Inter- and intraplane softening of the vortex structure in $Bi_{2.1}Sr_{1.9}Ca_{0.9}Cu_2O_{8+\delta}$: a two-step transition

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High Q mechanical oscillator and ac susceptibility techniques have been used to study vortex dynamics in high quality single crystals of $Bi_{2.1}Sr_{1.9}Ca_{0.9}Cu_2O_{8+\delta}$ over a wide range of magnetic fields and different relative orientations between the magnetic field and the crystalline c axis. Our results confirm the existence of two transitions in the vortex response. We show that the transition at lower temperatures is associated to currents flowing across the CuO planes and the other one to currents in the planes. This means that the reversible region of the phase diagram is reached in two steps when increasing temperature.

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Recent experiments[1] in single crystals of $Bi_{2.1}Sr_{1.9}Ca_{0.9}Cu_2O_{8+\delta}$ showed that the melting transition[2] takes place in two steps at two different temperatures, rather than in a single one as previous experiments have indicated. These two processes are characterized by two distinct dissipation peaks and the corresponding changes in the resonance frequency of the mechanical oscillator used in the experiment.

The softening of the vortex structure was shown[1] to be anisotropic: the temperatures associated to both peaks change with the angle θ between the applied field, H, and the crystalline c axis of the sample. When H is parallel to c, i.e. $\theta = 0$, the amplitude of the peak at the lower temperature, T_M, is maximum while the peak at the higher temperature, T_I, is small. When the field is rotated the temperatures T_M and T_I increase with θ. At the same time the amplitude of the peak at T_M diminishes while that at T_I increases. At angles close to $\theta = 90^o$ the amplitude at T_I goes through a maximum while the peak at T_M dissappears within the experimental sensitivity. The peaks define two lines in the H-T phase diagram. It was also shown that these two lines are completely determined by the field component parallel to the c axis, $H cos\theta$.

The presence of two lines indicates that the complete reversibility of the vortex state takes place only at temperatures higher than T_I. The existence of two steps in the softening of the vortex structure has very important consequences for the controversial interpretation of the mechanisms leading to a reversible region in the H-T phase diagram.

The changes in the oscillator resonance frequency associated to the dissipation peaks are related to changes in the magnitude of the shielding currents induced by the movement of the sample in the presence of the magnetic field. The peak at T_M was suggested[1] to be due to a softening of the coupling between CuO layers (currents flowing through the planes) and the one at T_I to a complete depinning of the pancake vortices (currents in the planes). In the oscillator experiments the relative movement between sample and field cannot be precisely established, which implies that the actual current paths are unknown. Hence, to prove the picture given previously [1] it would be necessary to perform an experiment where the direction of the shielding currents could be chosen a priori. The ac mutual inductance technique used to measure both components of the susceptibility, χ' and χ'', is adequate for accomplishing such a requirement.

In this paper we report ac susceptibility and mechanical oscillator measurements performed on the same single crystal of $Bi_{2.1}Sr_{1.9}Ca_{0.9}Cu_2O_{8+\delta}$ and at the same frequency. The ac measurements were carried out in two different geometries; in one of them the ac field was applied parallel to the c axis, hence the shielding currents flow only in the Cu-O planes. This is the usual configuration found in the literature. In the other geometry, the ac field was parallel to the layers inducing shielding currents through the Cu-O planes. The oscillator measurements reproduce the field and temperature dependence of the two dissipation peaks reported previously[1]. The ac susceptibility results unequivocally show that the low temperature dissipation peak is induced by the loss of phase coherence between the Cu-O planes while the peak at higher temperature is induced by the dissipation of currents flowing in the planes.

The mechanical oscillator measurements reported here were carried out up to fields of 4T using a superconducting magnet. The measurements were made at $\theta = 0^o$ as depicted in the inset of figure 1 a). For more details regarding the experimental set-up, see refs. [1–3]. The ac susceptibility set-up designed to probe the shielding capability of the Cu-O planes is sketched in the inset of figure 1 b). The primary as well as the secondary consist each of two coils wound astatically , in order to diminish the temperature dependent background and coupling with the environment. All four coils were wound coaxially on a sapphire rod, which was glued by one of its ends to a copper holder. The sample was glued on the other end of the rod as close as possible to one of the secondaries. The set-up for the other current configuration shown in the inset of fig. 1 c) was designed to allow the sample to be placed inside of one of the secondaries. In order to achieve a high filling factor, the secondaries had a flat shape. In both configurations χ' and χ'' were simultaneously measured by means of a lock-in amplifier. The sample holder was weakly thermally connected to a liquid helium bath, the temperature was raised by means of an electrical heater and measured with a carbon glass resistance. The dc magnetic field was applied by means of a rotating iron core magnet, which allowed us to change the angle θ in a precise and reproducible way ($\Delta\theta \simeq 0.2^o$). The amplitude of the ac field in the measurements reported here was kept constant at $\simeq 0.2Oe$, and its frequency was chosen equal to the resonance frequency of the oscillator used in the mechanical measurements ($\simeq 1.5kHz$).

The sample was a single crystal with composition $Bi_{2.1}Sr_{1.9}Ca_{0.9}Cu_2O_{8+\delta}$ grown and characterized as reported elsewhere[4]. The high quality of these samples has been further checked through low field high resolution magnetization[1] and flux lattice decorations[5, 6].

Figure 1 shows mechanical oscillator and ac susceptibility measurements performed as a function of temperature on the same sample at an applied field of $5kOe$. In all cases the dc field was directed along the sample c axis, and the measuring frequency was $\simeq 1.5kHz$.

In figure 1 a) we have plotted the dissipation and frequency shift measured by means of the mechanical oscillator. The dissipation peak observed at $T_M \simeq 31K$ is a consequence of a softening of the vortex structure[1, 2]. The existence of another peak, at $T_I \simeq 44K$, reflects[1] that the vortex structure remains coupled to the sample in spite of the softening at T_M. This is also evident from a residual stiffness in the frequency shift. At temperatures higher than T_M the vortex structure is completely decoupled from the sample motion. Shown in part b) of the same figure are the two components of the susceptibility χ' and χ'' when the ac field is parallel to the c axis of the sample. The maximum of χ'' at $\simeq 45K$ defines a temperature that coincides with the T_I obtained from the oscillator measurements. Shown in part c) of the same figure is the susceptibility when the ac field is parallel to the Cu-O planes. In this configuration χ'' shows a peak at $\simeq 32K$. Most of the shielding capability is lost at this temperature, as indicated by χ'. This transition coincides with the softening detected by the oscillator at T_M . The data also show a minor peak in χ'' at T_I , which is likely to be due to a small misalignment of the $Cu-O$ planes relative to the ac field.

In the H-T phase diagram, see fig 2, we have plotted $T_M(H_\parallel)$ and $T_I(H_\parallel)$ obtained from the mechanical oscillator and the susceptibility measurements at $1.5kHz$. It was shown[1] from mechanical oscillator measurements, that the relevant magnetic field component which defines the phase diagram is $H_\parallel = H cos\theta$. This universal behavior is also demonstrated by the susceptibility data in fig. 2.

The results show that the transition to the reversible region of the vortex state at constant field is made in two steps, at different temperatures. This fact together with the experimentally found $H cos\theta$ scaling, imposes unique conditions that have to be incorporated in a proper understanding of the vortex dynamics in the high temperature superconductors.

On one side the presence of two peaks shows that the behavior of the transitions is independent of the technique used to study the vortex dynamics. On the other hand the simplicity of the technique allows to choose the direction of the exciting current to explore which is the particular response of the vortex structure. The low temperature peak shows that the shielding capability of the currents flowing across the planes is drastically reduced at $T_M(H)$, while the shielding capability of the currents in the planes is reduced at $T_I(H)$.

Until very recently, the theoretical effort has been focused either on a single step phase transition[7–10] or on a thermally activated depinning picture[11, 12].

When the experimental work was finished we became aware of the very recent work by Glazman and Koshelev [13], where a phase diagram quite similar to that showed in figure 2 was predicted. They also suggested an experiment with the same geometry we have used to determine $T_M(H)$. According to ref. 13 the nature of the two steps transition in the phase diagram has different origin depending on the intensity of the applied field. In the high field regime, the low temperature line is related to the loss of phase coherence along the c direction and the high temperature transition is due to the melting of a quasi-two dimensional vortex lattice. In the low field region Glazman and Koshelev predict a complete change in the character of the transitions. The low temperature one is the transition from a vortex lattice to a vortex line liquid, while the high temperature one is associated to the destruction of the vortex lines. The features of the transitions characterizing the change in regime from the high to the low field limit is not made explicit in their paper. The calculations in ref. 13 are made assuming no pinning and the field parallel to the c axis. The influence of pinning is suggested on a general basis without including a detailed calculation of the phase diagram.

The quantitative comparison between our experimental data and the calculated phase diagram is not yet possible. The theoretical description of the high field regime coincides quite remarkably with the experiments. In this context and assuming that due to pinning the stable low temperature phase is a vortex glass, the low temperature transition would correspond to the loss of phase coherence between planes, as described in ref. 13. The transition at higher temperatures would be the theoretically predicted two dimensional melting. In the low field regime the agreement between theory and experiment is more questionable. It is difficult to believe that a dissipation peak can arise from the transition between a vortex glass and a "pinned liquid state".

It is also important to point out that the experimental dissipation peaks do not show any special feature indicating a possible change in behavior when going from the high to the low field regime. It is shown that the peaks at $T_M(H)$ and $T_I(H)$ are characteristic of dissipation induced by interplane and intraplane currents, respectively, in the whole field range. The universal behavior followed by both transitions, see fig. 2, is another constraint that theory should obey.

In conclusion, the results reported here demonstrate the existence of two nearly independent dissipative processes induced by currents flowing in two crystallographic directions, parallel and perpendicular to the c axis. This is an unusual result showing that dissipation can take place in some regions while in others the magnetic flux remains in a non-dissipative state. Similar behavior has been recently reported in ceramic materials [14–16] .The important difference is that while in ceramics the results are due to spatial macroscopic inhomogeneities of the order parameter, in single crystals the spatial inhomogeneity is at a microscopic level.

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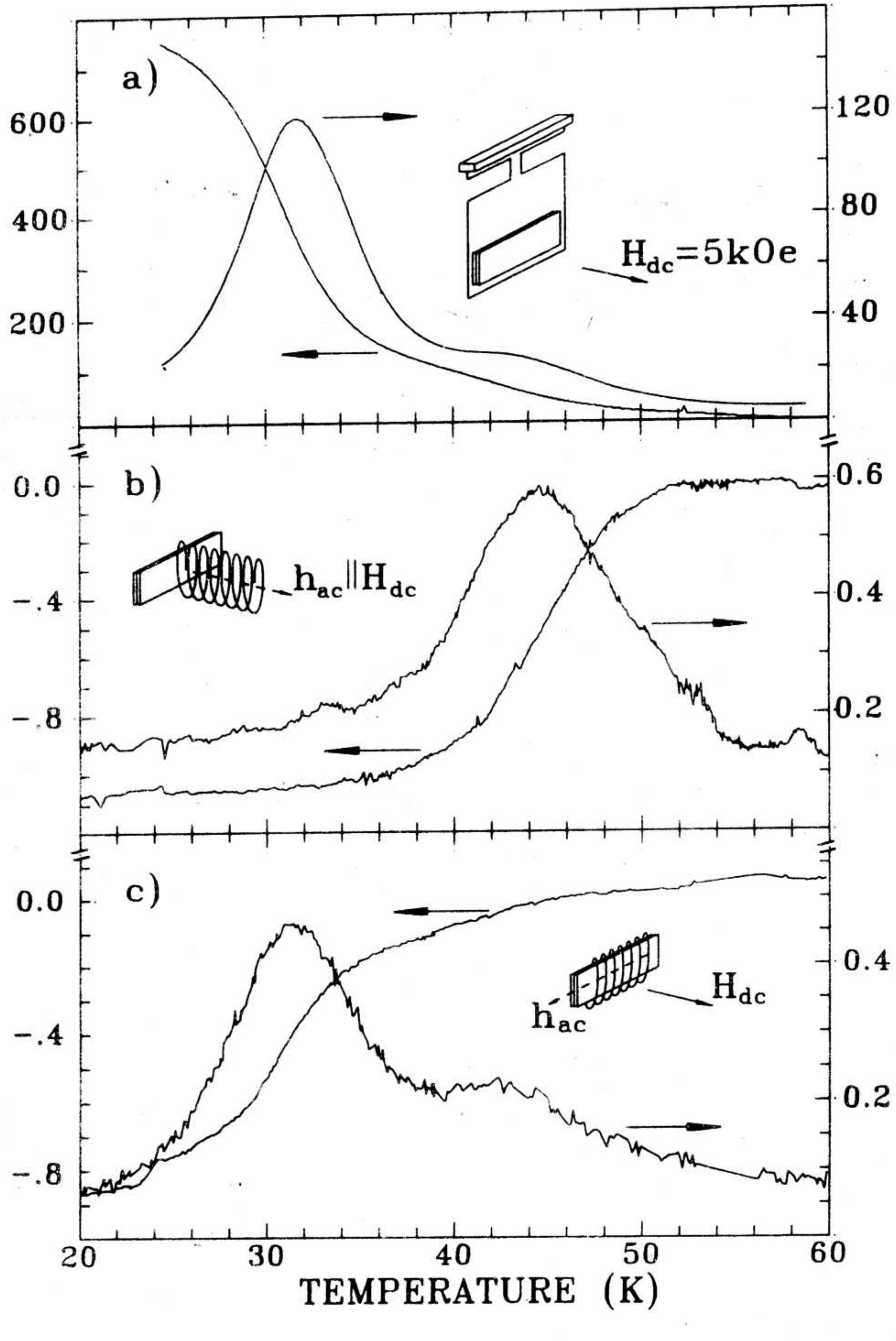
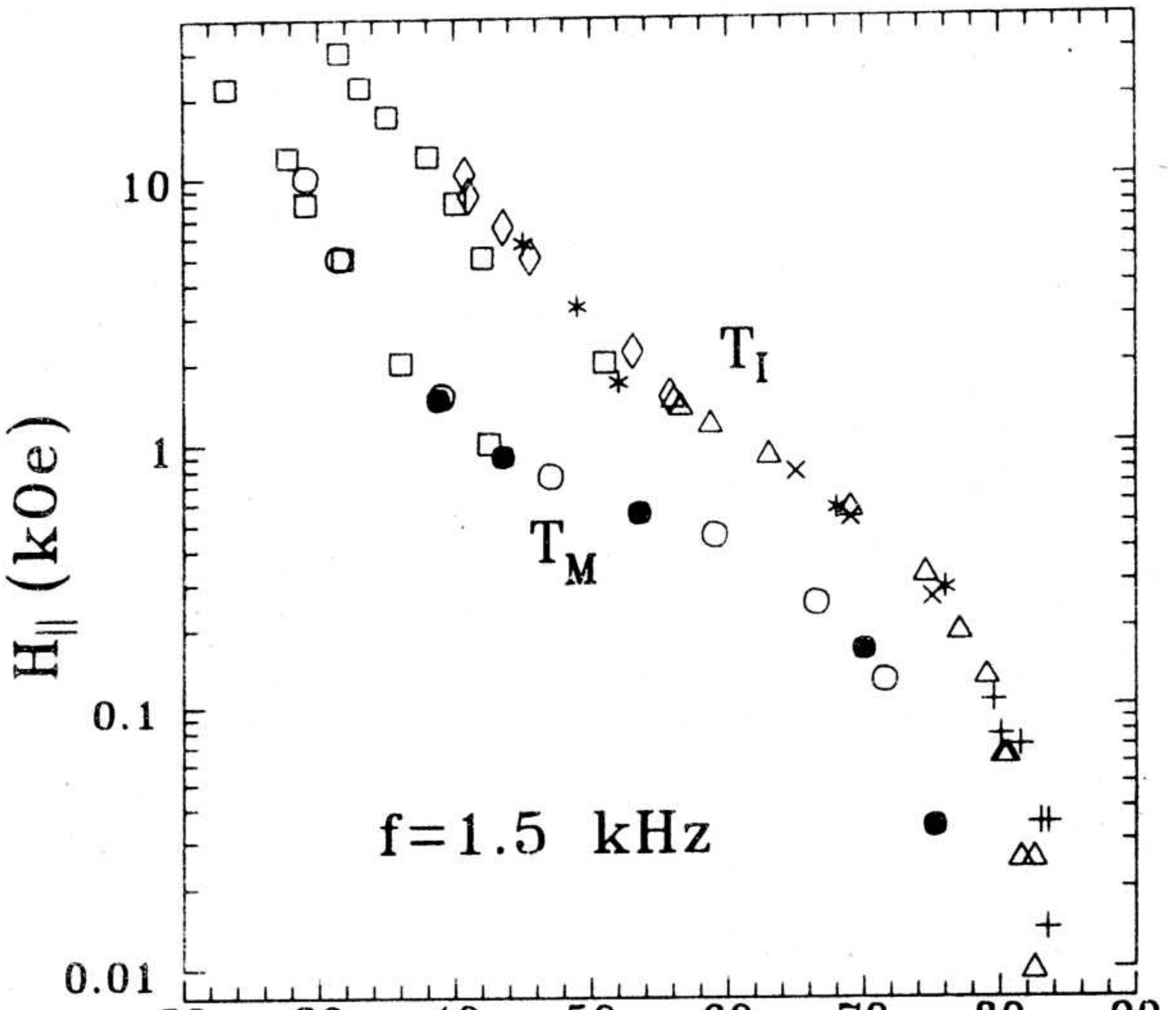
FIGURES

FIG. 1. Temperature dependence of the mechanical oscillator response and ac susceptibility in a field parallel to the *c* axis at 1.5 kHz. a) Dissipation and frequency shift measured by the mechanical oscillator. b) Dissipative and inductive components of the susceptibility for the ac field parallel to the *c* axis. c) Same as b), with the ac field parallel to the $Cu-O$ planes. The corresponding insets show the configurations used in each case.

FIG. 2. Phase diagram for the field component $H_{\|} = H cos\theta$ at a frequency of $\simeq$ $1.5kHz$. The □ indicate the dissipation peaks measured with the mechanical oscillator. T_M as measured by the susceptibility (ac field parallel to the planes) is indicated by the ∘ for different fields at $\theta = 0^o$, and by • at different angles for $|H| = 1.5kOe$. T_I from the susceptibility (ac field parallel to the c axis) is indicated by ◇ for different fields at $\theta = 0^o$, **and at different angles for fixed values of $|H|$ by: $*$: $|H| = 6.5kOe$; $\times$: $|H| = 3kOe$; Δ: $|H| = 1.5kOe$, and $+$: $|H| = 0.8kOe$.**


a)
H_{dc}=5kOe
Δf (ppm)
600
400
200
Dissipation (a.u.)
120
80
40
b)
h_{ac}||H_{dc}
χ' (a.u.)
0.0
-.4
-.8
χ'' (a.u.)
0.6
0.4
0.2
c)
h_{ac}
H_{dc}
χ' (a.u.)
0.0
-.4
-.8
χ'' (a.u)
0.4
0.2
20
30
40
50
60
TEMPERATURE (K)



$H_\parallel$ (kOe)
10
1
0.1
0.01
20
30
40
50
60
70
80
90
TEMPERATURE (K)
T_I
T_M
f=1.5 kHz