Slow relaxation of low temperature vortex phases in Bi$_2$Sr$_2$CaCu$_2$O$_8$

F. Portier, G. Krizza, B. Sas, L.F. Kiss, Pethes, K. Vad, B. Keszei, and F.I.B. Williams

1Service de Physique de l’Etat Condensé, Commissariat à l’Energie Atomique, Saclay, F-91191 Gif-Sur-Yvette, France
2Research Institute of Solid State Physics, POB.49 H-1525 Budapest, Hungary
3Institute of Nuclear Research, POB.51 H-4001 Debrecen, Hungary
4Research Institute for Materials Science, POB.49 H-1525 Budapest, Hungary

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Nonlinear transport in the low temperature vortex glass state of single crystal Bi$_2$Sr$_2$CaCu$_2$O$_8$ has been investigated over long times (up to two weeks) with fast current pulses driven along the ab plane. It is found that at low temperature and high magnetic field both zero field cooled (ZFC) and field cooled (FC) samples relax towards the same equilibrium state, which is much closer to the original ZFC state than to the FC state. The implication of this FC metastability for the vortex phase diagram is discussed in the context of previous measurements.

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The interest in vortices in strongly anisotropic layered high $T_c$ superconductors like BSCCO (Bi$_2$Sr$_2$CaCu$_2$O$_8$) arises firstly from the weak interplane coupling which makes the basic vortex entity a quasi-2-D vortex segment (“pancake vortex”) within a layer and renders the interaction-disorder problem particularly rich by the interplay between intraplane repulsion, interplane attraction, random bulk pinning and thermal fluctuations [1, 2]. Secondly the configuration and dynamics of the vortices play a vital role in the current carrying capacity of the superconductor and in this respect the low temperature pinned vortex solid phases are expected to be the most resistant to forces from transport currents.

Recently an unexpected phenomenon of metastability and conversion has been reported [3] for this phase in BSCCO, recalling what was found in two low $T_c$ superconductors, NbSe$_2$ [4] and pure Nb [5] where the field cooled (FC) preparation (sample cooled from above $T_c$ with field applied) is metastable below a certain temperature and can be converted into a state resembling that produced by a zero field cooled (ZFC) preparation (sample cooled in zero field and field applied only on reaching the measurement temperature). Motivated by the possible coexistence of competing low temperature solid phases and by aging of a semi-ordered system in a random field we have followed the evolution over long times of both FC and ZFC prepared states in BSCCO.

The experiment probes the state of the vortex system by measuring the voltage response to short - to avoid heating - high current (25-100µs, maximum $\sim$1.3×critical current) triangular pulses. The threshold current for dissipation is taken as the principal indicator of the state of the vortices. We distinguish, conceptually, non-equilibrium stationary states, such as the Bean critical state, from thermodynamically stable and metastable equilibrium states by the time scales: measurements of the threshold current are made in $\sim 10^{-5}$s whereas stationary Bean type density profiles from vortex transport decay typically in $10^2 - 10^3$ s while the relaxation discussed in this paper occurs in $10^3 - 10^6$ s. For the present purposes, we define a metastable state as showing equilibrium over $10^3 - 10^4$ s.

Previously [3], we reported ab plane measurements of the VI characteristics of freshly FC and ZFC prepared BSCCO monocrystals at large currents, using the same fast current pulse technique. For perpendicular magnetic fields $H > 1$ kOe and low temperatures $T < 12$ K, the VI characteristic showed FC to result in a higher threshold current $I_{th}$ FC than ZFC. On warming, $I_{th}^{ZFC}$ increases and $I_{th}^{FC}$ decreases to merge at a temperature $T_p(H)$ beyond which the VI characteristic no longer depends on preparation (insert of Fig.1). Unlike ZFC, the FC threshold current is not a unique function of $(H, T)$ but depends on the cooling rate and is found to be metastable in the sense that a small temporary perturbation of the field $\Delta H \approx 300$ Oe induces a change in the VI characteristic which though it depends on the duration of the perturbation always tends towards the ZFC characteristic. Furthermore if one ZFC prepares a sample at low temperature and warms, the threshold is the same as for direct ZFC preparation at that warmer temperature; however on subsequent cooling it does not return along the ZFC line, but instead behaves rather like the FC line, with lower starting value and similar metastability.

We present data for two melt cooling fabricated single crystals [6] of about $1 \times 0.5 \times 0.003$ mm$^3$ oriented with c-axis parallel to the magnetic field and critical temperatures of 83 K and 81 K with a transition width of $\sim 2$ K at zero field. The anisotropy coefficients $\gamma \approx 500$ were estimated from normal state resistivity at 90 K where $\rho_{ab} \approx 100 \mu \Omega \text{cm}$ . The current pulses were injected and withdrawn through two symmetrically placed contacts in a way to keep the mean potential of the sample at ground; the potential drop was measured between two symmetrically interspaced potential contacts with a differential amplifier. The temperature was electronically regulated and the magnetic field provided by a superconducting magnet in persistent mode. FC samples were cooled from above $T_c$ at 240 K $h^{-1}$ to 30 K and at 60 K $h^{-1}$ thereafter. ZFC samples were cooled in the same way before applying the field at 100 Oe $s^{-1}$.

The first experiments (Fig3) showed the VI charac-
teristics of FC and ZFC samples to relax towards one another. To characterise the state of the sample we choose the threshold current $I_{th}$ which signals when the force exerted by the transport current depins the vortices in the top superconducting plane. But because the shapes of FC and ZFC $V I$ are different, a modification of the form accompanies the relaxation and requires us to define $I_{th}$ to have the same meaning throughout the relaxation. Since from the $V I$ plot in Fig.1 we see that at voltages $V < V_{th} \approx 50 \mu V$ both FC and ZFC $V I$ are well described by a Kim-Anderson type relation, we define the threshold current by $V(I_{th}) = 50 \mu V$. Although the exact voltage value is somewhat arbitrary, the dependence of $I_{th}$ on $V_{th}$ is only logarithmic. The inset of Fig. 1 shows the temperature variation of $I_{th}^{FC}$ and $I_{th}^{ZFC}$ at $t = 0$ for $\mu_0 H = 1.5T$.

Fig. 2 shows the time evolution of $I_{th}$ for FC and ZFC preparations at $T = 4.5K$ and $\mu_0 H = 1.5T$ for two different samples with different threshold currents. One sees immediately that the total variation of $I_{th}^{FC}$ is much greater than that of $I_{th}^{ZFC}$ and that the aging produces the same ultimate effect as a short term field perturbation including the diminishing of the $IV$ hysteresis. The results for the second sample (blue curve) have been scaled by a multiplicative factor of 0.45 which maps the initial evolution onto that of the first sample. Both show a delayed logarithmic decay in $I_{th}^{FC} = I_0 - I_1 \log_{10} t[s]$ after remaining nearly constant for $\sim 10^8$s. For the first sample $I_{th}^{FC}(t)$ evolves until it meets $I_{th}^{ZFC}(t)$, after which it becomes indistinguishable from it. The second sample behaves similarly except that the experiment was curtailed before the two curves met. The ZFC threshold varies only weakly and on the same $10^2 - 10^3$s time scale as in the Josephson Plasma Resonance and AC Campbell length experiments. On this time scale, which is compatible with relaxation of the Bean profile seen in the direct observation of local induction, there is no variation of a FC sample.

What drives the conversion? We note first that the Bean-Livingston surface barrier, which can block the flow of vortices, vanishes above $H_c \simeq 10^5Oe$, whereas we have observed FC metastability and relaxation up to $H = 1.8 \times 10^6Oe$. The relaxation is slower the higher the temperature: the rate $I_1 = |dI_{th}^{FC}/d\log_{10}(t)|$ shown on Fig. 3 decreases linearly with increasing temperature and vanishes at $T_p$, the temperature at which $I_{th}^{ZFC}(t = 0)$ reaches its maximum and where the metastability evoked earlier ceases. Remarkably the ratio $I_1/(I_{th}^{FC}(t = 0) - I_{th}^{ZFC}(t = 0))$ remains constant within 5%. The interrogation pulses themselves seem to have no effect: pulses giving a vortex displacement estimated from $s = \int v_y dt = c \int E_x/B_z dt \geq (c/B) \int V(t) dt$ greater than the width of the sample do not modify $I_{th}$ for either preparation, indicating that the remnants of
a critical density profile left by the drive current do not alter the difference between the two states. We checked that the interrogation pulse sequence does not induce aging by verifying that a single or $2 \times 10^3$ alternated phase full wave $25\mu s$, or $2 \times 10^3$ unipolar half wave $100\mu s$ pulses per day gave the same result on the same sample. Each $100\mu s$ half-wave pulse induces an average vortex displacement of $s \sim 10\mu m$ while the $25\mu s$ full wave pulse displaces a vortex by $\sim 10nm$. Alternating the phase eliminates directional bias so that the total displacement should be a random sum. Although the blue and red symbols on Fig. 2 were obtained with different samples, the form of the evolution is the same; when all the values are rescaled by a single constant, the ZFC evolution is identical for both samples whilst the FC starts identically with about half the logarithmic slope. It was also established that field variation catalyses aging: in experiments in a very stable magnet ($1.10^{-4}$ day$^{-1}$ decay) reset every day, no evolution was detectable in any of the three interrogation procedures whereas application of a small field step makes the FC threshold age monotonically towards the ZFC value whereas if the variation in threshold were to result from a Bean-type density profile, it would be expected to return towards its FC value as the profile diffuses away. Fig. 2 should be viewed as a convolution of the basic response to a field step with the natural decrease in magnetic field of the magnet used ($2.10^{-3}$ day$^{-1}$). Bearing in mind that, due to the anisotropy, tipping the sample by $10^{-3}$ rad gives rise to screening current densities of $\sim 10^5$ A cm$^{-2}$, we were careful about mechanical stability; indeed a careless cryogen transfer sometimes reduced $I_{th}$ for several minutes, but unlike mechanical shock on NbSe$_2$ [11], did not result in permanent conversion.

Without further reasoning, we conclude that the FC state is metastable at low temperatures and decays to a state which, judging by the threshold current, is very similar to the ZFC state, that the conversion is catalysed by a small field variation and is slower the smaller the difference in threshold currents and that Bean type density profiles do not play a significant role.

To say more we must understand the meaning of the lower threshold current for ZFC and this in turn requires an evaluation of the relative contributions of c-axis and ab-plane currents. We have shown in other experiments [13] that the resistive front spreads out from the contacts, indicating that the current penetrates progressively into the layers. This implies that phase slips occur between adjacent superconducting planes and the $VI$ characteristic reflects a mixture of c-axis and ab-plane transport properties [13, 14]. Thus although the voltage is a direct measure of the vortex velocity in the top superconducting plane, the threshold current reflects both ab-plane pinning and c-axis Josephson link properties. We can estimate their relative importance from the magnetic field dependence of $I_{th}$ below $T_p$ shown on Fig. 4. Both FC and ZFC samples exhibit a power-law behavior $I_{th} \propto B^{-\nu}$, with $\nu^{ZFC} = 0.55 \pm 0.01$ and $\nu^{FC} = 0.50 \pm 0.01$. This is similar to BSCCO (2212) thin films [9] and BSCCO(2212)/BSCO(2201) superlattices [10] where, due to the small number of superconducting planes, the current distribution is expected to be uniform ($J_c = 0$) and dissipation to arise only from the motion of flux lines. On the other hand the c-axis critical current [7] of BSCCO mesa structures of small lateral extension showed $J_{th} \propto 1/H$ at $T = 5K$ and $H > 10$Oe. Compatibility imposes that the contribution to the critical current that we measure be dominated by $J_{th}$. This allows us to say something about the nature of the pinning and the dimensionality of the order. The low exponents in the magnetic field dependence of $I_{th}$ are in accord with weak pinning Larkin-Ovchnikov theory which leads to $J_{th} \propto B^{-1}$ for both 2D and 3D vortex configurations [3]. Strong pinning of 2-D ordered vortex segments where the pinned vortices remain trapped, however, does lead to the $I_{th} \propto B^{-0.5}$ that we observe.

Also, on the grounds that greater order means less pinning, the fact that $I_{th}^{ZFC} > I_{th}^{FC}$ indicates that the ZFC preparation is more ordered, as in Nb and 2H-NbSe$_2$. Neutron diffraction on FC prepared BSCCO shows low temperature ordered and disordered states respectively below and above $\sim 5000$Oe [18]; unfortunately no neutron measurements on ZFC samples were reported.

Recent numerical simulations by Exartier and Cugliandolo [9] show the $VI$ of a disordered vortex state to have higher threshold current and stronger hysteresis than an ordered one, consistent both with the above argument that FC is more disordered than ZFC and with the observed decreasing hysteresis for FC with aging.

Similar FC metastability has been observed in 2H-NbSe$_2$ [6] and in Nb [8], where in addition it was shown by neutron diffraction that the stable ZFC state is more ordered than the metastable FC state. However there are also differences: in 2H-NbSe$_2$, the ZFC $I_{th}$ increases with increasing temperature only in a narrow temperature range close to the melting line, in agreement with the weak pinning Larkin-Ovchinkov picture of the peak effect [20], whereas in BSCCO $T_p(H) \lesssim T_m/2$ and there is no clear sign of a peak-effect near the melting line and

![Fig. 4: FC and ZFC threshold current $I_{th}$ at $T = 5K$ as a function of $\mu_0HM$. The dotted line shows $H^{-0.5}$.](image)
the low temperature linear temperature dependence of $I^{ZFC}\text{}_p$ persists to at least $80\text{mK}$ \[3\].

A microscopic model which collates these observations starts with the idea that the thermodynamically stable zero temperature, zero disorder ground state must consist of an Abrikosov lattice of continuous vortex lines. Introducing the vortices at zero temperature can result in a state close to this in the limit of small fractional volume of pins. Upon heating, thermal fluctuations induce the lines to explore the space about their (also metastable) equilibrium positions and if a line encounters a pin it sticks to it, resulting in a greater number of anchor points and greater threshold current. However if the pinning potential is deep, the lines remain pinned on subsequent recooling with the same sort of metastability as an FC prepared state, giving rise to the type of hysteresis in temperature observed for ZFC. A magnetic field variation, in changing the vortex density, tends to push the lines out of their traps and liberate them to reconnect as for the ZFC preparation. The peak in ZFC threshold current corresponds either to full exploration of the disorder potential - but that can only occur near melting - or to a new ground state. Evidence for two distinct phases is to be found in the fact that the conversion rate is slower closer to the peak; a single phase description would give to be found in the fact that the conversion rate is slower closer to the peak in the ZFC preparation. This behavior, although catalysed by field variation, is neither associated with a stationary critical density profile nor with the measurement perturbation and because it is slower closer to the peak in the ZFC threshold it reinforces the idea that the metastability line of the previous study \[3\] reflects a first order phase boundary, probably connected with the absence of the second magnetization peak \[21\] for $T \leq 14\text{K}$ \[22\]. More tentatively it appears that the ZFC preparation results in a more ordered state and that a strong pinning scenario applies.

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