Absence of the Zeeman Effect on the Maki-Thompson Fluctuation in Magnetoresistance of $YBa_2Cu_3O_7$ Single Crystals

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We experimentally demonstrated the absence of the Zeeman effect on the Maki-Thompson fluctuation (MZT) in the Aronov-Hikami-Larkin theory. Moreover, we find that clean-limit analysis without the MTZ component closely fits the experimental data. Our analysis provides a quantitatively consistent picture of Y-Ba-Cu-O including transport and optical studies.

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It is very important to study the intrinsic carrier dynamics in the CuO_2 plane to understand the mechanism of high-T_c superconductivity. Recently, Aronov, Hikami, and Larkin (AHL) proposed a theory of fluctuation-induced magnetoresistance [1], including the Zeeman effect on the Aslamazov-Larkin (AL) fluctuation and the Maki-Thompson (MT) fluctuation. Especially, the MT term includes the Cooper-pair phase relaxation time τ_ϕ. It provides information on the strength of the pair-breaking interaction in a high-T_c superconductor. Though the $YBa_2Cu_3O_7$ (YBCO) superconductor is thought to be in the clean limit [2] [$l \gg \xi_{ab}(0)$], magnetoresistance studies hitherto reported are mostly analyzed assuming the applicability of the dirty-limit [$l \ll \xi_{ab}(0)$] approximation [1,3,4] where l is the carrier mean free path (~110 Å at 100 K) and $\xi_{ab}(0)$ is the in-plane Ginzburg-Landau coherence length at 0 K. Bieri and Maki [5] proposed a clean-limit theory of fluctuation-induced magnetoresistance and they tried a clean-limit theory of fluctuation-induced magnetoresistance and they tried a clean-limit analysis using the data of a c-axis-oriented film [3]. However, the larger the $l/\xi_{ab}(0)$ value they chose, the worse their analysis became. In this sense, the understanding of the fluctuation-induced magnetoresistance in YBCO is far from complete.

On the other hand, from the theoretical point of view, the existence of the MT-Zeeman effect in the form of the AHL theory itself is a subject for discussion [6]. One of the main purposes of this work is to clarify this point experimentally.

We measured for the first time the anisotropic magnetoresistance of YBCO bulk single crystals. Our analysis showed no evidence of MTZ contribution in the form of the AHL theory, contrary to the early thin-film experiment [1,3]. At the same time, the clean-limit theory gives an excellent fit to the experiment. These results show that the paraconductivity observed in the YBCO can be well described by the conventional fluctuation theory based on the Fermi-liquid theory. In the following sections, the experimental details, the result of the analysis, and the relevance to the other transport properties will be discussed.

The samples used in this experiment are YBCO single crystals grown within the partial melting region of the ternary phase diagram [7]. We used a Pt crucible. A typical sample dimension is 1 mm×3 mm×0.04 mm. As-grown samples are oxygenated by annealing in an O_2 gas flow of 2.5 liter/min at 500 °C for 100 h, and then measured with a dc SQUID magnetometer at ~3 Oe to check the bulk superconductivity. The crystal is fixed on a sapphire plate and gold wires are attached with gold paste. It is annealed at 850 °C to reduce the contact resistance to less than 0.2 Ω and then reoxygenated under the same conditions as the first annealing.

Applying the four-probe method, resistivity and magnetoresistance were measured under a magnetic field of up to 12 T. The zero-field ac (63 Hz) resistivity of a sample is shown in Fig. 1. Characteristic T-linear resistivity is clearly observed, which guarantees the high quality of these samples. Some important data on the sample

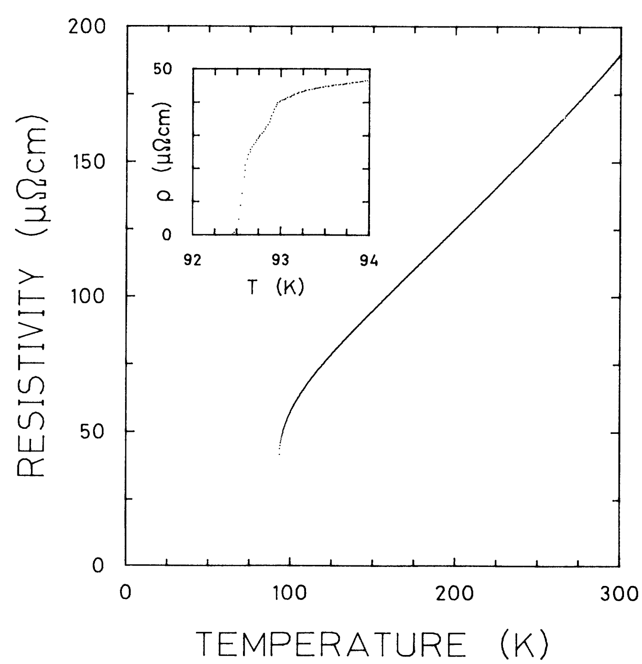

FIG. 1. ac (63 Hz, I=0.83 mA) resistivity of the YBCO bulk single crystal. Inset: Expanded view around T_c.

are listed in Table I.

Instead of the zero-field fluctuation-induced conductivity $\Delta\sigma(T)=\sigma(T)-\sigma_0(T)$, we measured the magnetoconductivity $\Delta\sigma(T,H)=\sigma(T,H)-\sigma(T,0)$. Here $\sigma_0(T)$ is the conductivity without superconducting fluctuation. Since there is no way of estimating $\sigma_0(T)$ experimentally, it is impossible to determine it as accurately as the theoretical analysis requires. However, this method raises another uncertainty, that is, whether all the $\Delta\sigma(T,H)$ comes from the superconducting fluctuation. Hereafter we assume that all of the observed $\Delta\sigma(T,H)$ comes from the superconducting fluctuation.

Each sample was mounted on a rotatable copper block with Apiezon grease. The direction of the magnetic field parallel to the CuO_2 plane was determined from the direction of minimum T_C shift in a field of 1 T. Even in the magnetic field, the sample temperature was held to an accuracy of 10 mK by capacitance sensor control. Magnetoresistance measurements were carried out by an ordinary dc method. At each temperature, we calculated the maximum magnetic-field strength $H_{\max}$ below which we could use the lowest-order H^2 term in a weak-field expansion of the magnetoconductivity $\Delta\sigma(T,H)$. The field-induced changes in ρ at 1 T^2 were calculated by the least-squares method as the slope of ten data points taken at even intervals in H^2 up to $H^2_{\max}$ because, in a weak magnetic field, $\Delta\rho(H)$ is proportional to H^2. Each data point is the average of from five to eighteen voltage values. By this method, $\Delta\rho(H)/\rho(0)$ of 1 part in 10^{-6} is detectable at 1 T^2.

The fluctuation-induced magnetoresistance is given in terms of two different types of collective-mode diagrams, i.e., the Aslamazov-Larkin (AL) term and the Maki-Thompson (MT) term. The Al fluctuation is not sensitive to whether a system is in the clean limit or not. On the other hand, the MT fluctuation is considerably more sensitive to carrier mean free path by way of the vertex renormalization effect. Each type of fluctuation is again divided into two groups. The first originates from orbital angular momentum, AL-orbital (ALO) and MT-orbital (MTO), and the second from spin angular momentum, AL-Zeeman (ALZ) and MT-Zeeman (MTZ). Following Bieri and Maki [5], we use the clean-limit form of the AHL theory [1]:

$$\Delta\sigma_{\mathrm{ALO}}=-\frac{e^2}{64\hbar d\epsilon^3}\frac{2+4\alpha+3\alpha^2}{(1+2\alpha)^{2.5}}h^2, \tag{1}$$

$$\Delta\sigma_{\mathrm{MTO}}=-\frac{e^2}{48\hbar d(1-\alpha/\delta)\epsilon^3}\left[\frac{\delta^2}{\alpha^2}\frac{1+\delta}{(1+2\delta)^{1.5}}-\frac{1+\alpha}{(1+2\alpha)^{1.5}}\right]h^2, \tag{2}$$

$$\Delta\sigma_{\mathrm{ALZ}}=-\frac{7\zeta(3)}{16}\frac{e^2}{\hbar d\epsilon^2}\frac{1+\alpha}{(1+2\alpha)^{1.5}}\left[\frac{\omega_s}{4\pi k_B T_c}\right]^2, \tag{3}$$

$$\Delta\sigma_{\mathrm{MTZ}}=\frac{e^2}{8\hbar d\epsilon}\left[\frac{\omega_s\tau_\phi}{\hbar}\right]^2\left[\frac{1}{1-\alpha/\delta}\right]\left[-\left(\frac{\alpha}{\delta}\right)^2\frac{1}{(1-\alpha/\delta)^2}\ln\left(\frac{\delta}{\alpha}\frac{1+\alpha+(1+2\alpha)^{1/2}}{1+\delta+(1+2\delta)^{1/2}}\right)-\frac{1}{2}\frac{1+\delta}{(1+2\delta)^{3/2}}+\frac{1}{(1+2\delta)^{1/2}}\frac{1}{1-\alpha/\delta}\left(\frac{\alpha}{\delta}\right)\right]. \tag{4}$$

Here, the reduced temperature is $\epsilon=(T-T_c)/T_c$, $\alpha=2\xi_c^2(0)/d^2\epsilon$, $\delta=1.203[l/\xi_{ab}(0)]\{16\xi_c^2(0)\tau_\phi T/\pi d^2\hbar\}$, $h=2e\xi_{ab}^2(0)H/\hbar$, interlayer spacing $d=11.65$ Å, and Zeeman energy $\omega_s=g\mu_B H$, where μ_B is the Bohr magneton and we use $g=2$. Equations (1)-(4) are derived by modeling YBCO as a quasi-two-dimensional superconductor weakly coupled in the c-axis direction. Each double CuO_2 layer including CuO chains is replaced by a single fictitious superconductive layer. The layer to which derived coherence lengths are parallel (ξ_{ab}) and perpendicular (ξ_c) is this fictitious layer. We neglect the contribution from the interlayer orbital motion. In a perpendicular field $H_{\perp ab}$, the measured magnetoconductivity will be the sum of all terms, $\Delta\sigma_\perp=\Delta\sigma_{\mathrm{ALO}}+\Delta\sigma_{\mathrm{MTO}}+\Delta\sigma_{\mathrm{ALZ}}+\Delta\sigma_{\mathrm{MTZ}}$, while in a parallel field $H_{\parallel ab}$, only the Zeeman terms will be detectable, $\Delta\sigma_\parallel=\Delta\sigma_{\mathrm{ALZ}}+\Delta\sigma_{\mathrm{MTZ}}$.

The temperature dependence of ALZ and MTZ are different, $-\Delta\sigma_{\mathrm{ALZ}}\propto\epsilon^{-1.5}$ (notice $\alpha\propto\epsilon^{-1}$) and $\Delta\sigma_{\mathrm{MTZ}}\propto\epsilon^0(\epsilon\to 0)\sim\epsilon^{-1}(\epsilon\to 1)$. In Fig. 2 experimental data on the YBCO single crystal are shown. The $\epsilon^{-1.5}$ dependence on the parallel-field data $-\Delta\sigma_\parallel$ over the measured temperature range $(0.002<\epsilon<0.2)$ is clearly observed. This temperature dependence is that of ALZ itself. The magnitude of our $-\Delta\sigma_\parallel$ data is about one-fifth that of the film data [3] (at $\epsilon\sim 0.1$). We confirmed the $-\Delta\sigma_\parallel\propto\epsilon^{-1.5}$ temperature dependence in the other single crystal (not shown). Using our data, the upper limit of MTZ contribution at 1 T is estimated as $|-\Delta\sigma_{\mathrm{MTZ}}|<0.01$ $\Omega^{-1}\mathrm{cm}^{-1}$. This upper limit value is roughly $\frac{1}{20}$ of the

TABLE I. Some characteristic values of the YBCO bulk single crystal. A C factor was not used (i.e., $C=1$).

T_c (K)	ΔT_c (K)	ρ ($\mu\Omega$ cm) at 100 K	$d\rho/dT$ ($\mu\Omega\,\mathrm{cm\,K^{-1}}$)
92.3	0.3	67	0.76

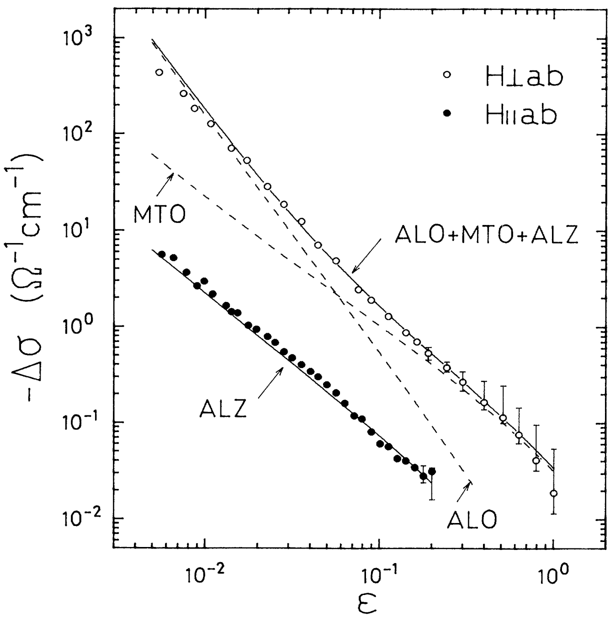

FIG. 2. Experimental data of the magnetoconductivity $-\Delta\sigma = -[\sigma(H)-\sigma(0)]$ at $H=1$ T vs reduced temperature $\epsilon=(T-T_c)/T_c$. A clean-limit ALO+MTO+ALZ fitting is also shown. The parallel-field ($H_{\parallel ab}$) data $-\Delta\sigma_{\parallel} \propto \epsilon^{-1.5}$, indicating the absence of MTZ fluctuation in the AHL theory. The fitting parameters $\xi_{ab}(0)=13.3$ Å, $\xi_c(0)=3.8$ Å, and $\tau_\phi=5.4\times10^{-14}$ s at $T=100$ K are used. τ_ϕ is assumed to have temperature dependence of $\tau_\phi \propto T^{-1}$.

MTZ terms in the early analysis [1,3,5] using the c-axis-oriented film data of Matsuda *et al.* [3]. It was impossible to obtain reasonable parameters when including the MTZ term in the analysis, so we decided to analyze without the MTZ term.

In Fig. 2 we show the result of our analysis using the three-component fluctuation model (ALO+MTO+ALZ) in the clean limit. Fitting is excellent. We chose $\xi_{ab}(0)$, $\xi_c(0)$, and τ_ϕ as fitting parameters. In a clean-limit analysis, we must consider the temperature dependence of the coherence length of the fluctuating Cooper pair [5,8]: $\xi \propto T^{-1}$ $(T>T_c)$. At T_c, it becomes the $\xi_{\mathrm{GL}}(0)$. τ_ϕ is assumed to have a temperature dependence of T^{-p}. Table II presents the parameters obtained. The coherence length perpendicular to the layer, ξ_c, is almost uniquely determined from the $-\Delta\sigma_{\parallel}$ data as $\xi_c(0)=3.8 \pm 1.0$ Å. The coherence length parallel to the layer is obtained as $\xi_{ab}(0)=13.3\pm0.05$ Å. The phase relaxation time obtained is $\tau_\phi=(5.4\pm0.5)\times10^{-14}$ s at 100 K, with $\tau_\phi \propto T^{-1}$ $(p=1)$ the temperature dependence. This τ_ϕ is about half that obtained in the early analysis [1,3]. The mean free path l is obtained from $l=v_F\tau_{\mathrm{tr}} \approx v_F\tau_\phi$, where τ_{tr} is the transport mean free time. The Fermi velocity is obtained as $v_F \sim 2\times10^7$ cm/s from the experimental value of the in-plane energy gap [9] $2\Delta/k_BT_c \sim 8$ and the relation $\xi_{ab}(0) \sim \hbar v_F/\pi\Delta$. The derived mean free path $l \approx v_F\tau_\phi \sim 110$ Å at 100 K confirms the validity of the clean-limit analysis $[l \gg \xi_{ab}(0)]$. We assume $\tau_\phi \approx \tau_{\mathrm{tr}}$ including the anomalous T^{-1} temperature dependence, because we think the T-linear dependence in ρ or τ_{tr}^{-1} indicates that the scattering in question is an energy relaxation type, and therefore it equally contributes to the Cooper-pair phase relaxation process. The transport relaxation time is known [10] to be $\tau_{\mathrm{tr}} \cong \hbar/1.35k_BT$. From this relation, $\tau_{\mathrm{tr}} \sim 5.6\times10^{-14}$ s at 100 K is obtained. This τ_{tr} value supports our assumption. Using the Hall carrier density [11] at 100 K, $n_H=(4\pm0.6)\times10^{21}$ cm^{-3}, the Drude effective mass of the carrier is estimated to be $m^* \sim 3.5m_e$, which is consistent with the recent estimation from an infrared light reflectivity measurement [9]. Thus, the experimental values of optical and transport studies including the magnetoresistance begin to converge quantitatively. It is necessary to draw a correct physical picture of YBCO.

TABLE II. Obtained parameters including the mean free path l. $T=100$ K values are shown for τ_ϕ and l. τ_ϕ is assumed to have a temperature dependence of $\tau_\phi \propto T^{-p}$.

$\xi_{ab}(0)$ (Å)	$\xi_c(0)$ (Å)	τ_ϕ (10^{-14} s)	p	l (Å)
13.3 ± 0.5	3.8 ± 1.0	5.4 ± 0.5	1	108 ± 10

Using the Abrikosov-Gor'kov theory [12], the transition temperature without pair-breaking interaction T_{c0} satisfies

$$\ln\left(\frac{T_c}{T_{c0}}\right)+\psi\left(\frac{1}{2}+\frac{\hbar\tau_\phi^{-1}(T_c)}{2\pi k_BT_c}\right)-\psi\left(\tfrac{1}{2}\right)=0, \quad (5)$$

where $\psi(z)$ is the digamma function. T_{c0} then becomes $\sim$210 K. Taking this value seriously, it is very interesting to identify the origin of the pair-breaking interaction and try to control it. If we apply the usual BCS equation to T_{c0}, $2\Delta/k_BT_{c0} \cong 3.5$, then we obtain $2\Delta/k_BT_c \cong 7.8$. This ratio is very close to the adopted experimental value $\sim$8. It indicates the consistency of our analysis.

We calculate the magnetoconductivity by simply taking the difference of the inverse resistivity. At high temperature $(\epsilon>0.5)$, a correction from the off-diagonal elements of the Hall tensor [6], $\Delta(\rho_{xy})^2 \sim (\omega_c\tau)^2$, may be required.

In summary, we measured the magnetoresistance of YBCO bulk single crystals, applying a magnetic field both parallel ($H_{\parallel ab}$) and perpendicular ($H_{\perp ab}$) to the CuO_2 plane. We found the parallel-field data $-\Delta\sigma_{\parallel}$ obeys $\epsilon^{-1.5}$ $[\epsilon=(T-T_c)/T_c]$, indicating the absence of the MTZ fluctuation in the AHL theory. Without MTZ, the ALO+MTO+ALZ model in the clean limit gives excellent agreement with the experimental data (shown in Fig. 2). The derived values are consistent with recent optical [9] and transport [10] studies of YBCO. The present study shows that the conventional theory of paraconductivity, which is based on the Fermi-liquid theory and applies well to ordinary superconductors, is equally applicable to high-T_c superconductors. This result strongly restricts the theory of high-T_c superconductivity.

After completing this work, we received the recent theoretical work of Bieri and Maki [8]. Their analysis concerning the absence of the MTZ term in the AHL theory is consistent with our experiment. However, it seems that the nonlocal effect given in their work is not needed to explain our data.

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