Resistivity, Hall effect, Nernst effect, and thermopower in the mixed state of $La_{1.85}Sr_{0.15}CuO_4$

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Measurements of the resistivity, Hall effect, Nernst effect, and thermopower in the normal and in the mixed state of $La_{1.85}Sr_{0.15}CuO_4$ for magnetic fields between 0 and 7 T and temperatures between 20 and 300 K are reported. In the normal state the resistivity shows a linear temperature dependence, while thermopower and Hall effect are only weakly temperature dependent. The Nernst effect in the normal state is about two orders of magnitude smaller than in the mixed state and of opposite sign, with a sign change occurring at about 60 K. Resistivity and thermopower show a strong broadening of the superconducting transition in a magnetic field. The Hall coefficient is positive, i.e., there is no sign change near T_c in the mixed state in the whole temperature and magnetic-field range examined.

I. INTRODUCTION

The thermomagnetic and galvanomagnetic transport phenomena in the mixed state of the high-temperature superconductors (HTSC's) have attracted considerable interest in the last few years. One of the reasons is that these effects can be studied experimentally in a rather wide range of temperatures and magnetic fields above the irreversibility or melting line, where the pinning of flux lines is weak or absent.

In this paper we present a study of the resistivity, the Hall effect, the Nernst effect, and the thermopower in the mixed state of $La_{1.85}Sr_{0.15}CuO_4$ (LSCO). Whereas in $YBa_2Cu_3O_x$ (YBCO) and in the Bi- and Tl-based HTSC's these effects have been studied in detail (see, e.g., Refs. 1–3) in La-Sr-Cu-O to our knowledge some of these transport properties have not been measured up to now. On the other hand, a study of LSCO can yield important information. It is well known that the transport properties in the mixed state have at least in part to be attributed to the response of normal quasiparticles to the electric field set up by the vortex motion. In YBCO and the Bi- and Tl-based superconductors this response possibly includes that of "normal" subsystems like the CuO chains in YBCO or the BiO layers in the Bi systems. In contrast, such normal subsystems are not present in LSCO and therefore the transport properties in this material have to be attributed entirely to those of the CuO_2 planes.

II. EXPERIMENTAL

The preparation of granular bulk samples of $La_{1.85}Sr_{0.15}CuO_4$ as well as a study of the structural and magnetic properties and of the specific heat have been described in detail in Ref. 4. The sample used in this study shows a sharp resistive transition in zero field ($\Delta T_c \approx 1.4$ K) with zero resistance at $T_{c0}=36$ K.

Measurements of the Hall effect and the magnetoresistivity as a function of temperature and magnetic field have been carried out using standard experimental techniques described elsewhere.[5,6]

The Nernst coefficient Q was measured as a function of the magnetic field (swept at about 0.3 T/min) at fixed temperatures stabilized within about 0.1 K with an imposed temperature gradient of about 1.3 K in the mixed state and of about 5–7 K in the normal state. The temperature gradient, built up by a small manganin heater using a constant heating current, was measured with a AuFe-Chromel thermocouple mounted to the ends of the sample. The thermopower S was measured as a function of temperature at constant magnetic fields with a temperature drift of about 0.5–1 K/min.

The thermomagnetic voltages were measured using calibrated Cu wires with an accuracy of about 50 nV. The zero-field voltages for temperatures $T<T_{c0}$ (where the thermopower of LSCO is zero) revealed the thermopower of Cu, S_{Cu}, within a few percent. The magnetic-field dependence of S_{Cu} was neglected when calculating the absolute thermopower of LSCO [$S(B,T)=(\Delta U(B,T)/\Delta T)+S_{Cu}(T)$]. For magnetic fields $B<4T$ this leads only to a minor inaccuracy; however, for $B>4T$ and for temperatures between 15 and 25 K the error in the absolute magnitude of S is of order $1 \mu V/K$, as is visible in Fig. 6.

We mention that the sample temperature for the thermomagnetic effects corresponds to the mean value of the temperatures at the hot and cold end of the sample. A more detailed description of the experimental setup is given in Ref. 7.

III. RESULTS AND DISCUSSION

A. Resistivity

The value of the resistivity at 150 K is 1.6 mΩ cm, which is in good agreement with Ref. 8 and somewhat larger than reported in Refs. 9 and 10. The resistivity is linear in temperature between about 50 and 180 K (see inset of Fig. 1). Below 60 K the resistivity decreases faster with decreasing temperature, probably due to superconducting fluctuations.

As commonly observed for the HTSC's the resistive

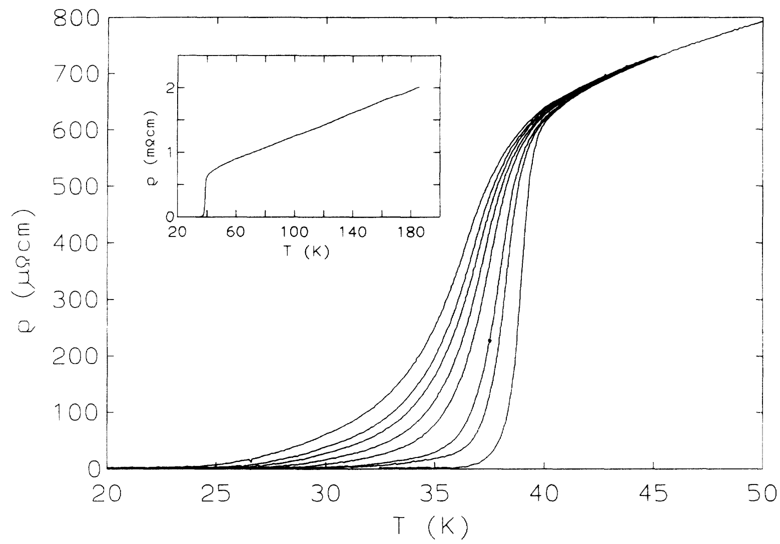

FIG. 1. Resistivity ρ as a function of temperature between 20 and 50 K for various fixed magnetic fields $B=0$, 0.5, 1, 2, 3, 4, 5, and 7 T (from right to left). The inset shows the resistivity at $B=0$ T.

transition broadens strongly in a magnetic field (Fig. 1). We observe a relative broadening of $\Delta T_c/T_c \approx 30-40\,\%$ at $B=5$ T. Note that the resistivity of a polycrystal reflects the behavior of the in-plane resistivity ρ_{ab} of a single crystal with B perpendicular to the planes (parallel to the c axis). In this configuration the relative broadening $\Delta T_c/T_c$ of the resistive transition at $B=5$ T is about 30–40 % (Ref. 11) in LSCO single crystals, in good agreement with our results. $\Delta T_c/T_c$ in LSCO is much larger than in YBCO [$\Delta T_c/T_c \approx 10\%$ at $B=5$ T (Ref. 12)] and less than in the BiSrCaCuO (BSCCO) superconductors ($\Delta T_c/T_c \approx 60\%$ at $B=5$ T).[1] This reflects the anisotropy of the material: The weaker the coupling between the CuO layers, the larger is the broadening of the transition. While BSCCO has an anisotropy factor of $\Gamma=\sqrt{m_c/m_{ab}} \approx 50-100$, LSCO is less anisotropic with $\Gamma \approx 25-30$.[11] In YBCO Γ is of order 7.[13]

We note that an Arrhenius plot of the resistivity yields a thermally activated behavior[14] with activation energies of 360 K at 7 T up to 540 K at 1 T in a temperature range of $\Delta T \approx 2.5-3$ K in the lowest part of the resistive transition.

B. Hall effect

The normal-state Hall coefficient has a value of $(2.5-3)\times 10^{-9}$ m^3/C between 40 and 80 K and decreases weakly with increasing temperature. With $R_H = 1/ne$ this yields a hole concentration of $(2.1-2.5)\times 10^{21}$ cm^{-3}. This is in good agreement with literature data.[10,15] The Hall coefficient R_H (Fig. 2) is positive and field independent in the normal state well above T_c. Below about 30 K, R_H vanishes within the limits of our experimental resolution. At low magnetic fields we find a rapid decrease of R_H with decreasing temperatures near T_c. With increasing magnetic field the transition broadens strongly in a fashion reminiscent of the broadening of the resistive transition.

The qualitative behavior of the tangent of the Hall angle is in agreement with the predictions of the Bardeen-

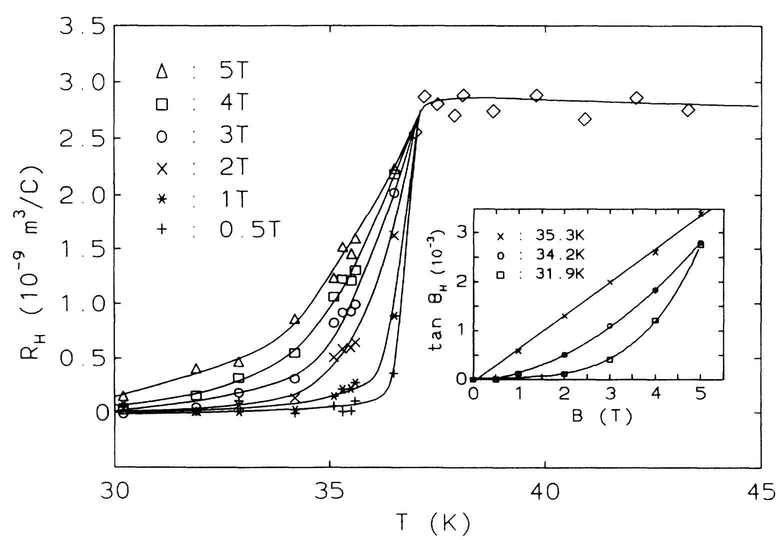

FIG. 2. Hall coefficient R_H as a function of temperature between 30 and 45 K for various fixed magnetic fields. The symbol ◊ shows the magnetic-field-independent Hall coefficient. The inset shows the tangent of the Hall angle as function of the magnetic field for various fixed temperatures below T_c (see text). The solid lines are guides to the eye.

Stephen model[16] close to T_c (inset of Fig. 2): At the highest temperature shown $\tan\Theta_H$ varies linearly with the magnetic field. However, at lower temperatures $\tan\Theta_H$ shows a stronger field dependence.

The Hall coefficient stays positive in the whole temperature and field range. This result has been reproduced on other $La_{1.85}Sr_{0.15}CuO_4$ samples. We can not exclude the existence of a negative Hall coefficient for magnetic fields $B \leq 0.5$ T, because of the limited resolution of our measurements ($\Delta\rho_H \approx \pm 0.4 \times 10^{-9}$ Ωm) and the smallness of the effect for small magnetic fields. However, apparently the Hall coefficient behaves rather differently compared to that of the other HTSC's. There a negative R_H exists up to values of the magnetic field of ≈ 5 T or even in higher fields[5,6,17–20] and the negative peak of R_H close to T_c has an absolute value larger than R_H in the normal state.

There have been various attempts to explain the sign change of the Hall effect near T_c observed in YBCO and the Bi and Tl-based superconductors. One possible way is to describe the Hall effect within a two-band model.[21] Some modifications to the transport equations are suggested by Hagen *et al.*[22] and Wang and Ting.[23] However, there is no parameter in these models which can be regarded as specific to LSCO, i.e., it is unclear why a sign change of R_H should be absent in this system in constrast to the other HTSC's.

Recently it has been proposed that the interaction between drifting thermally excited quasiparticles with the vortices via Andreev reflection gives rise to a drag force on the vortices, which yields a Hall angle opposite in sign to that in the normal state.[24] This extra contribution to R_H is of order $k_B T_c / 4\epsilon_F$. This contribution is therefore smaller in LSCO compared to the other HTSC's, which may explain the absence of a sign change.

Recently it has been found that in the mixed state the Hall resistivity scales with the resistivity according to the law $|\rho_H| \propto \rho^\nu$, with $\nu = 2$. Luo *et al.*[25] and Rice *et al.*[26] find such a scaling of the negative Hall resistivity with the resistivity with $\nu = 1.7 \pm 0.2$ and $\nu = 1.6 \pm 0.1$, respectively. In $Bi_2Sr_2CaCu_2O_x$ (Bi-2212) the Hall resistivity shows a local, positive maximum at a temperature $T_m \approx 70$ K. Samoilov[27] finds that the positive Hall resistivity for temperatures $T < T_m$ scales with the resistivity with $\nu = 2.0 \pm 0.1$. In La-Sr-Cu-O we find a scaling of Hall resistivity and resistivity according to $\rho_H \propto \rho^\nu$ with $\nu = 1.74 \pm 0.15$ in the whole mixed state (see Fig. 3).

A model explaining this behavior has been proposed by Vinokur *et al.*[28] They use an equation of motion of the vortices given by

$$\phi_0 \mathbf{j} \times \mathbf{n} - \alpha \phi_0 \mathbf{v}_\phi \times \mathbf{n} = \eta \mathbf{v}_\phi \ , \tag{1}$$

where $\mathbf{v}_\phi$ denotes the flux-line velocity, ϕ_0 is the flux quantum, η is the viscosity parameter, α is a phenomenological parameter, and $\mathbf{n}$ is a unit vector in the direction of the magnetic field. Vinokur *et al.* show that pinning leads only to a renormalization of the viscosity parameter η and that the Hall resistivity is given by

$$\rho_H = \frac{\alpha}{\phi_0 B} \rho^2 \ . \tag{2}$$

A possible deviation from the exponent $\nu = 2$ may be due to the temperature dependence of α.

C. Nernst effect

The normal state Nernst coefficient of LSCO is of order $(-0.2$ to $-0.8) \times 10^{-8}$ V/K T$\pm 0.4 \times 10^{-8}$ V/K T between 70 to 200 K (inset of Fig. 4). This order of magnitude is typical for what is observed in conventional metals (Table I).[29]

The most prominent feature in the inset of Fig. 4 is the sign change of Q well above T_c followed by a strong increase with decreasing temperature. This is most probably related to the onset of superconducting fluctuations.[30] Thus the measurement of the Nernst effect is a promising tool for the study of superconducting fluctuations above T_c, since the fluctuation contribution exceeds the normal contribution by far. Nevertheless, for a comparison of the data to theoretical predictions it is neces-

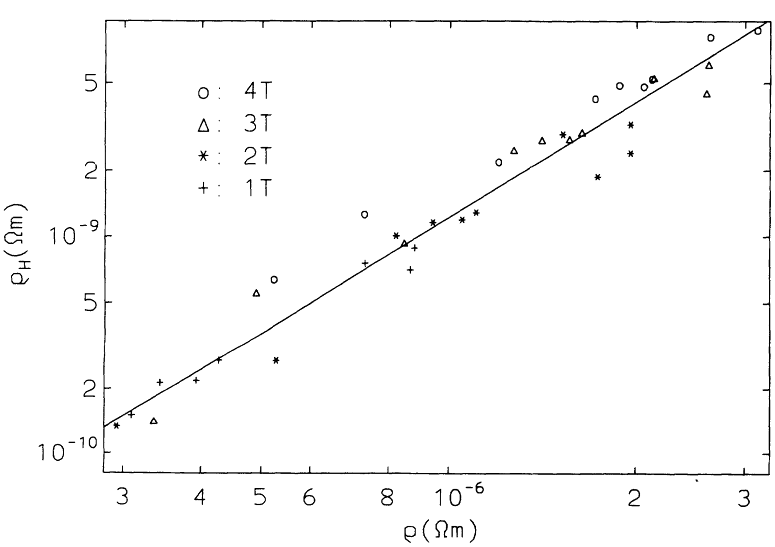

FIG. 3. Scaling of Hall resistivity ρ_H and resistivity ρ of $La_{1.85}Sr_{0.15}CuO_4$ for several magnetic fields ($B = 1$, 2, 3, and 4 T) in a double-logarithmic plot. The straight line is a fit to the data according to $\rho_H \propto \rho^\nu$ with $\nu = 1.74 \pm 0.15$ (see text).

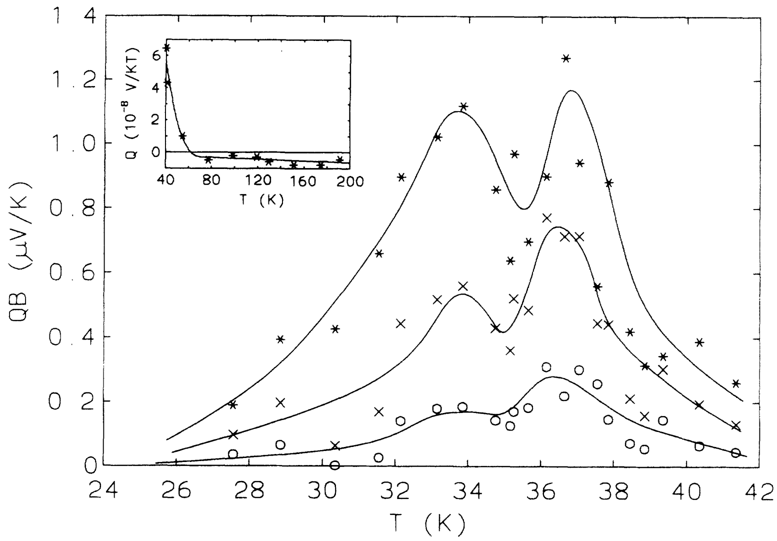

FIG. 4. Nernst coefficient QB as a function of temperature between 26 and 42 K for various fixed magnetic fields: ✱: 6 T; ×: 3 T; ○: 1 T. The Nernst coefficient shows a maximum near $T_{c0} \approx 36$ K. The solid lines are guides to the eye. The inset shows the Nernst coefficient Q as a function of temperature between 40 and 200 K. The normal-state Nernst coefficient is negative and of the order of several 10^{-9} V/K T. It shows a sign change and a rapid increase below about 60 K with decreasing temperature to positive values probably due to the onset of superconducting fluctuations. The solid line is a guide to the eye.

sary to extend the measurements to higher magnetic fields, which due to the larger Nernst voltage allows for smaller imposed temperature gradients and thus for a better temperature resolution.

The Nernst effect in the mixed state arises from the motion of vortices in response to the thermal force (per unit length)

$$\mathbf{f}_{\text{th}} = -S_\phi \nabla T \ . \tag{3}$$

This force arises, since a vortex transports an entropy S_ϕ (per unit length). We mention that the Nernst coefficient in the mixed state of a superconductor should always be positive, since vortices carry an excess entropy compared to the superconducting surrounding and therefore always move from the hot to the cold end of the sample, thereby "inducing" the Nernst voltage. Thus the sign of the Nernst coefficient in the mixed state is independent of the sign of the charge carriers and accordingly Q must change its sign with the onset of superconductivity in any material with a negative normal-state Nernst coefficient. An overview of the theories concerning the normal-state Nernst effect can be found, e.g., in Ref. 31.

Figure 4 shows the product QB of the Nernst coefficient Q with the magnetic field as a function of temperature at fixed magnetic fields. In the superconducting

TABLE I. Nernst coefficient Q of several metals (from Ref. 29).

	Q [10^{-8} V/K T]	T [K]
Ag	-1.8–-4.3	≈ 320
Au	-1.81	298–330
Cu	-2.1	298–328
Tl	-0.37	333
Ir	-0.05	323
Al	$+0.2$	328
In	$+0.32$	333

state with decreasing temperature the Nernst coefficient rapidly increases and reaches a maximum at temperatures rather close to T_{c0}. At the maximum QB is of the order of 1 μV/K at 6 T. A second maximum is seen at somewhat lower temperatures. We mention that—looking apart from the double maximum—these results are comparable to what is found for the Nernst effect of other HTSC's.[32,33]

Figure 5 shows the transport entropy versus temperature for some fixed magnetic fields derived from the Nernst effect and the magnetoresistivity[34]

$$\frac{S_\phi}{\phi_0} = \frac{QB}{\rho_f} \ . \tag{4}$$

Here ϕ_0 is the flux quantum and ρ_f is the resistivity in the mixed state under the assumption that it is completely due to vortex motion. The maximum value is $S_\phi \approx (2-3) \times 10^{-15}$ J/K m, comparable to values of the transport entropy usually found for the HTSC's (see Table II).

The transport entropy is often compared to the result of Maki[35] derived from the time-dependent Ginzburg-Landau theory (TDGL):

$$S_\phi = -\frac{\phi_0}{T}\langle M \rangle L(T)$$
$$= \frac{\phi_0}{1.16(2\kappa^2-1)+1} \times \frac{L(T)}{T} \times \frac{B_{c2}(T)-B}{\mu_0} \ . \tag{5}$$

Here κ denotes the Ginzburg-Landau parameter, $\langle M \rangle$ is the space-averaged magnetization, and $L(T)$ is a function with $0 \le L(T) \le 1$, which is only weakly temperature dependent in the dirty limit and close to $L \approx 1$ at $T \lesssim T_c$. In the clean-limit $L \propto l/\xi$ with $L = l/\xi$ at $T \approx T_c$. Using $\kappa \approx 100$ and a value for the upper critical field $B_{c2}(0) = 50$ T, for a magnetic field of $B = 3$ T and $L(T) \approx 1$, one finds for La-Sr-Cu-O

$$S_\phi(0.95 \times T_c) \approx 3 \times 10^{-15} \text{ J/K m} \ . \tag{6}$$

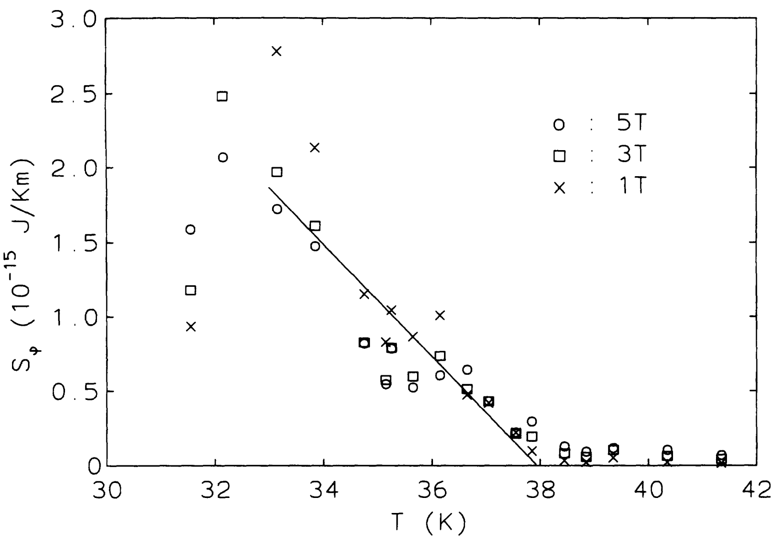

FIG. 5. Transport entropy S_ϕ as a function of temperature between 30 and 42 K for various fixed magnetic fields. The solid line is a linear fit to the magnetic-field-independent transport entropy between 33 and 38 K with a slope of $d(S_\phi/\phi_0)/dT=-0.19$ A/K^{2}m.

This is in good agreement with the experimental value.

Let us compare the result of Eq. (5) with that obtained from a much simpler model, in which it is assumed that in the mixed state of a superconductor only the normal cores of the vortices carry entropy and that this entropy per unit volume is equal to the electronic entropy per unit volume of the normal metal. With this one finds for the entropy S_m of a superconductor in the mixed state[36]

$$S_m=\gamma T\frac{B}{B_{c2}(T)}\propto\frac{\xi(T)^2}{d^2}\ . \tag{7}$$

Here $d=\sqrt{\phi_0/B}$ denotes the distance between vortices and γT is the entropy per volume of the normal metal. [The electronic specific heat is given as $c_v=\gamma T$. The entropy S per volume is related to the specific heat via the relation $c_v=T(dS/dT)$.]

The entropy (per unit length) of *one* vortex is then given by

TABLE II. Transport entropy S_ϕ for Y-Ba-Cu-O, Bi- and Tl-based superconductors at $B=4$ T, $T=T_c$ and $T=0.95\times T_c$. (sc = single crystal, pc = polycrystal, ef = epitaxial film, pf = polycrystalline film).

Material Reference	T_{c0} [K]	$S_\phi(T_{c0})$ [10^{-15} J/K m]	$S_\phi(0.95\times T_{c0})$ [10^{-15} J/K m]
Y-Ba-Cu-O (sc)(38)	86	12	50
Y-Ba-Cu-O (ef)(39)	88	20	60
Y-Ba-Cu-O (ef)(3,40)	84	9	16
Y-Ba-Cu-O (ef)(41,42)	91	1.5	8.3
Y-Ba-Cu-O (ef)(33)	88	0.03 (0.54 T)	/
Y-Ba-Cu-O (pf)(3)	83	0.36	0.44
Y-Ba-Cu-O (pf)(43)	80	0.0012 (0.54 T)	0.0012
Bi-2212 (ef)(44)	88	10	13
Bi-2212 (sc)(32)	94	0.7	1
Bi-2223 (pc)(45,7)	108.5	0.24	0.6
Tl-2212 (sc)(46)	92	0.1 (1T)	0.18
Tl-2212 (ef)(47)	95	500	1500
Tl-2223 (pc)(7)	117.2	0.04	0.07

$$S_\phi=\frac{S_m}{n}=\gamma T\frac{\phi_0}{B_{c2}(T)}\ , \tag{8}$$

where $n=B/\phi_0$ is the vortex density.

Equation (8) is at first glance not very similar to the Maki result. Nevertheless, with some results from BCS and Ginzburg-Landau theory, $(v/2\mu_0)B_{cth}(0)^2=\frac{1}{4}N(\epsilon_F)\Delta(0)^2$, $\Delta(0)=1.764k_BT_c$, $B_{c2}(0)=\sqrt{2}\kappa B_{cth}(0), B_{c2}(T)\approx B_{c2}(0)(1-T^2/T_c^2)$ and using the free-electron-gas value $\gamma=(\pi^2/3)N(\epsilon_F)k_B^2$, where $N(\epsilon_F)$ denotes the density of states at the Fermi energy and $\Delta(0)$ the energy gap at $T=0$, one obtains

$$S_\phi\simeq\frac{\phi_0}{\kappa^2}\times\frac{TT_c^2}{(T_c^2-T^2)^2}\times\frac{B_{c2}(T)}{\mu_0}\ . \tag{9}$$

Let us now calculate the transport entropy for an extreme type-II superconductor with $\kappa\gg1$ for magnetic fields not too close to B_{c2} and temperatures not too close to T_c, e.g., at $T=T_c/2$:

$$S_\phi(T_c/2)=0.89\times\frac{1}{T_c}\times\frac{\phi_0}{\kappa^2}\times\frac{B_{c2}(T_c/2)}{\mu_0}\ , \tag{10}$$

$$S_\phi(T_c/2)^{(\mathrm{Maki})}\simeq0.6\times\frac{1}{T_c}\times\frac{\phi_0}{\kappa^2}\times\frac{B_{c2}(T_c/2)}{\mu_0}\ , \tag{11}$$

where we used $L(T_c/2)\approx0.6$.[37]

For small magnetic fields and temperatures not too close to T_c the results from TDGL and of this very simple model agree within a factor of 2. This confirms the interpretation of the transport entropy as arising mainly from the normal excitations in a vortex core.

Equation (8) can be used to estimate the relative orders of magnitude of the transport entropy of conventional and high-temperature superconductors. γ_{el} has a typical value of 1–10 mJ/mol K^2 (Refs. 48 and 49) for both normal metals and HTSC's. Typical values of T_c and the coherence length are about 10 and 100 K and 1000 and 10 Å for conventional and for high-temperature superconductors, respectively. Therefore one finds:

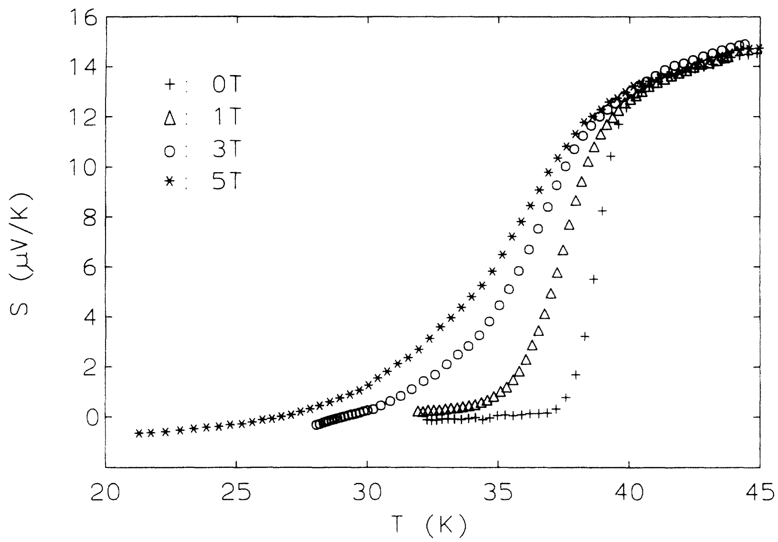

FIG. 6. Thermopower S as a function of temperature between 15 and 50 K for various fixed magnetic fields $B=0$, 1, 3, 5 T (from right to left). The negative values of S below about 30 K are due to the uncorrected magnetic-field dependence of the thermopower of the copper leads (see text).

$$\frac{S_\phi^{\mathrm{HTSC}}}{S_\phi^{\mathrm{conv.SC}}}=\frac{(\gamma T\xi^2)^{\mathrm{HTSC}}}{(\gamma T\xi^2)^{\mathrm{conv.SC}}}\approx 10^{-3} . \tag{12}$$

The transport entropy in HTSC's should be about three orders of magnitude smaller than in conventional superconductors, mainly due to the much smaller coherence length. For conventional superconductors the transport entropy has maximum values of the order of 10^{-12}–10^{-11} J/K m.[50,51] Therefore one expects for the HTSC values of 10^{-15}–10^{-14} J/K m, in good agreement with experimental results.

D. Thermopower

The absolute value of the thermopower of $La_{1.85}Sr_{0.15}CuO_4$ is somewhat controversial in the literature. It ranges from room-temperature values of about 15 μV/K (Ref. 52) up to about 55 μV/K,[53] which is possibly due to the strong sensitivity of the thermopower with respect to the strontium (and oxygen) content.[54] We find a room-temperature value of the thermopower of $S\approx 18$ μV/K, which is at the lower end of the values reported. Between room temperature and 150 K the thermopower increases from about 18 to ≈ 21 μV/K with decreasing temperature. This weak temperature dependence of S is in fairly good agreement with what is reported in the literature.[52,54] Below 150 K it decreases again to a value of 15 μV/K just above T_c.

The thermopower S shows a sharp superconducting transition at T_c in zero field. In the superconducting state for $B=0$ the absolute thermopower of LSCO vanishes. For finite magnetic fields the behavior of S is rather similar to that of the resistivity (Figs. 1 and 6). We mention again that the negative values of S seen in Fig. 6 are due to the magnetic-field dependence of the thermopower of the copper leads, which is strong (of order 1 μV/K) at 5 T between 15 and 40 K.[55]

We emphasize that the thermopower in the mixed state is of order 10 μV/K. This is larger than the absolute magnitude of the Nernst voltage, i.e., we find $QB<S$. According to the conventional theories of flux motion the flux-flow contribution to the thermopower depends on the Hall angle, i.e., flux lines move at the Hall angle with respect to the thermal force $\mathbf{f}_{\mathrm{th}}$. Therefore this contribution to S is by far smaller than the Nernst effect: The Hall angle $\tan\alpha=\rho_H/\rho$ as extracted from the resistivity and the Hall voltage is of order of a few degree, which yields $(S/QB)\approx 10^{-3}$.

It is well accepted that the large thermopower found in the mixed state of the HTSC's has to be attributed to the dynamics of quasiparticles. A detailed discussion has been given in several publications, to which we refer the reader.[1,32,45,56,57] We point out here that the occurrence of the thermopower in LSCO excludes the possibility that normal subsystems like the CuO chains in YBCO or the BiO layers in the Bi-based systems are responsible for the longitudinal quasiparticle heat current, which determines the thermopower. In LSCO such normal subsystems are not present, yet the broadening of the thermopower is very similar to that observed in other HTSC's.

IV. CONCLUSIONS

We have reported measurements of resistivity, thermopower, Hall effect, and Nernst effect in the mixed and in the normal state of $La_{1.85}Sr_{0.15}CuO_4$. Resistivity and thermopower show a strong broadening of the transition to superconductivity in a magnetic field, similar to what is observed in other HTSC's. The Hall coefficient shows no sign change near T_c for 5 T > B > 0.5 T. The Nernst effect in the normal state is two orders of magnitude smaller than in the mixed state and negative. It shows large superconducting fluctuations above T_c. The transport entropy, due to the normal excitations in the vortex cores, is in agreement with calculations from TDGL.

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