temperatures and drops sharply with increasing temperature. Our experimental results show in Fig. 5(a) just accord with the con-

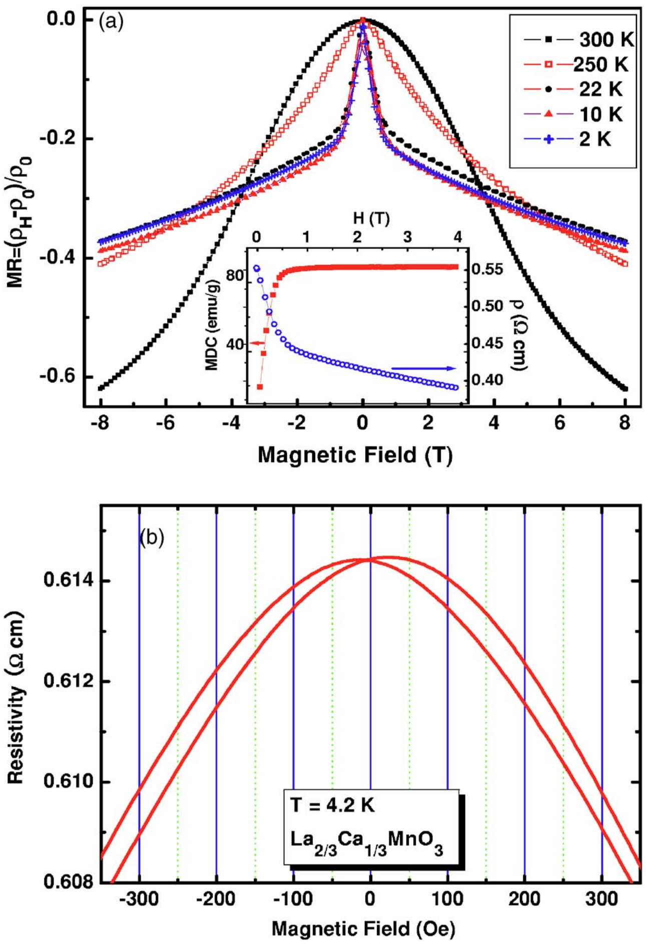

FIG. 5. (Color online) (a) MR vs magnetic field (−8 T-0-+8 T) curves at different temperatures (2 K, 10 K, 22 K, 250 K, and 300 K) for the $La_{2/3}Ca_{1/3}MnO_3$ sample. The inset is the dependence of resistivity and magnetization on the applied magnetic field at 2 K, below 4 T for $La_{2/3}Ca_{1/3}MnO_3$. (b) MR vs H curves at 4.2 K plotted on an enlarge scale for the case of low fields.

clusion that at low temperatures, the MR in the field below 1.0 T drops sharply with the increase of the applied field, which reflects the general behavior of the polycrystalline samples with a large LFMR, followed by a slower varying MR at a comparatively high field regime ($H > 1.0$ T), where MR is almost linear on the applied field. Figure 5(b) also gives the low field MR-H curve on an enlarged scale to illustrate the MR hysteretic for the GB effect. But the unconspicuous MR hysteretic, about 30 Oe at 4.2 K, may attribute to the average grain size of our sample is relatively larger compared with other group's samples.[34,37,39] The inset of Fig. 5 shows that M-H curve has typical magnetization characteristics as a general ferromagnetic system. Here, the magnetization increases abruptly below 0.6 T, accompanying an upturn between 0.4–0.6 T and then almost saturates above 1.0 T. The resistivity has a similar reverse change correspondingly, i.e., it sharply decreases below 0.6 T and then an upturn appears between 0.6 and 1.0 T. However, it is important to notice that instead of a saturate, a linear dependence on applied magnetic field above 1.0 T is observed in the electrical transport measurement. In fact, this linear dependence should be the reflection of MR effect in the manganites. The correlation between electrical transport and magnetic properties at lower applied field reflects the GB's contribution to the resistivity minimum at low temperatures. When the field is larger than 1.0 T, the magnetization is saturation and the GB's contribution to the resistivity minimum almost disappears. Such a behavior as closely correlating with the magnetization process via the ferromagnetic domain rotation is the characteristics of tunneling magnetoresistance (TMR) of spin-polarized carriers through the domain boundaries or the GB.[42] According to Wagenknecht,[43] the magnetotransport properties of any TMR element are affected by the magnetization of the ferromagnetic electrodes close to the barrier, and, in particular, by magnetic domain formation and domain wall motion during field switching. An applied field can align the spins of the magnetic domains to the field direction and induce deconfinement of the motion of the spin polarized carriers, then increase the tunneling of conduction electrons between the adjacent grains, namely, the field suppressing the GB barrier's contribution to the resistivity.

Therefore, all the data indicate that the observed resistivity abnormal behavior may arise from the GB effect. This would make the resistivity upturn weaken with increasing applied field, which results in $\Delta\rho$ decreases and T_{min} shifts to lower temperature. This is the reason why the temperature dependence of resistivity only have $T^{1/2}$ dependence and no Kondo's logarithmic term $\ln T$ for higher applied field, $H \geq 1.0$ T. Here, both the GB and the magnetic domain that caused the resistivity upturn can attribute to the weak spin disorder, which may be the intrinsic characteristics of polycrystalline ferromagnetic materials. Hence, we conclude that the resistivity minimum is partly due to the spin disorder GB tunneling because a magnetic field aligns the spins and increases the tunneling of the conduction electrons to reduce the resistivity at lower fields.

IV. CONCLUSION

The behavior of the resistivity minimum and its dependence on magnetic fields at low temperatures is systemically studied for the optimal doped $La_{2/3}Ca_{1/3}MnO_3$ polycrystal. The results show that the $\Delta\rho$ and T_{min} move rapidly to lower temperature with field increasing and then reachs low saturation when the field is higher than 1 T. Our results do not support that the T_{min} moves first to higher temperature at lower applied fields and then to lower temperature for high applied fields as in Ref. 13 and the resistivity upturn disappears at a certain field H_{cr} as in Ref. 21. The fittings are carried out using the phenomenological analysis, accompanying a disappearance of Kondo term; the electrical resistivity only follows $T^{1/2}$ dependence with a characteristics of enhanced e-e interactions in 3D disorder systems under higher field ($H > 1$ T). The e-e interaction is also supported by the specific-heat measurement. Under lower field, we cannot neglect the contribution from the GB which is the characteristics of the polycrystalline sample. Our results suggest the existence of Kondo-like transport in FM ground state.

The unique transport behavior in manganites at low temperatures can be understood taking account both e-e interaction and weak spin disorder scattering including the spin polarization and grain boundary tunneling. This kind of e-e interaction is a general characteristic and verifies the strong correlated interaction between electrons in manganites. Also, to thoroughly understand this behavior, more experiments on single crystal samples and theoretical works are needed.

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