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Oscillatory dynamics in the vortex matter of twinned and untwinned $YBa_2Cu_3O_7$ crystals

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Experiments of oscillatory dynamics in twinned $YBa_2Cu_3O_7$ (YBCO) crystals in a dc magnetic field tilted with respect to the twin planes indicate that history effects (HEs) in these samples cannot be ascribed to an equilibration process but have its origin in the oscillatory character of the vortex dynamics. However, the role that extended twin boundaries play in the HEs of YBCO crystals has been the subject of controversies until now. In this work, we study the role of correlated defects in the dynamic history effects by performing angular ac susceptibility measurements in twinned and detwinned YBCO crystals. We confirm that in any case, whenever HEs are observed, the temporal symmetry of the shaking ac field plays a major role.

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The study of the driven vortex lattice (VL) in type II superconductors has been the subject of continuous efforts in the last years. It is nowadays well established that in the vicinity of the anomaly known as "peak effect" (PE),[1] history effects (HEs) are observed in a wide variety of low[2,3] and in high T_c materials.[4–6] A great amount of work was devoted to understand if this phenomenology is dominated by surface or bulk pinning properties. In $NbSe_2$ (Ref. 3) and $Bi_2Sr_2CaCu_2O_8$ (Ref. 7) samples, surface and geometrical barriers seem to play an important role. However, in materials with moderate anisotropy and high density of pinning centers, as is the case of well oxygenated twinned YBCO, transport properties at $H_{dc} \gg H_{c1}$ are generally well described by bulk pinning forces.

A general feature of the observed driven dynamics is the increased mobility of the VL after assisting it with a temporarily symmetric (e.g., sinusoidal) ac field.[2,4–6] Among the various proposed mechanisms,[8] the most invoked is an equilibration process assisted by the ac magnetic field from a supercooled disordered metastable phase to an ordered stable Brag Glass phase.[9,10]

However, experiments in twinned YBCO single crystals with the dc field tilted out of the twin boundaries (TBs) indicate that, in these samples, this framework does not apply. In a recent work, we have shown evidence that the PE in $YBa_2Cu_3O_7$ (YBCO) crystals arises from a drastic change in the dynamics of the VL.[11] It has been shown previously[6] that a VL free from bulk field gradients assisted by an asymmetric ac field (e.g., sawtooth—although a small asymmetry is enough) becomes less mobile. Moreover, mobility is also reduced if a temporarily symmetric ac field forces vortices into large excursions.[12] These reported features indicate that in well oxygenated YBCO crystals, the VL dynamics is the key element in the physics underlying the PE and HE. In fact, these HEs are mainly originated by the oscillatory character of the vortex dynamics. Defects (e.g., dislocations), their creation or annihilation being controlled by the different driven histories, might play a major role in the bulk VL response to an applied force.[13] A plausible picture is that the repeated interactions between vortex neighbors facilitate the healing of topological defects, while temporarily asymmetric ac fields or large vortex excursions promote their creation.[14]

In this framework, the role that extended TBs play in the HE of YBCO crystals has been the subject of controversies until now.[15] In this Brief Report, we focus on answering the following question: Is the presence of TBs a key element that determines the above described striking features observed in YBCO single crystals? With this scope, angular ac susceptibility measurements in detwinned and twinned YBCO crystals have been performed. In each case, the picture presented in the paragraph above has been tested.

Twinned YBCO crystals from two different sources have been used.[16,17] All samples were $YBa_2Cu_3O_{7-\delta}$ single crystals with $91\ \mathrm{K} < T_c < 92\ \mathrm{K}$ in accordance with slightly underdoped crystals.[18] The detwinning process was performed applying uniaxial stress in flowing oxygen at 450 °C. Results shown in this work correspond to a twinned sample with a critical temperature (defined as the middle point of the linear ac susceptibility transition at zero dc field) $T_c = 91$ K and a detwinned crystal (DT3) with $T_c \sim 91.6$ K.

Figure 1 shows the x-ray diffraction data, taken with Cu $K\alpha$ radiation for the detwinned crystal. The scattering angle was measured from the larger sharp edge of the triangular shaped DT3 sample: only one peak, corresponding to the (200) direction, is observed. The absence of the (020) diffraction peak indicates the lack of TBs. In the inset, x-ray diffraction data in the same range of scattering angles for a twinned sample are shown, and two peaks are clearly observed.

Global ac susceptibility measurements $\chi' + i\chi''$ were carried out with the usual mutual inductance technique. The measuring ac field is parallel to the crystal c axis. A cryostat with the static magnetic field H provided by a magnet was used, so that H could be rotated relative to the sample. Twinned crystals have been oriented in way that the dc field rotates out of twin planes. All the measurements have been made at the same frequency $f = 30$ kHz. Curves were normalized to a total step $\Delta\chi' = 1$ between the normal and superconducting responses with $H = 0$.

In ac susceptibility experiments, a larger VL mobility cor-

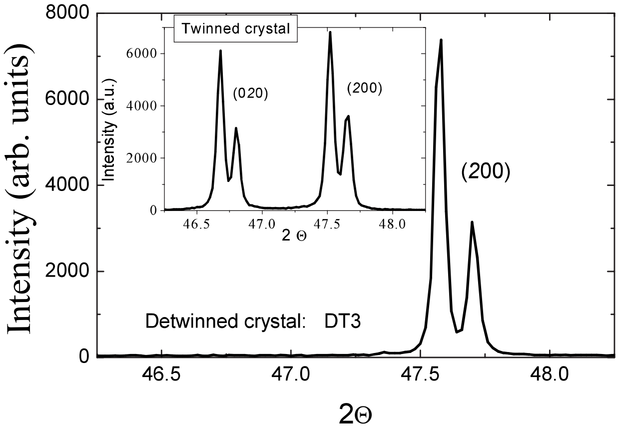

FIG. 1. X-ray diffraction data for the detwinned crystal taken with the scattering angle measured from the larger sharp edge of the sample: only the (200) is observed indicating the lack of TBs. Inset: comparison with typical data for a twinned sample.

responds to a larger ac penetration depth (i.e., a larger χ'). To test HE, various protocols or dynamical histories have been performed, where the sample is cooled in dc magnetic field avoiding bulk magnetic gradients, but each case differs in the applied assisting ac field.

A zero ac field cool warming (ZFCW) protocol corresponds to a dc field cool process without any assisting ac field, followed by a warming measurement. An ac field cool cooling (FCC) protocol is a cooling measurement during a dc field cool process. An Asy protocol consists in shaking the VL with an asymmetric (sawtooth) 30 kHz ac field of a large amplitude (~4 Oe) at a fixed temperature, whereas a Sy protocol consists in applying a symmetrical (sinusoidal) 30 kHz ac field of the same large amplitude (~4 Oe) after a complete Asy protocol. In both cases, the shaking field is applied for 30 s after that it is turned off and the measurement begins.

In the absence of correlated defects, the three-dimensional anisotropic scaling[19] predicts a monotonic decreasing penetration depth as a function of θ, i.e., a monotonic decreasing $\chi'(\theta)$ at fixed T. Twins affect both VL dynamics and effective pinning potential wells, and therefore, a difference in the angular dependence in the linear and nonlinear responses from twinned and detwinned samples is expected. As an example, in the insets of Fig. 2, $\chi'(T)$ curves in the linear Campbell regime at a few selected angles θ are shown for a (a) twinned and (b) detwinned sample.

In the nonlinear response, shown in the main panel of Figs. 2(a) and 2(b), other qualitative differences regarding PE and HE appear. In both panels, arrows indicate the direction of the temperature variation. Curves recorded in a ZFCW process are indicated with an arrow at right, and those recorded in a FCC process are indicted with an arrow at left. As has been reported in a past work,[5] in twinned YBCO crystals, HEs are clearly observed when H is tilted away from the c axis (i.e., from the TBs) in an intermediate angle θ. In Fig. 2(a), typical nonlinear $\chi'(T)$ curves recorded in both ZFCW and FCC processes at three characteristic angular regions are shown. These regions agree with those reported in Ref. 20, identified by means of Bitter decoration. At intermediate angles [$\theta = 40°$ in the example of Fig. 2(a)], when the predominance of correlated pinning due to TBs is expected to decrease, a broad PE develops (light gray curves in the figure) and HEs are well visible. Approaching the TB planes [$\theta = 1°$ in the example of Fig. 2(a)], the shape of the curves is very different and the PE diminishes (dark gray curves), while HEs become inappreciable within our resolution. Finally, when θ approaches 90° (black curves), the pinning is enhanced due to the CuO planes and mobility drastically diminishes. HEs completely disappear due to the strong dominating correlated pinning.

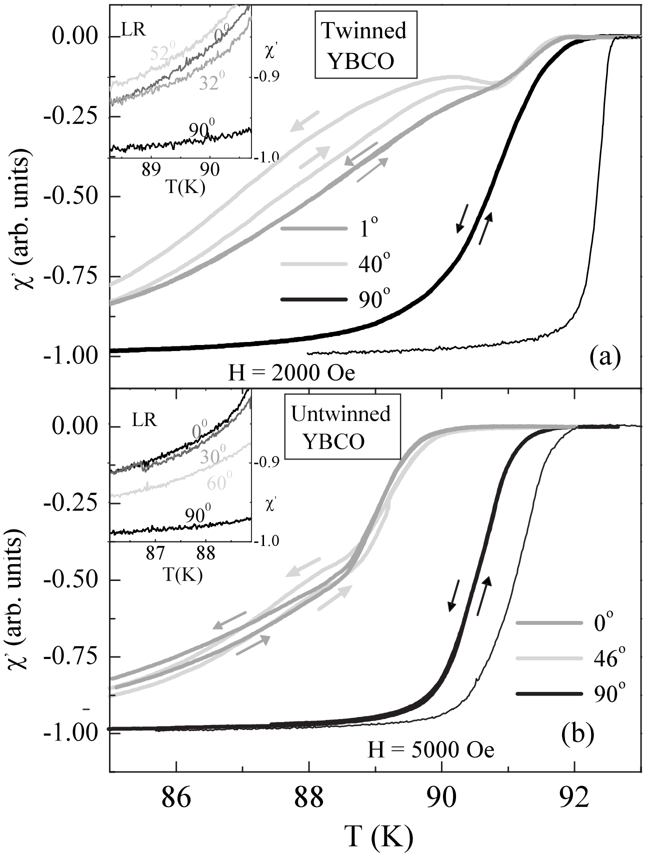

FIG. 2. Nonlinear $\chi'(T)$ curves recorded with ZFCW and FCC protocols (see text) at different orientations of the dc field H (a) in a twinned and (b) a detwinned sample. θ indicates the angle between H and the c axis. Arrows indicate the direction of temperature variation. Correlated disorder due to TB and CuO planes inhibits HE, whereas in the detwinned sample, responses at small and intermediate angles are very similar. The zero field transition is also shown. TBs modify the angular dependence of the linear response.

In Fig. 2(b), similar experiments are shown in a detwinned crystal. In this case, the $\chi'(T)$ curves at small and intermediate angles are very similar, and HEs are well visible at $\theta \sim 0°$.

Notice that in both samples, the VL is more mobile in the FCC curve, indicating that the measuring ac fields assist the VL to attain a more ordered configuration.[5]

Moreover, in both samples, whenever HEs are observed, the symmetry of the assisting ac field plays a major role. This fact is illustrated in Figs. 3 and 4. In both figures, the

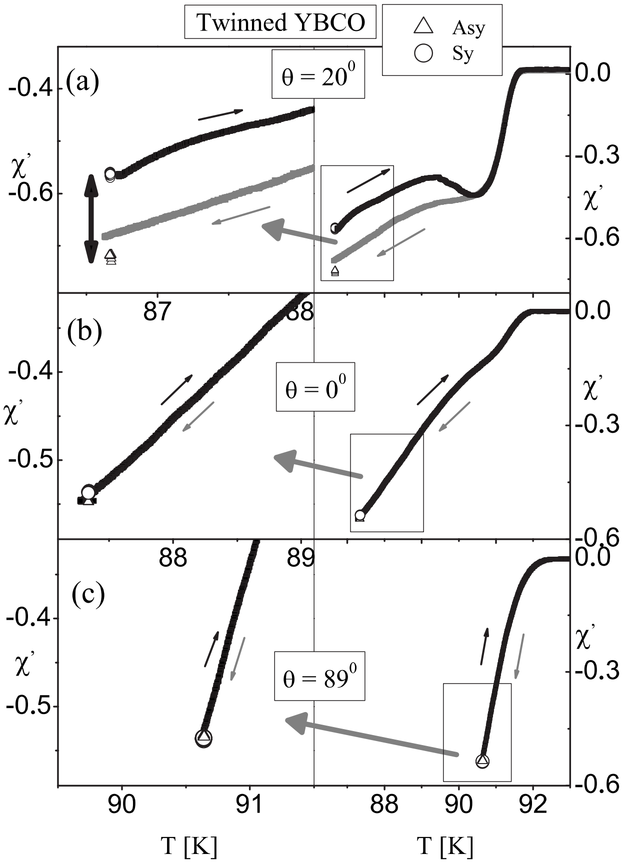

FIG. 3. Test performed in the twinned sample at various θ. Full curves are shown in the right side of each panel, and a zoom is shown in the left. After a FCC (gray curves), Asy and Sy protocols (see text) are applied three times each. Sample is warmed after the last Sy protocol (black curves). When correlated defects prevail [panels (b) and (c)], there is no effect.

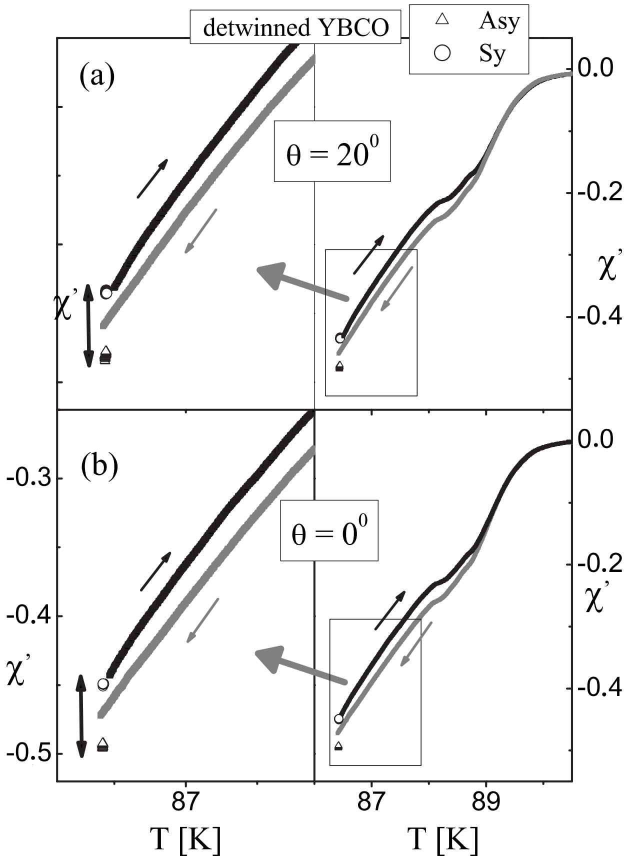

FIG. 4. The same test of Fig. 3 performed in the detwinned sample. Whenever HEs are relevant, the symmetry of the shaking ac field affects the VL mobility.

twinned (Fig. 3) and detwinned (Fig. 4) samples have been measured at various θ with the following sequence: The sample was field cooled (gray curves) to a fixed lower temperature T. Then, the Asy (open triangles) and Sy (open circles) protocols were performed, decreasing and increasing alternatively the FCC VL mobility. Both protocols were repeated two or three times at this fixed T, reproducing the observed change in mobility. Finally, after the last Sy protocol, the sample was warmed (black curve), showing a robust enhancement in the VL mobility until the PE is reached. Note that in the angular regions where HEs are not relevant, the Sy and Asy protocols do not produce any change in the VL. This is shown in Figs. 3(b) and 3(c), where the vortex direction is very close to the TBs and the *ab* planes. Open circles and triangles are hard to distinguish. On the contrary, in the regions affected by dynamical history [Figs. 3(a), 4(a), and 4(b)], the asymmetric shaking leads to a VL in a less mobile configuration, whereas the symmetric shaking promotes a more mobile VL. These configurations are robust and repetitive. This behavior holds in crystals coming from different sources, with and without TBs. Particularly, these features hold in detwinned crystals when the VL is aligned with the c axis.

We have shown that these characteristics hold in twinned and detwinned well oxygenated YBCO crystals. Therefore, they are not an artifact produced by twin boundaries, but they are intrinsic of the VL in these samples. In conclusion, we claim that the VL dynamics is the key element in the physics underlying the history effects of vortex matter in YBCO crystals.

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