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# Field cooling memory effect in Bi2212 and Bi2223 single crystals

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## Abstract

A memory effect in the Josephson vortex system created by a magnetic field in the highly anisotropic superconductors Bi2212 and Bi2223 is demonstrated using microwave power absorption. This surprising effect appears despite a very low viscosity of Josephson vortices compared to Abrikosov vortices. The superconductor is field-cooled in a DC magnetic field  $H_m$  oriented parallel to the CuO planes through the critical temperature  $T_c$  down to 4 K, with subsequent reduction of the field to zero and again above  $H_m$ . A large microwave power absorption signal is observed at a magnetic field just above the cooling field, clearly indicating a memory effect. The dependence of the signal on a deviation of the magnetic field from  $H_m$  is the same for a wide range of  $H_m$  from 1500 to 17 000 G.

(Some figures in this article are in colour only in the electronic version)

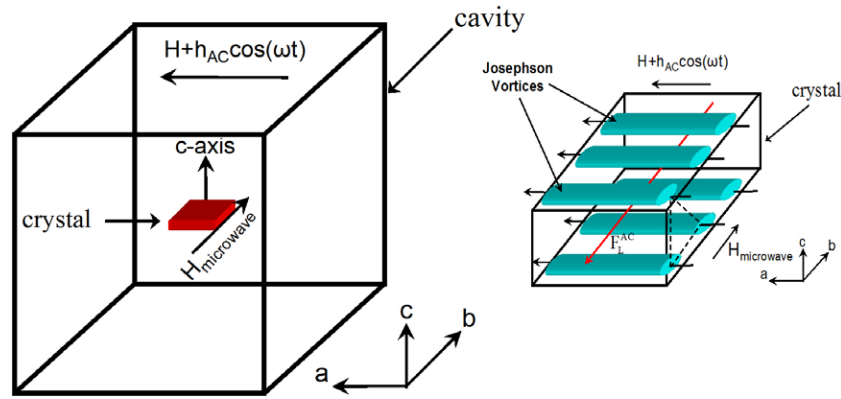
## 1. Introduction

Many complex disordered systems in nature fail to equilibrate with their environment below a certain temperature. Examples include the whole spectrum of glasses, from window glass to spin glass [1]. The glassy metastable frustrated state gives rise to novel and unusual behavior such as memory effects, aging and nonlinear dynamics. In recent years the family of glasses has significantly expanded and now includes additional effects such as domain walls [2], two-dimensional electron gas [3] and Abrikosov vortices in type II superconductors under magnetic fields (see [4] and references therein).

The glassy vortex state is usually prepared by field cooling (FC) a sample containing quenched disorder across the superconducting transition temperature  $T_c(H)$ . A memory phenomenon in superconductors is usually studied as a response to an applied perturbation which suddenly disturbs the superconductor. After removing the perturbation, the subsequent response reveals the memory effects, for example the rate of the magnetic relaxation is slower in ‘older’

systems than in ‘younger’ ones [4]. Experiments on different conventional superconductors [5] and in YBaCuO single crystals [6] demonstrated the presence of a history effect similar to those in Heisenberg spin glasses.

Here we report an entirely different manifestation of the memory effect in strongly anisotropic high  $T_c$  superconductors. In these superconductors, a magnetic field directed parallel to the layers penetrates the sample as a system of Josephson vortices (JV), thus qualitatively distinct from pancake vortices (PV) that appear when the magnetic field is perpendicular to the layers. In less anisotropic materials, as in most conventional superconductors and optimally doped YBaCuO, they appear as Abrikosov vortices (AV). It is well known that for sufficiently strong disorder the AV form a vortex glass [7]. In JV systems a randomly distributed set of defects of the layered structure (microresistances [8]) is analogous to the quenched disorder pinning AV in the conventional vortex glass. Apparently the pinning of JV is expected to be less effective than the pinning of AV since the JV are coreless. However it was shown (see [8, 9]) that both the individual and collective



**Figure 1.** Orientation of the superconducting crystal in the cavity with respect to the DC, AC and MW magnetic fields. Inset: JV structure in high  $T_c$  superconductors induced by DC magnetic field parallel to the  $a$ - $b$  plane. The AC eddy currents apply a Lorentz force on the JV as shown.

pinning of the Josephson vortices on the structural defects is an experimentally and theoretically well-studied phenomenon.

We demonstrate the formation of the glassy state of the JV [8] in  $\text{Bi}_2\text{Sr}_2\text{Ca}_1\text{Cu}_2\text{O}_\delta$  (Bi2212) and  $\text{Bi}_2\text{Sr}_2\text{Ca}_2\text{Cu}_3\text{O}_\delta$  (Bi2223) single crystals where the landslide pinning potential is formed by the structural defects. The memory properties are studied by measuring the microwave power absorption (MPA) of the sample subjected to colinear DC and AC magnetic fields parallel to the layers, see figure 1. This method is sensitive to register weakly pinned JV, while strongly pinned JV do not contribute to the signal [10]. In the present experiment the JV glass is prepared by field-cooling (FC) the sample from above  $T_c$  to  $T_m = 4.2$  K while a DC magnetic field  $H_m$  is applied parallel to the  $a$ - $b$  crystal plane. At this temperature the external field is decreased to zero and after applying a low frequency AC field it is subsequently increased again. No MPA signal is detected until the external magnetic field reaches the initial field  $H_m$ . The peak of the MPA signal appears just above  $H_m$ , demonstrating the memory effect. The dependence of the signal on the deviation of the magnetic field  $H - H_m$  is the same in a wide range of cooling fields.

## 2. Vortex matter in BSCCO

The Abrikosov (namely  $H \parallel c$  axis) vortex physics in Bi2212, whose anisotropy is  $\gamma = 250$  [11], was comprehensively studied. A complicated  $H$ - $T$  phase diagram contains the melting line and a transition to a glassy state. Magnetic flux penetrates the sample as 2D pancake vortices which are weakly linked by Josephson coupling and magnetic interaction along the  $c$  axis, and repel each other. As a result, PV form a periodic lattice structure at low temperatures and low fields. The PV lattice melts into a liquid with increasing temperature and magnetic field. This first-order transition is observed as a step in the equilibrium magnetization [12].

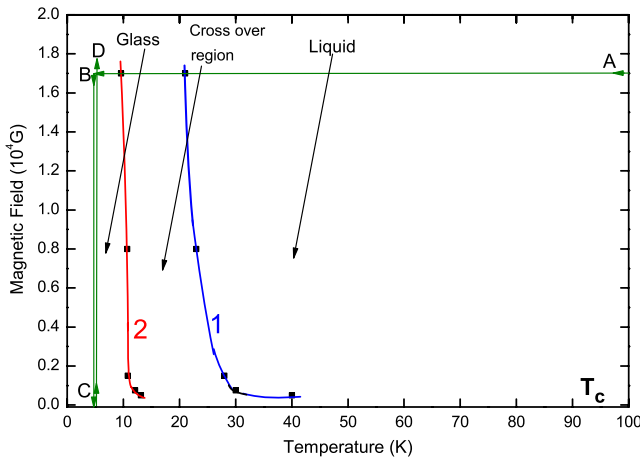
On the other hand, transverse fields penetrate between two superconducting planes as JV. Fundamental differences in vortex structures in  $H \parallel c$  and  $H \perp c$  naturally call for an interest in the vortex states under tilted fields in which both PV and JV segments are present [13]. A static arrangement

of PV on the  $a$ - $b$  plane in tilted fields was studied by Bitter decoration [14]. A one-dimensional arrangement of PV along the tilting direction concomitant with a triangular lattice between chains was visualized. Moreover, direct observation of PV by a scanning Hall probe microscope revealed the existence of the chain state [15]. The melting line in tilted fields was established recently [16].

Disorder plays a prominent role in vortex matter in BSCCO. The effect of disorder on melting processes was visualized using magneto-optics [17]. In addition, the irreversibility line or glass line appears around 40 K for  $H \parallel c$ . This was first determined in transport measurements. Recent magnetization measurements established the thermodynamic nature of this continuous transition. For titled fields pinning will be dominated by the PV segments. A theoretically conjectured phase diagram was proposed in [15]. In the extreme case of  $H \perp c$  axis, when only JV exist, pinning is much weaker and has not been studied so far. Generally JV are not sensitive to oxygen defects, but are pinned by microresistances [8] which reside between the superconducting CuO planes. Such kinds of disorder can result in a novel type of glassy state. The microwave technique described below enables us to approach it.

## 3. Experiment

The memory properties of the Josephson glass are investigated using a Bruker ELEXSYS continuous-wave electron spin resonance (ESR) spectrometer working at the X-band frequency,  $\omega_{mw}/2\pi = 9.3$  GHz, see [10, 18] for details. A microwave source feeds a rectangular H102 cavity where an optimally grown Bi2212 or Bi2223 crystal (sizes  $1 \times 1 \times 0.1$  mm<sup>3</sup>) is placed in the center of the cavity region with only a microwave magnetic field present. The microwave (MW) magnetic field was parallel to the  $a$  axis in the  $a$ - $b$  plane. The sample, whose temperature was varied continuously down to helium temperatures using a helium continuous-flow cryostat (Oxford Instruments), was exposed to colinear DC and AC ( $\omega_{AC}/2\pi = 100$  kHz) magnetic fields parallel to the  $a$  axis



**Figure 2.** The field-cooling protocol  $A \rightarrow B \rightarrow C \rightarrow D$  on the  $B$ - $T$  phase diagram. Memory effect does not exist above the crossover region (line 1) (reversible or JV liquid state). A precursor appears below this line and becomes well pronounced below the glass line (line 2).

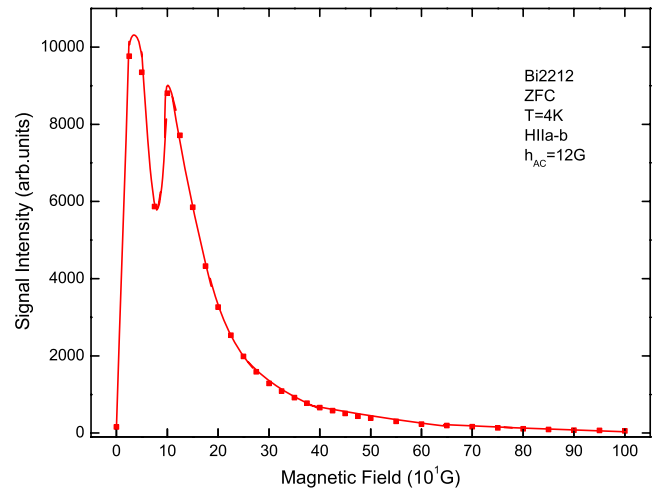
in the  $a$ - $b$  plane (see figure 1). The microwaves reflected from the cavity are rectified by a diode that feeds a lock-in detector.

The MW absorption is directly connected with JV due to the following reason. Our method can detect absorption of the MW radiation in the cavity and, in principle, it can be exploited to observe the usual AV. However, in our case (BiSCCO material) both JV and PV are pinned and thus cannot absorb the MW radiation. The physical reason for this is the large frequency determined by the ratio  $\omega_0 = K/\eta \approx 10^{10}$  Hz in BiSCCO. Here  $K$  is the pinning spring constant, while  $\eta$  is the viscosity. In this regime the MW frequency is much smaller than  $\omega_0$ , ( $\omega_{MW} \ll \omega_0$ ). Consequently both the pinned JV and PV are in the non-dissipative regime and no MW absorption occurs [19]. However, the presence of a small AC component of the induced AC eddy current results in the appearance of the MPA signal since it depins the weakly pinned JV by the Lorentz force, thus only the PV remains pinned (see figure 1). (A similar phenomenon was detected by the authors of [20] where the external MW was modulated by the AC signal.) This phenomenon is known as ‘shaking’ and was used extensively to ‘speed up’ the thermalization of Abrikosov vortices in [12]. The shaking is caused by the eddy currents along the  $c$ -axis direction (the component of the AC current within the  $a$ - $b$  plane does not affect the JV). The Lorentz force of that current shakes the JV during a period of time of order  $\omega_{AC}^{-1}$  (which significantly exceeds the microwave period) sufficiently for JV depinning to occur [10].

Note that, due to the lock-in technique, the measured quantity is not the MW absorption power (MPA)  $P$ , but rather the electronically detected peak-to-peak difference  $S$  as a function of the DC magnetic field  $H$  parallel to the layers:

$$S(H) = \max_i P - \min_i P \approx dP/dH. \quad (1)$$

The high quality Bi2212 single crystal used in the present study was grown by the floating zone technique using an image furnace. We controlled oxygen content by annealing at 350 °C



**Figure 3.** Zero-field-cooled signal versus magnetic field of the Bi2212 sample.

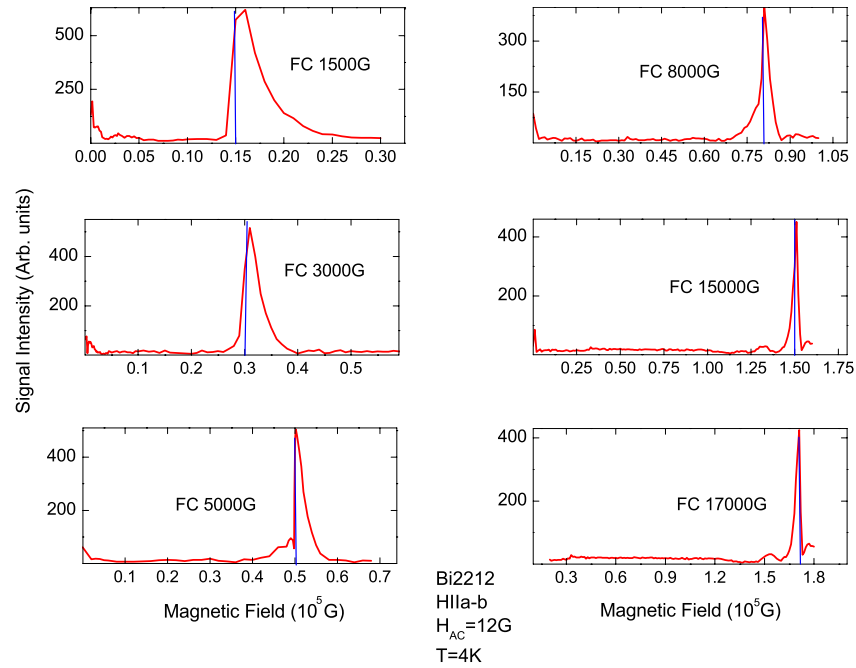
in an appropriate partial oxygen pressure. In this paper we used samples optimally doped with  $T_c = 90$  K. Crystals from the same source have previously been used in various investigations of the vortex matter, in particular in [21, 22].

In the less anisotropic material Bi2223,  $T_c = 110$  K and  $\gamma = 60$  [11], the JV physics in this compound has not been extensively studied. Although the Bi2223 crystal has inherent defects due to intercalations of other phases (which are always present [23]), the memory effect is only slightly affected compared to that in Bi2212.

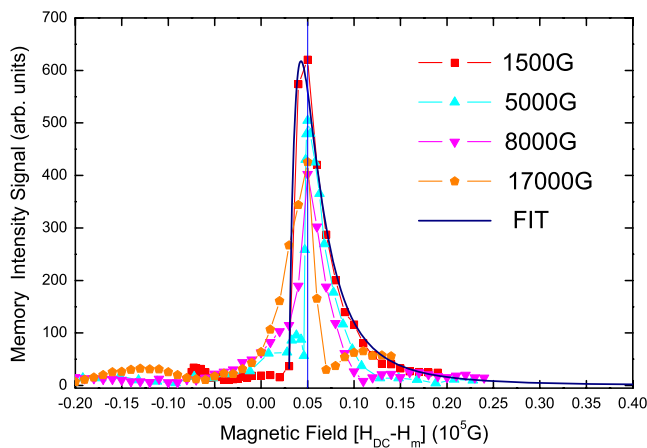
#### 4. Memory effects

In order to study irreversible properties (memory effects) we execute a field-cooling protocol presented in figure 2. The samples are field-cooled in a DC field  $H = H_m$  parallel to the  $a$ - $b$  plane from above  $T_c$  (point A in figure 2) to a low temperature  $T_m$  (point B). Unless otherwise specified,  $T_m$  is equal to 4 K. Then the field is reduced to zero (point C) at a rate  $500 \text{ G s}^{-1}$ , after which it is raised again to above  $H_m$  (point D) at a rate  $100 \text{ G s}^{-1}$ . (A comparison with ZFC curves on the same crystal and the same experimental parameters is shown in figure 3.)

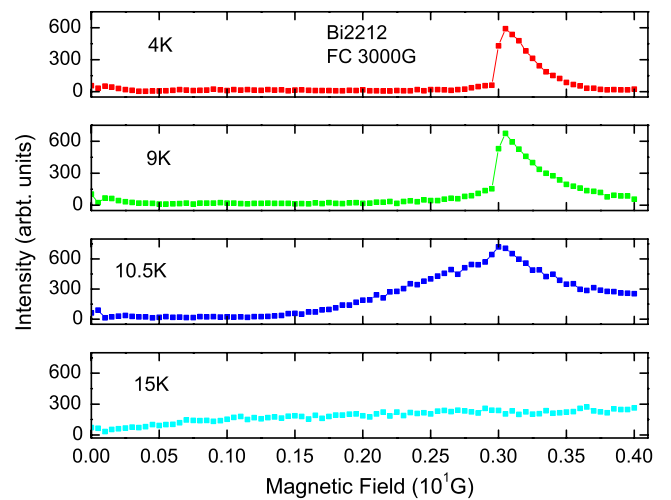
A characteristic peak is observed slightly above  $H_m$ , indicating that it results from a memory effect. The signal intensity in Bi2212 as a function of the DC magnetic field in the range 1500–17000 G (17000 G is slightly below the limiting field of the spectrometer) is presented in figure 4. The signals’ intensity heights and their positions relative to the cooling field  $H_m$  are the same for magnetic fields in a wide range, as demonstrated in figure 5. Their sharp maxima on this plot appear at about 500 G, indicating that the memory signal occurs at the same field at a value slightly above  $H_m$  for all cooling fields. The dependence of the signal intensity and the signal shape for different cooling temperatures are presented in figure 6 for  $H_m = 3$  G. The effect persists even if the cooling temperature was increased to 10 K, but disappeared at about 15 K. This indicates that the glass transition temperature  $T_g(H)$



**Figure 4.** Signal intensity as a function of DC magnetic field in Bi2212 crystal for different  $H_m$  values up to 17 000 G, obtained by field-cooling at  $H_m$  from above  $T_c$  to 4 K and then dropping the field to zero. The signal’s maxima are slightly above  $H_m$ , implying a memory effect.



**Figure 5.** The memory signals shown in figure 4 as a function of the difference  $(H - H_m)$  demonstrates scaling behavior. The signals are superimposed, with their maxima at about 500 G. The intensities and shapes are similar. The blue solid line is a theoretical fit for  $H_m = 1500$  G,  $A = 0.13$ ,  $H_0 = 170$  G, where  $|H - H_m| > H_0$ .



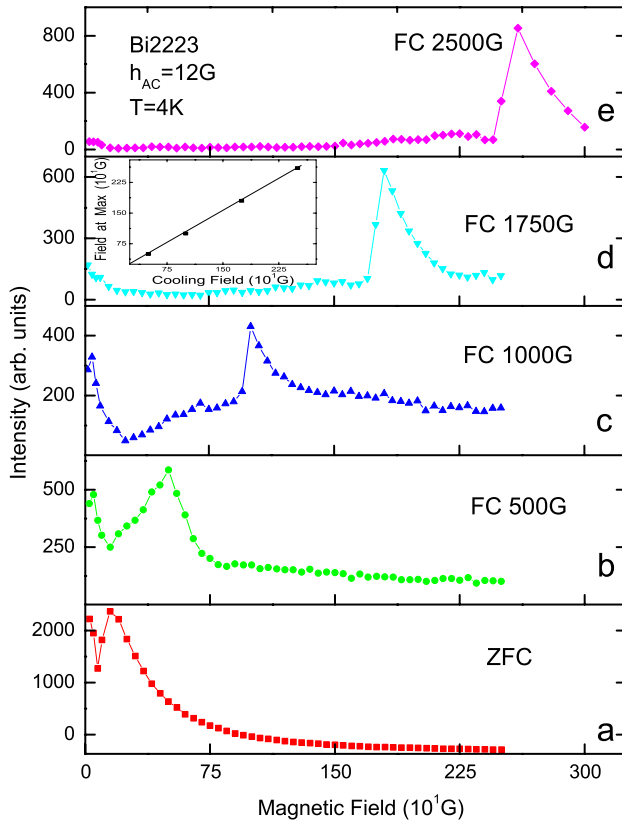
**Figure 6.** Signals as a function of DC magnetic field cooled at 3000 G to 4, 9, 10.5 and 15 K. The similar signal intensity and shape at 4 and 9 K and the signal broadening at 10.5 K indicates a glass phase transition at about 10 K.

(line 2 in figure 2) is between 10 and 15 K, depending weakly on the magnetic field. We found that in the range of fields studied the precursor of the glass transition appears at much higher temperatures around 30 K. In the crossover region the memory effect is not fully developed, see the  $T = 10.5$  K line in figure 6.

Experimental results similar to those presented in figure 4 for Bi2212 were observed in a less anisotropic Bi2223 superconductor which was field-cooled to 4 K. In figure 7 MPA intensity as a function of the DC field is presented for magnetic fields  $H_m$  up to 2500 G.

## 5. Discussion

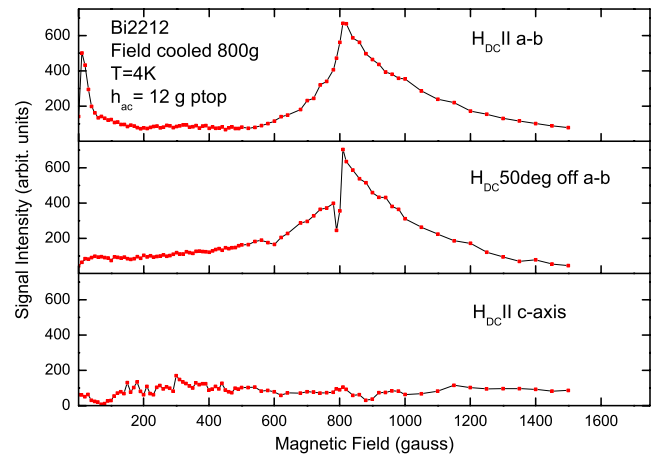
The glassy behavior observed in JV systems in BSCCO for the first time is reminiscent of those observed in other glassy systems. One can explain the memory effect described above using the hierarchical model of a glassy state commonly used in spin glass theory [24]. When the sample is adiabatically field-cooled (cooling speed around  $10 \text{ K s}^{-1}$ ) from above  $T_c$  to a low temperature  $T_m$  well below  $T_c$  the JV fill the deepest valleys of the landslide potential, forming a quasi-equilibrium



**Figure 7.** Signal intensity as a function of DC magnetic field in Bi2223 crystal for different  $H_m$  values up to 2500 G, obtained by field-cooling at  $H_m$  from above  $T_c$  to 4 K and then dropping the field to zero. The signal's maxima are slightly above  $H_m$ , implying a memory effect. The inset indicates a linear behavior of the signal's maxima.

JV glassy state. The landslide potential responsible for JV glass is formed by a randomly distributed set of the microresistances in the layers. These short-range pinning potentials (in comparison with the Josephson penetration length) are weak enough to allow the AC eddy current to depin the JV and thus to contribute to MWP. The PV also might, in principle, contribute to the memory effect, playing a role of a strong pinning mechanism of JV which are tied to them. However, on the basis of our experiments one can conclude that the memory effect depends on the PV number only slightly. In fact, the memory signal is not changed in a wide range of angles of the magnetic field tilted with respect to the CuO plane ( $a$ - $b$ ), from  $0^\circ$  to  $50^\circ$  (see figure 8). There is no memory effect and no MPA signal at all in the MW experiment when the magnetic field is perpendicular to the layers, namely in the case when only PV exist [18, 25]. This demonstrates that only the JV contribute significantly to the signal observed by our technique.

The cooling in the present experiment is definitely slow enough and the temperature high enough, so that the most favorable pinning positions are effectively found. When the external DC magnetic field is dropped to zero, while holding the temperature at  $T_m$ , the vortices are still confined inside the deep pinning landslide minima and cannot effectively absorb the microwave radiation. As the field is subsequently increased



**Figure 8.** Memory signal versus magnetic field for  $H_m = 8000$  G with magnetic field tilted by an angle of  $50^\circ$  away of the  $a$ - $b$  plane; both the JV and the PV coexist. There is no change in memory effect as the number of PV is increased.

(with the temperature still kept at  $T_m$ ), the fluxons remain immobile and prevent penetration of new JV till its starting 'equilibrium' field  $H_m$  is reached. When the field is further increased beyond  $H_m$  the JV glassy state loses its quasi-equilibrium and new vortices penetrate the sample populating unoccupied shallower valleys of the pinning landscape (in which the pinning constant is smaller). These are the vortices responsible for the experimentally observed sharp MPA signal. It is important to emphasize that the MPA signal depends on the magnitude of the external magnetic field rather than on the magnetic induction, which is dominated by the magnetic field of the pinned vortices (hysteresis). Thus the present memory signal has a universal shape. The shape can be understood using a simple formula derived in [10]:

$$S = A \frac{|H_0^3 - 2(H - H_m)^3|}{[H_0^3 + (H - H_m)^3]^2}, \quad (2)$$

which, for  $|H - H_m| > H_0$ , demonstrates a well-pronounced scaling behavior in the coordinate  $|H - H_m|$  (solid line in figure 5). The only parameters describing the ability of the system to absorb the microwave energy [10] are  $A \simeq 0.13$  and  $H_0 \simeq 170$  G for  $T = 4$  K. At temperatures below 10 K,  $H_0$  is temperature-independent.

The memory should be destroyed at higher temperature  $T > T_g$  since the pinning potential will be smeared (thermal depinning). This is the 'glass transition' in the JV system. Since the basic mechanism is the single-vortex pinning (for not too high fields) it is clear that the glass transition temperature  $T_g$  is only weakly dependent on the field. The situation is not expected to change qualitatively at larger fields in which JV will be pinned collectively.

To summarize: although the 'memory effect' in the context of vortex matter has been extensively discussed, our experiments allow its demonstration in a qualitatively different Josephson vortex system. In the highly anisotropic compounds Bi2212 or Bi2223, when field-cooled to 4 K, an MPA signal is retrieved at a magnetic field close to the cooling field, clearly

indicating a memory effect. We conclude that the two materials demonstrate very similar behavior because for a glassy system the details of the individual JV pinning are less important than the random pinning landslide potential, which is similar in both samples. The most striking observation in the ‘memory effect’ is that the microwave absorption peak obeys a universal scaling.

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