ac response of the vortex system in a $Pr_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal

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(Received 12 November 1992)

We have studied the field, frequency, and amplitude dependence of the ac susceptibility on a single crystal of the electron-doped superconductor $Pr_{1.85}Ce_{0.15}CuO_{4-y}$. We show that a thermally activated flux motion over effective energy barriers $U(T,H)=U_0(1-T/T_c)H^{-0.6}$, with $U_0 \approx 40$ meV, can account for the dc-field and frequency effects. The amplitude dependence of the ac response in this superconducting system is discussed and it is argued that it is a signature of the critical state.

I. INTRODUCTION

The existence of a so-called "irreversibility line" in the H-T plane in the high-temperature superconductors (HTSC) has been a subject of considerable interest and controversy. This line is typically revealed by ac or dc susceptibility measurements,[1,2] though other methods such as resistivity[3] and mechanical-oscillator experiments[4] have also been used. From a theoretical point of view, the irreversibility line has been incorporated in a variety of scenarios, which include thermally activated vortex motion, vortex-lattice (VL) melting, or vortex-glass freezing.

The irreversibility line [$H^*(T)$ or $T^*(H)$] has been extensively studied in the HTSC cuprates belonging to the $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$ families, where it has been shown that it lies well below $H_{c2}(T)$; $H^*(T)$ typically displays an upward curvature which can be described by a power law $H^*(T) \approx (1-t)^{\beta}$, where $t=T/T_c$ is the reduced temperature and β lies between 1.5 and 4; this behavior contrasts with the linear $H_{c2}(T)$ expected from the Ginzburg-Landau mean-field theory close to T_c.

The onset of dissipation when crossing the $H^*(T)$ line is manifested in a variety of forms, depending on the measuring technique. A pronounced broadening is commonly observed in resistive transitions;[3] in ac susceptibility measurements a small ac field (h_{ac}) is superposed to a large dc magnetic field (H) and the ac response is studied as a function of temperature. The out-of-phase component of the ac susceptibility, $\chi''(T)$, shows a peak at a certain temperature which has been interpreted as a signature of $T^*(H)$,[5] though the critical-state model also accounts for the observation of a peak in $\chi''(T)$.[6] Frequency-dependent effects have been interpreted as a manifestation of thermally activated flux motion, which might be relevant because of the high critical temperatures of the HTSC.

The electron-doped superconducting cuprates $M_{2-x}Ce_xCuO_{4-y}$ (M =Nd, Pr, Sm), having critical temperatures of about 20 K, show some remarkable features which contrast with those of the hole-doped HTSC, one of the main ones being the rather low in-plane κ values reported recently.[7] Besides, when the resistive transition is measured under a magnetic field $H \| c$, it shifts parallel without any dramatic broadening; the ac susceptibility shows a similar behavior.[8] These observations, resembling those in most conventional type-II superconductors, suggest that flux motion in these materials hardly takes place; thus, the effective pinning energy $U(T,H)$ should be correspondingly higher than in hole-doped HTSC. In fact, large $U(T,H)$ values and the low temperatures involved in these experiments should lead to a reduced or even negligible flux creep rate. Under such circumstances, the $H^*(T)$ line, determined from either ac susceptibility or resistive data, should lie very close to $H_{c2}(T)$, or even be coincident with it. However, the reported $H^*(T)$ curves[8,9] display an upward curvature that cannot be easily reconciled with the expected $H_{c2}(T)$ dependence, thus supporting its identification as an irreversibility line.

Estimates of the effective pinning energies can be obtained in several ways. Fàbrega *et al.*[8] used the frequency dependence of the ac susceptibility on a $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal to extract energies in the range of 100 meV at the lowest fields. Similar results were reported from resistive data on $Nd_{1.85}Ce_{0.15}CuO_4$ thin films[10] and $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ single crystals.[11] In all these cases the analysis of the electromagnetic response of the material was performed by using thermally activated flux motion models.

In this paper we report ac susceptibility data on a $Pr_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal. The ac response is studied as a function of the dc magnetic field and the measuring frequency. We show that the shift of the maximum losses, χ''_{max}, with frequency can be described in terms of an Arrhenius law, thus pointing to the thermally activated nature of flux motion in this material. However, the extracted effective pinning energies are rather large, leading to an extremely low flux jump frequency, which contrasts to the strong frequency dependence of the ac response. This clear contradiction raises some important questions as to whether analyzing the data with this commonly used procedure is appropriate. We show that if the temperature dependence of $U(T,H)$ contains a dominant term of the type $U(T,H)=U(T=0,H)(1-t)$, a consistent description of the ac response is obtained.

In order to go deeper into the nature of the activated flux motion, we also explore the dependence of χ_{ac} on the amplitude of the driving field; it turns out that even for small fields ($<3\times10^{-4}$ T) the magnetic response is nonlinear, i.e., χ depends on h_{ac} and thus the resistivity is non-ohmic. Through detailed analysis of the ac susceptibility in different scenarios (thermally activated flux flow and flux creep in the critical state) we will show that the available data can be better described in terms of a critical state, provided frequency effects are also included.

II. EXPERIMENT

We have studied the ac susceptibility of a $Pr_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal grown by the self-flux method,[12] with dimensions $1.90\times0.95\times0.03$ mm^3 and mass $m=0.43$ mg.

Both components of the ac susceptibility, χ' and χ'', have been measured at frequencies between 10.87 and 5565 Hz; driving fields $\mu_0 h_{ac}=3\times10^{-5}$, 3×10^{-4}, and 10^{-3} T have been used. The dc magnetic fields, parallel to the c axis of the crystal, ranged from 0.06 to 2 T. All the measurements have been performed after a field cooling process, in order to minimize the presence of nonuniform flux distributions in the sample, which are known to lead to a nonintrinsic nonlinear ac response.[13]

III. RESULTS

Figure 1 shows the in- and out-of-phase components of χ_{ac} at $f=234$ Hz and $\mu_0 h_{ac}=3\times10^{-5}$ T for different dc fields, after correction for the sample holder contribution. Two features are worth emphasizing. First, when increasing the dc field, both components of the susceptibility shift to lower temperatures without a noticeable broadening. A similar parallel shift of the superconducting transition was previously observed in susceptibility measurements on a $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal[8] and is in agreement with the reported shift without broadening of the resistive transition measured under a dc field H.[10,11,14] This result is in sharp contrast to the results obtained in p-type HTSC, where a remarkable broadening of the resistivity and both components of χ is typically found. As a second feature, it should be noticed that the loss peak does not change with the dc field but remains fixed at $\chi''_{max}\approx0.35$.

The peak of the out-of-phase component of the susceptibility and its shift when measuring the sample under a dc field have been largely used as a signature of the irreversibility line in p-type cuprates.[2,5] Although much controversy still remains on the precise definition of the onset of irreversibility,[15] we will still use this criterion for $T^*(H)$. Below we will discuss the convenience of this choice in greater depth.

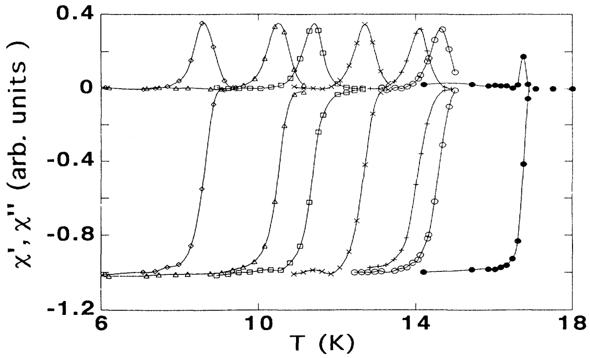

FIG. 1. In-phase (χ') and out-of-phase (χ'') components of the ac susceptibility measured at $\mu_0 h_{ac}=3\times10^{-5}$ T and $f=234$ Hz, for $\mu_0 H=0$, 0.06, 0.1, 0.2, 0.35, 0.5, and 1 T (from right to the left).

More information about the origin of this H-T line can be obtained from the study of its dependence on the driving field frequency; our data show that $T^*(H)$ moves to higher temperatures when increasing the measuring frequency; the diamagnetic transition and the dissipation peak shift parallel, and there is no increase of the ac losses, i.e., the height and width of χ'' remain roughly constant. Figure 2 shows the irreversibility lines obtained from the peak in χ'' at three different frequencies; the curves follow a power law $H(t)\approx H(t=0)(1-t)^n$, with $n\approx2$ and $\mu_0 H(0)\approx5$ T. These values are in good agreement with the ones obtained from ac susceptibility for a $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal[8] and for polycrystalline samples;[16] other authors[17,18] report some lower values of the exponent from magnetization and resistivity data in this family of cuprate superconductors.

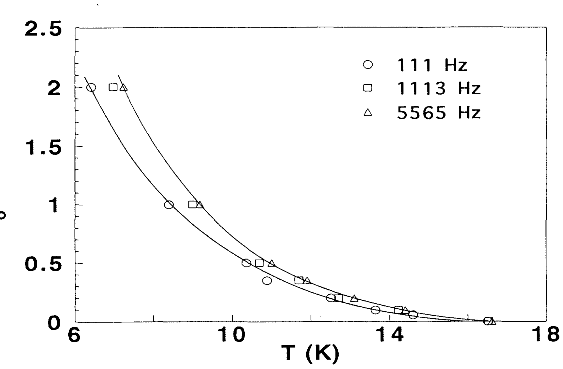

FIG. 2. Loci of the temperature where the losses peak takes place, T^*, as a function of the dc magnetic field, for frequencies $f=111$ (○), 1113 (□), and 5565 (△) Hz. The lines connecting the experimental points are for a guide to the eye.

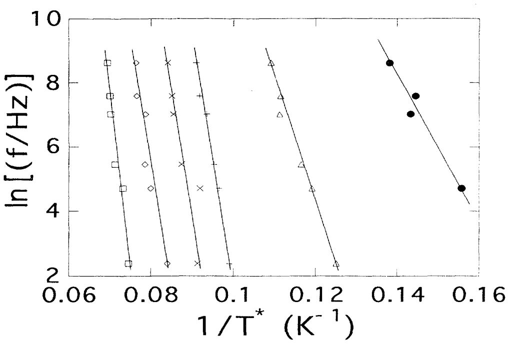

FIG. 3. $\ln(f)$ vs $1/T^*$, measured at $\mu_0 h_{ac}=3\times10^{-5}$ T, for dc fields $\mu_0 H=0.1$ (□), 0.2 (◇), 0.35 (×), 0.5 (+), 1 (△) and 2 (●) T.

Almasan *et al.*[9] report, from dc magnetization in a $Sm_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal, a change in the power-law behavior at $H_0\approx1$ kOe; we have not seen any clear evidence of such a change in our data.

In Fig. 3 we plot $\ln(f)$ vs $1/T^*$, where T^* is the temperature where the maximum losses take place for a given ac field ($\mu_0 h_{ac}=3\times10^{-5}$ T) of frequency f, at different dc magnetic fields H. It is shown that the data can be described by a straight line, that is,

$$f=f_0\exp[-U(T^*,H)/kT^*]\ , \tag{1}$$

suggesting that the observed dissipation is due to a thermally activated process. $U(T,H)$ can be interpreted as an effective activation energy which depends on the magnetic field and may have a weak temperature dependence.

In Fig. 4 the response of the in- and out-of-phase components of χ under three different excitation fields is shown. As in the previous study,[8] they exhibit a common behavior at different dc fields: the onset of the χ' and χ'' shift to lower temperatures as h_{ac} is increased, while the peak in χ'' broadens in the low-temperature side and becomes slightly higher, indicating a larger energy dissipation. This amplitude dependence is surprisingly independent of the dc magnetic field.

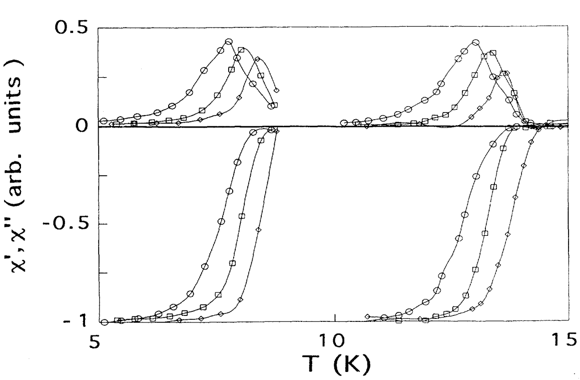

FIG. 4. In- and out-of-phase components of χ for $\mu_0 h_{ac}=3\times10^{-5}$ (◇), 3×10^{-4} (□), and 10^{-3} (○) T, measured at $f=111$ Hz and $\mu_0 H=0.1$ T and 1 T.

IV. DISCUSSION

In the presentation of the experimental data, we have seen that the shift of the maximum loss peak with the frequency points to the fact that the ac response of the VL is due to thermally activated flux motion.

There are two mechanisms that may lead to a significant motion of vortices assisted by thermal activation: (a) first, when the induced current J is of the order of the critical current $J_c(T,H)$ and $U\gg kT$, vortices move due to the existence of a rather important Lorentz force $F_L=\mu_0 JH$ acting on them, comparable to the opposite bulk pinning force F_p; this motion is enhanced by thermal jumps, which effectively reduce the critical current $J_c(T,H)$ by a factor $g[kT/U(T,H)\ln(f_0/f)]<1$,[19] where f_0 is a normalizing frequency and f is the measuring frequency; this is the so-called flux creep regime. (b) Second, even when $J\ll J_c(T,H)$, so that $F_L\ll F_p$, vortices can move if the thermal activation is important enough, i.e., when $U(T,H)\approx kT$; this regime corresponds to the so-called thermally assisted flux flow (TAFF).[20,21]

It has been shown[22] that in a critical-state model the out-of-phase component of χ should show a peak ($\chi''=0.239$ for an infinite slab with h_{ac} along the surface), when the flux profile reaches the center of the sample, that is, $h_{ac}\approx J_c(T,H)\,a$, where a is the sample size. When flux creep is incorporated in this model, we have at the peak,

$$h_{ac}=J_c(T^*,H)g[kT^*/U(T^*,H)\ln(f_0/f)]a\ , \tag{2}$$

which leads to both a frequency dependence of the Arrhenius type and to a nonlinear ac response.

On the other hand, in the TAFF regime flux profiles are exponential, $\delta B\approx\exp(-x/\lambda_{ac})$; the ac penetration depth can be written as[20]

$$\begin{aligned}\lambda_{ac}&=(\rho_{TAFF}/\pi f\mu_0)^{1/2}\\&=(\rho_{FF}/\pi f\mu_0)^{1/2}\exp[-U(T,H)/2kT]\ .\end{aligned} \tag{3}$$

Here, the normal fluid contribution to the ac response, which is small because of the low temperatures used, and the London penetration depth have been neglected; ρ_{FF} is the flux-flow resistivity, which can be approximated by $\rho_{FF}(T,H)=\rho_n[H/H_{c2}(T)]$,$\rho_n$ being the normal-state resistivity. Equation (3) reveals two main features of the TAFF: (1) λ_{ac} is equivalent to the skin depth of a normal metal, and thus χ'' reaches a maximum value ($\chi''\approx0.39$ for an infinite slab with the field parallel to its surface) when λ_{ac} is of the order of the sample size; within this model, changing the measuring frequency is therefore equivalent to mapping the resistivity of the material; (2) the ac response in the TAFF regime is linear, that is, independent of the ac field amplitude, and the I-V curves must be linear.

From the above discussion it turns out that the slopes of the experimental Arrhenius plots of Fig. 3 can provide an estimate of the energy barriers for thermally activated flux motion, whether its origin is related to diffusion or creep. In Fig. 5 we plot the field-dependent energy

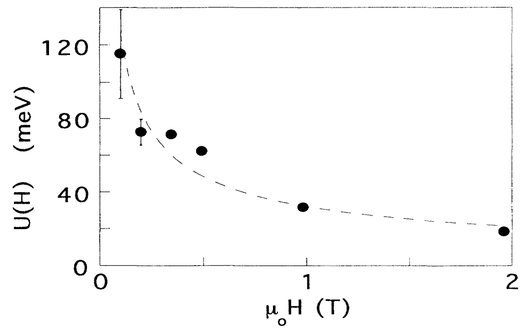

FIG. 5. Field dependence of the slope $U(H)$ of the Arrhenius plots in Fig. 3. These slopes can be interpreted as an energy barrier against thermally activated flux motion.

values, $U(H)$, so obtained. The effective pinning energy $U(T,H)$ is expected to have a smooth and weak temperature dependence of the type $(1-t)^n$, because of its dependence on the fundamental lengths and critical fields,[23] and thus the measured $U(H)$ is expected not to differ too much from $U(T=0,H)$. Although there is some scatter in these experimental values, a power law $U(H)\approx U_0 H^{-n}$ with $n\approx 0.6$ can be used to describe the data. A similar $U(H)$ dependence was observed in a $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal.[8] It can be noted that these measured effective pinning barriers at the lowest fields are higher ($\approx$90 meV) than the corresponding values typically reported for the Bi-Sr-Ca-Cu-O,[21,24] but comparable to the values in Y-Ba-Cu-O.[25] This fact, together with the lower temperatures involved, leads to a smaller flux jump frequency and thus accounts for the absence of a significant broadening of the susceptibility and resistive superconducting transitions.

In fact, after inserting a typical energy value $U(H=1T)\approx 40$ meV and a frequency of $f=1$ kHz into Eq. (1), it turns out that thermally activated motion is so small that the normalizing frequency must have an extremely large and unphysical value ($f_0\approx 10^{24}$ Hz) to explain the observed peak in χ'' at T^* (1 T). Expected values would be $f_0\geq 10^7-10^8$ Hz.[24] Consequently, at fist sight it may appear that a thermally activated process can hardly be responsible for our data. Very recently, Steel and Graybeal[26] have faced a similar difficulty when analyzing the frequency effects in the ac response of a $Bi_2Sr_2CaCu_2O_8$ single crystal; they have argued that a distribution of pinning energies should be included to account for the observed shift of the energy absorption maximum with frequency. Here, we will show that inclusion of a linear temperature dependence in $U(T,H)$ also provides a natural explanation for this effect. Indeed, a closer inspection of Eq. (1) reveals that a linear temperature dependence of the activation energy, of the type $U(T,H)=U(t=0,H)(1-t)$, will result in a temperature-independent term $\exp[U(t=0),H)/kT_c]$ which can seriously modify our estimates of f_0 and $\lambda_{ac}(T^*)$. Explicitly, the pre-exponential temperature-independent term in Eq. (1) will be given by $f_0 \exp[U(t=0,H)/kT_c]=f_0'(H)$. As in these cuprates $U(H)/kT_c$ is rather large, it turns our that $f_0'(H)$ could be much higher than f_0, thus leading to a much higher apparent value for the jump frequency and solving our initial contradiction.

Assuming the linear temperature dependence of $U(T,H)$ described above, the constant term of the Arrhenius fits in Fig. 3 should be $c(H)=\ln(f_0)+U(H)/kT_c$, where $U(H)$ are the slopes in the same fits [now coinciding with $U(t=0,H)$]. Thus, $c(H)$ should be linear in $U(H)$; Fig. 6 shows $c(H)$ vs $U(H)$; we have also included data from Ref. 8. The linear behavior is reasonably well verified, being the slope inversely proportional to T_c. From the linear fits to both sets of data we find $f_0\approx 10^{12}$ Hz, a much more reasonable value which supports our assumption of an effective barrier of the form $U(T,H)=U(H)(1-t)$.

The obtained dependences for the energy barriers, $U(T,H)=U_0 H^{-0.6}(1-t)$, should reflect the microscopic flux pinning mechanism. In these electron-doped cuprates, flux pinning by oxygen vacancies has been investigated within the scope of the collective pinning model, and it has been shown that it fails to account for the observed $U(T,H)$ dependences.[8] Vinokur *et al.*[27] have explored the flux motion by plastic creep; they have shown that in this case the activation barriers can be written as $U_{pl}(T,H)\approx\Gamma^{-1/2}H^{-1/2}(1-t)$, where $\Gamma\equiv m_c/m_{ab}$ is the anisotropy ratio. Thus, this model not only provides a physical reason for the observed temperature dependence but also predicts a field dependence which is in rather good agreement with our data. In addition, the irreversibility line $H^*(T)$ that one can deduce from $U_{pl}(T,H)$ is $H^*\propto(1-t)^2$, which is just the shape of the measured one (see above).

Plastic creep is known to be relevant in highly anisotropic systems, because of the $\Gamma^{-1/2}$ dependence, thus suggesting that, if this is an appropriate description of the data, the anisotropy in these superconductors should be higher than the one previously reported.[28] Indeed, some recent magnetic measurements of $H_{c1}\|ab$ and $H_{c1}\|c$ point in this direction.[29] To what extent the coincidence of the predictions of this model is significant is at present unknown, but this is an important guideline for future work.

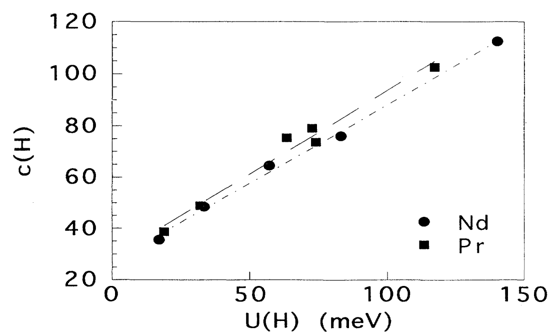

FIG. 6. Constant term $c(H)$ in the Arrhenius fits in Fig. 3, as a function of the slopes $U(H)$; data from Ref. 8 are also shown. The observed linear behavior, with slopes inversely proportional to T_c, points to a linear temperature dependence of the effective activation energy, $U(T,H)=U(H)(1-T/T_c)$.

Once the thermally activated origin of the ac response of the VL in our measurements has been settled, we might try to look deeper into the mechanism causing this thermally activated flux motion. The observed amplitude dependence of the susceptibility, even at very low h_{ac} fields, seems to rule out an explanation in the framework of a diffusion process (TAFF), since this is expected to be an ohmic regime.

Estimates for the minimum h_{ac} value leading to nonlinear ac response, $h_{ac,lim}$, are given in Ref. 30 for flux creep in different temperature and field regimes. The first possibility is that the vortex lattice is in a liquid, possibly entangled, state. The creep barriers are then due to vortex entanglement,[31] and the crossover to nonlinear ac response can be estimated using the Anderson flux creep model; assuming creep of individual vortex segments of length L, and using $B_{c2}(0)=6$ T, $r_f=\xi_{ab}=80$ Å, $\rho_n=3\times10^{-5}$ Ω m, $f=1$ kHz, and $U(T,H)/kT \approx 25$ at $T=10$ K, $B=1$ T, we find $h_{ac,lim} =(kT/\Phi_0 L\xi)(\rho_{TAFF}/\mu_0\pi f)^{1/2}=0.5$ Oe,[32] a value somewhat higher than the lowest h_{ac} fields used in experiment. Thus, the observed amplitude dependence may indeed be due to the fact that the TAFF regime is left, and the description in terms of a critical-state model is more appropriate.

Further indications that a critical state is established in the crystal can be obtained from a closer inspection of the susceptibility curves in Fig. 4. In the critical-state model, the ac susceptibility is a function of the modified Bean penetration length $L_p=h_{ac}/J_c(f,T,H)$ only; here $J_c(f,H,T)$ is the effective critical current when flux creep is present. Thus, at fixed H and f, a certain value $\chi'=m$ corresponds to $J_c(f,T,H)=h_{ac}/L_p$. The ratios of the $J_c(f,T,H)$ values at the temperatures where $\chi'=m$ intersects the experimental curves are thus equal to the ratios of the ac field amplitudes used in measuring the different curves. If the critical-state model is indeed appropriate, ratios obtained for different values of m, chosen such that the intersections with the data overlap the same temperature range, should yield a unique temperature dependence of $J_c(f,T,H)$. Figure 7, depicting $J_c(f,T,H)$ for $\mu_0 H=0.1$ T, shows that this is indeed the case. The data can be well scaled using the L_p values shown in the inset; a similar good quality collapse has been obtained for $\mu_0 H=0.5$ T and 1 T. It is worth noticing that the $m(L_p)$ dependence is in good agreement with the function predicted for an infinite circular cylinder by the critical-state model,[6] the small deviation observed near the complete screening being likely due to finite size or shape effects; thus, these fact provide additional support for the assumption of such a regime in our data.

We turn now to the temperature dependence of $J_c(f,T,H)$ shown in Fig. 7. In order to describe the data, two models have been used: (a) in the Anderson regime (creep of individual vortices) a law

$$J_c(f,T,H)=J_c(T,H)[1-kT/U(T,H)\ln(f_0/f)]$$

is predicted; (b) in the collective creep theory[33] the activation energy shows a dependence on the driving current of

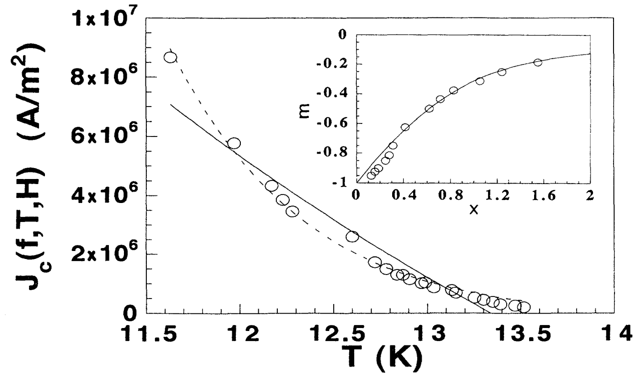

FIG. 7. Temperature dependence of the frequency-dependent critical current $J_c(f;T,H)$ at $\mu_0 H=0.1$ T, obtained from cuts of $\chi'=m$ in a critical-state model (see text); the solid (dashed) line corresponds to the fit to the Anderson (collective creep) model. Inset: m vs $x=L_p/a$ values ($a=0.74$ mm is the sample dimension), obtained from the above cuts; the solid line is the $\chi'(x)$ obtained in the critical-state model for an infinite cylinder of radius a (Ref. 6).

the type $U(J)\alpha J^{-\mu}$, which leads to a law

$$J_c(f,T,H)=J_c(T,H)[kT/U(T,H)\ln(f_0/f)]^{-1/\mu} .$$

The lines depicted in Fig. 7 show fits to both models, using the experimental $U(T,H)=U_0 H^{-0.6}(1-t)$ dependence; for the critical current, a dependence $J_c(T,H)=J_c(H)(1-t)^n$, with $n=3/2$, has been used.[34] It can be clearly seen that the collective creep law, with fitting parameters $\mu\approx1/4$ and $f_0\approx10^{12}$ Hz, describes the data much better than the Anderson model; thus, this result is an indication of the presence of collective creep in our data.

Finally, we would like to mention an experimental observation which remains somewhat puzzling. The height of the χ'' peak at $T^*(H)$ slightly increases with the amplitude h_{ac} of the driving field. This result is not expected in a critical state and at present is not fully understood. More complete measurements, exploring the frequency and field dependence of the nonlinear ac response, would be therefore needed to draw a conclusion on this particular issue.

V. SUMMARY

We have presented a set of experimental data on the ac susceptibility of a $Pr_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal measured under several dc magnetic fields, driving field amplitudes, and frequencies. We have shown that the maximum of energy absorption at a fixed frequency shifts with the dc magnetic field in a way similar to that found in most p-type HTSC, where it has been used to identify the irreversibility line. For this particular crystal we have found $H(T)\approx H(0)(1-T^*/T_c)^n$, with $n\approx2$ and $\mu_0 H(0)\approx5$ T, similar to the reported data for other electron-doped superconductors.

The shift of $\chi''(T^*,H)$ at different frequencies has been interpreted as a signature of thermally activated flux motion. The effective pinning energies involved in this process can be described by $U(T,H)=U_0(1-t)H^{-0.6}$, with $U_0=40$ meV. This remarkably large barrier and a similar field dependence was already reported on a similar $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ single crystal;[8] although their meaning within a microscopic picture of the flux pinning is still unclear, they appear to be a common feature of these electron-doped cuprates. We have argued that the observed $U(T,H)$ dependences and the shape of the irreversibility line could be described as having originated by plastic motion. The linear temperature dependence of $U(T,H)$ is important because it reduces the effective barrier against flux jump at high reduced temperatures, providing a temperature-independent enhancement of the flux jump attempt frequency and making possible the observation of the activated flux motion contribution to the ac losses.

We have shown that the dependence of the susceptibility on the driving field amplitude and frequency can be well described in terms of a critical-state model into which flux creep is incorporated; a detailed analysis of the $\chi(f,T,H,h_{ac})$ curves has allowed us to extract the temperature dependence of the flux creep critical current, which turns out to be well described by a collective creep regime with $\mu \approx 1/4$.

ACKNOWLEDGMENTS

We are indebted to the CICYT-MIDAS program (Project MAT91-0742) for financial support of this research. One of us (L.F.) would like to acknowledge DGCYT for financial support, and the Kamerlingh Onnes Laboratory for their hospitality during the time the experimental work was done.

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