Dissipation mechanism in a high-T_c granular superconductor: Applicability of a phase-slip model

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The magnetoresistance and *I-V* characteristics for the 110-K phase of a polycrystalline Bi-Pb-Sr-Ca-Cu-O superconductor are reported. The Josephson-junction model of Ambegaokar and Halperin fits well to the data and yields the temperature and field dependence of the phase-slip activation energy U_0. The field dependence of U_0 is explained by Fraunhofer interference under magnetic field within weak links originated from the sample microstructure. We suggest that this model may have general applicability to dissipation in both granular and single-crystal materials.

Recent attention has focused on the question of how one may characterize the dissipative behavior of the high-T_c superconducting oxides just below T_c, with or without an applied magnetic field. A subtler issue is whether or not polycrystalline and single-crystal material can be described by the same phenomenological picture for this behavior. Palstra *et al.*,[1] using single-crystal material, have pointed out that a thermally activated flux creep model describes the data quite well for very low levels of the resistivity. They found a temperature-independent energy barrier U_0 and obtained its field dependence from the slopes of the Arrhenius resistivity plots. The physical picture here separates a flux creep regime when $U_0 \gg k_B T$ from a flux flow regime when thermal energies become comparable to barrier heights.

An alternative approach to the problem of vortex motion has been to apply the model of Ambegaokar and Halperin[2] (AH) to a medium of Josephson weak links regarded as a single effective junction.[3,4] The AH model describes the effects of thermal fluctuations of the phases of the order parameters across a highly damped, current driven Josephson junction. Both granular and single-crystal high-T_c materials have been examined from this point of view.[3,4] In particular, Tinkham[4] has discussed magnetoresistance using the AH model, although he phenomenologically derived the magnetic-field dependence of U_0 as proportional to H^{-1}.

Using material of nominal composition $Bi_{1.7}Pb_{0.2}Sb_{0.1}Sr_2Ca_2Cu_3O_{10}$, we present here the measured magnetoresistance as a function of temperature and magnetic field (*R-T* curves), as well as the current as a function of voltage (*I-V* curves) in the same temperature range for the 110-K phase. We fit the observed dissipation from a weakly coupled array of grains to the AH model, as originally done by Tinkham for single-crystal data.[4] Most significantly, we obtain the temperature and field dependence of U_0 without a phenomenological assumption, and find that this single-junction parameter exhibits a magnetic-field dependence characteristic of Fraunhofer interference averaged over a Josephson-junction network. Although the field dependence of the Josephson coupling energy has been related to that of an averaged critical current of multiple junctions in a granular material by Dubson *et al.*,[5] use of this concept within the AH formalism has not been explored previously. The AH model directly relates the activation energy U_0 to the critical current of the weakly coupled system, which is determined by the sample microstructure. This method of analysis is further appealing because it can treat the full range of magnetoresistance with one functional form, without making a distinction between the flux creep regime and the flux flow regime.

Our samples were prepared by solid-state reaction using lead and antimony to stabilize the 110-K phase. Optical microscopy revealed the grain size to be in the range of 2–3 μm. Four-point probe measurements were made on bar-shaped specimens with four vapor-deposited gold contacts, having contact resistance of about 0.1 Ω. A closed-cycle refrigeration unit was used with a silicon diode temperature sensor, which was negligibly affected by the low-level dc magnetic fields applied. Voltage-current data were obtained by using dc currents. Resistance-temperature data were obtained via lock-in detection with ac currents of 8.7 mA at 295 Hz. All transport currents were perpendicular to the applied fields. Successive resistance-temperature runs under different magnetic fields were made by allowing the sample to warm to 160 K before cooling again, in order to eliminate trapped flux which could cause magnetic-field hysteresis of the critical current. Our theoretical curve fitting was performed using a nonlinear least-squares routine.

Figure 1 shows the magnetoresistance as a function of temperature under various applied magnetic fields, truncated at the point of onset of broadening. The inset shows the full transition and the location of the field-induced broadening. The solid lines are a fit of the AH model's expression in the low-current limit[2]

$$R = R_n [I_0(\gamma/2)]^{-2} , \tag{1}$$

where R_n is the average normal resistance of the junctions and I_0 is the modified Bessel function. γ is the normalized barrier height for thermal phase slippage U_0/k_BT. We can assume $\gamma = U_0/k_BT_c$, for T close to T_c. At least two temperature dependences of U_0 for T near T_c have been proposed: a $(1-t)^2$ power law[6] ($t = T/T_c$), and the $(1-t)^{3/2}$ law used by Tinkham.[4] We

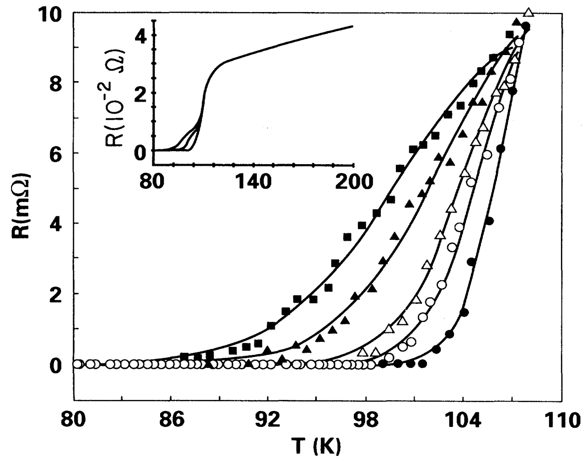

FIG. 1. Magnetoresistance as a function of temperature under different magnetic-field values, truncated at onset of broadening. The solid lines show the fits to Eq. (1). Applied magnetic fields: 0 G (●), 6 G (○), 11 G (△), 43 G (▲), 130 G (■). Inset: Resistance from 80 to 200 K showing entire transition region for fields 0, 22, and 130 G.

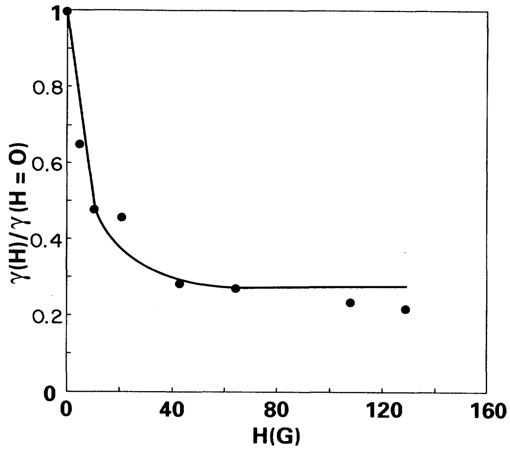

FIG. 2. Field dependence of normalized activation energy γ, as obtained from R-T data, fitted with the averaged Fraunhofer diffraction function. The solid line shows the result of the fit.

chose $\gamma = A'(1-t)^{3/2}$ for the fits shown in Fig. 1, where A' is a magnetic-field-dependent parameter. Our fit yields average values for R_n and T_c of 10 mΩ and 111.7 K, respectively, which remain constant for different fields to within 5% and 1%, respectively. The fitted value of A' for $H = 0.5$ G corresponds to a zero-temperature critical current of $J_{cJ}(0) \cong 10^4$ A/cm^2, where $J_{cJ}(0) = A' e k_B T_c / \hbar a^2$ and a is the average grain size. Fitting was also attempted using $\gamma = A'(1-t)^2$, but T_c varied too greatly, suggesting that the temperature dependence of γ more closely follows the two-fluid empirical approximation.[4]

The AH model defines the parameter γ as $I_1 \hbar / e k_B T_c$ for temperatures close to T_c, where I_1 is the Josephson critical current without the effect of thermal fluctuations. In a single junction, I_1, and therefore γ, varies with applied magnetic field as a Fraunhofer interference function if λ_J, the Josephson penetration distance, is much larger than the typical grain-boundary junction dimension.[7] This condition is satisfied here. In an array of Josephson junctions, having a distribution of effective junction lengths and orientations relative to the applied field, the effective I_1 would be an average over contributions from multiple junctions, and would exhibit a nonoscillatory, power-law-like falloff with field.[8] The latter is, in fact, the behavior we observe for γ as a function of field in a certain limited range of magnetic fields, as shown in Fig. 2.

Figure 2 shows γ versus magnetic field, obtained by curve-fitting to the R-T data of Fig. 1, after normalizing to the zero-field value $\gamma(H=0)$. We note that it was possible to fit the $\gamma(H)$ data in Fig. 2 to a $H^{-1/3}$ power law by excluding the low-field points ($H < 6$ G) where a rounding is noticeable. However, to demonstrate that the field dependence of γ is better explained by an averaged critical current, we averaged the Fraunhofer function over the junction lengths and orientations, and fitted this to the data points of Fig. 2 (solid line). For averaging, integration ranged from 0.25 to 22.5 μm over the effective junction lengths, assuming a log-normal distribution[9] with peak at about 2.5 μm, and also from 80° to 90° over the junction orientations as in Ref. 8, assuming for these a uniform angular distribution. Three parameters were varied: the Fraunhofer period H_0, where $H_0 = \Phi_0 / \mu_0 d L_m$ and Φ_0 is the flux quantum; a scaling prefactor; and a constant term which shifted the curve vertically. H_0 was found to be 15 G, which leads to a reasonable value of junction thickness $d = 500$ nm, using $L_m = 2.5$ μm. Here $d = 2\lambda + \delta$, where λ is the London penetration depth and δ is the barrier thickness.

Regarding the necessity of an added field-independent constant in the fitting, we suggest that an additional set of Josephson weak links within our material, having a much larger Fraunhofer period H_0 and correspondingly smaller size, could contribute a nearly constant component to $\gamma(H)$ in low levels of applied magnetic field. Alternatively, a field-independent component to the critical current may arise due to random variations of the barrier thickness[10] within each granular weak link, as recently suggested by Malozemoff.[11]

Figure 3 shows voltage as a function of transport current at various temperatures in zero applied magnetic field. Each solid line is the result of fitting data obtained at a fixed temperature, using the simplified analytic AH expression[2]

$$V = 2 I_c R_n (1-x^2)^{1/2} \times \exp\{-\gamma[(1-x^2)^{1/2} + x \sin^{-1} x]\} \sinh(\pi \gamma x / 2) \quad (2)$$

for $x < 1$ and large γ. Here, $x = I/I_c$, and R_n is as defined above. We define $I_c = N I_1$ as the sum of the critical currents I_1 of N parallel superconducting channels, containing the averaged Josephson junctions, which presumably exist across the width of the current path be-

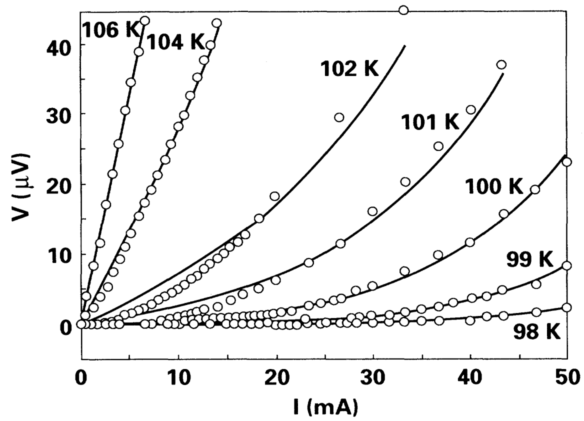

FIG. 3. Voltage-current curves at various temperatures in zero field. The solid lines show the results of the fits to Eq. (2).

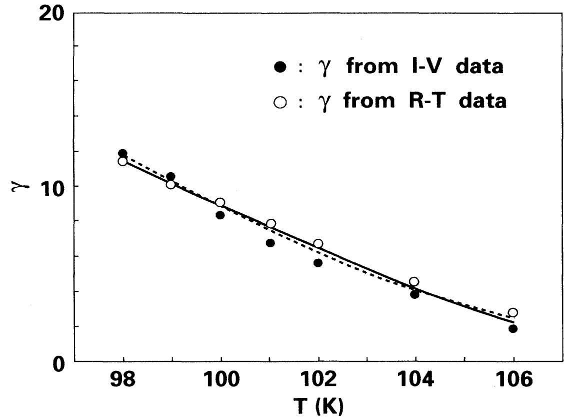

FIG. 4. Temperature dependence of normalized activation energy γ in zero field from R-T data (○) and from I-V (●). The plotted curves are the result of fitting, by including all the data points, to a function $C(1-T/T_c)^m$, where the solid line is for $m=\frac{3}{2}$ and the dashed line is for $m=2$.

tween two gold contacts. For each temperature, R_n was held constant at 10 mΩ, the average value from our R-T fitting, while I_c and γ were varied as parameters. The values of I_c and of I_1, which are obtained from γ, give a value for N which changes slightly with temperature, but remains on the order of 10^4. By fitting to Eq. (2), γ as a function of temperature was obtained directly, and plotted in Fig. 4 (solid circles). Figure 4 shows both sets of data points obtained for γ in zero applied field as a function of temperature from the R-T data (open circles) and the I-V data (solid circles). Here one can see the agreement of γ values obtained from two completely independent measurements. This agreement strongly supports the validity of the use of the AH model to explain dissipation in an effective medium.[3] One can see that the $(1-t)^2$ and $(1-t)^{3/2}$ power-law dependences for $\gamma(T)$ (dashed line and solid line, respectively) produce equally good fits to the data points of Fig. 4, if T_c is allowed to vary. The value of the exponent was found to be highly correlated[12] with T_c, requiring $T_c=111.3$ K for $(1-t)^2$ and $T_c=109.0$ K for $(1-t)^{3/2}$. From this we conclude that the temperature range of our data is not wide enough to differentiate between these two temperature dependences, although R-T fitting suggested the latter as discussed earlier.

Regarding the general applicability of this AH analysis to single crystal as well as polycrystalline materials, we note that in both cases $U_0(H)$ has been found to exhibit varied power-law-like behavior over narrow ranges of magnetic fields.[1,4] In each case, one can say that the rate of falloff of $U_0(H)$ depends upon the size and orientation of the Josephson junctions, which are determined by the sample microstructure. Moreover, when sets of weak links with very different length scales are involved, a length scale can be associated with each set by examining the $U_0(H)$ falloff. For example, since the junction upper critical field $H_{c2J}=3\pi\Phi_0/8a^2$,[3] where a is the lattice spacing of the Josephson-junction array, the falloff of γ at about 10 G in Fig. 2 leads to a value for a of 2 μm, which is comparable to the grain size observed in our samples. This suggests the contribution of intergranular weak links for the field dependence of γ. If weak links with a much smaller length scale provide the field-independent contribution to γ, we speculate that these are located within the grains. However, more work is required to determine their exact location.

In summary, we conclude that magnetic-field-induced dissipation in high-temperature superconductors can be discussed in terms of phase slips through an effective medium of Josephson weak links. This dissipation in the granular, 110-K phase of the Bi-Pb-Sr-Ca-Cu-O system can be described by the AH theory in both the flux creep and the flux flow regimes as originally suggested by Tinkham.[4] The field dependence of the activation energy for phase slips, as derived from magnetoresistance measurements, is then explained by suitable averaging of the critical currents for weak links under magnetic field. Magnetoresistance measurements can thus provide information about the microstructure of superconducting materials.

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