Electron-doped high-$T_c$ cuprate superconductors have their own features in comparison with hole-doped ones, such as the $T^2$ dependence of the resistivity in the optimally and overdoped regions, the anomalous behavior of the Hall effect and magnetoresistivity, the two kinds of charge carriers, and so on.1–3 So transport measurements should be an effective way to address the important issues of the cuprate superconductors, such as the development of the Fermi surface,4,5 the existence of the pseudogap6 and the quantum critical point,7 etc. If such study can be done extensively, great progress will be achieved for the mechanism of high-$T_c$ superconductivity. During the past years, the concept of two kinds of charge carriers and related transport properties became an attractive topic for electron-doped superconductors. The angle-resolved photoemission spectroscopy experiment showed that in the electron-doped superconductor (Nd,Ce)$_2$CuO$_4$ (NCCO), the electron pocket centered at $(\pi, 0)$ and the holelike pocket centered at $(\pi, \pi)$ of the Brillouin zone successively formed when the Ce concentration was increased from underdoping to optimal doping.8 Other works, such as on the Nernst and Hall effects, were also reported about the two kinds of charge carriers.9,10 However, these experiments were mainly carried out on NCCO since the high-quality single crystals can be obtained. For the (La,Ce)$_2$CuO$_4$ system, which is a member of the electron-doped cuprate superconductor family, a few works about the transport properties were obtained from the thin films11–13 since no $T^2$-phase (the superconducting phase with single CuO$_2$ plane) single crystal can be grown.

To deeply explore the transport issue of (La,Ce)$_2$CuO$_4$, especially to distinguish the role of the electrons and holes in the transport (i.e., to understand the evolution of charge carriers in the transport), we carefully measured the Hall resistivity ($\rho_{xy}$) and longitudinal resistivity ($\rho_{xx}$) of the optimally doped (La,Ce)$_2$CuO$_4$ [i.e., the (001)-oriented La$_{1.89}$Ce$_{0.11}$CuO$_4$ (LCCO)] thin films when the temperature and magnetic field are varied. We find that both $\rho_{xy}$ and $\rho_{xx}$ are linear in $B^2$ in the temperature range of 40–50 K, which seems to show an indication of two kinds of charge carriers in LCCO. In addition, in the temperature range of 14–50 K, two sign reversals of the Hall resistivity occurs in the normal state with varying $T$ and under certain magnetic fields, which may also give an indication of the existence of two kinds of charge carriers. The sign reversal may be attributed to the competition between $\tau_e/\tau_h$ (the relaxation time ratio of electrons to holes) and the change of cyclotron orbits induced by the magnetic field.

The process of the film growth has been reported in detail in our previous work.15,16 The thickness of the LCCO thin films is ~120 nm, and the transition temperature $T_c$ is ~24 K. The thin films were patterned into the bridge with 2100 $\mu$m (length) $\times$ 100 $\mu$m (width) by photolithography and ion milling techniques. All the measurements were performed by the Quantum Design PPMS-14 equipment. ac source with amplitude of 0.1 mA and frequency of 333 Hz is used. In order to understand the evolution of effective electrons and holes in the normal state, the measuring temperature is selected to be in the range of 14–50 K, because the electrons are responsible for the transport above 50 K, and in the temperature range far lower than $T_c$, it is difficult to distinguish whether the sign reversal is due to the vortex motion or the evolution of effective electrons and holes. The magnetic field is selected to be high enough (up to 12 T) to drive the LCCO to be in the normal state below $T_c$. The measurements were performed in two ways: the temperature and magnetic-field ($B$) dependences of $\rho_{xy}$ and $\rho_{xx}$ with $B \perp ab$ plane, and the temperature and angular ($\theta$) dependences of $\rho_{xy}$ and $\rho_{xx}$, with $\theta$ the angle between $B$ and $ab$ plane. [A sketch is shown in the inset of Fig. 1(b).]

In Fig. 1(a), we show the contour map of $\rho_{xy}$ versus $B$ and $T$ for the case of $B \perp ab$ plane. In order to distinguish the mixed and normal states, the upper critical field $B_{c2}$, which is determined by the inflexion of $\rho_{xx}$ versus $B$ at different temperatures, is also marked by crosses. It can be clearly seen that the sign of $\rho_{xy}$ is positive in the temperature region of 15–29 K and magnetic fields of 0–5 T, the Hall coefficient anomaly; i.e., the sign reversal of $\rho_{xy}$ due to the dissipation...
In detail, the \( \rho_{xy} \) increases, and decreases after reaching a maximum value at \( \sim 3.5 \) T; a sign reversal of \( \rho_{xy} \) is clearly observed at the field \( \sim 9.3 \) T in the normal state. This fact obviously indicates that both electrons and holes contribute to the transport in the lower temperature region and that the electrons make more contribution to \( \rho_{xy} \) than the holes with increasing magnetic field. The field dependence of \( \rho_{xx} \) at 14 K is also shown in Fig. 1(c) and no obvious change can be found when the sign reversal occurs.

To understand the evolution of effective electrons and holes of LCCO thin films in the normal state at a relatively wide temperature region, we focus our measurements on the field angular dependence of \( \rho_{xy} \) and \( \rho_{xx} \) at \( T > T_c \). The \( \rho_{xy}(\theta) \) is shown in Fig. 2(a). With increasing \( T \) from 25 to 50 K, \( \rho_{xy} \) experiences a remarkable change. Under 10 T, from 25 to 30 K, the sign of \( \rho_{xy} \) remains positive while the magnitude is reduced by \( \sim 60\% \). With increasing angle, the \( \rho_{xy} \) gradually shows a tendency to be negative. When the temperature is increased to 40 K, the sign of \( \rho_{xy} \) changes to negative entirely, and the magnitude increases with increasing \( \theta \). At 50 K, the magnitude of \( \rho_{xy} \) is about two times larger than that at 40 K. Therefore it is obvious that in the temperature region from 25 to 50 K, there is a strong competition between effective holes and electrons. Especially, it is observed that the magnetic field can induce a dramatic change of the effective charge carrier in a small temperature region from 32 to 35 K. At magnetic field of 6 T, the \( \rho_{xx} \) of LCCO thin film shows a positive sign from 0° to 90° at 32 K. While in the same temperature range and at magnetic field of 12 T, the \( \rho_{xx} \) at 14 K in the case of \( B \perp ab \) plane. At 35 K and 12 T, the sign of \( \rho_{xx} \) becomes entirely negative as shown in Fig. 2(b). It is obvious that the larger field can change the sign of \( \rho_{xy} \), because a large \( \theta \) corresponds to a large field along the \( z \) axis, \( B = B \sin \theta \). In order to confirm the role of \( B \), on the sign and magnitude of \( \rho_{xy} \), we compare the \( \rho_{xy} \) \( \rho_{xx} \) to \( |B_z| \) under the cases of \(-90° -0°, 0°-90°, \) and \( \theta = 90° \) (the case of \( B \perp ab \) plane) at the same temperatures, and find that the same \( |B_z| \) has the same \( \rho_{xx} \) \( \rho_{xy} \). That is, the curves of \( \rho_{xy} \) \( \rho_{xx} \) versus \( |B_z| \) under these three cases overlap each other well. Typically, as shown in Figs. 2(c) and 2(d), the curves overlap well whenever we change the magnitude of \( |B_z| \) and the orientation \( \theta \) of \( B \) at 25 K \( |B_z| \) \( B \perp ab \) plane is also shown here. So we can draw the conclusion that in the present LCCO thin films, the \( \rho_{xx} \) and \( \rho_{xy} \) are just determined by \( |B_z| \), and the role of \( B (cos \theta \) on \( \rho_{xy} \) \( \rho_{xx} \) can be neglected at \( T > T_c \). This is reasonable because the LCCO thin films exhibit basically two-dimensional behavior, and the coupling between the \( CuO_2 \) layers is very weak,\(^15\) so the charge carriers are mainly in the \( CuO_2 \) plane. \( \rho_{xy} \) and \( \rho_{xx} \) are hardly affected by \( B_z \). On the other hand, for the optimally doped \( (La,Ce)_2CuO_4 \) thin films, no antiferromagnetic exchange in-

**FIG. 1.** (Color online) (a) The temperature and magnetic-field dependences of \( \rho_{xy} \) under the case of \( B \perp ab \) plane, with \( B \) from 0 to 5 T and \( T \) from 15 to 29 K. The gray scale represents \( \rho_{xy} \) from 0 to 0.24 \( \mu \Omega \) cm. The upper critical field \( B_{c2} \) is indicated by crosses. (b) \( \rho_{xy} \) versus \( B \) at 14 K also for \( B \perp ab \) plane. The arrow points to the upper critical field \( \sim 5.2 \) T. It is clear that in the normal state, the sign of \( \rho_{xy} \) is reversed from positive to negative with increasing \( B \rightarrow -9.3 \) T. Inset: a sketch of angular dependence measurement. (c) Corresponding \( \rho_{xx} \) versus \( B \) at 14 K.
The behavior of $\rho_{xy}$ and $\rho_{xx}$ with the case of 6 T at 32 K caused by the magnetic field. The curves of $B_z$ changes to negative, and the sign reversal occurs at 32 K and $B_z=9.6$ T. In comparison with the case of 6 T at 32 K (triangles), such sign reversal is clearly caused by the magnetic field. The curves of (c) $\rho_{xy}(B_z)$ at 25 and 32 K, and (d) $\rho_{xx}(B_z)$ at 25 K; they overlap very well under the following from cases of $\theta=90^\circ$ to 0°, from 0° to 90°, and $\theta=90^\circ$ (the case of $B \perp ab$ plane), which indicates that the $\rho_{xy}$ and $\rho_{xx}$ are dominated by $B_z$, and the effect of $B_x$ can be neglected.

In order to definitely know if both the electrons and holes contribute to the transport in LCCO, we plot the $\rho_{xy}$ versus $B_z^2$ in Fig. 3(a). It is obvious that when the applied field is larger than a certain value and the temperature is in the range of 40–50 K, the $\rho_{xy}$ shows a linear relationship with $B_z^2$. $\rho_{xx}$ also shows the same field dependence in this temperature region (not shown here), similar to the $\rho_{xx}$ behavior in Nd$_{1.85}$Ce$_{0.15}$CuO$_4$.

The behavior of $\rho_{xy}$ and $\rho_{xx}$ is proportional to $B_z^2$ looks like the feature of a compensated metal, in which nearly equal effective concentrations of holes ($n^*_h$) and electrons ($n^*_e$) in LCCO is suggested. This is a further evidence that both electrons and holes contribute to the transport in LCCO at lower temperature. While at higher temperature (>50 K), only the electrons play a dominant role in the transport. Then we may map the evolution of the role of electrons and holes in the transport in the present LCCO thin films. Above 50 K, the electrons are the dominant charge carriers in the transport. From 50 to 40 K, the electrons and holes that contribute to the transport are nearly equal, i.e., $n^*_h=n^*_e$, in the larger field region. From 35 K to near $T_c$, $n^*_h/n^*_e$ likely increases rapidly with decreasing $T$, and holes are the dominant carriers in the transport, while a large field can enhance the contribution of electrons to Hall resistivity and lead to a sign reversal occurring at 32 K ($\theta \sim 51^\circ$, and $B \sin \theta \sim 9.6$ T). When the temperature is decreased further, the larger field and lower $T$ induce a relatively large contribution of electrons to Hall resistivity again; that is, the sign reversal from positive to negative occurs at 14 K and 9.3 T. In order to conclude the evolution of the role of electrons and holes in transport with temperature, the temperature dependence of $\rho_{xy}$ is plotted in the fixed magnetic fields as shown.
in Fig. 3(b). It is obvious that the high field (~10 T) induces two sign reversals of \( \rho_{xy} \) at 14 K and ~32 K.

Now, we make a discussion on the possible origin of the sign reversal of \( \rho_{xy} \). Owing to the two kinds of charge carriers, we can express the \( \rho_{xy} \) using the two-band model,\(^{21,22} \)

\[
\rho_{xy} = \frac{A_e \gamma_e + A_h \gamma_h}{(A_e + A_h)\gamma_e^2 + (A_e \gamma_e + A_h \gamma_h)^2},
\]

with

\[
A_i = \sigma_i (1 + \gamma_i^2),
\]

where \( \sigma_i \) is the conductance of \( i \)-th band; the subscripts \( e \) and \( h \) represent electron and hole, respectively; and \( \gamma_i = \omega_i \tau_i \), with \( \omega_i \) and \( \tau_i \) the cyclotron frequency and average relaxation time, respectively. Obviously, the sign reversal occurs under the condition \( A_e \gamma_e + A_h \gamma_h = 0 \) \((\rho_{xy} = 0)\), i.e.,

\[
\frac{n_{eh}^* \tau_e \omega_e}{m_e (1 + \omega_e \tau_e^2)} = \frac{n_{eh}^* \tau_h \omega_h}{m_h (1 + \omega_h \tau_h^2)}.
\]

For \( \omega \tau \ll 1 \), the above equation can be simplified as

\[
n_{eh}^* \tau_e \omega_e / m_e = n_{eh}^* \tau_h \omega_h / m_h.
\]

Note that \( \omega_e = eB/m_e c, \omega_h / \omega_b \approx m_h / m_e \); if we assume that \( m_h / m_e \) (the ratio of cyclotron masses) is constant when \( T \) and \( B \) are varied, then the sign reversal should be associated with \( \tau_e / \tau_h \) and \( n_{eh}^* / n_{eh} \). If these ratios increase, the sign of \( \rho_{xy} \) trends toward positive, or else it trends toward negative. In fact, these two terms may not increase (or decrease) simultaneously, so sign reversal can occur naturally. At 32 K, the sign is positive at lower field and negative at higher field. One possible way to interpret the sign reversal with increasing \( B \) is that the cyclotron orbits of charge carriers can be divided into open and closed ones; for the latter, due to the intersection of the Fermi surface and the Brillouin zone, it can behave as either electron- or hole-like orbits,\(^{19} \) so the sign lies in the closed orbits. At lower field, the relatively lower value of \( \omega_e \) results in the case that a large number of cyclotron orbits behave as open ones; larger \( n_{eh}^* / n_{eh} \) makes the sign positive. On the other hand, a high field results in the suppression of the open cyclotron orbits, the \( \omega_e \) will be increased higher than \( \omega_h \) and relatively more open orbits change into the \( n \)-type closed orbits; that is, increasing \( B \) corresponds to increasing the effective concentration ratio of electrons to holes \( (n_{eh}^* / n_{eh}^*) \), and so the sign reversal of \( \rho_{xy} \), from positive to negative occurs. If \( T \) is decreased, \( n_{eh}^* / n_{eh} \) increases,\(^{3,14} \) and the holes become the dominant charge carriers in the transport. We should also note that when decreasing \( T, \tau_e / \tau_h \) is reduced. This is because the scattering in a \( n \)-type band is stronger than that in a \( p \)-type band at high temperature; when the temperature is reduced, the umklapp processes for a \( n \)-type band tends to be “frozen out,” so \( \tau_e \) in a \( n \)-type band is increased\(^{22} \) and \( \tau_e / \tau_h \) is reduced. From \( \tau_e = \Theta(K, K') (1 - \cos \eta) dK'/2p \eta \) \((\eta \) is the scattering angle),\(^2^{23} \) we know that decreasing \( T \) can reduce the large-angle scattering, so the integral is reduced and \( \tau_e \) increases. Experimentally, in the temperature region near \( T_c \), the sign reversal of \( \rho_{xy} \) from negative to positive usually occurs. It seems that \( n_{eh}^* / n_{eh} \) increases more quickly than \( (\tau_e / \tau_h)^2 \) with decreasing \( T \), so holes become the dominant carriers in the transport in this region. However, when \( T \) is decreased further, \( (\tau_e / \tau_h)^2 \) increases more steeply than \( n_{eh}^* / n_{eh} \), then a larger field may cause the sign reversal again (such as the case at 14 K and at 9.3 T). Therefore, we assume \( \tau_e / \tau_h \approx 1/T \) \((\tau_e \approx 1/T^2, \) Refs. 2 and 24\), and \( n_{eh}^* / n_{eh} \approx B^{-\alpha} T^{-\beta} \), with \( \alpha \) and \( \beta \) the positive constants in the low-temperature region.\(^{10} \) Then a schematic map of the sign of \( \rho_{xy} \) versus \( B \) and \( T \) (+ and − regions represent positive and negative, respectively) is shown in Fig. 4 (color online). The circles mark the two sign reversals we observed. It is obvious that through the + region, sign reversal due to the evolution of the two kinds of charge carriers occurs. The upper critical field is also plotted (triangles).

For the \( \Sigma\)-type band at high temperature; when the temperature \( T \) increases. Experimentally, in the temperature region near \( T_c \), the sign reversal of \( \rho_{xy} \) from negative to positive occurs. If \( T \) is decreased, \( n_{eh}^* / n_{eh} \) increases,\(^{3,14} \) and the holes become the dominant charge carriers in the transport. We should also note that when decreasing \( T, \tau_e / \tau_h \) is reduced. This is because the scattering in a \( n \)-type band is stronger than that in a \( p \)-type band at high temperature; when the temperature is reduced, the umklapp processes for a \( n \)-type band tends to be “frozen out,” so \( \tau_e \) in a \( n \)-type band is increased\(^{22} \) and \( \tau_e / \tau_h \) is reduced. From \( \tau_e = \Theta(K, K') (1 - \cos \eta) dK'/2p \eta \) \((\eta \) is the scattering angle),\(^2^{23} \) we know that decreasing \( T \) can reduce the large-angle scattering, so the integral is reduced and \( \tau_e \) increases. Experimentally, in the temperature region near \( T_c \), the sign reversal of \( \rho_{xy} \) from negative to positive usually occurs. It seems that \( n_{eh}^* / n_{eh} \) increases more quickly than \( (\tau_e / \tau_h)^2 \) with decreasing \( T \), so holes become the dominant carriers in the transport in this region. However, when \( T \) is decreased further, \( (\tau_e / \tau_h)^2 \) increases more steeply than \( n_{eh}^* / n_{eh} \), then a larger field may cause the sign reversal again (such as the case at 14 K and at 9.3 T). Therefore, we assume \( \tau_e / \tau_h \approx 1/T \) \((\tau_e \approx 1/T^2, \) Refs. 2 and 24\), and \( n_{eh}^* / n_{eh} \approx B^{-\alpha} T^{-\beta} \), with \( \alpha \) and \( \beta \) the positive constants in the low-temperature region.\(^{10} \) Then a schematic map of the sign of \( \rho_{xy} \) versus \( B \) and \( T \) can be made as shown in Fig. 4. By the way, it should be emphasized that we cannot tell which kind(s) of charge carriers is essential to superconductivity merely from the Hall measurements, because both the two kinds of charge carriers contribute to the transport at low \( T \). In order to get a definite decision, further investigations on electron-doped cuprate superconductors are required.\(^{16} \)

In summary, to reveal the evolution of the role of electrons and holes in the transport in LCCO, we carefully measured the temperature, field, and angular dependences of Hall resistivity and longitudinal resistivity, and find evidence of two kinds of charge carriers \((\rho_{xy}, \rho_{xx} \sim B^2)\). In the normal state, two sign reversals of the Hall resistivity occurs with varying \( T \) for a certain magnetic-field region, which may be attributed to the strong competition between \( \tau_e / \tau_h \) and \( n_{eh}^* / n_{eh} \) in the temperature range of 14–50 K. The possible reason of sign reversal by tuning the field is attributed to the change of cyclotron orbits of the charge carriers, and the sign reversal against \((B, T)\) is concluded in Fig. 4.

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EVOLUTION OF CHARGE CARRIERS FOR TRANSPORT IN

25. Y. Ando et al. [Y. Ando, Y. Kurita, S. Komiya, S. Ono, and K. Segawa, Phys. Rev. Lett. 92, 197001 (2004)], have reported that in slightly doped YBa2Cu3O7−x and La2−xSrxCuO4, in-plane resistivity ρ changes as ~T^2. If \( \sigma = ne^2/2m^* \) we may get \( n_e \propto 1/T \). \( n_e/n_h \times B^{1/2} \) is obtained from the experimental data, which is still puzzling and not shown here. We mention that though all the assumptions may be simplified, the sign reversal due to changing \( T \) and \( B \) is convinced.