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Magnetoconductance of $Tl_2Ba_2CaCu_2O_x$ films in the fluctuation regime

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Magnetoconductance (MC) has been measured above the mean-field transition temperature T_c in the highly anisotropic high-temperature superconductor $Tl_2Ba_2CaCu_2O_x$ for fields parallel and perpendicular to the CuO plane. Recent theoretical expressions for the magnetoconductance in the layered superconductors provide a good fit for the temperature range T_c+10 K $< T <$ 160 K. Using the additional constraint of the zero-field fluctuation conductivity, we obtain the in-plane coherence length $\xi_{ab}(0)\approx 11.8\pm0.4$ Å and a linear temperature dependence for the phase relaxation rate, with $1/\tau_\phi \approx (3.5\pm0.5)\times10^{13}$ sec^{-1} at T_c. For $T_c < T < T_c+10$ K, we found a significant enhancement of the negative MC compared to the prediction based on the Gaussian approximation. A possible origin of such deviation is discussed.

I. INTRODUCTION

Recently, Hikami and Larkin[1] calculated the magnetoconductance (MC) for high-temperature superconductors above the mean-field transition temperature, T_c. They extended the existing two-dimensional (2D) MC formulas of the Aslamazov-Larkin (AL) and Maki-Thompson (MT) terms, for fields perpendicular to the film surface,[2,3] to the case of a layered superconductor by including a small coupling term between the layers. Such a model is appropriate to high-T_c superconductors (HTS) for fields, **H**, perpendicular to the CuO planes, i.e., parallel to the *c* axis ($\mathbf{H}\|c$). These formulas successfully explained the contribution to the MC due to the orbital motion of electrons in their Landau levels for $YBa_2Cu_3O_{7-x}$ with $\mathbf{H}\|c$.[4] However, for a field parallel to the CuO plane ($\mathbf{H}\|a$), the orbital contribution is absent in the 2D limit, and thus a spin pair breaking due to the paramagnetic effect becomes important for both the AL and MT terms. Aronov, Hikami, and Larkin[5] later included the spin-splitting Zeeman effect on the Maki-Thompson and Aslamazov-Larkin terms to account for the MC with $\mathbf{H}\|a$ as well as $\mathbf{H}\|c$. Subsequent studies of the MC of a single-crystal film of $YBa_2Cu_3O_{7-x}$ by Matsuda *et al.*[6] showed quantitative agreement with the theory including the Zeeman effect for both $\mathbf{H}\|a$ and $\mathbf{H}\|c$.

Since the physical properties of $Tl_2Ba_2CaCu_2O_x$ are much closer to a 2D system than those of $YBa_2Cu_3O_{7-x}$, it is of interest to study the MC in this highly anisotropic material. In this paper magnetoconductance of the highly anisotropic HTS, $Tl_2Ba_2CaCu_2O_x$, has been measured from T_c to 160 K for fields parallel and perpendicular to the CuO plane. The experimental results for the temperature range T_c+10 K $< T <$ 160 K are in good agreement with the formulas considering both orbital and Zeeman effects,[5] however for $T_c < T < T_c+10$ K, substantial deviations from the theory were observed for both field orientations.

Sputtered films of $Tl_2Ba_2CaCu_2O_x$ were prepared in a three-gun dc magnetron sputtering system on (100) single-crystalline MgO substrates. The films were wrapped in Au foil together with Tl-Ba-Ca-Cu-O bulk materials and annealed in flowing O_2. Electrical contact was made by sputtering Ag through a mask and lead wires were attached by pressing In dots. Contact resistance was found to be less than 1 Ω at room temperature and negligibly small below T_c. X-ray diffraction analysis indicated a high degree of orientation of the 2:2:1:2 phase, with its *c* axis perpendicular to the substrate, and the half-width at half maximum (HWHM) of the rocking curve was $\leq 0.4°$. These films are extremely well oriented and thus emulate single crystals as regards the *ab* plane–*c* axis anisotropy. Further evidence of single-crystal-like anisotropy comes from torque magnetization measurements on similarly made thin films,[7] which indicated the HWHM was $\leq 0.35°$.

Experiments were performed in a ^{4}He gas-flow cryostat equipped with a 9-T superconducting solenoid. All data were measured by sweeping the field up and down while holding a constant temperature with a capacitance thermometer and controller. Magnetoconductances for both $\mathbf{H}\|c$ and $\mathbf{H}\|a$ were measured without thermal cycling to room temperature by using a rotating sample holder, in which the films were aligned to the magnetic field within 0.3°. Magnetoconductances were measured on two $Tl_2Ba_2CaCu_2O_x$ films, samples 1 (4000-Å thick) and 2 (5000-Å) thick, prepared with the identical method but from different batches. Generally, the resistivity, ρ is a tensor in a field, however, the off-diagonal elements of ρ are quite small compared to diagonal elements and can be safely neglected. Thus the relation $\sigma(T,H)=1/\rho(T,H)$ was used to obtain the conductivity, where $\rho(T,H)$ is the resistivity along the current direction. Magnetoconductivity is defined as $\Delta\sigma(T,H)\equiv\sigma(T,H)-\sigma(T,0)$.

II. THEORY OF MAGNETOCONDUCTANCE IN THE FLUCTUATION REGIME

We begin with zero-field fluctuation conductivity, $\sigma'(0)$, in which two different mechanisms contribute: The Aslamazov-Larkin term[8] is due to the excess current carried by fluctuating Cooper pairs; and the other is the forward-scattering effect on quasiparticles due to Cooper pairs, as first calculated by Maki[9] and later modified by Thompson.[10] The model for fluctuation conductivity most relevant to the HTS, introduced by Lawrence and Doniach[11] many years ago, considers a collection of superconducting layers coupled via Josephson tunneling. One result is a dimensional crossover from 2D to 3D when the coherence length perpendicular to the layers (along the c axis for HTS), ξ_c, becomes comparable to the layer spacing d. This occurs as T approaches T_c from above, and the excess conductivity in zero field is given as

$$\sigma'_{\mathrm{LD}}(0)=\frac{e^2}{16\hbar d\varepsilon}\frac{1}{\sqrt{1+2\alpha}}, \tag{1}$$

where $\varepsilon=\ln(T/T_c)$ is the reduced temperature and $\alpha=2\xi_c^2(0)/d^2\varepsilon$ with the coherence length evaluated at $T=0$.

The Maki-Thompson (MT) term[9,10] for a layered superconductor is[1]

$$\sigma'_{\mathrm{MT}}(0)=\frac{e^2}{8\hbar d(\varepsilon-\delta)}\ln\left[\frac{\varepsilon}{\delta}\frac{1+\alpha+\sqrt{1+2\alpha}}{1+\alpha\varepsilon/\delta+\sqrt{1+2\alpha\varepsilon/\delta}}\right], \tag{2}$$

where $\delta=\pi\hbar/8k_BT\tau_\phi$ is the pair-breaking parameter, τ_ϕ is the phase relaxation time, and k_B is Boltzmann's constant. If $\alpha=0$, Eqs. (1) and (2) reduce to the 2D AL and MT results, respectively. The total zero-field fluctuation conductivity is given as sum of the AL and MT terms.

In a magnetic field parallel to the c axis, orbital motion of the electrons gives rise to a negative magnetoconductance. Hikami and Larkin[1] obtained the fluctuation part of this conductivity in a field for the orbital Aslamazov-Larkin (ALO) and Maki-Thompson (MTO) terms ($\Delta\sigma_{\mathrm{ALO}}$ and $\Delta\sigma_{\mathrm{MTO}}$, respectively) of layered superconductors by extending the 2D result of Abraham *et al.*[2] and Larkin.[3] The results can be expanded for small $h\equiv2e\xi_{ab}^2(0)H/\hbar c\ll\varepsilon$ and the leading terms are given as

$$\Delta\sigma_{\mathrm{ALO}}(H)=-\frac{e^2}{64\hbar d\varepsilon^3}\frac{2+4\alpha+3\alpha^2}{(1+2\alpha)^{5/2}}h^2 \tag{3}$$

$$=-\frac{e^2}{32\hbar d\varepsilon^3}h^2\quad(\text{for }\alpha=0), \tag{3a}$$

$$\Delta\sigma_{\mathrm{MTO}}(H)=-\frac{e^2}{48\hbar d(1-\alpha/\beta)\varepsilon^3}\left[\frac{\beta^2}{\alpha^2}\frac{1+\beta}{(1+2\beta)^{3/2}}-\frac{1+\alpha}{(1+2\alpha)^{3/2}}\right]h^2 \tag{4}$$

$$=-\frac{e^2}{48h\,d(\varepsilon-\delta)\varepsilon^2}\left[\frac{\varepsilon^2}{\delta^2}-1\right]h^2\quad(\text{for }\alpha=0), \tag{4a}$$

where $\beta=8\alpha\varepsilon k_BT\tau_\phi/\pi\hbar=\alpha\varepsilon/\delta$, $\xi_{ab}(0)$ is the coherence length in the CuO plane evaluated at $T=0$, and $\varepsilon=\ln(T/T_c)$, where T_c is the zero-field transition temperature. For the 2D case, i.e., $\alpha=0$, Eqs. (3)–(6) can be simplified to Eqs. (3a)–(6a), respectively.

Magnetoconductivties due to the Zeeman effect on the Aslamazov-Larkin (ALZ) and Maki-Thompson (MTZ) terms, $\Delta\sigma_{\mathrm{ALZ}}$ and $\Delta\sigma_{\mathrm{MTZ}}$, respectively, are,[5]

$$\Delta\sigma_{\mathrm{ALZ}}(H)=-0.526\frac{e^2}{\hbar d\varepsilon^2}\frac{1+\alpha}{(1+2\alpha)^{3/2}}\left[\frac{\omega_s}{4\pi kT_c}\right]^2 \tag{5}$$

$$=-0.526\frac{e^2}{\hbar d\varepsilon^2}\left[\frac{\omega_s}{4\pi kT_c}\right]^2\quad(\text{for }\alpha=0), \tag{5a}$$

$$\Delta\sigma_{\mathrm{MTZ}}(H)=-\frac{e^2}{16\hbar d\varepsilon}\left[\frac{1+\beta}{(1+2\beta)^{3/2}}-\frac{1+\beta+\beta/\alpha}{[1+\beta/\alpha)(1+2\beta+\beta/\alpha)]^{3/2}}\right]\left[\frac{\omega_s\tau_\phi}{\hbar}\right]^2 \tag{6}$$

$$=-\frac{e^2}{16\hbar d\varepsilon}\left[1-\frac{1}{(1+\varepsilon/\delta)^2}\right]\left[\frac{\omega_s\tau_\phi}{\hbar}\right]^2\quad(\text{for }\alpha=0), \tag{6a}$$

where $\omega_s=g\mu_BH$, μ_B is the Bohr magneton, and g is the Landé g factor. For $\mathbf{H}\|c$, magnetoconductivity is the sum of all four terms [Eqs. (3)–(6)] and for $\mathbf{H}\|a$ only the Zeeman terms [Eqs. (5) and (6)] contribute.

III. ANALYSIS OF THE FLUCTUATION CONDUCTIVITY

A. Zero-field fluctuation conductivity

Previous studies on the zero-field fluctuation conductivity in $Tl_2Ba_2CaCu_2O_x$ films showed an excess conductivity in very good agreement with the 2D Aslamazov-Larkin term [Eq. (1) with $\alpha=0$] for $T_c+2\text{ K}<T<200\text{ K}$. This result indicates that the Maki-Thompson term and α can be neglected in such a temperature range, presumably due to the very weak coupling between the CuO planes and a large inelastic-scattering rate.[13] However, a more detailed study should consider the effects of those terms. In the present study these terms, represented by the Lawrence-Doniach (LD) model and the Maki-Thompson (MT) term, are necessary in the analysis of zero-field conductivity in order to later check the consistency of the fluctuation conductivity between zero and finite fields.

We fit the zero-field conductivity data to

$$\sigma(0)=\frac{1}{aT+b}+c\left[\frac{1}{\varepsilon\sqrt{1+2\alpha}}+\frac{2}{\varepsilon-\delta}\ln\left[\frac{\varepsilon}{\delta}\frac{1+\alpha+\sqrt{1+2\alpha}}{1+\alpha\varepsilon/\delta+\sqrt{1+2\alpha\varepsilon/\delta}}\right]\right], \tag{7}$$

where $c\equiv e^2/16\hbar d$ and a linear temperature of the normal-state resistivity, $aT+b$, is assumed. This expression contains six parameters. If the parameter $\alpha=2\xi_c^2(0)/d^2\varepsilon$ is left free, it sometimes converges to unphysical values, presumably because its magnitude is much less than one and thus it is unimportant in the temperature range, $\varepsilon>0.02$, where the data are taken. Fixing α reduces the number of parameters and prevents the fitting procedure from settling into local minima. We estimate α to be $\sim 1.3\times10^{-4}/\varepsilon$ from other experimental results: the layer spacing d is 14.7 Å (Ref. 14) and an estimation of $\xi_c(0)\sim 0.12$ Å comes from the coherence length anisotropy of ~ 94 found in the torque magnetization on similar films[7] and the upper critical field slope of ~ 2 T/K for $\mathbf{H}\|c$, assumed to be the same as for $YBa_2Cu_3O_{7-x}$.[15] It should be noted that the quality of the fit was insensitive to the choice of α, as long as it was smaller than $5\times10^{-3}/\varepsilon$. The fitting procedure was repeated for various ranges of temperatures to further assure that the result is not from a local minimum.

From the fit shown in Fig. 1 we obtain $a=5.4\pm0.2$ $\mu\Omega$ cm/K, $b=80\pm1.5$ $\mu\Omega$ cm, $c=40\pm 4\Omega^{-1}$ cm^{-1}, $\delta=1.0\pm0.2$, and $T_c=102.0\pm0.3$ K for sample 1. The error comes from varying the fitting ranges. For sample 2 we obtain $a=2.8\pm0.2$ $\mu\Omega$ cm/K, $b=59\pm1.4$ $\mu\Omega$ cm, $c=60\pm 4\Omega^{-1}$ cm^{-1}, $\delta=0.40\pm0.1$, and $T_c=102.4\pm0.3$ K showing a slightly higher T_c and conductivity. The results of the fit and other parameters evaluated for two samples are listed in Table I. For simplicity we have assumed a temperature independent δ, which is equivalent to $1/\tau_\phi\sim T$ (it will be shown below that this works best). The pair-breaking parameter δ is about 10 to 1000 times larger than those found of Pb and Al films,[16,17] suggesting a very large inelastic-scattering rate for $Tl_2Ba_2CaCu_2O_x$.

Note that since $c=e^2/16\hbar d$ the value of the 40-Ω^{-1}cm^{-1} for sample 1, for example, implies that $d=38$ Å. This value is larger than the distance between the adjacent CuO planes, 14.7 Å.[14] This problem was also found in studies of $YBa_2Cu_3O_{7-x}$ and was interpreted[4,6,18] as an inhomogeneous current flow due to the sample morphology. However, this subject is still unclear,[12,19] and in the following analysis we use $c=40$ and 60 Ω^{-1} cm^{-1} for samples 1 and 2, respectively, instead of the value of 104 Ω^{-1} cm^{-1} which would correspond to the CuO layer spacing.

When we fix $\alpha=0$ in the fit, which is the 2D case, the same quality of the fit was obtained. Such a fit resulted in slightly higher δ and c($\sim2\%$), and almost identical a, b, and T_c, indicating that the excess conductivities of $Tl_2Ba_2CaCu_2O_x$ are equally well described by the 2D formula. This result suggests that the coupling between the layers can be safely neglected, however, $Tl_2Ba_2CaCu_2O_x$ is not a perfect 2D system, thus the coupling term is included in the further analysis of MC.

B. Magnetoconductance for $\mathbf{H}\|a$

The analysis begins with the data for $\mathbf{H}\|a$, in which only the Zeeman term is important. The reduced temperature, $\varepsilon=\ln(T/T_c)$, was obtained using the zero-field transition temperature from the above fit. Typical normalized magnetoconductivities for sample 1 are shown in Fig. 2 as a function of H, and the H^2 dependence of $\Delta\sigma(H)$ expected from Eqs. (5) and (6) was observed up to 1 T and higher [solid line in Fig. 2(a)] for the temperature range of $\varepsilon>0.04$. The corresponding temperature dependences are shown for sample 1 in Fig. 3 for $\mu_0H=1$ and 9 T. The magnitude of $\Delta\sigma(H)$ for sample 2 display the very similar trend as sample 1 for all temperature ranges, but shifted higher by a factor of ~1.7 for both field orientations probably due to the larger zero-field conductivity. Such a trend, for example, can be seen in $\mu_0H=9$ T data for $\mathbf{H}\|c$ in Fig. 3(b).

For small α, Eqs. (5) and (6) predict that $\Delta\sigma_{\mathrm{ALZ}}\sim-1/\varepsilon^2$ and $\Delta\sigma_{\mathrm{MTZ}}\sim-1/\varepsilon$ and these approximate equations are valid for the present field range

TABLE I. Physical properties of samples 1 and 2 are listed. Parameters a, b, c, and T_c are determined from the fit of the zero-field conductivity to Eq. (7), and the other parameters are determined from the fit of the magnetoconductance.

Sample	T_c (K)	a ($\mu\Omega$ cm/K)	b ($\mu\Omega$ cm)	c (Ω^{-1} cm^{-1})	$\xi_{ab}(0)$ (Å)	$1/\tau_\phi(T_c)$ (10^{13} sec^{-1})	g
1	102.0±0.3	5.4±0.2	80±1.5	40±4	11.5±0.4	4±0.5	1.7±0.1
2	102.4±0.3	2.8±0.2	59±1.4	60±4	12.2±0.3	3±0.5	1.65±0.05

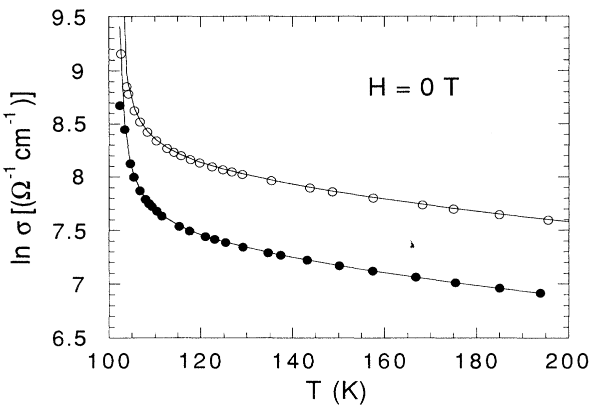

FIG. 1. Zero-field conductivity as a function of temperature for two $Tl_2Ba_2CaCu_2O_x$ films of samples 1 (solid circle) and 2 (open circle) are shown. Solid curves are the best fit described in the text.

($\omega_s \tau_\phi \hbar \ll 1$), except very near T_c. However, the data in Fig. 3 show a stronger ε dependence than the prediction of the Zeeman term for $\varepsilon < 0.1$, and thus we have to restrict the fitting range to $\varepsilon > 0.1$. A possible origin of the deviation for $\varepsilon < 0.1$ will be discussed in Sec. III D. Although the data are over a limited range of ε, by using $\alpha = 1.3 \times 10^{-4}/\varepsilon$ and c from the zero-field fit, we have in principle, a single-parameter (δ) fit. However, the most reasonable fit was found for $\delta = 1.2 \pm 0.3$, and, surprisingly, $g\mu_B = 1.6$ and $1.5 \pm 0.02 \times 10^{-23}$ J/T, for samples 1 and 2, respectively, compared to 1.85×10^{-23} J/T for $g = 2$. These δ values agree very well with that obtained from the zero-field fit, and although $g \sim 1.65 - 1.7$ is unexpected, we have no independent knowledge of g for $Tl_2Ba_2CaCu_2O_x$. The results of the fit for sample 1 are shown in Fig. 3 as dotted lines.

We have also analyzed these results using a more general expression of δ, i.e., $1/\tau_\phi$. Since in normal metals at low temperature, and in superconductors for $T \gg T_c$, the

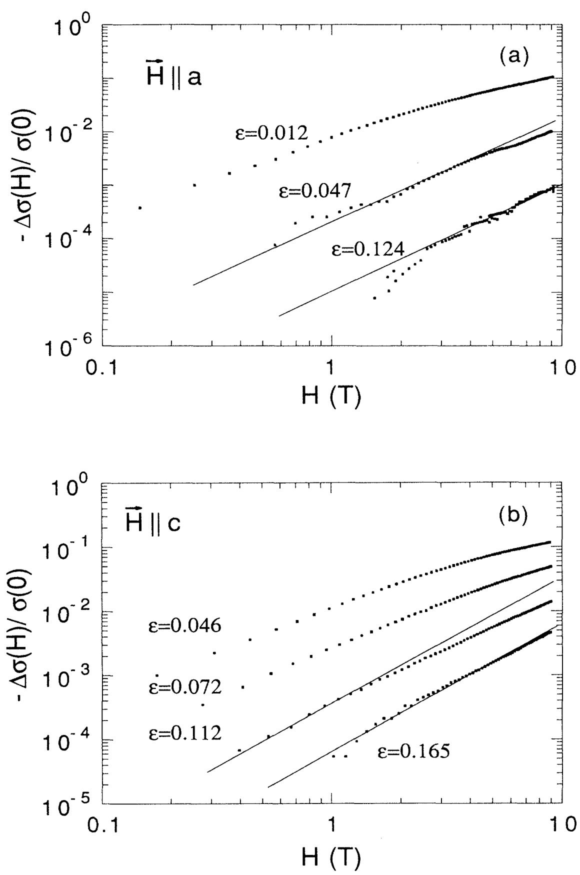

FIG. 2. Typical normalized magnetoconductivity for sample 1 as a function of applied field for $\mathbf{H}\|a$ (a) and $\mathbf{H}\|c$ (b) are shown. The reduced temperature $\varepsilon = \ln(T/T_c)$ was obtained using T_c as the zero-field transition temperature listed in Table I. Solid lines represent H^2 dependence.

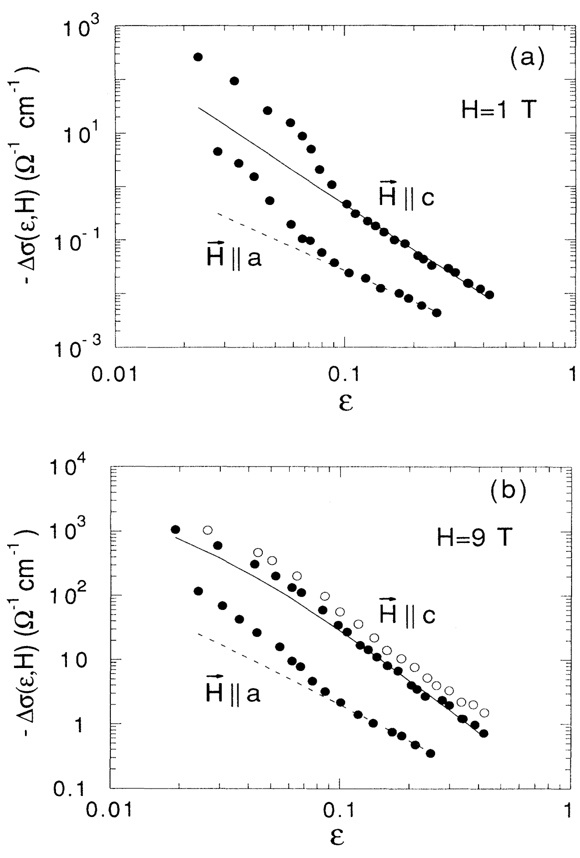

FIG. 3. Magnetoconductivities for $H = 1$ (a) and 9 T (b) for sample 1 (solid circle) as a function of the reduced temperature are shown. Solid curves ($\mathbf{H}\|c$) and dashed curves ($\mathbf{H}\|a$) are the best fits to the fluctuation theory described in the text. A significant deviation from the theoretical prediction is observed for $\varepsilon < 0.1$ for both field orientations. The data of sample 2 (open circle) are shown only for $\mathbf{H}\|c$ and 9T for comparison. They display very similar trend to those of sample 1.

phase-relaxation rate, $1/\tau_\phi$, is equivalent to the electron inelastic-scattering rate, $1/\tau_i$, we can apply the usual expression for metals at low temperatures, i.e., $1/\tau_\phi \approx 1/\tau_i = C_{e\text{-}e}T + C_{e\text{-ph}}T^3$ [17,20], with $C_{e\text{-}e}$ and $C_{e\text{-ph}}$ electron-electron and electron-phonon scattering rates, respectively. If we fit the data with a dominant electron-phonon scattering rate, proportional to T^3,[17,20] the phase-relaxation rate is smaller in a magnetic field than for zero field: this behavior is not expected, since fields should act as an additional pair breaker. Hence, we rule out strong electron-phonon scattering in the fluctuation regime, and retain the above values for δ and g.

C. Magnetoconductance for H‖c

For **H**‖c, the H^2 dependence of $\Delta\sigma(H)$ was also observed up to 1 T and higher [Fig. 2(b)] for the temperature range $\varepsilon > 0.1$. To analyze this data, the Zeeman terms determined above are subtracted out, and the remainder is fit to the orbital terms [Eqs. (3) and (4)]. With determined α, δ, and c, the single parameter, $\xi_{ab}(0)$ is varied to obtain a best fit for 11.5 ± 0.4 Å for sample 1 and 12.2 ± 0.3 Å for sample 2. $\Delta\sigma(H)$ for sample 2 is higher, but a larger c value partially compensates to give rise to the similar $\xi_{ab}(0)$. Only data for $\varepsilon > 0.1$ was used, since for $\varepsilon < 0.1$, the condition of $h/\varepsilon \ll 1$ for these small-h-limit formulas [Eqs. (3) and (4)] may break down. To overcome this, the ALO expression, which is dominant over the MTO term for small ε (Note that for small $\varepsilon < \delta$, the AL term is more important than the MT term, e.g., in a 2D theory, the ratio of the MT term to the AL term goes to zero at $\varepsilon = 0$, is two at $\varepsilon = \delta$, and diverges logarithmically for $\varepsilon \gg \delta$), was calculated including the higher order terms in h,[1] and the parameters obtained from the fit for $\varepsilon > 0.1$ are used in the calculation. The results, shown as solid curves for sample 1 in Fig. 3, also deviate from theory for $\varepsilon < 0.1$, as for the **H**‖a case.

D. Discussion

Although the experimental results deviate from theory for $T_c < T < T_c + 10$ K, we have established the parameters which give the best overall agreement of our MC data in the HTS $Tl_2Ba_2CaCu_2O_x$ within the conventional Al and MT theories. We discuss the implications of these parameters individually, and then possible sources of the deviation. The conductivities and $\Delta\sigma(H)$ differ for two samples by about a factor of 2, but the physical parameters, such as $1/\tau_\phi$, $\xi_{ab}(0)$ and the g factor turn out to be very close to each other indicating those are intrinsic properties of the materials. Such behavior also suggests that an error in determining the dimensions of the strips due to the rough surfaces could be partially responsible for the factor-of-2 difference in σ and $\Delta\sigma(H)$.

The phase-relaxation rate for two samples, determined from the data for **H**‖a and the zero field, is proportional to T with $1/\tau_\phi \approx 3.5 \pm 0.5 \times 10^{13}$ sec^{-1} at T_c. Such a large inelastic-scattering rate is expected because of the strongly temperature-dependent normal-state resistivity in HTS materials. Lemberger and Coffey[13] estimated $1/\tau_\phi \approx 3.0 \times 10^{13}$ sec^{-1} near T_c for $YBa_2Cu_3O_{7-x}$ using a simple Drude picture with known band structure, and Matsuda *et al.*[6] found $1/\tau_\phi \approx 1.0 \times 10^{13}$ sec^{-1} at 100 K in $YBa_2Cu_3O_{7-x}$ films with a temperature dependence of either T or T^2. An implication of these large $1/\tau_\phi$ is that the contribution of the Maki-Thompson term in the fluctuation regime is not very important for the HTS materials. The temperature dependence of $1/\tau_\phi$ suggests that electron-electron scattering is dominant in the fluctuation regime.

We found it necessary to vary the g factor from 2 for consistency with the zero-field fit. Previous MC studies on $YBa_2Cu_3O_{7-x}$ films[5,6] used $g = 2$, but did not include the zero-field data in the analysis, so further comparison is not possible.

The coherence length $\xi_{ab}(0) \approx 11.8 \pm 0.4$ Å found here is nearly equal to that of $YBa_2Cu_3O_{7-x}$,[5,6] and implies upper-critical-field slopes at T_c of ~ 2.3 T/K from the Ginzburg-Landau formula. Magnetization measurements, which give $H_{c2}(T)$, have not been reported for $Tl_2Ga_2CaCu_2O_x$, but a value of ~ 2 T/K is found for $YBa_2Cu_3O_{7-x}$.[15]

The parameters $c = e^2/16\hbar d = 40$ and 60 Ω^{-1}cm^{-1}, which actually measure the width of the resistive transition, are smaller than the 104-Ω^{-1}cm^{-1} value corresponding to d being the CuO layer spacing of $d = 14.7$ Å. There can be two possible explanations. First, the resistivity can be overestimated by using the macroscopic dimensions of the film if the ratio of the actual film cross section to length is smaller due to inhomogeneous current paths. This will lead to an effective narrowing of the transition, but it should be noted that morphological inhomogeneities usually act to broaden the transition. Second, the clean limit expression used to derive the prefactors of Eqs. (1)–(3) may not work in this material resulting in an ambiguity in the overall factor.[21]

We now turn to the deviation of the MC from the theoretical prediction below $T < 112$ K ($\varepsilon > 0.1$). It is seen as an enhancement of the negative MC which corresponds to excess dissipation. Since the MC of $YBa_2Cu_3O_{7-x}$ showed good agreement with Eqs. (3)–(6) down to $\varepsilon = 0.05$, [6] the excess dissipation could be a material (or sample) property. Assuming the cause is a distribution of T_c in the sample, would require $\Delta T_c \sim \pm 10$ K, which seems unlikely since the zero-field data agree to within ~ 2 K of T_c as shown in Fig. 1. Therefore the deviation must be a magnetic field effect other than an orbital motion or the Zeeman effect. Note that for **H**‖c and 9 T, the data are closer to the theory presumably due to the fact that the reduction of $T_c(H)$ is the greatest in this case. Hence the deviation could be more spread out.

Another explanation is that the mean-field results become inapplicable, in the critical region where fluctuations are large, so that the Gaussian approximation of the AL term breaks down and interaction terms quartic in Ψ are needed to obtain the magnitude of the fluctuations. Recently Ikeda, Ohmi, and Tsuneto[21] suggested that critical fluctuations become important for

$$\varepsilon < \left[\frac{k_B H}{\Delta C \phi_0 \xi(0)} \right]^{2/3} , \tag{8}$$

which is the so-called Ginzburg criterion modified for the strong field case. Here $\phi_0 = hc/2e$ is the flux quantum, ΔC is the specific heat jump, and $\xi(0)$ is the coherence length along H. They found an extra dissipation, at the resistive transition of $YBa_2Cu_3O_{7-x}$ for $\mathbf{H} \| c$ and $T < 95$ K, when compared to the theoretical prediction based on the Gaussian approximation, which is well described by including a $|\Psi|^4$ interaction term. Unfortunately, the data by Matsuda *et al.*[6] are not available in the critical region below $\varepsilon \approx 0.05$ ($T \approx 95$ K) for further comparison.

One expects $Tl_2Ba_2CaCu_2O_x$ to show stronger fluctuations than $YBa_2Cu_3O_{7-x}$ because of the shorter ξ_c and hence more ideal 2D behavior. Therefore, it is possible that the critical region may reach as high as $\varepsilon \approx 0.1$ in this material, but the lack of information about ΔC prevents any quantitative estimation of the critical region. For $\mathbf{H} \| a$, the critical region determined by Eq. (8) is reduced by a factor of $(\xi_c/\xi_{ab})^{2/3}$ compared to the case of $\mathbf{H} \| c$, and it is in disagreement with the experiments where comparable deviations are also observed for $\mathbf{H} \| a$ near $\varepsilon \approx 0.1$. However, an extension of the Ginzburg criterion to the layered structure may not be applicable particularly to this orientation in highly anisotropic $Tl_2Ba_2CaCu_2O_x$.

For a superconductor in a magnetic field, the motion of quantized flux lines gives rise to dissipation. Above T_c the superconducting order parameters are still correlated over a distance of $\sim \xi(T)$, thus vortices can exist in a local fluctuating superconducting patch. But there is experimental evidence to rule out this possibility: there is no linear dependence of the magnetoresistivity on H (see Fig. 2) as expected from the Bardeen and Stephen[22] theory; and there is no Lorentz-force dependence of the MC for $\mathbf{H} \| a$ [as found also for $T < T_c$ (Ref. 23)].

IV. CONCLUSIONS

Measurement of magnetoconductance in the highly anisotropic high-temperature superconductor, $Tl_2Ba_2CaCu_2O_x$, above T_c for $\mathbf{H} \| a$ and $\mathbf{H} \| c$ showed good agreement with recent theoretical expressions for the layered superconductors for the temperature range $T_c + 10$ K $< T < 160$ K. From this fit, we obtain that $\xi_{ab}(0) \approx 11.8 \pm 0.4$ Å and $1/\tau_\phi \approx 3.5 \pm 0.5 \times 10^{13}$ sec^{-1} at T_c with a temperature dependence of $\sim T$. However, it was necessary to use a g value of ~ 1.7, rather than 2, in order to achieve consistency between the zero- and finite-field results. The same quality of the fit with pure 2D formulas indicates that $Tl_2Ba_2CaCu_2O_x$ is very close to the ideal 2D system. In addition, for $T_c < T < T_c + 10$ K, there was a significant deviation from the theory. Various causes, including sample inhomogeneity, critical fluctuations, and flux motion, were considered, but could not give an adequate explanation.

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