Magnetic–Field Induced Localization in the Normal State of Superconducting $La_{2-x}Sr_xCuO_4$

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Abstract

Magnetoresistance measurements of highly underdoped superconducting $La_{2-x}Sr_xCuO_4$ films with $x = 0.051$ and $x = 0.048$, performed in dc magnetic fields up to 20 T and at temperatures down to 40 mK, reveal a magnetic–field induced transition from weak to strong localization in the normal state. The normal–state conductances per CuO_2–plane, measured at different fields in a single specimen, are found to collapse to one curve with the use of a single scaling parameter that is inversely proportional to the localization length. The scaling parameter extrapolates to zero near zero field and possibly at a finite field, suggesting that in the zero–field limit the electronic states may be extended.

The unusual normal–state transport properties of high–T_c superconductors include strongly anisotropic resistivities, a temperature–dependent Hall effect, and anomalous magnetoresistance [1]. The character of the electronic ground state underlying superconductivity is the subject of experiment and speculation, and is expected to be different according to different models, with suggestions that it is insulating [2], or weakly localized in two dimensions (2D) [3], as recently reported in $La_{2-x}Sr_xCuO_4$ (LSCO) in very high magnetic fields [4].

Extremely high magnetic fields are required to quench superconductivity when the transition temperature is high. We have therefore investigated strongly underdoped, but still superconducting specimens, with values of T_c reduced below 4 K, in magnetic fields up to 20 T, at temperatures down to 40 mK. We show that the field localizes the carriers, leading to variable–range hopping at the highest fields and lowest temperatures, so that the behavior observed in strong fields is not a reliable guide to the nature of the zero–field electronic "ground state" in the absence of superconductivity.

We also show that the normal–state conductance per CuO_2 plane, measured at different fields in one specimen, may be collapsed to a single curve by adjusting a single scaling parameter. The scaling indicates a gradual transition from weak localization at low fields to strong localization at high fields, similar to the disorder–induced localization observed in conventional 2D and 3D metals and semiconductors [5–8]. However, within our experimental accuracy, the scaling parameter T_0, which is inversely proportional to the localization length, extrapolates to zero at fields that are close to zero and possibly finite, suggesting that in the zero–field limit the electronic state underlying superconductivity may be extended.

The specimens were c–axis aligned epitaxial films, grown by pulsed laser deposition on $SrLaAlO_4$ substrates [9]. They were patterned by photolithography, and silver pads were evaporated for four–point resistivity measurements. The magnetoresistance (MR) measurements were made in magnetic fields up to 20 T, generated by Bitter magnets, in two different low–temperature setups to check for consistency. One was a He^3 cryostat with dc measurements and temperatures down to 600 mK. The other was a dilution refrigerator in which

3 Hz–ac was used, with temperatures down to 40 mK. Most of the data were accumulated by sweeping the field. Several runs were also made by sweeping the temperature, and were found to be consistent with the others. The data from the two setups differred by less than 5%. This difference reflects slightly different field calibrations and small differences in current, and is insignificant for the discussion of this paper.

We measured two films with a nominal composition given by $x = 0.051$. The values of T_c, ρ and MR differred only slightly, so that we present the results for only one of them. It is designated as specimen S1, with a value of T_c of 3.8 K, and ab–plane resistivity, ρ_{ab}, at 40 K equal to 2.9 $m\Omega cm$. The temperature dependence of ρ_{ab} in zero field is shown in the inset of Fig. 1. We also measured the MR of a third film, S2, with nominal composition $x = 0.048$, and $T_c = 400$ mK, which was measured earlier up to 6 T [10].

In all cases the magnetic field was perpendicular to the ab–plane. In Fig. 1 ρ_{ab} for specimen S1 is plotted against $\ln T$ for fields from 7 to 10.6 T, and in Fig. 2 for fields from 7 to 20 T. It is apparent that the field gradually quenches superconductivity and induces a superconductor–insulator transition, similarly to the behavior described previously for specimen S2 [10], except for the higher fields that are necessary to suppress superconductivity in S1. In Ref. [10] we analyzed the nature of this S–I transition, and found that it differs from the Cooper–pair localization predicted by Fisher [11].

The inset to Fig. 2 shows ρ_{ab} for specimen S1, plotted as ln ρ_{ab} against $T^{-1/4}$. For the highest fields the data follow straight lines to $T^{-1/4} = 2$ (corresponding to $T = 60$ mK), consistent with 3D Mott variable–range hopping [12]. The slopes of the straight lines increase with increasing field, pointing to field–induced localization of the carriers. In the field and temperature range of this experiment the MR was positive for all films, approaching an approximately linear dependence on field at the highest fields. This differs from the results of Ref. [4] on single crystals of LSCO with $x = 0.08$ and 0.13, where the MR in the limit of high fields was found to be negative.

The saturation of ρ_{ab} below 60 mK is presumably a result of superconducting fluctuations. For lower fields the fluctuations occur at higher temperatures, and the T–dependence of ρ_{ab}

becomes weaker than exponential. It may be seen that for some fields and temperatures the T–dependence is close to $ln(1/T)$, as observed in Ref. [4] down to about 0.7 K. It is apparent, however, that this is only an intermediate stage in the gradual evolution from variable–range hopping to weakly localized and eventually metallic behavior, so that the logarithmic dependence by itself does not seem to have any special significance.

Fig. 3a shows the data for film S1 as a log–log graph of the conductance per single CuO_2 plane, G, against temperature, at different fields. We now adopt the scaling procedure used in several previous studies of disorder–induced localization in various 2D and 3D systems [5–8]. We find that shifting the data for the different fields along the $\ln T$–axis allows the collapse of the normal–state data to a single curve, as shown in Fig. 3b. In this procedure we plot the data against $\ln \alpha T$, where $\alpha(B)$ is set equal to one for $B = 20$ T, and chosen for other fields so as to superimpose the curves, as on Fig. 3b. The deviations on the low–T side result from superconducting fluctuations. The $\ln G$ scale is normalized by the constant G_{00}, equal to $e^2/2\pi^2\hbar$, to allow a direct comparison with the results of Ref. [6], where G_{00} was found to separate the strong and weak localization regimes in metallic disordered 2D films. We find variable–range hopping in the limit $G/G_{00} \ll 1$, changing to a weaker T–dependence as G/G_{00} approaches one. This behavior resembles the transition from strong to weak localization described in Refs. [5] and [6].

The strong–localization region is characterized by the parameter T_0 in the Mott variable–range hopping law, which is inversely proportional to the localization length. Since the conductance depends on temperature only in the combination T_0/T, a shift from T to αT is equivalent to a shift from T_0 to T_0/α, so that $T_0(B) = T_0(20\mathrm{T})/\alpha$. We therefore use the factor $\alpha(B)$, determined as the factor in the scaling procedure that superposes the curves on Fig. 3b, to determine also $T_0(B)$, even in the regime where the charge carriers are no longer strongly localized and Mott's law no longer applies. At some lower, possibly inaccessible temperature, Mott's law can be expected to hold again, with this value of T_0. This definition of T_0 allows us to plot the scaled conductance as a function of $\ln T/T_0$, as on the upper scale of Fig. 3b.

In Fig. 4 we plot the normal–state curve constructed in this way for the two films S1 ($x = 0.051$) and S2 ($x = 0.048$). In order to cause the two curves to be superimposed to form a single curve, it is necessary to rescale not only the horizontal, but also the vertical axis. This is different from the case of disorder–induced localization in metallic 2D films [5,6], where the conductance approaches a constant value, independent of disorder, in the high–T limit. This difference may be related to the fact that the metal–insulator transition in LSCO is inherently different, apparently driven primarily by band filling [13].

The figure also shows the data from Ref. [4], for an LSCO crystal with $x = 0.08$, in a pulsed field of 50 T, scaled to join the other curves at the high–T end of their data. It may be seen that for this specimen even the 50 T–field does not induce strong localization, and that the curve departs from the shape of the other two curves as the temperature is lowered. If, as stated in Ref. [4], the field is sufficient to suppress superconducting fluctuations, the curve from their data on Fig. 4 seems to indicate the likelihood of metallic character for their specimen. This conclusion differs from that of Ref. [4], where specimens up to the optimally doped, i.e. for values of $x \leq 0.15$, are said to be insulating. There are two reasons for the difference in our conclusions. First, Ando *et al.* characterize a specimen as "insulating" when the slope of $R(T)$ is negative, while we use the much more stringent criterion that there must be a finite value for T_0 and hence for the localization length. Second, as we show, the localization in the field does not necessarily imply localization in the absence of a field. These differences in interpretation are not likely to be affected by differences in the specimen characteristics, such as that implied by the negative MR of the specimen of Ref. [4], which suggests differences in spin scattering, presumably resulting from differences in structure and composition.

Strict adherence to scaling would lead to the conclusion that the transition to strong localization must take place regardless of the value of the magnetic field. It must be remembered, however, that the scaling procedure superimposes curves for different fields, and is valid only as long as the magnetic field dominates the localization. The validity of the scaling procedure breaks down when the field becomes so small that the magnetic length,

$\sqrt{c\hbar/eH}$, becomes larger than other scattering lengths, and other processes dominate.

In order to assess what happens at small fields we plot T_0 as a function of B for specimens S1 and S2 in Fig. 5, using the values determined by the scaling procedure. The random errors associated with the scaling procedure are about the size of the data points. There is also a systematic error resulting from the fit of the hopping expression at the highest fields, indicated by the error bars at the highest–field points. We find that the best description of the field variation is given by the power law shown in Fig. 5 by the dashed lines, $T_0(B) = A[(B - B_{cr})/B_{cr}]^\nu$, with the parameter B_{cr} equal to 2.5 ± 0.5 and 1.1 ± 0.2 for samples S1 and S2 respectively, A equal to 19.3 ± 3.9 and 65.7 ± 14.0, and ν essentially the same in both samples, 0.64 ± 0.04 and 0.62 ± 0.06. Taken literally this formula suggests that there is a finite field, B_{cr}, below which T_0 is equal to zero, a field below which the electronic states would be extended and at which a metal–insulator transition would then take place. Experimentally the region near B_{cr} is masked by superconducting fluctuations, so that the extrapolation must be treated with caution. Nevertheless this analysis of the data suggests the possibility that in the zero–field limit the electronic states in these two specimens may indeed be extended.

In summary, we find that the magnetic field induces a transition from weak to strong localization in LSCO, in many respects similar to the disorder–induced transition in conventional disordered systems. The extrapolation to zero magnetic field suggests that the extrapolated electronic "ground state" in the absence of superconductivity is extended rather than localized.

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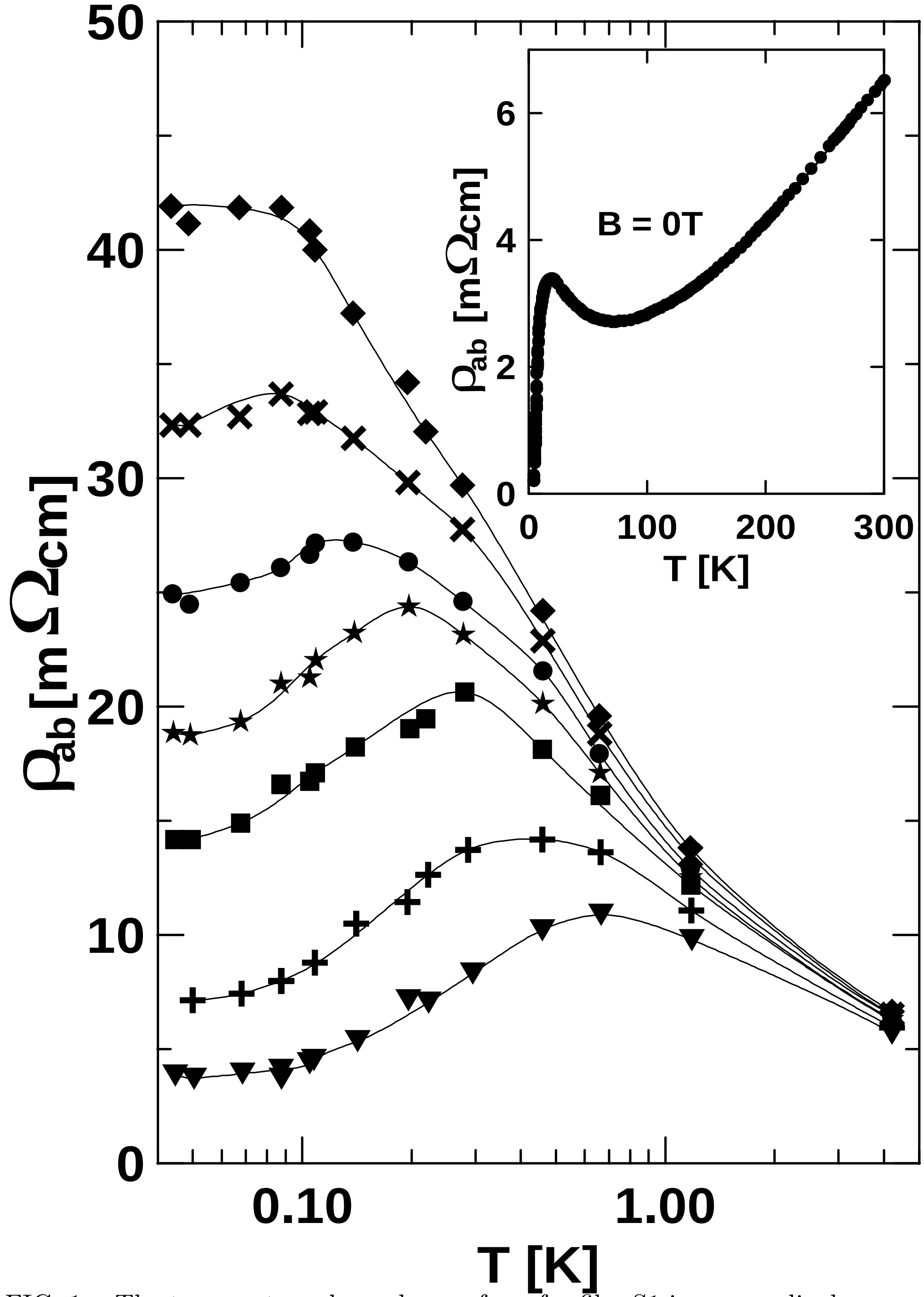

FIG. 1. The temperature dependence of ρ_{ab} for film S1 in perpendicular magnetic fields. The fields are, from below, 7, 8, 9, 9.4, 9.8, 10.2, 10.6 T. The open circles between $T = 0.7$ K and $T = 1$ K show the data obtained with dc as explained in the text. The lines are guides to the eye. The inset shows $\rho_{ab}(T)$ in zero field.

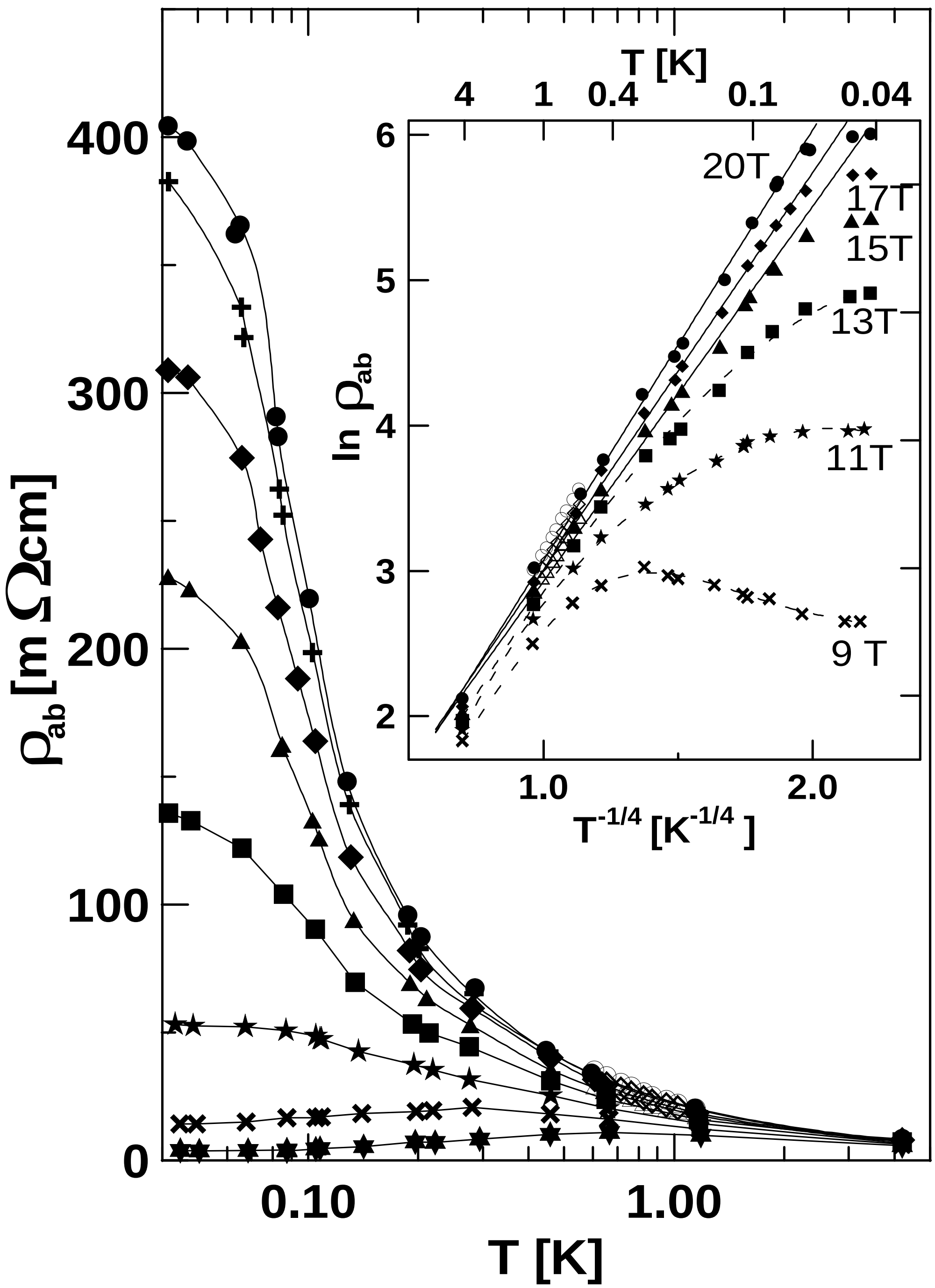

FIG. 2. The temperature dependence of ρ_{ab} for film S1 in perpendicular magnetic fields. The fields are, from below, 7, 9, 11, 13, 15, 17, 19, and 20 T. The open circles between $T = 0.7$ K and $T = 1$ K show the data obtained with dc as explained in the text. The lines are guides to the eye. The inset shows $\ln \rho_{ab}$ versus $T^{-1/4}$ for several magnetic fields.

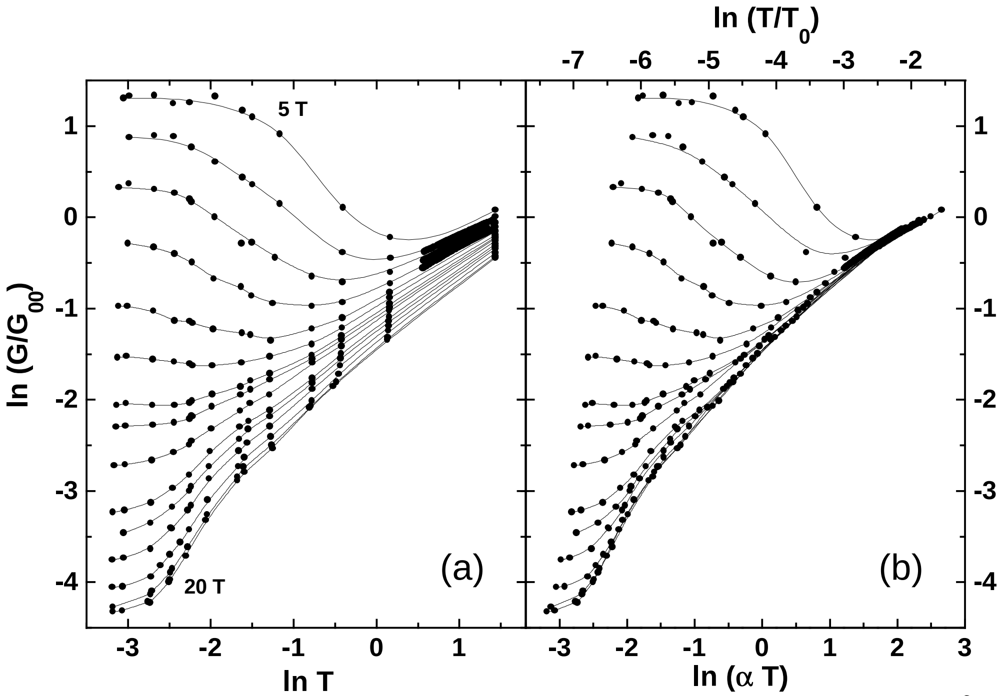

FIG. 3. Conductance per single CuO_2 plane, G, normalized to $G_{00} = e^2/2\pi^2\hbar$ for film S1 in magnetic fields ranging from 5 T (topmost curve) to 20 T (lowest curve), plotted (a) versus temperature on a logarithmic scale, and (b) versus temperature scaled by the factor $\alpha(B)$, or, equivalently (upper scale), by $T_0(B)$.

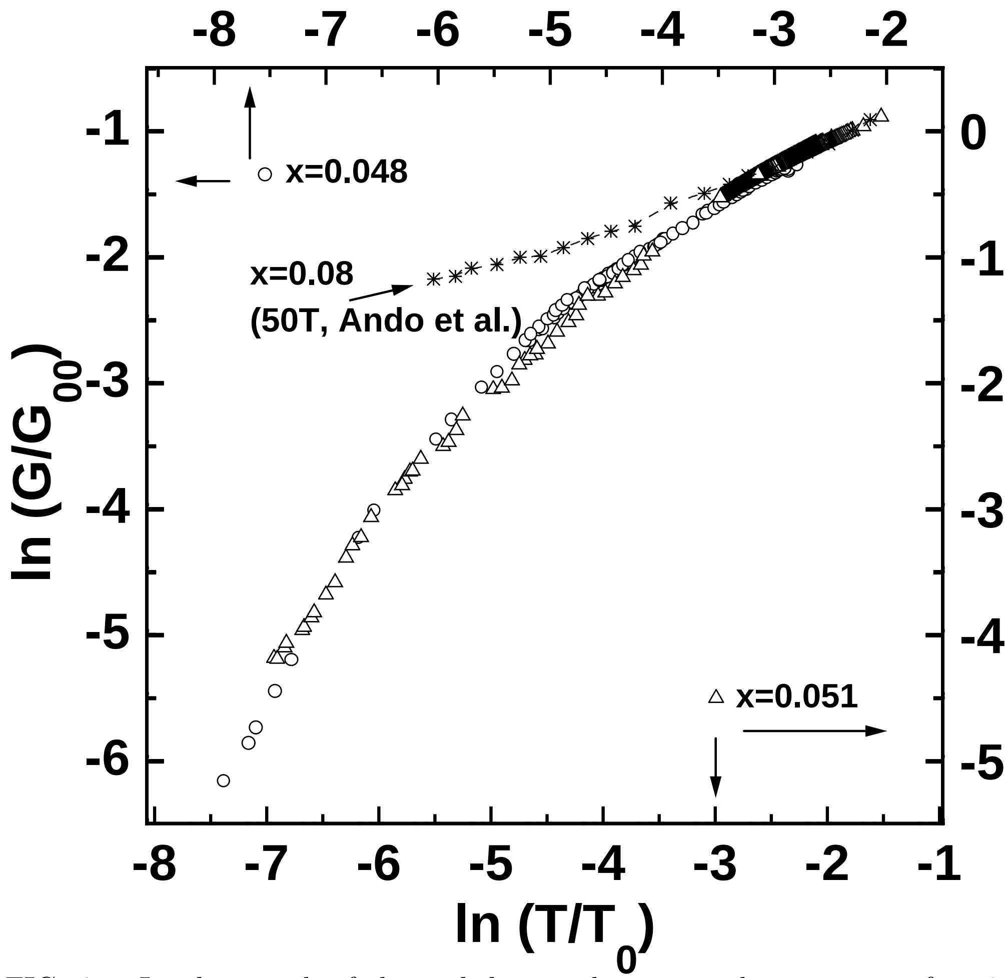

FIG. 4. Log-log graph of the scaled normal–state conductance as a function of the scaled temperature for films S1 and S2, and for the single crystal from Ref. [4].

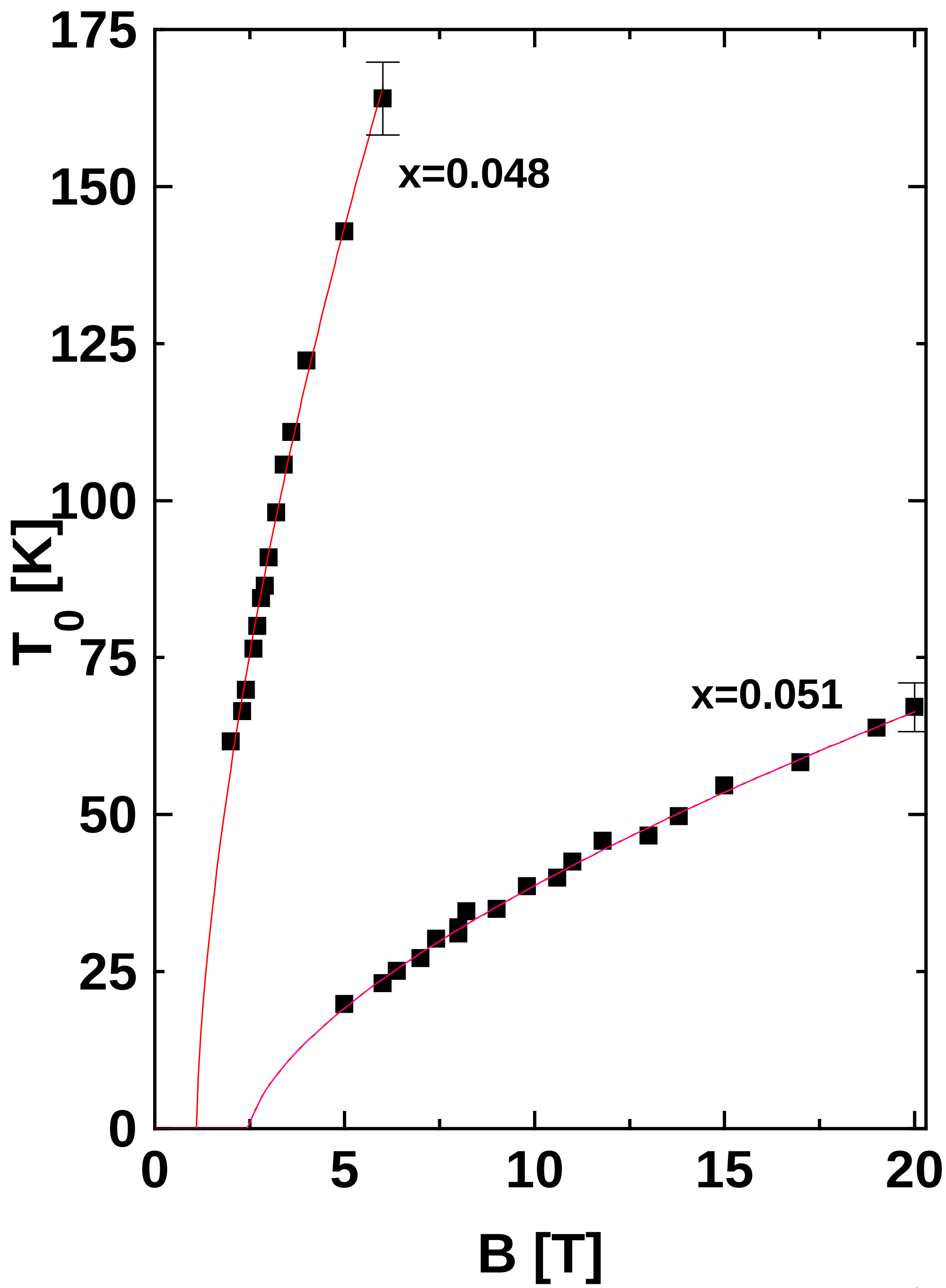

FIG. 5. The dependence of the parameter T_0 on magnetic field for films S1 ($x = 0.051$) and S2 ($x = 0.048$). The error bars show the uncertainty resulting from the fit of the Mott relation to the data for the highest magnetic field. The dashed lines show the expression $T_0 = A[(B - B_{cr})/B_{cr}]^{\nu}$, fitted to the data, with the parameters A, B_{cr}, and ν, as described in the text.