Magnetic dissipation in high-T_c superconductors: Evidence for a vortex-glass-to-vortex-liquid transition

M. Giura, R. Marcon, E. Silva, and R. Fastampa
Dipartimento di Fisica, Università di Roma La Sapienza, Piazzale Aldo Moro, 2, I-00185 Roma, Italy
(Received 2 March 1992)

The experimental behaviors of the resistivity as a function of both magnetic field, $\rho_T(H)$, and temperature, $\rho_H(T)$, in Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O high-quality samples, are interpreted by means of a phenomenological theory based on two hypotheses: (i) the irreversibility line at zero frequency is the glass-to-liquid-vortex transition, (ii) the dissipation mechanism is that found by Ambegaokar and Halperin and applied by Tinkham to high-T_c superconductors. The results of the fits performed on the whole range of resistivity variation (five decades) give strong support to the glass model.

The magnetic field dependent transport properties of the high-T_c superconductors have been the subject of a great number of papers. The interest has been focused on statics and dynamics of the fluxoids in the mixed state.

The main experimental result is the existence, in the H-T phase diagram of high-T_c superconductors, of a new line $T_{\rm irr}(H)$ called the irreversibility line, dividing the Abrikosov mixed phase in two regions. The nature of this line was associated with thermally activated depinning of the flux lines in magnetization relaxation measurements.[1] Also the transport experimental results have been interpreted in terms of thermally activated flux-flow (TAFF) and flux creep.[2] However, to explain the temperature dependence of magnetization relaxation in the flux creep frame a distribution of activation energies was required to reproduce the experimental data.[3] Another model was discussed by Tinkham in terms of thermal activation:[4] Tinkham, following the work by Ambegaokar and Halperin,[5] assumed the resistive dissipation to be the same as the dissipation due to thermally activated phase motion in a damped current-driven Josephson junction. This model, as has been shown by Palstra *et al.*,[6] is able to fit the experimental results of d.c. resistive measurements in magnetic field only for high values of the normalized resistivity ($\rho/\rho_N \simeq 0.1-1$). At lower resistivities the experimental data are no more reasonable fitted, even if different exponents for the thermal and magnetic dependence of the activation energy are used. Therefore, a simple unified picture which satisfactorily explains the observed experimental results is not still available.

Recently, by considering the effects of thermal fluctuations and random disorder, Fisher *et al.*[7] predicted the existence for high-T_c superconductors of a second-order phase transition from a vortex glass, in which the d.c. dissipation is zero, to a resistive vortex-fluid phase. This transition determines the curve $T_g(H)$ in the H-T phase plane. Experimental evidence for such a transition has been reported in the narrow temperature ranges where the logarithmic behavior of resistivity is a linear function of temperature,[8-10] a result that cannot be described in a thermally activated flux flow picture. In the theoretical approach proposed by Fisher *et al.*,[7] the irreversibility line corresponds to the dynamically determined glass transition curve $T_g(H)$, meaning that $T_{\rm irr}(\omega,H)\rightarrow T_g(H)$ when the frequency ω goes to zero. In this frame, the field H_{c2} is no longer a critical field and the onset of a nonzero superconducting order parameter occurs at the irreversibility line. This picture provides an elegant explanation of the experimental fact that the magnetic field H^* for the onset of dissipation found by us in Bi-Sr-Ca-Cu-O has the same angular behavior as the true critical field H_{c2} in the traditional layered superconductors.[11]

The aim of this paper is to show that it is possible to give a unitary interpretation of all the magneto-resistive measurements in Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O for the experimental ranges of temperature and magnetic field available, assuming the following two statements suggested by the presence of thermal fluctuations and quenched disorder: (i) the irreversibility line is a glass-to-liquid-vortex transition, as proposed by Fisher *et al.* and a phenomenological Vogel-Fulcher equation applies for the activation process. The irreversibility line in the $\omega\rightarrow 0$ limit is then the $T_g(H)$ curve which gives the behavior of the glass temperature as a function of the external magnetic field H; (ii) the dissipation mechanism is again that found by Ambegaokar and Halperin,[5] (who consider the thermal noise connected to the nonhomogeneity of the order parameter phase), and applied by Tinkham[4] to

TABLE I. Fit values $T_g(H)$ and $A_1(H)$ for Y-Ba-Cu-O from data of Refs. 12 and 13.

$H(T)$	0.5	1	2	5	7.5	10	12
$T_g(H)(K)$	84.6	83.3	81.1	75.0	70.2	65.5	61.7
$A_1(H)$	1.5	2.8	3	5.5	7.6	8.3	10

high-T_c superconductors in terms of thermally activated phase motion. These assumptions can be summarized in the following equation for the magnetic contribution to the resistivity:

$$\rho(H,T)=\rho_N[I_0(\gamma)]^{-2}\ , \tag{1}$$

where ρ_N is the normal state resistivity, I_0 the modified Bessel function of zero order, and the argument γ is given by

$$\gamma=\frac{A(H,T)}{T-T_g(H)}\ , \tag{2}$$

with $A(H,T)$ smoothly dependent on T, for T not close to T_c. Equation (1) is valid for low current density J ($J \ll J_c$), while Eq. (2) is first proposed in this paper.

The fit has been carried out on measurements of the resistivity as a function of the magnetic field at fixed temperatures, $\rho_T(H)$, and as a function of the temperature at fixed magnetic fields, $\rho_H(T)$, both in Y-Ba-Cu-O and Bi-Sr-Ca-Cu-O, and for different samples.

Let us briefly explain the fitting procedure. To obtain the functions $A(H,T)$ and $T_g(H)$ from the $\rho_T(H)$ data, we proceed in a self-consistent way. First of all, we suppose that $A(H,T)=A_1(H)A_2(T)$, so that the magnetic field and the temperature contributions can be separated. As a first step, supposing $A_2(T)$ to be a constant (as we will see *a posteriori,* this is valid for $T<0.9T_c$), we fit the

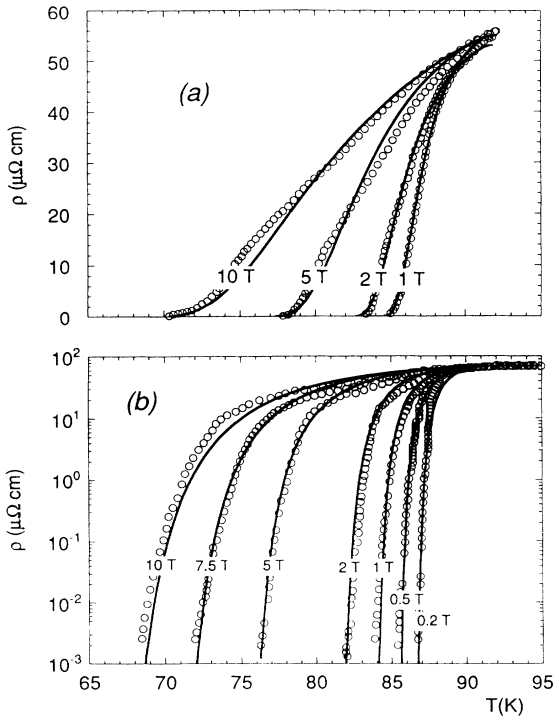

FIG. 1. Measurements of the resistivity ρ as a function of the temperature T in Y-Ba-Cu-O at various magnetic fields. Open circles are experimental data from Ref. 12, solid line is the fit obtained with Eq. (1) (fit parameter $A_0=3.8$ K). The results are shown both in linear (a) and logarithmic (b) scales. The magnetic field is given in tesla (T).

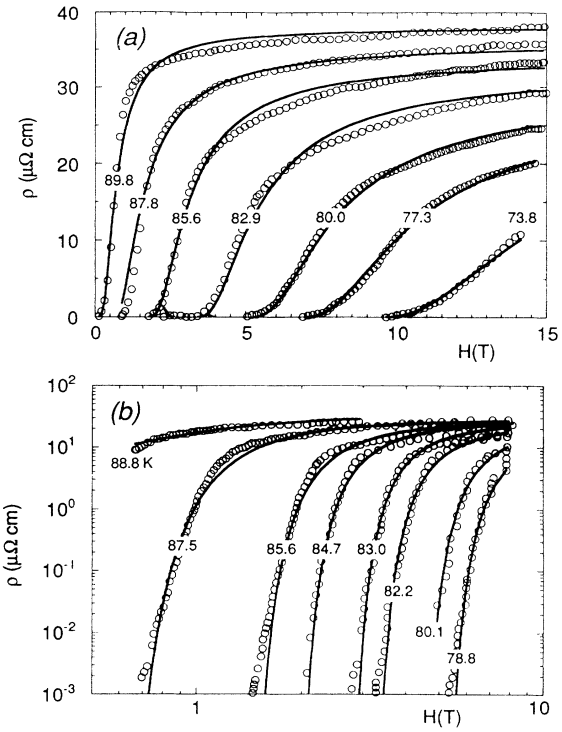

FIG. 2. ρ vs H measurements in Y-Ba-Cu-O at various temperatures. Open circles are experimental data from Ref. 13, solid line is the fit obtained with Eq. (1) (fit parameter $A_0=2.5$ K). (a) linear scale, (b) log-log scale.

$\rho_H(T)$ data with $A_1(H)$ and $T_g(H)$ as fit parameters. In a second step, by using the expressions obtained in this way for $A_1(H)$ and $T_g(H)$, we fit the $\rho_T(H)$ data, and we obtain $A_2(T)$. We then go back to $\rho_H(T)$, introducing $A_2(T)$ into the expression for γ, and we repeat the first and second steps until the process does not need further adjustment. At the end of the fitting process we come out with $A(T,H)=A_0A_1(H)A_2(T)$, $A_1(T)$ and $A_2(H)$ being point-defined functions, and A_0 a H- and T-

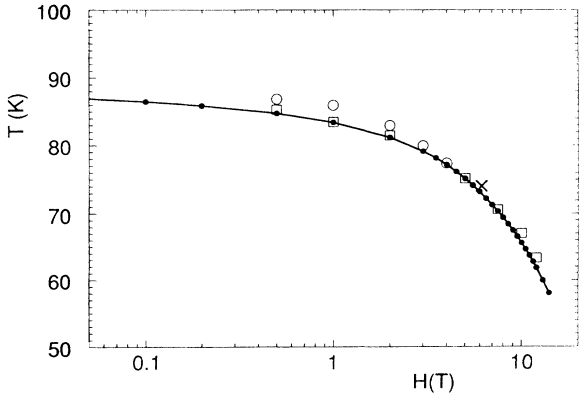

FIG. 3. The irreversibility lines of Ref. 12 (open circles), Ref. 8 (open squares) and from our fits (solid dots) are shown. The cross is the (T_g,H) value from Ref. 9 (continuous line is a guide for the eye).

TABLE II. Fit values $T_g(H)$ and $A_1(H)$ for Bi-Sr-Ca-Cu-O from data of our measurements and Ref. 2.

$H(T)$	0.002	0.01	0.1	0.25	0.5	1	2	5
$T_{g,our}(H)(K)$	63.1	57.4	44.8	38.3	32.9	27	20.6	15.5
$A_1(H)$	180	156	141	124	113	93	83	75

independent parameter. It has to be noted that the H dependence of T_g is only determined by the first step of the fitting procedure. In Table I the values $A_1(H)$ and $T_g(H)$ for Y-Ba-Cu-O are reported.

Due to the lack of data for both $\rho_T(H)$ and $\rho_H(T)$ on the same sample, we have performed this procedure on Y-Ba-Cu-O using the data by Palstra *et al.*[12] for $\rho_H(T)$ and by Chien *et al.*[13] for $\rho_T(H)$. We have found that only the parameter A_0 is sample dependent. The temperature function $A_2(T)$ takes the form $A_2(T)=[1-(T/T_c)^4]^{1/2}$, while $A_1(H)$ has a less impressive formulation.

In Figs. 1 and 2 the resulting fits for $\rho_H(T)$ (data from Ref. 12) and for $\rho_T(H)$ (data from Ref. 13), respectively, are shown in both linear and logarithmic scales. The fitting results are striking, considering the whole range of variation of the resistivity (five decades). The parameter A_0 is 3.8 K for data of Ref. 12 and 2.5 K for data of Ref. 13.

In Fig. 3 we report the curve $T_g(H)$ obtained from our fit, together with the irreversibility lines obtained by Palstra *et al.*[12] and Koch *et al.*[8] The statement (i) has a good confirmation, considering the different samples and the different measurement techniques employed.

A completely analogous procedure has been used for Bi-Sr-Ca-Cu-O samples. The data for $\rho_H(T)$ have been taken from Palstra *et al.*[2] and from Martin *et al.*[14] whereas for $\rho_T(H)$ some data have been obtained by us in an epitaxial film, grown on a $LaGaO_3$ substrate, and others from Ref. 14. The fit values $A_1(H)$ and $T_g(H)$ obtained from our measurements are reported in Table II. The temperature dependence of A is $A_2(T)=[1-(T/T_c)^4]^{\alpha}$, with $\alpha=0.4$ for the fit of data of Ref. 14 and $\alpha=0.15$ for the fit of our and Ref. 2 data. The final fits of our data are reported in Fig. 4. Fits of the data from Refs. 14 and 2 are reported in Figs. 5 and 6, respectively.

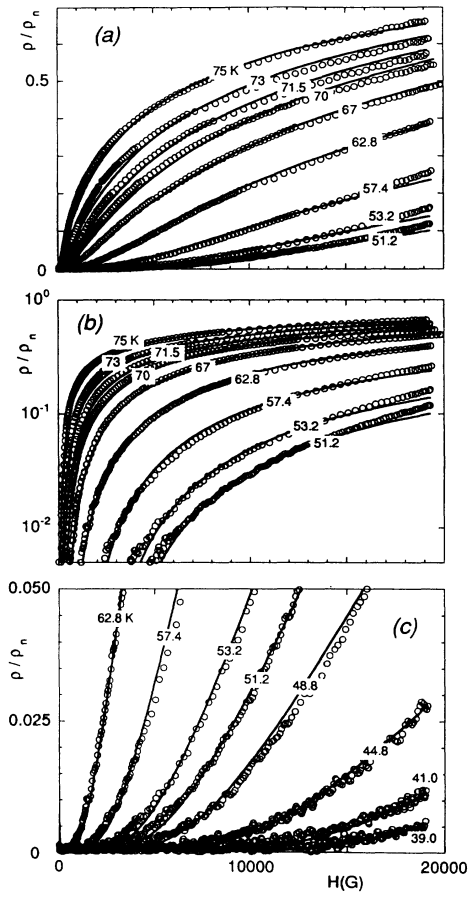

FIG. 4. Normalized resistivity ρ/ρ_N vs the magnetic field H data at various temperatures (open circles) in a Bi-Sr-Ca-Cu-O epitaxial film (our measurements). The fits (continuous lines) are obtained by means of Eq. (1). The results are shown in different scales and temperature ranges.

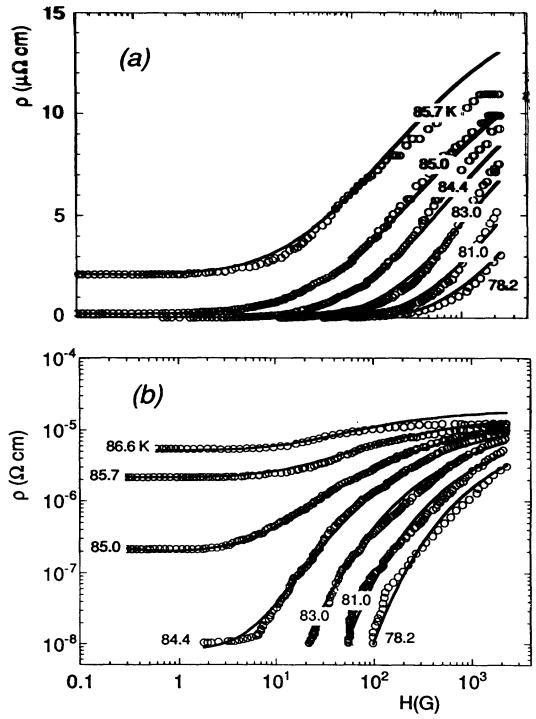

FIG. 5. ρ vs H measurements in Bi-Sr-Ca-Cu-O at various temperatures. Open circles are experimental data from Ref. 14, solid line is the fit obtained with Eq. (1). (a) linear-log plot, (b) log-log plot.

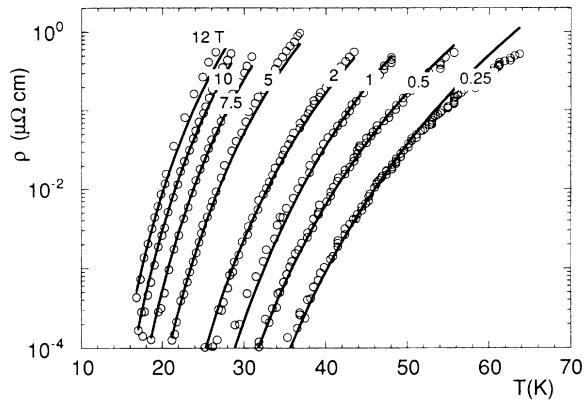

FIG. 6. ρ vs T measurements in Bi-Sr-Ca-Cu-O at different magnetic fields. Open circles are experimental data by Palstra *et al.* Ref. (2) solid line is the fit obtained with Eq. (1).

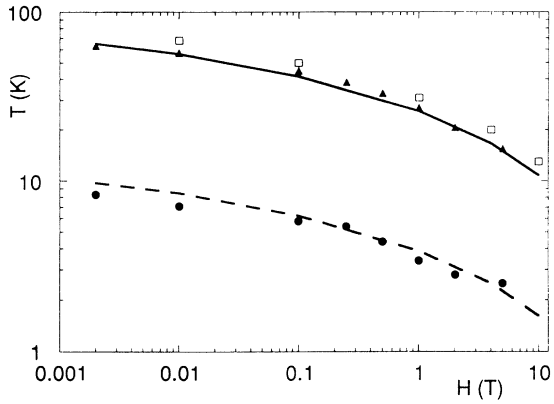

FIG. 7. Irreversibility lines obtained in Bi-Sr-Ca-Cu-O: $T_{irr}(H)$ from Ref. 15 (open squares), $T_{irr}(H)/1.2$ from Ref. 15 (continuous line). Glass lines: $T_g(H)$ from the fitting of our data (solid triangles), from the fitting of the data of Ref. 2 (solid dots), and $T_{irr}(H)/8$ from Ref. 15 (dashed line).

Comparing the irreversibility lines obtained with our data, with the data of Palstra *et al.*[2] and Martin *et al.*[14] and those reported by Kes *et al.*[15] (obtained from loss peak in the a.c. susceptibility), we have the interesting result that all the lines are parallel to each other, i.e., the H dependence of T_g is the same for different samples and measurement frequencies, apart from a scale factor. In particular $T_{g,our}=T_{g,Martin}=T_{irr,Kes}/1.2=6.7T_{g,Palstra}$. The A_0 parameter takes the values 150 K for our data, 16 K for Martin *et al.*,[14] and 300 K for Palstra *et al.*[2]

The main result of the fit procedure is that, once $T_g(H)$ and $A(H,T)$ have been obtained, it is possible to accurately describe the resistivity of each sample of Y-Ba-Cu-O by determining the only parameter A_0 [because the function $T_g(H)$ is practically the same for all the samples, as shown in Fig. 3]; while for Bi-Sr-Ca-Cu-O we need the two parameters A_0 and α, and the scale factor for $T_g(H)$, as shown in Fig. 7. The values of the fit parameters are critical: a variation of some percent reflects in a poor fit.

Some general comments on the fit results are in order. For Y-Ba-Cu-O the procedure to obtain from $\rho_T(H)$ and $\rho_H(T)$ the $A_1(H)$ and $A_2(T)$ functions is rapidly convergent, the α exponent in the equation $A_2(T)=[1-(T/T_c)^4]^\alpha$ is $\frac{1}{2}$ and sample independent; also the $T_g(H)$ curve (Fig. 3) is sample independent. In the Bi-Sr-Ca-Cu-O case the fit procedure is more hard working due to the dependence of $T_g(H)$ on the sample (Fig. 7). Moreover, the α parameter changes from 0.2 to 0.4 and the magnetic field dependence of the $A_2(H)$ function is more complicated with respect to the linear behavior in the Y-Ba-Cu-O case. The complexity in the fitting of Bi-Sr-Ca-Cu-O data is probably due to higher anisotropy and to the larger dishomogeneity of the available samples.

As a conclusion, we have shown that a phenomenological theory, based on both the existence of a transition line (irreversibility line) from a vortex-glass to a vortex-liquid (for which a Vogel-Fulcher equation is valid for the activation process) and a dissipation mechanism of the type worked out by Ambegaokar and Halperin, is able to fit the great variety of the magnetic resistivity data. Once the phenomenological behavior of the function $A(H,T)$ in Eq. (1) is obtained, it is possible to fit in a striking way the specific sample data from the knowledge of only one fit parameter in the case of the Y-Ba-Cu-O and two in the case of the Bi-Sr-Ca-Cu-O. Regarding to the $T_g(H)$ function obtained from the fit procedure, in the Y-Ba-Cu-O case $T_g(H)$ is the same for different samples and measurement techniques; while in the Bi-Sr-Ca-Cu-O case $T_g(H)$ changes with the sample only for a scale factor.

[1]Y. Yeshurun and A. P. Malozemoff, Phys. Rev. B **38**, 7203 (1988).
[2]T. T. Palstra *et al.*, Phys. Rev. Lett. **61**, 1662 (1988); M. Inui *et al.*, *ibid.* **63**, 2421 (1989).
[3]C. W. Hagen and R. Griessen, Phys. Rev. Lett. **62**, 2857 (1988).
[4]M. Tinkham, Phys. Rev. Lett. **61**, 1658 (1988).
[5]V. Ambegaokar and B. I. Halperin, Phys. Rev. Lett. **25**, 1364 (1969).
[6]T. T. Palstra *et al.*, Phys. Rev. B **41**, 6621 (1990).
[7]D. S. Fisher *et al.*, Phys. Rev. B **43**, 130 (1991).
[8]R. H. Koch *et al.*, Phys. Rev. Lett. **63**, 1511 (1989).
[9]P. L. Gammel *et al.*, Phys. Rev. Lett. **66**, 953 (1991).
[10]M. K. Wu *et al.*, Physica C **185-189**, 332 (1991).
[11]R. Fastampa *et al.*, Phys. Rev. Lett. **67**, 1795 (1991).
[12]T. T. Palstra *et al.*, Appl. Phys. Lett. **54**, 763 (1989).
[13]T. R. Chien *et al.*, Phys. Rev. Lett. **66**, 3075 (1991).
[14]S. Martin *et al.*, Phys. Rev. Lett. **62**, 677 (1989).
[15]P. H. Kes *et al.* (unpublished).