Hall coefficient of $La_{1.88-y}Y_ySr_{0.12}CuO_4$ ($y=0,0.04$) at low temperatures under high magnetic fields

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The Hall coefficient in the low-temperature tetragonal phase and the midtemperature orthorhombic phase of $La_{1.88-y}Y_ySr_{0.12}CuO_4$ ($y=0,0.04$) single crystals is measured under high magnetic fields up to 9 T in order to investigate the detailed behavior of the transport properties at low temperatures in the stripe phase. When the superconductivity is suppressed by high magnetic fields, the Hall coefficient has negative values in low temperatures, and the temperature region of the negative values spreads as increasing magnetic fields. This result indicates that the Hall coefficient in the stripe phase around $x=0.12$ is a finite negative value, not zero.

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Curious properties associated with the "1/8 probrem" have been investigated over the last decade and yet this is one of the centers of wide interest in high-T_c superconductors. Let us begin this paper by reviewing something rather old. $La_{2-x}Ba_xCuO_4$ (LBCO) and $La_{2-x}Sr_xCuO_4$ (LSCO) show the local minimum of T_c around $x\sim0.12$.[1,2] It has been predicted that the disappearance in LBCO or suppression in LSCO of the superconductivity is correlated with a structural change:the structural phase transition from the midtemperature orthorhombic phase (OMT, the space group $Bmab$) to the low-temperature tetragonal phase (TLT, the space group $P4_2/ncm$) in LBCO and the precursor of the transition in LSCO around $x=0.12$.[3,4] This prediction is verified by analysis of the crystal structure in the rare-earth-doped LSCO system, which undergoes a structural phase transition to the TLT phase.[5–7] In addition to the disappearance or suppression of the superconductivity, two related phenomena appear in these system. One is magnetic order,[8,9] and the second is anomalous changes of transport properties, such as the Hall coefficient and the thermoelectric power.[10,11] It is suggested that the suppression of the superconductivity around $x=0.12$ will be related to not only the crystal structure but also changes in the magnetic and electronic states.

The recent development of this problem is followed from the "stripe model."[12–14] According to this model, long-range-modulated charge and spin ordering is stabilized in the TLT phase. Afterwards, magnetic superlattice peaks are observed by neutron diffraction in the orthorhombic superconducting phase $La_{1.88}Sr_{0.12}CuO_4$ single crystal, while no peaks associated with charge ordering have been observed.[15–17] Notwithstanding no signal of the charge ordering by the scattering technique, the magnetic order affects the character of the superconductivity in LSCO around $x=0.12$.[18] Therefore, a change in electronic states must appear more or less in the case of the orthorhombic phase. It is necessary for a full understanding of this problem to discuss changes in the electronic state and in the crystal structure by investigating the detailed behavior of the transport properties of the so-called stripe phase in the TLT phase and of the magnetically ordered state in the OMT phase. More recently, Noda *et al.* reported the temperature dependence of the Hall coefficient in the stripe phase $La_{2-x-y}Nd_ySr_xCuO_4$.[21] However, the detailed behavior of the Hall coefficient at low temperature below 25 K is unknown yet. In this paper, we report the experimental results of the temperature dependence of the Hall coefficient at low temperatures and under high magnetic fields in the TLT and OMT phases.

The samples used in this work, $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$ (LYSCO) and $La_{1.88}Sr_{0.12}CuO_4$ (LSCO), are single crystals grown by the traveling-solvent-floating-zone (TSFZ) method under oxygen atmosphere. The resistivity and Hall coefficient are measured by the usual four-probe dc method. Six probes are put on one sample and the Hall coefficient and the resistivity are measured simultaneously. Current and magnetic field are reversed in each temperature to eliminate thermoelectric voltage of lines and resistive voltage between Hall probes. The typical size of the measured samples is $\sim0.25\times1\times3$ mm^3. The direction of the current (20 mA) is parallel to the CuO_2 plane and magnetic fields are applied perpendicular to the CuO_2 plane. Neutron scattering measurement in LYSCO is carried out using the KSD double-axis spectrometer installed in the JRR-3M Guide Hall at the JAERI in Tokai, Japan. The incident neutron beam has a wavelength of 1.53 Å, obtained using a PG(002) monochromator. The horizontal divergence of incident neutron beam is 12′ and the acceptance angle of scattered beam is 30′. The sound velocity V_s is measured by the phase comparison method with the $\sim$12 MHz longitudinal waves generated by the PZT transducer. All measurements of the temperature dependence under magnetic fields in this study were carried out with increasing temperature after field cooling from 80 K in each time.

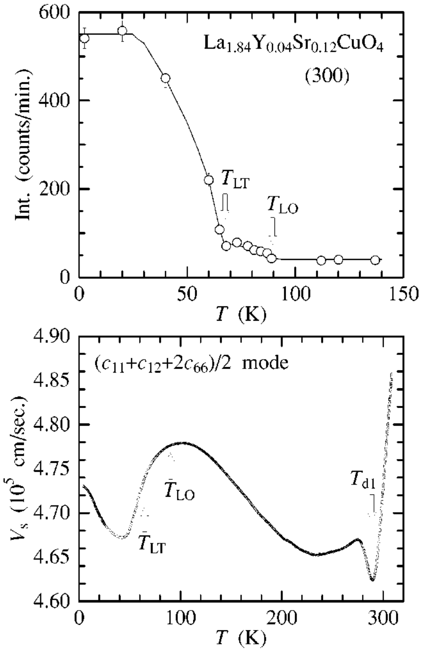

FIG. 1. Top: the temperature dependence of the neutron scattering intensity at the (300) position in tetragonal notation. The solid line is a guide for the eyes. Bottom: the temperature dependence of the longitudinal sound velocity of $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$. Open arrows in figures indicate structural phase transition temperatures. The temperature T_{d1} is the structural phase transition temperature from the high-temperature tetragonal phase to the midtemperature orthorhombic (OMT) phase.

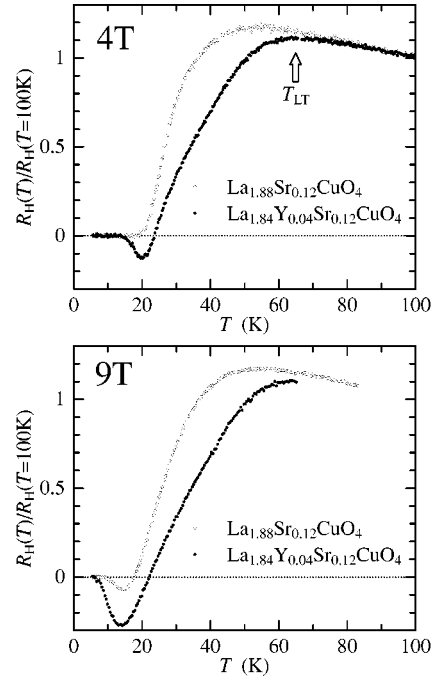

FIG. 2. The temperature dependence of the Hall coefficient of $La_{1.88-y}Y_ySr_{0.12}CuO_4$ ($y=0$: open circles, $y=0.04$: solid circles) in 4 and 9 T. The arrow in the figure indicates the structural phase transition temperature to the TLT phase in the case of $y=0.04$.

The dc magnetization measurement is carried out in the two samples by a superconducting quantum interference device (SQUID) magnetometer. A sharp superconducting transition is observed in both compounds, and the transition temperature T_c is 17 K in LYSCO and 27 K in LSCO, respectively.

The upper panel of Fig. 1 shows the temperature dependence of the neutron scattering intensity at (300) position of $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$. The index is defined as the notation in the tetragonal ($I4/mmm$). The solid line is a guide for the eyes. As decreasing temperature, the intensity begins to increases slightly at 90 K and shows a rapid increase at 65 K. Comparing with results of the structural analysis in a similar rare-earth-doped LSCO system,[5,6] two structural phase transition temperatures are determined as $T_{LO}=90$ K and $T_{LT}=65$ K in $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$. T_{LO} is the structural phase transition temperature to the low-temperature orthorhombic (OLT) phase, and T_{LT} is that to the TLT phase. The lower panel in Fig. 1 shows the temperature dependence of the longitudinal sound velocity V_s corresponding to $(c_{11}+c_{12}+2c_{66})/2$ mode in $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$. On cooling, V_s begins to decrease at 90 K and increases below 40 K. This type of change in V_s is the typical behavior around T_{LT}.[7,22] The large change of V_s suggests that the structural phase transition occurs in the bulk of this sample.

Elastic magnetic incommensurate peaks are comfirmed at 2.1 K in LYSCO. In the two samples which undergo the structural phase transition to the TLT phase, such as $La_{2-x-y}Nd_ySr_xCuO_4$ (Refs. 12–14 and 19) and $La_{1.875-x-y}Ba_xSr_yCuO_4$ (Ref. 20), the existence of magnetic and charge peaks are comfirmed by the elastic neutron scattering. It is expected that the stripe phase appears in LYSCO at low temperatures.[23]

Figure 2 shows the temperature dependence of the Hall coefficient R_H of LYSCO and LSCO. For comparison between the two compounds, R_H is normalized by the value at 100 K, which is 0.0055 cm^3/C in LYSCO and 0.0052 cm^3/C in LSCO. The arrow in Fig. 2 indicates the structural phase transition temperature T_{LT} of $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$. As decreasing temperature in 4 T, R_H of LYSCO shows the drastic decrease below the vicinity of T_{LT} and sign reversal occurs in the low-temperature region from 25 to 15 K. In orthorhombic LSCO, only a gradual decrease in R_H is observed below 50 K which is far above $T_c=27$ K, but no sign reversal is detected. These experimental results seem to be commonplace, since the anomalous change of R_H is observed in the TLT phase but not in the OMT phase and R_H in the TLT phase goes to zero at low temperatures as expected in the simplified stripe model.[21] In 9 T, however, the sign reversal of R_H in low temperatures is enhanced. In LYSCO, the temperature range where the sign is negative spreads and the absolute value at minimum point becomes larger, though the temperature where R_H begins to fall is not changed in 9 T. Surprisingly, in orthorhombic LSCO, sign reversal does appear below 20 K though no change of the sign is observed in 4 T.

The discontinuous change of R_H at T_{LT}, which is observed in $La_{2-x-y}Nd_ySr_xCuO_4$ for $x<1/8$,[11,21] does not appear in LYSCO. It seems that the broadeness of the structural phase transition vignettes the discontinuity in R_H at T_{LT}.

Figure 3 shows the temperature dependence of R_H and the

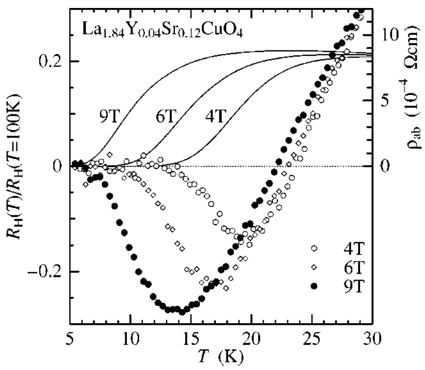

FIG. 3. The temperature dependence of the Hall coefficient and the resistivity of $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$ in 4, 6, and 9 T. Marks and solid lines denote the Hall coefficient and the resistivity, respectively.

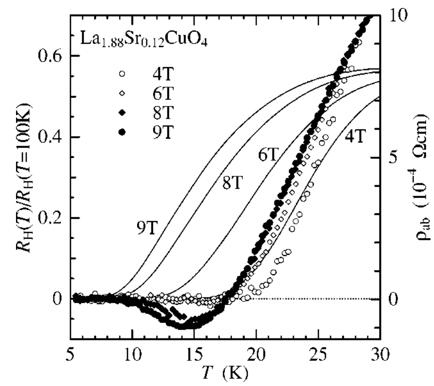

FIG. 4. The temperature dependence of the Hall coefficient and the resistivity of $La_{1.88}Sr_{0.12}CuO_4$ in 4, 6, 8, and 9 T. Marks and solid lines denote the Hall coefficient and the resistivity, respectively.

resistivity ρ_{ab} of LYSCO in 4, 6, and 9 T. The anomalous change of R_H becomes more significant as the superconducting transition temperature is reduced by magnetic fields. With decreasing temperature, R_H changes its sign and goes to zero along a curve similar to the temperature dependence of ρ_{ab}. Quantitatively, the temperature where $d\rho_{ab}/dT$ becomes maximum coincides with that of $-dR_H/dT$ in each magnetic field. Therefore, the reason that R_H goes to zero from the negative side at low temperature is the superconductivity, and the real behavior of R_H is concealed by zero resistivity. We conclude that the Hall coefficient in the ground state of the stripe phase of $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$ has a finite negative value when the superconductivity is suppressed by magnetic fields. A similar temperature and magnetic field dependence of R_H is reported in $La_{2-x}Ba_xCuO_4$ ($x=0.11$) single crystal which undergoes a structural phase transition to the TLT phase.[24]

Our measurement results are consistent with the new theoretical calculation by Prelovšek *et al.*[25] They reported a numerical calculation within the *t-J* model and conclude that $R_H<0$ for $x<1/8$ and $R_H\sim 0$ for $x=1/8$ at $T=0$ in the stripe phase.

Here, we touch upon the recent report on measurements of R_H in $La_{2-x-y}Nd_ySr_xCuO_4$.[21] They insist that R_H goes to zero at low temperature in the stripe phase of $x=0.12$ and that the charge transport is one dimensional, but their measurement is stopped at 25 at which R_H changes its sign in LYSCO (Fig. 3). Measurements below 25 K under high magnetic fields should be carried out in order to discuss the behavior in the ground state of the stripe phase.

Figure 4 shows the temperature dependence of the Hall coefficient and the resistivity of $La_{1.88}Sr_{0.12}CuO_4$ in various magnetic fields. Sign reversal occurs in magnetic fields above 8 T. By analogy with the discussion in the case of LYSCO, it is in consequence of the suppression of the superconductivity by magnetic fields. This result indicates that, also in the orthorhombic phase, R_H has a negative value at low temperatures in the hole concentration of $x\sim 0.12$.

One thing which we would like to mention is that the origin of the negative R_H is by no means the contribution of vortex dynamics. The reason is as follows: (a) In high-T_c cuprates, sign reversal of R_H in the vortex states tends to vanish with increasing magnetic fields.[26,27] The data in this study are contrary to this tendency. (b) With decreasing temperature, R_H begins to decrease at the vicinity of T_{LT} in LYSCO or at ~ 50 K in LSCO rather than T_c, and changes its sign continuously in each magnetic field. (c) In LYSCO, the sign reversal of R_H occurs above T_c in zero field. (d) In polycrystalline samples of LYSCO, this anomaly is significant around $x=0.115$.[28] Therefore, we conclude that the sign reversal observed in this study is an intrinsic phenomenon in the stripe phase.

At last, we discuss the temperature dependence of the thermoelectric power, which shows a similar temperature dependence.[10,11] From the fact that the anomalous change of the Hall coefficient and of the thermoelectric power is the most significant around the hole concentration of $x=0.12$, the origin of this anomalous change will be the same electronic state appearing below T_{LT}. Therefore, the thermoelectric power will show an enhancement of this anomaly in high magnetic fields.

In summary, the Hall coefficient of $La_{1.84}Y_{0.04}Sr_{0.12}CuO_4$ and $La_{1.88}Sr_{0.12}CuO_4$ is measured in high magnetic fields up to 9 T. In the low-temperature tetragonal phase, with decreasing temperature, the Hall coefficient decreases and changes its sign at low temperatures. In the orthorhombic $La_{1.88}Sr_{0.12}CuO_4$, a sign reversal of the Hall coefficient appears under high magnetic fields above 8 T. The anomalous behavior of the Hall coefficient, which is the sign reversal, is enhanced under the condition that the superconductivity is suppressed by magnetic fields applied to a direction perpendicular to the CuO_2 plane. Therefore, the Hall coefficient has a finite negative value in the ground state of the stripe phase.

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