Interaction of vortices with oriented twin boundaries in single-crystal $YBa_2Cu_3O_{7-\delta}$

J. A. Herbsommer, G. Nieva, and J. Luzuriaga
Centro Atómico Bariloche and Instituto Balseiro, CNEA and UNC, 8400 Bariloche, Argentina
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We have studied the response of the vortex lattice (VL) in a $YBa_2Cu_3O_{7-\delta}$ sample with oriented twin boundaries (TB's) and in an untwinned sample. In the twinned sample the density of twin boundaries is estimated from decoration experiments. The TB's affect the liquid-to-solid transition in the vortex structure, which is of first order in the twin free crystal and to a Bose glass in the twinned sample. We measure the ac susceptibility, and find that the response strongly depends on the orientation of the probing ac field with respect to the TB's. The ac field produces a tilting stress on the vortices. With the applied dc magnetic field H_{dc} parallel to the c axis, the response of the VL is weaker when the tilt is parallel to the TB's than when it is perpendicular or at 45 degrees to the TB's. The results are explained by the fact that the VL is locked to the twin boundaries for small deviations of H_{dc} from the c axis and is partially pinned to them for larger angles. By measuring over the whole angular range we estimate the angles over which each regime is realized for different temperatures. The results of the detwinned sample are used for comparison.

I. INTRODUCTION

The interaction between correlated defects and vortices in high-T_c superconductors is important both in determining the order of the phase transitions of the vortex structure and the resultant pinning in the solid.[1–6] For this reason, it is important to characterize the behavior of the vortices in the presence of correlated disorder.

$YBa_2Cu_3O_{7-\delta}$ (YBCO) usually presents twin boundaries[7] (TB's) that introduce dramatic changes in the pinning of the vortex lattice.[1,8,9] The twin boundaries form planarly correlated defects parallel to the c axis with highly anisotropic pinning properties. They form an angle of approximately 45° with respect to both the a and the b axes.

The pinning by correlated defects, such as TB's, is expected to be maximum when both the defect and the applied field are almost aligned. Over a small angular range, in the *lock-in* regime the vortices will follow the defect, and not the direction of the field. For larger angles, an *accommodation* regime is expected, where the vortices are partially aligned with the defects, and for larger misalignment of field and defect a free vortex state is found.[1,6,10–13] Nelson and Vinokur[4,14] have proposed that in the presence of correlated defects the vortex lattice presents a Bose glass transition when the dc field is applied parallel to them. The correlated defects stabilize a new low-temperature glassy phase in which the vortices are localized inside the defects. Although the theory has been developed for columnar defects, the Bose glass phase has also been found experimentally in twinned YBCO.[5] Single crystals with no twin boundaries, on the other hand, show a first-order phase transition into a vortex crystal.[15,16]

Normally YBCO single crystals grow with TB's oriented at right angles to each other and this complicates the measurements of their directional properties and the way they affect the dynamics of the vortices. However, some crystals grow with twin boundaries in a single direction, and we have selected one with such characteristics for the present work.

We study the anisotropic behavior of the vortex lattice in this crystal by measuring the response to an ac magnetic field oriented in different directions with respect to the TB's. In addition we can rotate the external dc magnetic field so that we cover the whole angular range, from the direction parallel to the c axis to the direction of the a-b planes. A second sample which has been detwinned under uniaxial compression has also been measured. In this way, we probe the effect of the material anisotropy in the twinned sample with the different vortex-TB orientations, as compared to that of the detwinned sample first-order phase transition.

II. EXPERIMENTAL DETAILS

We have measured a single crystal of $YBa_2Cu_3O_{7-\delta}$ with oriented twin boundaries, identified as sample TW. We also study a detwinned single crystal of the same material referred to as sample DTW. The YBCO crystals come from a batch prepared using a flux-growth technique as described in Ref. 17.

Sample TW was fully oxygenated with a T_c value of 92.6 K and a zero-field transition width $\Delta T = 0.6$ K (taken from the width at half maximum of the peak in the dissipative component of the susceptibility measurement). Sample DTW was detwinned applying uniaxial stress following a procedure similar to that described in Ref. 18 and was fully oxigenated after that procedure. Under polarized light the sample showed no evidence of TB's and had a value of $T_c = 91.7$ K with a sharp zero-field transition $\Delta T = 0.5$ K.

In order to confirm that sample TW had twin boundaries in only one direction we used the magnetic Bitter decoration technique.[19–21] The decoration was made at 4.2 K using a field-cooling (FC) procedure with an applied field of 52 Oe perpendicular to the Cu-O planes. The images were obtained with a scanning electron microscope (SEM) at room temperature. More detailed information is available in Ref. 21. By analyzing images over the whole area of the sample we have found that around 65% of the vortices are locked to the parallel twin boundaries with TB free regions scattered in irregular bands in between and no evidence of TB's in a

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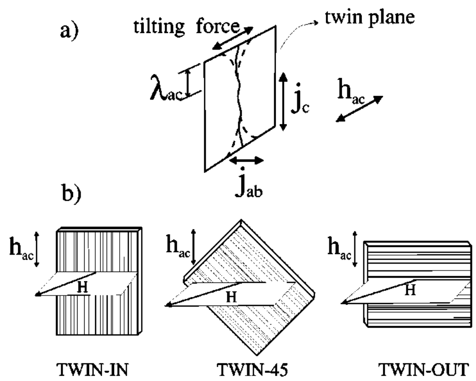

FIG. 1. (a) Configuration of ac field and induced currents with respect to the crystal axes and twin boundaries. (b) Plane of rotation of the dc magnetic field (H) and orientation of h_{ac} with respect to the twin boundaries in the three configurations used.

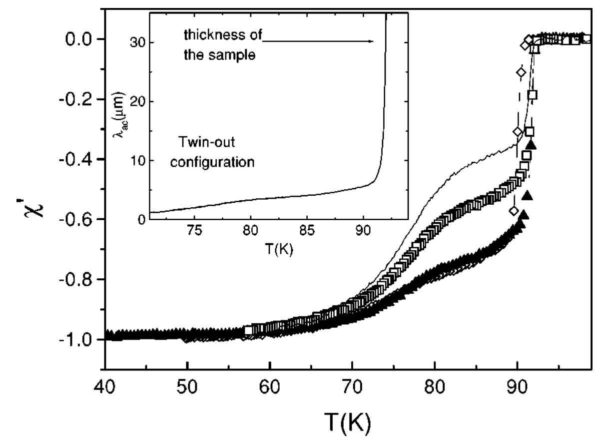

FIG. 2. Real component of the susceptibility as a function of temperature for the detwinned sample and the three configurations of h_{ac} in sample TW. Line: Twin-In configuration, open squares: Twin-45, full traingles: Twin-Out, open diamonds: sample DTW. Inset: Campbell penetration depth for the Twin-Out configuration. In all cases the dc field is in the c-axis direction and has a value of 1390 Oe.

different direction.[21] This confirms the observations made with polarized light, but the decorations have both a higher resolution, and refer specifically to the effectiveness of the TB's for pinning the vortices. It is important to remark that the proportion of pinned vortices was observed for an applied dc field of $H=52$ Oe and it may be different for higher fields. However, the experiment is, as far as we know, unique in giving a quantitative description of the effectiveness of the twin boundaries as pinning centers.

The results reported in this paper are obtained measuring the transverse ac susceptibility χ' in the linear regime. A small ac field is applied in the direction of the a-b planes. In this geometry, in contrast to the more usual one in which the ac field is parallel to the c axis, the ac currents induced in the sample are forced to flow in two directions: within the a-b planes and parallel to the c axis. Analysis of the Lorentz forces indicates that they exert a tilting stress on the vortex lattice (VL) as is shown in Fig. 1(a). In this sketch we can see that a vortex is subject to a tilting force which tends to move the vortex in a plane perpendicular to the a-b planes and in the direction of h_{ac}. From this analysis we see that choosing the direction of the ac field with respect to the sample we can get information on the response of the VL to a tilting stress in specific orientations.

In of Fig. 1(b) we show the three configurations of h_{ac} that we used in the measurements of the twinned sample. In the configuration Twin-Out; h_{ac} is normal to the planes of the TB's so the tilting stress would move the vortices out of the TB. The dc magnetic field H_{dc} is applied at different angles from the c direction and the axis of rotation is always parallel to the h_{ac} direction so in this case the plane of rotation of H_{dc} coincides with the TB planes and the vortices are always parallel to the TB's.

In the configuration Twin-In; h_{ac} is parallel to the TB planes so the stress produced would tilt the vortices in planes parallel to the TB's. The plane of rotation of H_{dc} is orthogonal with the planes defined by the TB's and this means that, in contrast to the previous configuration, this geometry forces the vortices to adopt a staircase pattern for some values of θ.[1,6,10–13] The last configuration is refired to as Twin-45 and h_{ac} is oriented so that the vortices are forced to tilt at 45 degrees from the planes of the TB's. The rotation plane of H_{dc} has a normal vector 45° from the normal vector of the TB planes. In this geometry, as in the Twin-In configuration, the vortices are forced to arrange in a staircase pattern in the accommodation regime. The force on the vortices has components parallel and perpendicular to the TB's.

The susceptibility measurements were carried out by means of a mutual inductance technique and the excitation and detection was made using a two-phase lock-in amplifier (PAR 5302). The proper phase of the lock-in amplifier was set by measuring the sharp transition of a niobium sample. All the susceptibility measurements reported here have been taken in field cooling experiments with the magnetic field H_{dc} applied at angle θ from the c axis and the plane of rotation of H_{dc} perpendicular to h_{ac}.

III. RESULTS

In Fig. 2 we show the real component of the susceptibility χ' as a function of temperature, for the three configurations of h_{ac}. The dc field $H_{dc}=1390$ Oe is parallel to the c axis in these measurements. The curves have been normalized by the value at low temperatures of the zero-field transition, where the shielding fraction is one ($\chi'=-1$). These curves were obtained using a excitation field of $h_{ac}=90$ mOe and frequency $f=2318$ Hz.

When the sample is cooled from above T_c, a sharp increase of the screening capability is observed at a temperature we will identify as T_j. This feature is frequency independent.

Lowering the temperature further, the absolute value of the screening increases smoothly and there is a plateau followed by a drop, reaching the total flux expulsion at a temperature $T\simeq 40$ K. This part is frequency dependent. In contrast to other experiments reported,[22] where shielding currents run only within the Cu-O planes, the shielding fraction only reaches its full value at rather low temperatures. At the plateau the shielding fraction is maximum for the Twin-Out configuration, when the force on the VL is perpendicular

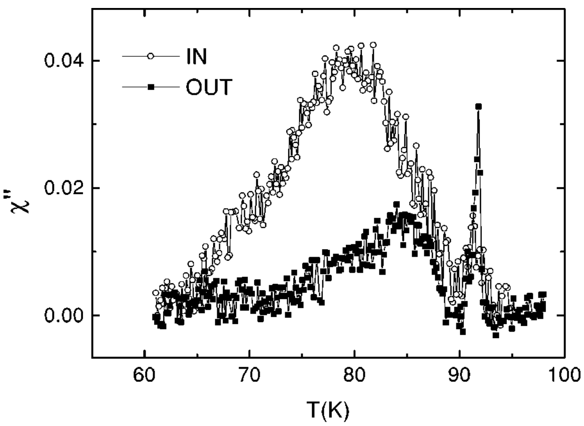

FIG. 3. Out-of-phase component of the ac susceptibility χ'' corresponding to the Twin-In (open circles) and Twin-Out (full squares) configurations, the dc field is in the c-axis direction and has a value of 1390 Oe.

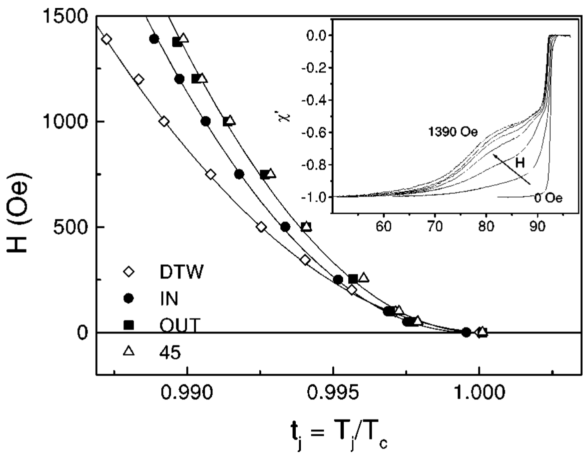

FIG. 4. H-T phase diagram. Open triangles: Twin-Out configuration, filled squares: Twin-45, filled circles: Twin-In, open diamonds: sample DTW. Inset: χ' vs T curves for the Twin-45 configuration of h_{ac} for different values of H_{dc}.

to the TB's and minimum in the Twin-In configuration, when it is parallel to the TB's. The step in χ' at T_j for the Twin-In configuration is also somewhat less abrupt than in the other two cases. The abrupt change in shielding at T_j could be interpreted as a transition from a vortex liquid to a solid, and the structure seen in χ' below T_j should be ascribed to changes in pinning of the solid vortex lattice.

In Fig. 3 we can observe the out-of-phase component of the ac susceptibility χ'' corresponding to the Twin-In and Twin-Out configurations, using the same normalization of χ'. These curves represent the dissipation of the screening currents induced by the probing ac field.[23] Both curves show a narrow peak at temperature T_j and a broad maximum that corresponds to the low-temperature structure of χ'. Although the features have similar characteristics in the two configurations there are important differences between them. In fact, the peak at T_j of the Twin-Out data is narrower and higher than the peak of the Twin-In configuration. This is related to the fact that the jump in χ' of the Twin-In configuration is smaller and broader to that corresponding to the Twin-Out geometry.

Another important difference is the broad low-temperature maximum in each curve. The Twin-Out maximum is lower than that seen in the Twin-In curve and we will show below that this is related with the degree of freedom in the solid state for the movement of the vortices in response to the different tilting forces induced by the excitation field h_{ac} in the different geometries.

As a general characteristic of the dissipation data we have to remark that our values are very low in comparison with dissipation values of the Bean critical state or diffusive regimes in the usual geometry of h_{ac} parallel to the c axis.[21,24] In fact, our maximum value of dissipation $\chi''_{\rm max}$ is always lower than 0.04, while in the critical-state regime $\chi''_{\rm max}=0.235$ and in the diffusive regime $\chi''_{\rm max}=0.44$.[23] We interpret this low dissipation as additional evidence that we are measuring in the Campbell regime in which the excitation field is so low that the vortices move slightly in the bottom of their pinning potential.

We have checked that the response is within the linear regime, by taking similar curves under different ac excitation, changing h_{ac} from 9 mOe to 1 Oe. For the lower values of $h_{ac}<0.1$ Oe, the curves superpose, while for higher excitation some amplitude dependence is seen. This dependence is much more marked in the region of the plateau and at lower temperatures, while the step at T_j is constant, within the experimental resolution, for all values of h_{ac}.

To determine the H-T phase diagram we have measured the susceptibility with the dc field oriented along the c axis for different values of the modulus of the dc magnetic field. The data are presented in Fig. 4. The inset shows the χ' vs T curves for the Twin-45 configuration. The point T_j in the H-T diagram was defined by taking the temperature where the value of $\chi'=-0.12$. This coincides with the temperature of the peak in the value of the imaginary component χ''.

It was found that the configuration of h_{ac} (i.e., the direction of the applied force) influences the position of T_j in the H-T diagram. For a given value of H_{dc} the temperature T_j is seen to be shifted towards lower temperatures when the force on the vortices is parallel to the twins, but when the force is at 45 degrees or perpendicular to the twins, both lines coincide within experimental error. This shift in T_j will be discussed further on, when analyzing the angular variation of T_j.

Sample DTW shows a T_j which is lower than for all h_{ac} configurations of sample TW. In this case the abrupt change in χ' (the inset of Fig. 4 is not due to the existence of TB's but to the formation of a vortex crystal through a first order phase transition. Magnetization,[25,26] transport,[27] flux transformer,[28] specific heat,[16] etc., show always jumps and sharp transition in detwinned samples and we understand that C_{44} has to show the same behavior. In the H-T diagram (see Fig. 4) the lines belonging to the twinned samples in all the configurations are always above the ''melting line'' of the detwinned sample. This fact is in agreement with the Bose glass theory[4] that predicts a higher liquid-solid transition temperature when the sample has correlated defects.[27]

All the H-T curves could be fitted very well by a parabola of the type $H=H_0(T_j-T_c)^2$. The solid lines in the graph are fits to this expression.

We have studied the angular dependence of the VL response, and Fig. 5 shows the χ' vs T curves corresponding to $H_{dc}=1390$ Oe for different values of the angle θ between

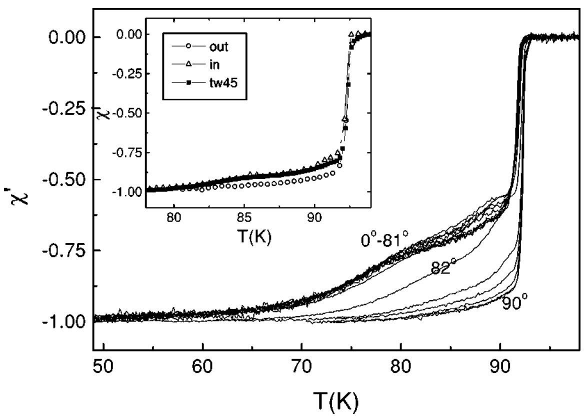

FIG. 5. χ' vs T curves corresponding to $H_{dc}=1390$ Oe for different values of the angle θ between the c axis and H_{dc} in the Twin-Out configuration. Inset: χ' vs T curves for the three h_{ac} configurations with $\theta=90$.

the c axis and H_{dc}. As in the previous results $h_{ac}=90$ mOe, $f=2318$ Hz. The ac field is in the Twin-Out configuration.

It can be seen that the curves change with angle in this anisotropic material. In particular there is a shift in the temperature T_j (defined by the $\chi'=0.12$ criterion) which is presented in Fig. 6, while the behavior below T_j follows a different pattern. The behavior below T_j seen in the Twin-In and Twin-45 configurations is more complicated, and will be treated in detail elsewhere. We will only remark that in general, the shielding fraction below T_j is smaller than in the Twin-Out configuration. In these other configurations, and for some values of θ, the shielding is nonmonotonic, showing a broad, shallow maximum, probably due to a softening of the solid which allows a better accommodation to the pinning centers as in the peak effect.[29]

The angular dependence of T_j/T_c at a fixed modulus $H_{dc}=1390$ Oe is shown in Fig. 6, including all the different h_{ac} configurations used in this work. The same χ' criterion and values of h_{ac} and frequency mentioned above were used to define T_j in all configurations.

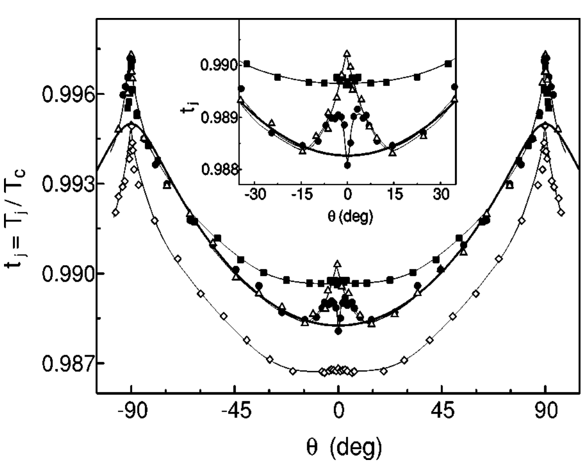

FIG. 6. Angular dependence of $t_j=T_j/T_c$ for a fixed modulus of 1390 Oe of the dc field. Open diamonds: sample DTW. Sample Tw; filled circles: Twin-In configuration, open triangles: Twin-45 configuration, filled squares Twin-Out configuration, full line: anisotropic superconductor with $\gamma=5.5$. Inset: Low angle detail.

It is evident that the curve for the Twin-Out configuration is the one showing simpler structure. In this configuration, because of our geometry (see Fig. 1) the dc field rotates inside a plane parallel to the twin boundaries. Therefore, the static magnetic field does not cut the twin boundaries and the TB-vortex interaction is that of a vortex parallel to the twin for all θ values. The difference in T_j with angle is then due mainly to the anisotropy of the material. However, close to the Cu-O planes ($\theta=90°$) the curve has the form of a cusp. However, the variation of critical current with angle expected from the anisotropy of the material,[6] plotted as a full line in Fig. 6, shows a maximum. The enhancement of T_j observed in this material as a cusp close to $\theta=90°$ is probably due to pinning by the Cu-O planes where a ''smectic phase'' could be nucleated.[30]

In the Twin-45 configuration the dc field rotates in a plane 45° away from the TB's and therefore the vortices are parallel to the TB's only for $\theta=0$. It is seen that for $\theta=0$, T_j is maximum, and its value coincides with that of the Twin-Out configuration. When the field is rotated, the vortex-TB interaction is reduced and this causes a decrease of T_j with increasing tilt of H_{dc} until around $\theta\approx15°$ the TB-vortex interaction is ineffective and there is an increase following the anisotropy. Close to the Cu-O planes, again an enhancement of T_j over the curve corresponding to the anisotropy is seen.

The Twin-In configuration shows the more complicated structure. Here the force on the vortices is parallel to the TB's and the dc field rotates in a plane perpendicular to the twin boundaries. At $\theta=0$ the value of T_j is lower than for the cases discussed previously, but when tilting H_{dc} away from the TB's direction there is an increase in T_j until $\theta=4°$, then a decrease, and for $\theta>15°$ the characteristic behavior of the anisotropy is followed.

The detwinned sample (DTW) shows fair agreement with the behavior expected from the anisotropy, but as in sample TW, the same enhancement of T_j is observed when H_{dc} is close to the Cu-O planes. The whole curve is shifted towards lower temperatures with respect to the twinned sample, as corresponds when the transition is to a vortex solid.

The angular dependence of T_j has also been studied for other values of the modulus of the dc magnetic field. Figure 7 shows the results, for the Twin-In configuration for values of the modulus of H_{dc} of 52, 750, and 1390 Oe.

The definition of T_j and the frequency and amplitude of h_{ac} are the same as in the previous figures. It can be seen that the features of the different curves are preserved, although the positions of the maxima and minima change with the modulus of the dc field. There is always a minimum in T_j at $\theta=0$ and then a maximum at θ_1 when the angle is increased, followed by a broad minimum at θ_2. Both θ_1 and θ_2 decrease with increasing modulus of H_{dc} giving a corresponding temperature dependence. In the inset of Fig. 7 we show the sine of these angles multiplied by the dc magnetic field plotted against $(1-T/T_c)$.

IV. DISCUSSION

Nelson and Vinokur[4,14] have predicted that the Bose glass should show special characteristics that differentiate it from the vortex glass.[31,32] One such characteristic is that, at the transition, the tilt modulus C_{44} diverges as

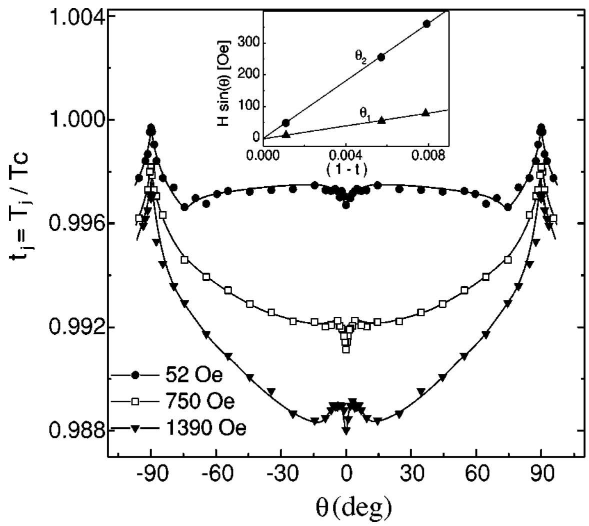

FIG. 7. Angular dependence of T_j for different values of the modulus of the dc field. Full circles: $H_{dc}=52$ Oe, open squares: $H_{dc}=750$ Oe, full triangles: $H_{dc}=1390$ Oe. Inset: Temperature dependence of $H\sin(\theta_1)$ and $H\sin(\theta_2)$.

$$C_{44}\sim\frac{1}{(T-T_{BG})^{\nu}}\tag{1}$$

and this implies that the superconductor is capable of screening perfectly a transversal dc field in a ''transversal Meissner effect.'' As we described above, the curves of Fig. 2 show a sharp increase of the screening capability of the system at a temperature T_j. This response is not usual for YBCO with more conventional probing forces[22] and we interpret this sharp increase of the screening at T_j as an important change of the response to the tilting stress produced by the probing ac field. The change in the C_{44} is a manifestation of the Bose glass transition from the liquid to the solid vortex lattice. To understand more quantitatively these results we can transform our susceptibility data to ac penetration length λ_{ac} by means of the expression[33,34]

$$\chi'=\frac{2\lambda_{ac}}{d}\tanh\frac{d}{2\lambda_{ac}}\tag{2}$$

corresponding to our slab geometry, where d is the thickness of the sample. As is shown in the inset of Fig. 2 for the Twin-Out configuration, λ_{ac} changes its value from ∞ in the liquid to 0.3 d in the solid in less than 1 K. This last value probably depends on the number of twin boundaries present and their effectiveness for increasing the tilt modulus of all the lattice (in our sample 65% of the vortices are pinned in TB's for $H_{dc}=52$ Oe as seen in Bitter decoration experiments). One remarkable characteristic of the jump is the frequency independence of this feature; we have measured from 416 to 10 000 Hz without detecting any change. In contrast, the low-temperature structure is frequency dependent.

One point that is interesting to discuss is how far is the jump from the critical region of the phase transition. Bracanovic *et al.*[35] have performed measurements of ac susceptibility (h_{ac} parallel to the c axis) and resistivity in a single crystal of YBCO in the linear regime also explored by us. They have found that the susceptibility starts to show a nonzero value of the screening and dissipation when the resitivity has an abrupt drop upon lowering the temperature. This result implies that in the critical region, where it is possible to make a scaling analysis using transport techniques, the susceptibility has a finite value. We cannot be certain that the jump we detect in χ' is in the critical region, but it is probable that T_j is very close below the Bose glass transition. Our experiment should be sensitive to a diverging C_{44}.

The χ' curve corresponding to the Twin-In configuration shows a jump that is smaller and broader than in the other configurations. We interpret that in this geometry the vortices that are in the TB free regions can move freely and the vortices that are in the TB's can move along the channel-shaped potential of the TB's determining that the sharp characteristic of the screening is lost. In this condition the perturbation ac field penetrates in the sample with a larger λ_{ac} determining a smaller jump and a worse screening.

The χ' curve of the Twin-45 configuration is intermediate between those of the Twin-Out and In configurations. Because the potential of the TB's is very directional, there could exist the possibility of ''channeling'' of the vortices when a force with components parallel to the TB's is applied. In this case, with force at 45 degrees, the displacement along the TB's should dominate, and the signal should be closer to the Twin-In configuration. This is not observed in the measurements, and an intermediate screening, compatible with an average anisotropic pinning is observed. In transport measurements, Pastoriza *et al.*[36] have seen a similar anisotropic behavior for vortex motion, when the critical current is very close to zero.

In the inset of Fig. 4 we can observe the curves χ' vs T for different values of the dc applied field H_{dc}. The data correspond to the Twin-45 configuration (all the configurations show qualitatively similar behavior). The more visible change is the variation of the low-temperature structure. In fact, the broad plateau washes out for lower values of the dc magnetic field. From an analysis of the λ_{ac} curves and relating them to the elastic constants involved in this experiment we found that the change is due to the field dependence of $C_{44}\propto B^2$. Due to the length of this analysis we will discuss it in detail in a future paper.

Referring to the lines of the different configurations we have to remark that although we can appreciate differences between them the temperature of the onset of the screening coincides in all the configurations for each value of H_{dc}. The differences are due to the broadness of the jump and the criterion adopted to determine T_j. Then the shift observed in the Twin-In configuration for example is an indication of the broadness of the jump discussed previously.

We turn to the question of how the χ' vs T curves change with the angle θ of the applied magnetic field. Figure 5 shows several typical curves for different angles of H_{dc} in the Twin-Out configuration. Observe that the curves from $\theta=0°$ to $\theta=82°$ look almost the same and for angles greater than this last value there is an abrupt transition to curves that show a better screening. From these observations we conclude that in this configuration, in which the plane of rotation of H_{dc} coincides with the TB planes, the dynamics of the lattice is not very much dependent on the anisotropy of the material but the Cu-O planes have a strong effect. In fact, we understand that in this configuration the vortices are always in the TB's but for angles close to the Cu-O planes probably they feel attracted by the intrinsic pinning of the planes. Following this idea we interpret the change at $\theta = 82°$ as a lock-in of the vortices in the Cu-O planes. In this case the vortices would be pinned in the Cu-O planes and the TB's at the same time and this fact would greatly reduce the degrees of freedom of the system, improving drastically the screening properties of the superconductor. Observe that the Twin-Out is the only configuration that allows the arrangement of vortices as proposed. In the other two configurations it is impossible for the whole length of the vortex to be in both correlated potentials at the same time. One measurement that confirms our interpretation is presented in the inset of Fig. 5. In this figure we show the curves obtained for the FC experiment of $H = 1390$ Oe applied in the Cu-O planes for the three configurations. We can observe that the Twin-Out configuration shows better screening than the other two, which approximately coincide between themselves. This effectively indicates that the configuration in which the vortices have the possibility to stay in both potentials at the same time screens better than the other two configurations, in which they are arranged in a staircase pattern.

The angular dependence of T_j seen in Fig. 6 varies strongly when changing the orientation of h_{ac}. The minimum in T_j for $\theta = 0$ in the Twin-In configuration corresponds to a maximum in the Twin-45 configuration. Both angular curves coincide for $\theta > \theta_1$, so the difference is restricted to the angles where we would expect a *lock-in* regime. Because the Twin-In configuration tends to move the vortices parallel to the TB's, the vortices inside and outside the TB's will be coupled through the shear modulus of the vortex lattice. The minimum seen in T_j at $\theta = 0$ corresponds to a configuration where the vortices outside the TB's and those inside are parallel. For $\theta \neq 0$ some vortices are locked to the TB's and those outside follow the field, which increases the coupling between these two types of vortex, increasing the effective shear modulus of the whole vortex structure and therefore increasing T_j. The divergence of C_{44} at the transition must be coupled to the shear modulus in order to be observed in the Twin-In configuration, and this is the origin of the different behavior seen with respect to the Twin-45 configuration.

For small angles, $\theta < \theta_1$ the vortices are expected to be in the *lock-in* regime. This interpretation was confirmed for low dc fields by the decoration experiments,[21] and because of the evolution seen when the modulus of H_{dc} is changed, (see Fig. 7), we believe this regime persists in all the fields studied. The evolution of θ_1 indicates how the frontier changes with temperature. According to Zhukov *et al.*[13], the maximum angle where the *lock-in* exists obeys the equation

$$H \sin(\varphi_L) = \frac{\varepsilon_0}{\phi_0} \sin(\varphi_T), \tag{3}$$

where ϕ_0 is the flux quantum, $\varepsilon_0 = (\phi_0/4\pi\lambda(T))^2$ is the line energy $[\sim(1-t)$ for small $t]$ and $\cos(\varphi_T) = \varepsilon_T/\varepsilon_0$, with ε_T the energy of the vortex inside the TB. From the inset of Fig. 7 it can be seen that both $H \sin(\theta_1)$ and $H \sin(\theta_2)$ follow a $(1-t)$ temperature dependence. If we identify θ_1 with the *lock-in* angle φ_L, Eq. (3) is satisfied as long as φ_T is constant in temperature, which can happen if ε_T and ε_0 have the same temperature dependence. The *accommodation* regime is more problematic to identify. The decoration experiments[21] at low fields show some evidence of pinning by the TB's above θ_2, and we believe the Cu-O planes may be playing a role in the response of the vortices, so that probably for angles greater than θ_2 the vortices do not form straight segments but other type of staircase pattern where they are partly pinned to the Cu-O planes.

V. CONCLUSIONS

We have studied the response of the vortex lattice for different orientations of the probing force on the vortices. Our measurements show that close to the line of the phase transition, the response depends strongly on this orientation. For H_{dc} close to the c axis the shielding is weaker when the tilt on the vortices is parallel to the twin boundaries, and this can be understood in terms of a *lock-in* of the vortices to the twins. In intermediate angles, the vortices are partly pinned to the TB's, and for higher angles the Cu-O planes probably start to play a role. The angular range over which these regimes are observed is strongly dependent on temperature at these low values of the dc magnetic field.

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