Anisotropic flux creep in Bi2212:Pb single crystal in crossed magnetic fields

L. S. Uspenskaya and A. B. Kulakov
Institute of Solid State Physics, Russian Academy of Sciences,
Chernogolovka, Moscow Distr., 142432, Russia, e-mail:uspeneka@issp.ac.ru

A. L. Rakhmanov
Institute for Theoretical and Applied Electrodynamics, 
Russian Academy of Sciences, Izhorskaya Str. 13/19, Moscow, 125412 Russia 
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An experimental study of magnetic flux penetration under crossed magnetic fields in Bi2212:Pb single crystals is performed by the magneto-optic technique. The anisotropy of the flux creep rate induced by the in-plane magnetic field is observed at $T < 54 \pm 2 \text{ K}$. This observation confirms the existence of the three-dimensional flux line structure in Bi2212:Pb at low temperatures. An asymmetry of the flux relaxation with respect to the direction of the in-plane field is found. This effect can be attributed to the influence of the laminar structure on the pinning in Bi2212:Pb single crystals.

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I. INTRODUCTION

The magneto-optic (MO) study of the dynamics of the magnetic flux in type-II superconductors in crossed magnetic fields is a convenient tool for the investigation of the vortex lines properties. In particular, the MO studies in crossed magnetic fields are employed to clarify the presence or absence of three-dimensional (3D) correlations in FLL of superconductors.$^{1,2,3,4,5,6,7,8}$ In our previous papers a strong magnetic field induced anisotropy was revealed in the single crystals of (Bi$_{0.65}$Pb$_{0.35}$)$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ (Bi2212:Pb) within the temperature range $T < T_m = 54 \pm 2 \text{ K}$. In these experiments, a plate like specimen of a single crystal is placed in a DC magnetic field directed in the sample plane, $H_{ab}$, and then a field, $H_z$, perpendicular to the plane is applied. In such geometry the MO technique is used to study the penetration of the magnetic flux induced by the field $H_z$. The experiments reveal two strikingly different types of flux behavior. The transverse flux moves into the Bi2212:Pb single crystals preferably along the direction of the in-plane magnetic field $H_{ab}$ if $T < T_m$. This type of the behavior is analogous to that observed in YBCO single crystals$^{9,10}$ and gives an evidence for the existence of the strong superconducting correlations between CuO planes in Bi2212:Pb at $T < T_m$. Quite the contrary, the transverse magnetic flux penetrates independent of the orientation of the in-plane magnetic field at $T > T_m$. Such a behavior is observed in undoped Bi2212 single crystals and indicates that flux lines in this system can be treated as 2D pancakes.$^8$

The in-plane field induced flux penetration anisotropy is observed in the 'ideal' crystals with uniform magnetic flux entering through the sample edges. However, this effect is the most vivid and demonstrative in the case of the crystal with strong defects (or weak points) near its edges.$^9,10$ In the studied Bi2212:Pb single crystals these defects were observed in the points where the twin boundaries cross the sample edges. The picture of the flux penetration near such defects is entirely reproducible from the test to test. The magnetic flux enters the sample near weak points in the form of some 'bubbles' or 'stripes' which remain attached to the weak point during the time of observation, Fig. 1. The transverse magnetic flux has a shape of the bubble if the in-plane magnetic field $H_{ab} = 0$. The bubble stretches along $H_{ab}$ and shapes of a stripe if $H_{ab} > 0$.

The anisotropy of transverse flux penetration is characterized by the 'geometric' factor (the evolution of the penetrated region from the bubble to stripe), by the screening current anisotropy (the current density along $H_{ab}$ is much larger than the current density across this direction), and by the flux creep rate anisotropy as well. In the present paper we analyze a peculiarity of the flux creep anisotropy in Bi2212:Pb single crystals in crossed magnetic fields by means of the MO imaging.

II. EXPERIMENTAL

The studied samples were Bi2212 single crystals doped by 35% of lead and with the optimal oxygen content. The

![Image](https://via.placeholder.com/150)

FIG. 1: 'Bubble' and 'stripe' picture of $H_z$ field penetration; $T = 36 \text{ K}$, $H_z = 77 \text{ Oe}$, $H_{ab} = 0 \text{ Oe}$ (a) and $H_{ab} = 650 \text{ Oe}$ (b).
same samples we used for MO imaging in our previous experiments. More detailed samples description is presented in Refs. 9,10. The visualization of the transverse with respect to the sample surface magnetic flux component was performed by the conventional real time MO technique. The graphs of the magnetic flux distribution were obtained by means of the MO images calibration procedure described in Ref. 10.

The typical evolution of the magnetic flux distribution with time \(t\) is illustrated by Fig. 2. The sample at temperature higher than critical temperature \(T_{c}\) was placed in the in-plane magnetic \(H_{ab}\) = 650 Oe directed perpendicular to one of the crystal edge. Than the sample was cooled to \(T = 36\) K and the transverse magnetic field \(H_{z}\) = 77 Oe was turned on. The picture in Fig. 2 is obtained by substraction of two images. The first image was recorded at \(t_{1} = 0.2\) s after turning on the field \(H_{z}\) and the second one at \(t_{2} = 90\) s. So, the bright region corresponds to the volume into which the magnetic flux penetrates during a time \(\Delta t = t_{2} - t_{1}\). Naturally, some decrease of the magnetic field occur near the sample edge (see dark region of the image). It is seen from Fig. 2 that the magnetic flux drifts along the vector \(H_{ab}\) significantly faster than across it.

The time variation of the flux penetration depth is illustrated by curves 1 and 2,2′ in Fig. 3. The first point corresponds to the time moment about 0.1 s after turning on the field \(H_{z}\). The curve 1 shows the change with time of the penetration depth \(l_{\parallel}\) along the in-plane magnetic field direction and curve 2 presents the change of penetration depth \(l_{\perp}\) across this direction. The creep anisotropy \(k_{l} = l_{\parallel}/l_{\perp}\) increases with the value of \(H_{ab}\). At fixed magnetic fields, this coefficient increases with temperature if \(T < T_{m} = 54 \pm 2\) K. The magnetic flux penetration anisotropy at \(t \approx 0\) also increases within the same temperature range and the magnetic field induced anisotropy disappears if \(T > T_{m}\).

The magnetic flux entering in crossed fields is characterized also by the anisotropy of the screening currents. The current anisotropy increases with the increase of the in-plane magnetic field and temperature if \(T < T_{m}\). For our crystals, the ratio of the current density along and across the direction of \(H_{ab}\), \(k_{j}\) achieves the value up to 10–15 at \(H_{ab} = 1800\) Oe. The magnetic flux creep results not only in the dipper flux penetration into the sample with time but also in the relaxation of the screening currents. The current density decay rate is different for different current components. The values \(\partial B_{z}/\partial y \propto j_{\perp}\) (curve 1) and \(\partial B_{z}/\partial x \propto j_{\parallel}\) (curves 2,2′) versus time are shown in Fig. 4 where \(x\) is a coordinate axis across the in-plane field direction and \(y\) is a longitudinal one. The magnetic field derivatives were taken at the ‘stripe’ peripheral where these values are almost constant (see the end of this section). The relaxation behavior of the currents along and across the direction of the vector \(H_{ab}\) is quite different. First, the relaxation rate of the longitudinal current is smaller than of the transverse one, as it follows from the figure. Moreover, the longitudinal current increases slightly with time which is rather unusual, while a common for the screening current decay is observed for the current component across the direction of the in-plane magnetic field.

Note also an interesting observation. The relaxation rate to the right and to the left with the respect of the stripe direction is different. This fact is indicated in Fig. 4 by curves 2 and 2′, which corresponds to the screening currents relaxation to the left and to the right direction with respect to the vector \(H_{ab}\) respectively. Their absolute values and relaxation rates are slightly different.
As it will be seen, the observed difference is due to the inclination of the in-plane field from the normal to the crystal edge. The inclination angle $\alpha$ is about 6° for the experimental data presented in Fig. 4. The difference in the creep rates increases with $\alpha$ at any rate in the range $0 < \alpha < 45^\circ$. At higher deviations of the in-plane field from the normal to the edge the flux stripes corresponding different weak points begin to overlap and the MO observation of the effect becomes difficult.

The asymmetry of the relaxation rate is clearly seen even at relatively small deviation of the field $H_{ab}$ from the normal to the sample edge. Fig. 5 illustrates the relaxation of the magnetic flux for the inclination angles $\alpha = 17^\circ$, 2°, and -23° ($T = 30$ K, $H_z = 116$ Oe, and $H_{ab} = 1800$ Oe). The pictures were obtained by subtraction of two MO images taken at $t_1 = 1$ s and $t_2 = 30$ s after turning on the field $H_z$. It should be emphasized that at the first moment after turning on the transverse magnetic field, the penetration lengths and screening currents at the right and left parts of the flux front were equal (with the experimental accuracy, of course). The asymmetry arises in the course of the relaxation process.

The asymmetry changes its sign if one of the fields $H_z$ or $H_{ab}$ changes the sign. Naturally, the change of the sign of the both of the fields does not affect the magnetic relaxation asymmetry. The direction of the preferable flux relaxation changes also if the sign of the angle $\alpha$ between the in-plane field and the normal to the specimen edge changes (see Fig. 5).

Fig. 6 shows the magnetic field profiles across the direction of the in-plane field taken at different moments of times for three different angles $\alpha$ at $T = 30$ K and $H_{ab} = 1800$ Oe. It follows from the figure, the flux penetration asymmetry increases rapidly with time and grows (but not too fast) with the inclination angle $\alpha$.

III. DISCUSSION

Our previous MO studies of Bi2212:Pb single crystals in crossed magnetic fields revealed that the transition occurs in the magnetic flux behavior at $T = T_m = 54 \pm 2$ K. The transverse magnetic flux at $T < T_m$ behaves like in YBCO spreading preferably along the in-plane magnetic field. At $T > T_m$ the transverse flux penetrates independent of the in-plane magnetic field as in Bi2212 system. The obtained results can be understood within the concept of the flux line melting giving rise to the transition of 3D correlated stacks of pancakes at $T < T_m$ into a disordered phase of 2D ones at $T > T_m$.

The results obtained in the present study confirm the existence of strong 3D correlations in the flux line structure in Bi2212:Pb at $T < T_m$. Really, the creep assistant penetration rate along the applied in-plane magnetic field is significantly higher than that across this direction, that is, the activation barrier for the flux line penetration transverse to $H_{ab}$ is higher than the barrier along it. The fact that the relaxation rate of the screening currents along the in-plane field is lower than the current relaxation in the perpendicular direction supports the above conclusion. In our experiments we cool the sample in the in-plane field (field cooled regime). Under such a condition, the in-plane structure of the flux lines arises in the sample. The in-plane vortices should evidently locate preferably between CuO planes. The applied transverse magnetic field $H_z$, induces the entering of the flux lines directed transverse with respect to the sample plane. The penetrating flux lines should intersect the in-plane vortices when moving in the direction perpendicular to $H_{ab}$. In the case of highly anisotropic (layered) superconductors the transverse to the layers magnetic flux has a form of 2D pancake-like vortices. As a result, in such extremely anisotropic superconductors as Bi2212, the transverse magnetic flux enters the sample volume independently of the density and direction of the in-plane vortices. On the contrary, in the less anisotropic systems such as in YBCO, the transverse flux...
magnetic flux penetrates preferably along the direction of the in-plane vortices since due to the strong superconducting coupling between CuO planes there exists an additional energy barrier for the intersection of the in-plane and transverse vortices. Thus, we conclude that in Bi2212:Pb single crystals the pancakes in different CuO planes are strongly correlated at $T < T_m$.

Some unusual effect is observed in transverse magnetic flux relaxation. The magnetic field gradient across the in-plane field direction increases with time, then, the corresponding component of the screening current increases also. This effect could be explained as follows. The entering of the transverse magnetic flux near a weak point should be evidently accompanied by some redistribution of the in-plane magnetic induction. The in-plane field prevents the transverse vortex penetration. Thus, due to the thermoactivated flux lines flow (TAFF), a part of the in-plane vortices should be expelled from the region near the weak point to the periphery of the region penetrated by the transverse flux. As a result in this region some thickening of the in-plane vortices arises with time. The current screening the flux penetration across the direction of $H_{ab}$ grows with the value of the in-plane magnetic induction. The described effect could be a reason for the found increase with time of the value $\partial B_z/\partial x \propto j_1$ (see Fig. 4 (curve 2)).

A rather interesting feature is the asymmetry of the flux creep rate with respect to the in-plane field direction described at the end of the previous section. This asymmetry can be attributed to the peculiarities of the defect structure of the studied samples. There are two types of characteristic planar defects in Bi2212:Pb system. The first one is system of twins. These defects are seen in polarized light and serves the weak points for the flux penetration in the studied single crystals. The second kind of planar defects in Bi2212:Pb is a so-called laminar structure. These defects revealed by means of X-ray diffraction are formed by modulation of the Pb concentration. The laminar structure contributes to the total pinning force and the screening current density along the laminae is higher than the current density across them. In our samples the laminae are parallel to two of the sample edges and the current anisotropy along and across the laminae is about 1.5–2, which is significantly lower than the in-plane magnetic field induced anisotropy.\textsuperscript{9,10} After the transverse field turning on, the flux penetrates the sample preferably along the in-plane magnetic field and later the smaller anisotropy due to lamina structure proves itself.

The appearance of the asymmetry could be understood as follows. The interaction of the transverse vortices with the currents flowing in the superconductor gives rise to the existence of the forces which drives the magnetic flux into the sample bulk. The directions along the in-plane magnetic field and along the laminae are more favorable for the flux line motion. In the case of the in-plane field directed normal to the sample edge and, consequently, perpendicular to the laminar structure, the motion of the transverse flux to the left and to the right with respect to $H_{ab}$ are equal. If there exists some angle $\alpha$ between the in-plane field and the normal to the laminar structure, the left and right directions become unequal since the component of the driving force along the ‘easy’ direction (parallel to the laminae) is different. This could give rise to the observed asymmetry. For illustration, we calculate below the value of the flux creep rate asymmetry using a simple model of TAFF.

Let us introduce a coordinate system $x, y, z$ with $z$ axis directed perpendicular the sample plane, $y$ axis along the in-plane field, and $x$ axis across it. The magnetic field has two components $B_z$ and $B_y$ and the components of the current in $ab$ plane are

$$j_x = \frac{c}{4\pi} \left( \frac{\partial B_z}{\partial y} + \frac{\partial B_y}{\partial z} \right), \quad j_y = -\frac{c}{4\pi} \frac{\partial B_z}{\partial x}. \quad (1)$$

The components of the Lorentz’s force acting on the transverse flux line can be written as follows

$$f_{||} = \frac{\phi_0 n_z}{4\pi} \left[ \frac{\partial B_z}{\partial x} \sin \alpha - \left( \frac{\partial B_z}{\partial y} + \frac{\partial B_y}{\partial z} \right) \cos \alpha \right], \quad (2)$$

$$f_{\perp} = -\frac{\phi_0 n_z}{4\pi} \left[ \frac{\partial B_z}{\partial x} \cos \alpha + \left( \frac{\partial B_z}{\partial y} + \frac{\partial B_y}{\partial z} \right) \sin \alpha \right], \quad (3)$$

where $\phi_0$ is the flux quantum, $n_z = 1$ if the transverse field $B_z$ is directed in the positive direction and $n_z = -1$ if $B_z$ is directed in the negative one, the value $f_{||}$ corresponds to the force component along the laminar structure, and $f_{\perp}$ is the force component across the laminae. Following a standard approach,\textsuperscript{11} we express the line velocity as a sum of TAFF probabilities for the flux line to move through a distance $l$ during a time interval $\tau$ down and against the Lorentz force. As a result, we get for the components of the flux line velocity along and across the laminar structure

$$v_i = 2v_0 \exp \left( -\frac{V_i}{kT} \right) \sinh \left( \frac{f_i L_z}{kT} \right), \quad (4)$$

where $v_0 = l/\tau$, $i = ||$ or $\perp$, $L_z$ is the flux line length along $z$ axis, and $V_i$ are the effective pinning barriers for the flux line motion along and across the laminar structure. The component of the TAFF velocity $v_x$ transverse to the vector of the in-plane field is defined now by evident formula $v_x = v_|| \sin \alpha - v_\perp \cos \alpha$. At this point we could start with the analysis of the flux penetration asymmetry. However, for simplicity we linearized Eq. (1) with respect to $f_i$ assuming $f_i L_z/kT \ll 1$ and find

$$v_x = \gamma n_z \left[ \frac{\partial B_z}{\partial x} \left( \sin^2 \alpha + \beta \cos^2 \alpha \right) - \frac{1 - \beta}{2} \left( \frac{\partial B_z}{\partial y} + \frac{\partial B_y}{\partial z} \right) \sin 2\alpha \right], \quad (5)$$
where

$$\gamma = \frac{v_0 \phi_0 |L_z|}{2\pi kT} \exp \left(-\frac{V_l}{kT}\right),$$

$$\beta = \exp \left(\frac{V_l - V_\perp}{kT}\right) \leq 1.$$  \hspace{1cm} (6)

The sign of the derivative $\partial B_y/\partial x$ is evidently different for the flux lines at the right and at the left side of the magnetic flux penetration front. In the case of the isotropic superconductor ($\beta = 1$) or if the in-plane magnetic field is directed perpendicular to the sample edge (that is, $\alpha = \pi/2$), these lines moves in opposite directions with the same absolute values of the velocity components $|v_x|$. If there exists in-plane anisotropy and the in-plane magnetic field deviates from the normal to the edge, then, the absolute values of the transverse velocity components are different and from Eq. (5) we find

$$\Delta v_x = |v_x^{\text{right}}| - |v_x^{\text{left}}| =$$

$$\gamma(1 - \beta)n_z \left(\frac{\partial B_z}{\partial y} + \frac{\partial B_y}{\partial z}\right) \sin 2\alpha.$$  \hspace{1cm} (7)

This asymmetry disappears at $\alpha = \pi/2$ as it is observed in the experiment. The obtained result is based on the simplest possible model of TAFF and could not be used for a quantitative analysis. Nevertheless, it describes the main features of the effect since the observed flux motion asymmetry follows from a general symmetry of the problem.

The velocity asymmetry $\Delta v_x$ changes if we change the direction of one of the fields $H_z$ or $H_{ab}$. Really, in these cases the sign of the product $n_z \partial B_z/\partial y$ in Eq. (7) remains unchanged while the sign of $n_z \partial B_y/\partial z$ changes. A simultaneous change of the signs of the both fields $H_z$ and $H_{ab}$ does not affect the asymmetry value $\Delta v_x$. As it follows from the experiment, the change of the direction of one of the field changes the sign of the velocity difference $\Delta v_x$. This means that $|\partial B_z/\partial y| \ll |\partial B_y/\partial z|$. It is a natural result since the pinning of the flux lines lying in $ab$ plane is usually higher than for the flux lines directed along $c$ axis. According to Eq. (7), the velocity asymmetry $\Delta v_x$ changes its sign if the angle between the in-plane field and the sample edge is changed from $\alpha$ to $-\alpha$, which also is in accordance with the experimental results.

Besides the discussed above mechanism, the Magnus force could be a reason for asymmetrical creep. However, in this case it would be impossible to explain the observed effect of the inclination angle $\alpha$ on the creep rate. In addition, the Magnus force should be small for an extreme type-II superconductor. The best symmetry of the flux creep with respect to the in-plane field direction is attained in the experiments at inclination angles different from zero (at $\alpha$ about $4^\circ$). Probably this is a consequence of Magnus force influence on relaxation.

In conclusion, the MO studies of the flux creep in the Bi2212:Pb single crystals placed in the in-plane magnetic field were performed. At $T < 54$ K, the experiments reveal a strong anisotropy of the flux creep rate and the rate of the screening current decay with respect to the direction of the in-plane magnetic field. This observation confirms the existence of the strong superconducting correlations between CuO planes in this superconductor at low temperatures. The asymmetry of the flux creep with respect to the in-plane field direction was also observed and explained in terms of the interaction of the flux lines with laminar structure.

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