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Shape- and orientation-dependence of surface barriers in single crystalline d-wave
Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$

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Magnetooptical imaging and Hall-probe array magnetometry are used to measure the field of first flux entry, $H_p$, into the same Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystal cut to different crystal thickness-to-width ratios $(d/w)$, and for two angles $\alpha$ between the edges and the principal in-plane crystalline $(a,b)$ axes. At all temperatures, the variation with aspect ratio of $H_p$ is qualitatively well described by calculations for the so-called geometric barrier [E.H. BRANDT, Phys. Rev. B 60, 11939 (1999)]. However, the magnitude of $H_p$ is strongly enhanced due to the square shape of the crystal. In the intermediate temperature regime ($T \lesssim 50$ K) in which the Bean-Livingston barrier limits vortex entry, there is some evidence for a tiny crystal-orientation dependent enhancement when the sample edges are at an angle of 45° with respect to the crystalline axes, rather than parallel to them.

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I. INTRODUCTION

Surface barriers are well-known to delay vortex penetration into high-$T_c$ cuprates (HTSC). As a consequence, the field of first flux penetration $H_p$ may be significantly higher than the lower critical field $H_{c1} = \Phi_0/4\pi\mu_0\lambda^2\ln\kappa$ ($\lambda$ is the London penetration depth, $\kappa \equiv \lambda/\xi$ the coherence length, $\Phi_0 = h/2e$ is the flux quantum, and $\mu_0 = 4\pi \times 10^{-7}$ Hm$^{-1}$). Among possible types of barriers, the Bean–Livingston (BL) barrier arises from the competition between the attraction of an entering vortex to the external surface (this can be described with an image vortex near the surface) and its repulsion by the screening (Meissner) current. The maximum value of the total free energy per unit length due to the introduction of a vortex, $\varepsilon_0 \ln \left( H_c/\sqrt{2}H_a \right)$, is attained when the latter is situated at a distance $\xi H_c/\sqrt{2}H_a$ from the superconductor-vacuum interface. Here, $H_a$ is the applied magnetic field, $H_c = \sqrt{2}\varepsilon_0/\Phi_0$ is the thermodynamic critical field, and $\varepsilon_0 = \Phi_0/4\pi\mu_0\lambda^2$ is the vortex line energy. Therefore, for fields close to the penetration field $H_p = \sqrt{2}H_c$, the BL barrier can be overcome by thermal activation. In long thin isotropic superconductors in parallel fields, this is thought to happen by the nucleation of a vortex loop in the sample bulk. In layered superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$, the vortex loop may encompass a single or several pancake vortices. Experiments supporting an important role of the BL barrier in HTSC are the observation of asymmetric hysteresis loops accompanied by magnetic relaxation over the barrier, near the critical temperature $T_c$ in YBa$_2$Cu$_3$O$_{7-\delta}$ and at temperatures below 50 K in layered Tl$_2$Ba$_2$CaCu$_2$O$_{8+\delta}$ and Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. Further evidence is the observation of the predicted sensitivity of the barrier to electron and heavy-ion irradiation. Namely, the presence of defects near the specimen surface perturb the screening current on the relevant length scale, larger than the coherence length $\xi$ but smaller than $\lambda$, thereby favoring vortex nucleation.

Following theoretical predictions of a possible crystal-orientation dependence of $H_p$ in HTSC, the BL barrier has recently returned to the center of attention. This orientational dependence would be due to the predominant $d_{x^2-y^2}$–symmetry of the superconducting gap in HTSC (for a review, see Ref. 26). In that case, quasiparticle scattering at surfaces oriented perpendicularly to the nodal directions give rise to Andreev bound states (ABS). The quasi-particle current carried by these bound states is responsible for the modification of the field of first flux penetration. In Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ the relevant surfaces are those that have a normal oriented near to $\alpha = 45^\circ$ with respect to the principal $(a,b)$ crystalline axes.

It should be noted that the BL barrier is effective only in the situation where the applied magnetic field is parallel to a large flat surface. In the opposite case of a superconducting platelet of rectangular cross-section in perpendicular magnetic field, flux entry is hindered by a barrier of geometrical origin. The geometrical barrier comes from the competition between the line tension of a vortex cutting through the upper and lower ridges at a sample edge, and the Lorentz force due to the Meissner current. The penetration field $H_p$ is reached when the total field at the sample equator attains $H_{c1}$; vortex sections penetrating from the top and the bottom ridge join, and the vortex line enters the bulk. A key experiment demonstrating the relevance of the geometrical barrier in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ is the measurement of the penetration field of crystals with similar aspect ratio $d/w$, but different shape: a prism-shaped or ellipsoidal crystal have a lower penetration field than a rectangular parallelepiped. Experiments reporting the accumulation of flux in the center of a superconductor sample immediately after first flux penetration cannot be taken as evidence for the presence of a geometrical barrier; such observations merely reflect the fact that the sample cen-
The flux density and current distributions accompanying vortex penetration into superconductors of rectangular cross-section and varying thickness-to-width ratio $d/w$ was numerically calculated by Brandt. The penetration field obtained from these calculations is well described by the formula

$$H_p = H_p^0 \tanh \left( \sqrt{\beta d/w} \right).$$

The constant $\beta$ was found to be $\sim 0.36$ for infinite strips (bars), and $\sim 0.67$ for rectangular cylinders; in the absence of a BL barrier or vortex pinning, $H_p^{0,\infty} = H_{c1}$. Tentative agreement of Eq. (1) with $H_p$ of micron-sized single crystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ was obtained for a few values of $d/w$ and temperature $T$ by Wang, et al. while Cabral et al. could fit their measured hysteresis loops to those calculated in Ref. [17], but only in the temperature interval $50 - 60$ K.

The purpose of the present paper is twofold. In a first step, we shall verify the dependence of the field of first flux penetration in square-shaped Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystals on a wide range of aspect ratios $d/w$, over the entire temperature range from 20 K to $T_c$. This is achieved by cutting the same crystal into successively smaller squares. These measurements establish the manner by which the Bean-Livingston barrier and magnetic relaxation influence $H_p$, and yield the geometrical factor $\beta$ for a crystal of square shape. The results are then used to verify whether any effect of crystalline orientation on Meissner screening and first flux penetration can be measured in single crystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$.

The expected orientation dependence should actually be largest in layered superconductors such as Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. In thin rectangular crystals of "continuous" superconductors such as YBa$_2$Cu$_3$O$_{7-\delta}$, there is no potential barrier stopping the progression of vortex lines into the interior once the geometrical barrier is overcome (Fig. 1). Furthermore, the boundary condition imposes that the vortex current runs parallel to the crystal lateral surface. In this situation, any effect of the ABS quasi-particle current should be confined to the volume near the crystal ridges. In layered superconductors, the progression of a vortex line is mediated by the successive penetration of pancake vortices. The entry of each pancake is counteracted by a potential barrier, since the pancake currents are always in a plane perpendicular to the lateral surface. These arguments hold for HTSC as long as the applied field is not exactly parallel to the $(a, b)$ plane, since the high crystalline anisotropy impedes vortex penetration along the $c$-axis. A possible contribution of ABS to the Bean-Livingston barrier in layered HTSC will come not only from the crystal ridges, but from all flat regions of the lateral surface that are oriented perpendicular to a nodal direction ($\alpha = 45^\circ$), and all wedge-shaped regions with bisector along the nodal direction. In what follows, we find a tiny enhancement of $H_p$ for $T < 50$ K, i.e., in the regime in which flux penetration is delayed by the Bean-Livingston barrier. This shows that, if any enhancement of the Bean-Livingston barrier due to ABS exists, it is either much smaller than theoretically expected, or marred by physical damage at the crystal edges. At higher temperature, no enhancement is found.

II. EXPERIMENTAL DETAILS

A rectangular Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystal is cut along its $a$ and $b$ axes from a seed rod grown by the travelling solvent floating zone method. The crystal orientation was determined from the growth direction of the rod, and verified by the precession X-ray diffraction method.

Flux penetration below 80 K was imaged using direct magneto-optical imaging (MOI) while for higher temperatures the Differential Magneto-Optical (DMO) method was used. In MOI, a ferrimagnetic garnet indicator with in-plane anisotropy is placed on top of the
In order to avoid any artifacts due to tiny variations in sample composition or doping, the same Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ crystal is chosen for all further experiments. The selected crystal, with $T_c = 88.7 \pm 0.5$ K, had initial dimensions $(l = 1400) \times (w = 500) \times (d = 28) \mu$m$^3$, and was checked using the differential magneto-optical (DMO) technique to be as homogeneous as possible: macroscopic and mesoscopic inhomogeneities are known to affect $H_p$. Nevertheless, some inhomogeneities arising from the crystal growth method remained. Fluctuations in crystal growth rate result in small spatial variations of the composition, with a arc-shaped topology reminiscent of the floating-zone meniscus (inset of Fig. 5). The associated spatial variation of the local $T_c$ leads to preferential flux penetration in the arc-shaped regions, above the temperatures marked by arrows in Fig. 5.

For the measurements of $H_p$ as function of $d/w$, the same roughly square shape is retained to eliminate the influence of sample shape, or ambiguities related to the difference between length and width. Using a W wire saw with 1 $\mu$m SiC abrasive grains, the initial crystal, with $d/w = 0.045$, is progressively cut into five ever smaller squares, down to $d/w = 0.47$, according to the scheme of Fig. 5. In the final step, one of the intermediate squares is cut at 45° with respect to the crystal axes; it had an aspect ratio of $d/w = 0.12$. Fig. 5 shows scanning electron micrographs of the edges obtained following the cuts. Typically, different layers of the crystal split at slightly different distances $x$ from the crystal center, yielding an edge roughness $\langle (x^2) \rangle^{1/2}$ $\sim 2 - 3$ $\mu$m. The edges of individual layers are smooth on the scale of the penetration depth, $\sim 200$ nm, with occasional protrusions. The local orientation of the edge meanders about the global orientation of the crystal, with a rms deviation of 10–25°, depending on the investigated edge. No systematic morphological differences could be observed between [100] or [010] “anti-nodal” and [110] “nodal” interfaces. The crystal edges therefore seem to be suitably

![FIG. 2: (a) DMO image of Meissner screening by the initial Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$ single crystal, at 86.0 K and $H_a = 0$; the field modulation $\Delta H_a = 1$ Oe. (b) Cutting scheme. The black rectangle represents the initial crystal, white numbered lines indicate successive cuts, in order.](image_url)
described by the model advocated in Ref. 33.

III. RESULTS

The main panel of Fig. 3 shows \( H_p \) of the different crystals cut from the initial sample in the vicinity of \( T_c \). One systematically observes a linear decrease of \( H_p \) upon approaching \( T_c \), followed by a steep descent to \( H_p = 0 \) (see also Ref. 33). DMO imaging shows that this drop is the consequence of flux penetration into areas of lower \( T_c \), and is therefore the hallmark of sample inhomogeneity. A similar depression of the field of first flux penetration was obtained by introducing heavy ion-irradiated regions. The measured values \( \beta \), ranging between \( 2 - 6 \) (inset to Fig. 3), are significantly larger than expected. The prefactor \( H_p^0 \), determined from the fits is presented in Fig. 3.

Above \( T \sim 45 \) K, it corresponds to \( H_{c1}(T) \) of the \( d \)-wave superconductor in the limit \( d/w \to \infty \), with the correct zero-temperature extrapolated \( H^0_{c1}(0) = 180 \) Oe and \( T_c = 88.7 \) K as obtained from DMO. Previously attempted comparisons to the two-fluid relation \( H_p^0(T) = H^0_{c1}(0) \left[ 1 - (T/T_c)^4 \right] \) yield an anomalously low value \( H_{c1}(0) \approx 100 \) Oe.

We note the observation of thermally activated flux entry at all temperatures, indicative of a role of the BL barrier. In particular, the width of the hysteresis loops of Fig. 3 progressively narrows as \( T \) increases, until the loops are all but closed for \( T \lesssim T_c \). As in Ref. 3, the temperature dependence of the penetration field in the regime 40 – 50 K is in qualitative agreement with the theory of Ref. 4, which has

\[
H_p = \frac{H_c}{\sqrt{2}} \left( \frac{t_0 + t}{\tau} \right)^{-k_B T/\varepsilon_0 s}.
\]

The relaxation rate is observed to be \( S \sim -0.03 \). However, if one attempts a quantitative fit by inserting this value, which should correspond to \( S = dH_p/d\ln t \equiv k_B T/\varepsilon_0(T)s \), into Eq. 2, one obtains \( H_p \)-values that, above 50 K, fall vastly short of the measured ones. Therefore, vortex entry above this temperature is not limited by the BL barrier (see also Ref. 33). Below \( T \sim 30 \) K, the relaxation rate is observed to be significantly larger than expected.
the shape of the hysteresis loops and the observation of remnant flux clearly indicate the effect of flux pinning. If \( H_p \) shows an associated steep exponential increase as \( T \) is lowered.

The fits to Eq. (1) yield a set of master curves allowing us to assess the dependence of \( H_p \) on the relative orientation of the sample edges with respect to the principal crystal axes. For this, we present, in Fig. 9, the measured data on the sample with \( d/w = 0.12 \), cut at 45°. These are compared to the interpolated values of \( H_p^{45} \) for a hypothetical sample with the same aspect ratio, cut parallel to the principal axes (\( \alpha = 0 \)). At temperatures above 50 K where the Bean-Livingston barrier is inoperative, we find \( H_p^{45} \) to be slightly smaller than \( H_p^0 \). However, in the regime where the Bean-Livingston barrier impedes pancake vortex entry into the crystal, there is a small enhancement \( H_p^{45}/H_p^0 \) of up to about 1.25. This enhancement increases with decreasing temperature.

**IV. DISCUSSION**

We first discuss the enhancement of the penetration field by the BL barrier and the effect of sample shape for \( \alpha = 0 \). The dependence of \( H_p \) on \( d/w \) is well described by Eq. (1) at all temperatures, not only at those where the barrier is of purely geometric origin. This is a consequence of the macroscopic distribution of the Meissner current, which depends only on sample shape and the value of the penetration depth. At temperatures below 50 K, pancake vortex entry is hindered additionally by the BL barrier, which leads to a larger penetration field \( H_p \). This enhancement is manifest through the increase of \( \beta \) as temperature is lowered. As temperature increases, pancake vortex penetration is accelerated due to thermal activation over the BL barrier. However, the field of first flux penetration can never drop below that of the geometrical barrier, since below this field \( H < H_{c1} \) at the crystal equator and the existence of vortices in the superconductor is thermodynamically unfavorable. Once \( H_p \) is overcome, thermal activation of pancakes leads to the rapid increase of the local induction at the sample boundary to values above \( H_{c1} \), and the concomitant closing of the magnetic hysteresis loops.

Even in the high temperature regime where the BL barrier has no effect whatsoever, the experimentally found \( \beta \) is much larger than that found in the calculations of Refs. 16 and 17. Such a large value of \( \beta \) expresses the fact that in thinner crystals, the measured penetration field is larger than what would be expected from calculations including the effect of the geometrical barrier only. An explanation is that, apart from opposing pancake entry from the side surfaces, the Bean-Livingston barrier opposes initial flux penetration across the top and bottom sample ridges, a finite size-effect that is expected to be more important for thinner crystals. Furthermore, \( \beta \) is enhanced because of the square shape of the sample surface perpendicular to the field direction. Although this is manifestly closer to the disk than to the strip geometry, the corners of a square superconductor are responsible for enhanced screening with respect to the disk, yielding a larger penetration field. The effect is similar to that of the ridges of a platelet of rectangular cross-section, which are responsible for additional screening.

![FIG. 6: (color online) Hysteresis loops of the magnetic flux density in the center of the crystal with \( d/w = 0.052 \), measured by a microscopic Hall probe array. The inset shows an expanded view of the loops at high temperature.](image)

![FIG. 7: (color online) The penetration field as evaluated from MO-imaging (open symbols) and Hall probe measurements (full symbols). The aspect ratio is \( d/w = 0.47, 0.33, 0.12(45°), 0.088, 0.052, 0.045 \), from the upper to the lower curves. The inset shows the experimentally determined factor \( \beta \) as function of temperature.](image)
when compared to an ellipsoidal superconductor of the same $d/w$. By extrapolating to $T_c$, at which all effects of the Bean-Livingston barrier have vanished, we find, experimentally, that $\beta \sim 1$ for a square superconductor with rectangular cross-section. Note that taking an incorrect value of $\beta$ may result in large error when determination of the first critical field $H_{c1}$ from $H_p$ of thin superconducting platelets.

We now turn to the relative enhancement $H_{c1}^{\delta} / H_{p0}$ of the field of first flux penetration for $\alpha = 45^\circ$, i.e. where the crystal edges are perpendicular to the nodal directions of the superconducting order parameter in Bi$_2$Sr$_2$CaCu$_2$O$_{8+\delta}$. The observation of an enhancement in the sole temperature regime where the BL barrier is important is in qualitative agreement with the theory of Iniotakis, Dahm, and Schopohl. 

The theoretically predicted enhancement $H_{c1}^{\delta} / H_{p0} \sim 1 + c \beta / \xi$ increases as temperature decreases (see Inset to Fig. 8). Its physical origin is that, in superconductors where the order parameter $\Delta$ undergoes a sign change on any given Fermi surface sheet, interference between quasiparticles with a relative phase difference of $\pi$ will result in the occurrence of Andreev bound states (ABS) on those parts of the superconductor-vacuum interface that are perpendicular, or nearly perpendicular, to the $k$-space direction for which $\Delta$ vanishes. For Bi$_2$Sr$_2$CaCu$_2$O$_{y}$ with $d_x^2-y^2$-wave symmetry of the order parameter these “nodal” directions correspond to $(\pm \pi, \pm \pi)$, i.e. $\alpha = 45^\circ$ with respect to the principal crystalline axes. The ABS have a spatial extent of several times $\xi$ in the direction perpendicular to the interface, and are accompanied by a local reduction of $\Delta$. Translational invariance along the interface allows these states to carry current. When a magnetic field is applied to the superconductor, this “anomalous” paramagnetic current adds to the diamagnetic screening current, and to the ordinary paramagnetic current resulting from the Doppler shift of quasiparticle states. In the region near a nodal surface, the total Meissner current is therefore reduced with respect to surfaces that are perpendicular to the $k$-space direction where the gap is maximum; hence, the magnetic field should penetrate somewhat further into the superconductor. The presence of a vortex near the nodal interface should also affect the Andreev bound states with the result of somewhat reducing the “anomalous” current. The BL barrier on the nodal surface must therefore be evaluated by the addition of the standard free energy contributions from the vortex-Meissner current repulsion and the attraction of the vortex to the surface; and the “anomalous” contributions arising from the extra repulsion due to the augmented field near the surface, and from the attraction between the vortex current and the bound state current. The net result is an enhancement of the barrier maximum, and a shift of its location towards the bulk of the superconductor. The en-

FIG. 8: (color online) Double-logarithmic plot of the penetration field of single crystalline Bi$_2$Sr$_2$CaCu$_2$O$_{8}$ as a function of aspect ratio for different temperatures. Open symbols show $H_p^0$ for the case where the edges are parallel to the principal axes. Drawn lines are fits to Eq. 1. Full symbols indicate $H_p^{\delta}$ (edges at $\alpha = 45^\circ$ with respect to the principal crystal axes).
enhancement of the BL barrier should be maximum when the orientation of the superconductor-vacuum interface is perpendicular to the nodal direction (and nil when the interface is parallel to the nodal direction), and be temperature dependent. For example, at $T/T_c = 0.2$, an increase of $H_p$ by a factor of 4 to 5 is expected on surfaces oriented at $\alpha = 45^\circ$, with respect to the situation where $\alpha = 0$.

The observation of an enhancement of $H_p$ for the crystal with the edges cut perpendicular to the nodal directions seems to confirm the prediction by Iniotakis et al. of an orientation-dependent $H_p$ due to a more important effect of Andreev bound states in this case. The inset to Fig. 3 shows that the magnitude of the experimentally measured effect is, however, far less than predicted. The prime factor that may influence the experimental result is the roughness of the edges cut by the wire saw. The undulating character of the crystal edges will entail a reduction of the local density of bound states, and should strongly diminish the total anomalous (paramagnetic) Meissner current. As for the observed wedge-shaped protrusions, recent work has shown even if the occurrence of ABS depends sensitively on quasiparticle reflection at the boundary as well as the shape and precise orientation of the latter, they are still expected as long as the wedge bisector is aligned close to a nodal direction. However, the localised quasiparticles near to such protrusions will not contribute to the total Meissner current, and will have no effect on the Bean-Livingston barrier. In summary, the area on which the Bean-Livingston barrier is effectively enhanced is much smaller than the total area of the lateral edges. Only a fraction of pancakes composing an entering vortex line will effectively be subjected to the influence of local ABS, entailing the decrease of $H_p$.

Finally, even in those parts of the surface where ABS would be fully developed, pancake vortices enter the crystal by thermal activation over the barrier. This implies that pancakes are nucleated at a distance that is farther removed from the edge than the predicted $\xi H_c/\sqrt{2} H_n$. In Ref. 23, the magnitude and temperature dependence of the enhancement factor $1 + c_f/\xi$ strongly depends on the distance of the vortex from the crystal edge. Any enhancement of this distance due to thermal activation would imply a much smaller modification of the Meissner current, and a significant reduction of the enhancement factor.

V. CONCLUSIONS

Summarizing, we have measured the field of first flux entry, $H_p$, for samples of different aspect ratio and orientation, cut from the same optimally doped $\mathrm{Bi}_2\mathrm{Sr}_2\mathrm{CaCu}_2\mathrm{O}_8$ single crystal. We find that at all temperatures, the penetration field of the square-shaped crystals is satisfactorily described by Eq. 6. The numerical factor $\beta$ is determined jointly by the shape of the sample surface perpendicular to the field direction and by the effect of the Bean-Livingston barrier, which, in layered superconductors, counteracts the penetration of individual pancake vortices. For the case of a square superconductor of rectangular cross-section, without the influence of a Bean-Livingston barrier, it is experimentally found that $\beta \sim 1$.

Moreover, we have investigated the enhancement of $H_p$ when the edges are perpendicular to the nodal directions of the order parameter, i.e., at $45^\circ$ with respect to the crystalline $a$ and $b$ axes. If discernible, the measured enhancement is tiny and occurs only in the temperature interval in which the Bean-Livingston barrier increases the field of first flux penetration over what would be expected from sole geometrical effects. The results are discussed in the framework of possible Andreev bound states present at the nodal surfaces of the $d$-wave superconductor. Notably, the small value of the enhancement in comparison to theoretical prediction is ascribed to edge roughness and thermal activation of pancake vortices over the Bean-Livingston barrier.

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