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Yuan S. L., Kadowaki K., Yang Z. J., Li J. Q., Chen J. L., Kimura T., Takeya H., Kishio K.

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Out-of-plane magnetoresistivity for fields parallel to the c axis in single-crystalline (La$_{1-x}$Sr$_x$)$_2$CuO$_4$

S. L. Yuan, K. Kadowaki,$^{a}$ Z. J. Yang,$^{b,c}$ J. Q. Li,$^{d}$ J. L. Chen, T. Kimura,$^{b}$ H. Takeya,$^{a}$ and K. Kishio$^{b}$

High Magnetic Field Laboratory, Institute of Plasma Physics, Academia Sinica, Hefei 230031, People's Republic of China

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The c-axis magnetoresistivity as a function of temperature $T$ and field $H$ for fields parallel to the $c$ axis is experimentally investigated for single-crystalline (La$_{1-x}$Sr$_x$)$_2$CuO$_4$ ($x=0.068$). It is argued that the observed Lorentz force free magnetoresistive phenomena cannot be accounted for by previously considered mechanisms. By contrast, they can be explained by the extended Josephson coupling model, which takes into account both effective thermal energy and anisotropy. Based on this extended model, it is shown that all the magnetoresistivity curves obtained in $H//c$ at various constant temperatures could be nicely scaled onto a single curve without any adjustable parameter in a wide transition region.

I. INTRODUCTION

Compared to conventional type-II superconductors, the following two features are unique to the high-temperature superconductors (HTSCs). One is their intrinsic layered crystalline structures, which contain superconducting Cu-O layers separated by some nonsuperconducting materials. Therefore, even in a perfect single crystal the amplitude of the superconducting order parameter should vary strongly between the layers. This situation leads to the idea, that the $c$-axis conduction could be viewed as a series stack of Josephson coupled junctions along the $c$ axis.\footnote{Department of Industrial Chemistry, University of Tokyo, Hongo 7-3-1, Tokyo 113, Japan.} Experimental evidence for such a picture arises from direct measurements of both dc and ac Josephson effects with currents flowing along the $c$ axis in zero field or in fields parallel to the superconducting layers for various HTSCs.\footnote{Present address: MCT 306, Argonne National Laboratory, Argonne, IL 60439-4825.} The other is the existence of the irreversibility (or depinning) line in this kind of material. Although its origin has been an issue of controversy, it is often noted that various unusual phenomena occur just above this line. A typical example is that a real superconducting state of zero resistivity is realized only below this line.\footnote{On leave from: Department of Physics, Wuhan Institute of Technology, Wuhan, People's Republic of China.}

A lot of dissipation models have been proposed to explain the observed Lorentz force free dissipation in HTSCs, including superconducting order-parameter fluctuations, vortex glass,\footnote{National Research Institute for Metals, Tsukuba Laboratory, Sengen 1-Z-1, Ibaraki 305, Japan.}\footnote{Department of Physics, Wuhan Institute of Technology, Wuhan, People's Republic of China.} one-dimensional phase slippage,\footnote{On leave from: Department of Physics, Wuhan Institute of Technology, Wuhan, People's Republic of China.} and interlayer Josephson coupling;\footnote{Present address: MC2 308, Argonne National Laboratory, Argonne, IL 60439-4825.} however, they fail to provide quantitatively a consistent explanation of the experimental observations in a wider temperature and field transition region. To better understand the origin of the Lorentz force free dissipation, we here study the out-of-plane magnetoresistivity as a function of $T$ and $H$ in a typical Lorentz force free configuration of $H//c$ for single-crystalline (La$_{1-x}$Sr$_x$)$_2$CuO$_4$ ($x=0.068$). We argue that the observed phenomena cannot be accounted for by previously considered mechanisms. By contrast, the extended Josephson coupling model,\footnote{On leave from: Department of Physics, Wuhan Institute of Technology, Wuhan, People's Republic of China.} which was recently developed by accounting for the effective energy $k_B(T-T_{in})$ (here $T_{in}$ being the irreversibility temperature) and the anisotropic parameter $\gamma$ in the conventional Josephson coupling model,\footnote{Department of Physics, Wuhan Institute of Technology, Wuhan, People's Republic of China.} is able to explain the observed experimental phenomena. As an indication of this argument, we show that all the observed curves are nicely scaled onto a single curve without any adjustable parameters in a wide transition region.

II. EXPERIMENT

The sample used in the present study is a (La$_{1-x}$Sr$_x$)$_2$CuO$_4$ single crystal with the nominal Sr content of $x=0.068$, close to that ($x=0.075$) with the highest $T_c$ in this family, which was grown by the traveling solvent floating-zone method at the University of Tokyo (Japan). The longest edge (of size $\sim$3 mm) is along the $c$ axis, which allows us to perform resistivity measurements directly by applying a current along the direction perpendicular to the superconducting layers in terms of standard either dc or ac four-probe methods. The magnetoresistivity measurement was performed at the National Research Institute for Metals (Japan). In zero field, the out-of-plane superconducting transition temperature $T_c$ is $35.7$ K (corresponding to a resistive transition at $\rho_{dc}=0.9\rho_{ac}$) and the transition width is about $2$ K (10%–90%). The temperature dependence of the $c$-axis normal-state resistivity exhibits a quasielectric behavior and can be empirically approximated by $\rho_{ac}=0.153+0.025 \exp(53.3/T)$ ($\Omega$ cm), which is obtained by fitting the corresponding data in zero field at $T>40$ K. Before the measurement of magnetoresistivity, the angular dependence of the resistivity was first investigated at various fixed temperatures by slowly varying the field orientation...
from the $a$-$b$ plane to the $c$ axis while keeping the field constant. In this way, the orientation of the field with respect to the $c$ axis of the single crystal was precisely determined with a deviation angle smaller than $0.001^\circ$ between $H$ and the $c$ axis. The measurement of the $c$-axis magnetoresistivity was performed in fields up to 6 T parallel to the $c$ axis with an increasing rate of about 0.1 T/min in a constant temperature regulated within $\pm 0.005$ K.

III. RESULTS AND DISCUSSION

Figure 1(a) displays the magnetoresistivity $\rho_c(T,H)$ data obtained in a typical Lorentz force free configuration of $H//c$ at various constant temperatures ranging between $\sim 17.9$ and $\sim 34.7$ K for single-crystalline (La$_{1-x}$Sr$_x$)$_2$CuO$_4$ ($x=0.068$). To see the behavior at low resistivity, the data shown in Fig. 1(a) are replotted in Fig. 1(b) on a semilogarithmic scale. As seen in Fig. 1(a), the $\rho_c$-$H$ curves have concave behavior at lower temperatures (e.g., at $T=33.744$ K) and convex behavior at higher temperatures (e.g., at $T=33.744$ K). At intermediate temperatures (e.g., at $T=30.785$ K), the curve varies smoothly from concave at lower fields to convex at higher fields. Similar behavior is also observed in single-crystalline Bi$_2$Sr$_2$CaCu$_2$O$_8$.15

We argue that the observed $c$-axis magnetoresistive phenomena for fields parallel to the $c$ axis cannot be accounted for by previously considered mechanisms. First, one should note the lack of a macroscopic Lorentz force in the present experimental configuration for $\rho_c$. A Lorentz force is needed to drive vortices in any flux creep or flux-flow scenario. It has been suggested that a nonzero Lorentz force might be generated through some sort of misalignment between the field $H$ and the transport current; however, misalignment due to random microscopic inhomogeneities in the current distribution will average to zero. Similarly, the Lorentz force on a randomly bent vortex (threading the sample parallel to the $c$ axis) should also average to zero; therefore, to explain the observed experimental phenomena, the problem must be argued within the framework of the Lorentz force free dissipation model.

Among various Lorentz force free models, both superconducting order-parameter fluctuations5,6 and vortex glass7,8 models are generally thought to be reasonable for the HTSCs. Although the effects of the order-parameter fluctuations are commonly thought to play an important role in dominating various physical properties, the expression for the resistivity5 developed by Ikeda and co-workers on the basis of the order-parameter fluctuation theory, as shown by themselves, can work well only in a narrow transition region near $T_c$. In the vortex glass model proposed by Fisher and co-workers,7,8 an observable resistive dissipation in a vortex fluid regime for arbitrarily small applied currents is explained to be a consequence of the fact that the phase of the local superconducting order parameter varies with the Brownian motion of the vortices. While this model is intellectually attractive, it has not yielded mathematical descriptions to which experimental data may be readily compared.

It is interesting to examine the phase slippage model, which contains thermal activation and also is independent of the presence of the Lorentz force. This model was first developed for conventional Josephson junctions in zero field by Ambegaokar and Halperin (AH).14 In their model, an essential quantity is $x(T) = E_J(T)/k_BT$, the ratio between the Josephson coupling energy $E_J(T) = E_J(T,H)$ and the thermal energy $k_BT$. Assuming $I_c(T,H) = I_c(T)/(1 + C_H H)$, where $C_H$ is constant, and neglecting the $T$- and $H$-independent constants, the quantity $x(T,H)$ could be expressed as

$$x(T,H) = E_J(T,H)/k_BT = I_c(T)/(1 + C_H H). \quad (1)$$

For instance: (1) letting $C_H = A_0/\phi_0$ ($A_0$ being the effective phase-coherent area), Eq. (1) reduces to the case presented by Kim and co-workers;10 (2) in the case of $C_H H >> 1$, Eq. (1) returns to Tinkham’s model6 by assuming $I_c(T,H) = I_c(T)/(1/T)_{3/2}$; (3) similarly, the model proposed by Briceno and co-workers9 is also obtained by assuming $I_c(T,H) = I_c(T)/(1/T)_{3/2}$ and $C_H H >> 1$. As is well known, according to the AH theory,14 in the limit of zero measuring current
there is only one variable, i.e., \( x(T) \) or \( x(T,H) \), in the expression of the normalized resistivity. This means that if their models\(^{8,10,16} \) were appropriate for HTSCs, the observed normalized resistivity as a function of \( T \) and \( H \) should be consistently scaled onto a single curve by using \( x(T,H) \) as a scaling variable. Our analysis shows that it is impossible to make such a scaling for the data shown in Fig. 1. Therefore, it is concluded that a model, which is developed simply by extending the conventional Josephson coupling theory,\(^{14} \) is unable to yield a reasonable explanation of the observed Lorentz force free magnetoresistive phenomena at least for the present system.

Quite recently, an extended Josephson coupling model\(^{11-13} \) has been developed for the resistive dissipation in \( H//c \) for HTSCs by accounting for the following two essential facts: One is the intrinsic layered structures in HTSCs, which urges us to consider the c-axis conduction to be that of a series stack of Josephson tunnel junctions between well-coupled units consisting of superconducting Cu-O layers. A similar picture has been proposed by Gray and Kim.\(^1 \) The other is that the resistive dissipation becomes observable only when the temperature is higher than the irreversibility temperature \( T_{irr} \). To emphasize this, in Fig. 2 we plot the field dependence of both \( T_{irr} \) and \( T_{c} \) (\( \rho_{c}=0 \)) for \( H//c \) for the present sample. They are determined by measuring magnetization \( M(T,H) \) [corresponding to a “kink” in \( M(T,H) \)] and the c-axis resistivity (using \( \rho_{c}(T,H) \)) for \( H//c \) should be obtained by measuring magnetization \( M(T,H) \) corresponding to a kink in \( M(T,H) \); and (solid line) a fit to the experimental \( T_{irr}(H) \) data by \( T_{irr}=31.9(1-(H/11.5)^{0.71}) \) (K) (\( H \) in T).

![FIG. 2](image)

The Lorentz force free magnetoresistive phenomena has also been reported for other high-\( T_{c} \) systems such as \( \text{YBa}_{2}\text{Cu}_{3}\text{O}_{7-\delta}, \) \( \text{Bi}_{2}\text{Sr}_{2}\text{CaCu}_{2}\text{O}_{8+\delta}, \) etc. This suggests that the thermal energy \( k_{B}T \) in the conventional \( \Delta H \) theory\(^{14} \) should be replaced with the effective thermal energy, \( k_{B}T(1-T_{irr}/T) \), where \( \Delta T=T-T_{irr} \). This is consistent with the effective contribution to the thermal energy, which is expected to observe actually in experiments. Then, the extended Josephson coupling model is summarized by a quantity \( x'(T,H) \), the ratio between the Josephson coupling energy \( E_j(T,H) \), and the effective thermal energy \( k_{B}\Delta T \). Neglecting all the constant factors, the quantity \( x'(T,H) \) in the present case becomes

\[
x'(T,H)=E_j/k_BT=J_c(T,H)/\Delta T,
\]

where \( J_c(T,H)=I_c(T,H)/A_0 \) is the maximum Josephson coupling current density in the absence of thermal noise and \( A_0 \) is the junction area in zero field.

A key problem is left, i.e., how to determine \( J_c(T,H) \) for \( H//c \). Its exact determination requires detailed knowledge of vortex dynamics in HTSCs, which is unavailable yet for the HTSCs at present. Because of this reason, we here adopt a rather general argument to describe the possible behavior of \( J_c(T,H) \). According to the Lawrence–Doniach model,\(^{17,18} \) which describes Josephson-coupled superconducting layers of thickness \( d \) and stacking periodicity length \( s \), the maximum Josephson current density \( J_c(T,H) \) in zero field could be expressed as

\[
J_c(T,H)=a_0/\lambda_0^{2},
\]

where \( a_0 \) is constant and \( \lambda_0 \) is the penetration depth parallel to the layers. On the other hand, the penetration depth \( \lambda_{ab} \) normal to the layers\(^{18} \) is \( \lambda_{ab}=\lambda_0(\pi/d)^{1/2} \), where \( \lambda_0 \) is the intrinsic bulk penetration depth. Therefore, one has

\[
J_c(T,H)=a_0/\lambda_0^{2}=a_0/\lambda_{ab}^{2}\gamma^2, (\gamma=1/(\lambda_{ab}/\lambda_0)^2),
\]

where \( \gamma_0=\lambda_{ab}/\lambda_0 \) is the intrinsic anisotropic parameter. For \( H//c \), such a dependence in its functional form is still assumed to be formally held for HTSCs, i.e.,

\[
J_c(T,H)=a_0/\lambda_0^{2}\gamma_0^{2} \gamma^2. \quad (3)
\]

Note that the unusual behavior in the HTSCs has been accounted for by introducing \( \gamma \). According to conventional theory for anisotropic type-II superconductors, the \( \gamma \) is a temperature-independent parameter. In the case of HTSCs, however, this parameter strongly depends on temperature. For instance, the reported \( \gamma \) value\(^{19} \) for \( \text{La}_{x-0.007}\text{Sr}_{0.007}\text{CuO}_4 \) varies from \( \sim 10 \) at \( T\sim 34 \) K to \( \sim 20 \) at \( T\sim 32 \) K. On the other hand, such an unusual temperature dependence is expected to be observed only at \( T>T_{irr} \) suggesting that the \( \gamma \) should also be a function of \( T_{irr} \). Taking into account the facts that the \( \gamma \) becomes substantially large as \( T\rightarrow T_{irr}^{+} \) and returns to its usual value at \( T=T_{irr} \), the \( \gamma \) as a function of both \( T \) and \( T_{irr} \) at \( T>T_{irr} \) has been argued\(^{20} \) to be

\[
\gamma=\gamma_0[(Tc-T_{irr})/(T-T_{irr})]^{b}, \quad (4)
\]

where \( b \) is a material constant between 0 and 1. Although Eq. (4) is proposed by a rather rough argument, by inserting it into the scaling rule for the resistivity developed by Hao and Clem,\(^{21} \) it has been shown\(^{20} \) that the resistivity as a function of field and its orientation measured at various constant temperatures could be consistently scaled onto a series of single curves for each given temperature by using \( \gamma_0 \) and \( b \) as adjustable parameters.

Inserting Eqs. (3) and (4) into Eq. (2), the quantity \( x'(T,H) \) in the case of \( H//c \) for HTSCs could be rewritten as

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where $J_c(T)$ has been assumed to be $J_c(T) = (1 - T/T_\text{c})$, and $T_{\text{irr}} = T_{\text{irr}}(H)$. Both $T_\text{c}$ and $T_{\text{irr}}$ can be directly experimentally determined. The parameter $b$ can be obtained by a scaling for the angular dependence of the resistivity. Therefore, there is no adjustable parameter involved in Eq. (2') for the present problem. Similar to the above argument, one suggests again that if such a model were appropriate for the HTSCs, the normalized resistivity as a function of $T$ and $H$ measured in $H//l//c$ should consistently map onto a single curve by using $x'(T,H)$ as a scaling variable, which is important for supporting this extended Josephson coupling model.

To make sure of the above extended Josephson coupling model, we now make a scaling to the data shown in Fig. 1. For the present sample, its $T_\text{c}$ is given to be 35.7 K, corresponding to a transition temperature at $\rho_c = 0.9 \rho_0$ in zero field. Its $T_{\text{irr}}$ is approximated by

$$T_{\text{irr}} = 31.9 \left[1 - (H/11.5)^{0.71}\right] \text{ (K)}$$

($H$ in T), which is obtained by fitting to the $T_{\text{irr}}(H)$ data $\Delta$ shown in Fig. 2. The parameter $b$ is estimated to be $\sim 1/3$ by making a scaling for resistivity as a function of $T$, $H$, and $\theta$ according to the extended scaling rule recently developed for HTSCs. Using these values, it is possible to make a consistent scaling for the data shown in Fig. 1 by using $x'(T,H)$ as shown in Fig. 2 as a scaling variable. The thus scaled results are shown in Figs. 3(a) and 3(b) for two different plots. It can be seen that all the curves shown in Fig. 1 have been consistently scaled onto a single curve quite nicely in the whole selected temperature and field region, which strongly supports the above extended Josephson coupling model.

Finally, we would like to argue the following three points.

1. In our case the parameter $b$ is given by a scaling for the angular dependence of resistivity according to the extended scaling rule; however, the exact measurement of the angular dependence is unavailable in most laboratories. In this case, one could use $b$ as an adjustable parameter. Therefore, this actually suggests a new method to determine the normalized anisotropic parameter $\gamma/\gamma_0$ as a function of $T$ and $T_{\text{irr}}$. In other words, the parameter $b$ (hence $\gamma/\gamma_0$) could be determined by scaling the resistivity as a function of $T$ and $H$ measured in $H//l//c$ onto a single curve by using $x'(T,H)$ shown in Eq. (2') as a scaling variable.

2. In this article we only account for the $c$-axis magnetoresistivity for $H//c$. In fact, Eq. (2') is easily extended to the general case, i.e., the field oriented at angle $\theta$ with respect to the $c$ axis, by replacing $H$ in Eq. (2') with the reduced field $h$, where $T_{\text{irr}} = T_{\text{irr}}(h)$ and $h = H((\sin^2 \theta/\gamma^2 + \cos^2 \theta)^1/2)$. In this way, all the $c$-axis resistivity $\rho_c(T,H,\theta)$ data could be nicely scaled onto a single curve by using $x'(T,h)$ as a scaling variable. Details will be reported elsewhere.

3. The present scaling approach is appropriate only for the resistivity measured in the case of $l//c$. In the case of the in-plane resistivity, one could not use $x'(T,H)$ shown in Eq. (2') as a scaling variable, since Eq. (3) is proposed only for the case of measuring current applied along the $c$ axis.

IV. SUMMARY

We have experimentally investigated the Lorentz force free magnetoresistive phenomena in $H//l//c$ for single-crystalline $(La_{1-x}Sr_x)_{2}CuO_4$ ($x = 0.068$). We argue that the observed phenomena cannot be accounted for by previously proposed mechanisms. By contrast, the extended Josephson coupling model is able to provide a consistent explanation of the observed Lorentz force free magnetoresistive phenomena. As an indication of this argument, we have nicely shown that all the magnetoresistivity curves obtained in $H//l//c$ for the present system could be consistently scaled onto a single curve quite satisfactorily without any adjustable parameter in the whole selected temperature and field region.

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20 S. L. Yuan, K. Kadowaki, Z. J. Yang, H. Takeya, T. Kimura, and K. Kishio (unpublished). Based on the anisotropic Ginzburg–Landau theory, Hao and Clem (HC) proposed the scaling rule (Ref. 71) for resistivity of HTSCs as $\rho(T,H,\theta) = \rho(T,e(\theta,y)H)$, where $e(\theta,y) = (\sin^2 \theta/2 + \cos^2 \theta/2)^2$ and $\theta$ is an angle between $H$ and $c$ axis. Our analysis shows that it is impossible to make a consistent scaling for $\rho(T,H,\theta)$ of HTSCs according to the HC rule. To give a consistent scaling, an extended scaling rule was recently developed by replacing $\gamma$ in the HC rule with $\gamma(T,T_m)$ shown in Eq. (4) of this article, where $T_m = T_{m0}[e(\theta,y)H]$. Note that $\gamma$ is hidden in the expression of $T_m$. To the first order, one can approximate $\gamma$ by $\gamma_0$ in the actual calculation of $T_m$. The extended scaling rule is then expressed by $\rho(T,H,\theta) = \rho(T,e(\theta,y)H)$ and $\gamma_0(T - T_m[e(\theta,y)H])^2$. Based on this extended rule, it has been shown that the $\rho(T,H,\theta)$ obtained in (La$_{1-x}$Sr$_x$)$_2$CuO$_4$ could be consistently scaled on a series of single curves for each given temperature. By this scaling, both material parameters are estimated to be $\gamma_0 = 12.5$ and $b = 1/3$ for this system.