Magnetic flux jumps in textured $Bi_2Sr_2CaCu_2O_{8+\delta}$

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(Received 30 January 2002; revised manuscript received 26 August 2002; published 31 January 2003)

Magnetic flux jumps in textured $Bi_2Sr_2CaCu_2O_{8+\delta}$ have been studied by means of magnetization measurements in the temperature range between 1.95 K and T_c, in an external magnetic field up to 9 T. Flux jumps were found in the temperature range 1.95–6 K, with the external magnetic field parallel to the c axis of the investigated sample. The effect of sample history on magnetic flux jumping was studied and it was found to be well accounted for by the available theoretical models. The magnetic-field sweep rate strongly influences the flux jumping and this effect was interpreted in terms of the influence of both flux creep and the thermal environment of the sample. Strong flux creep was found in the temperature and magnetic-field range where flux jumps occur suggesting a relationship between the two. The heat exchange conditions between the sample and the experimental environment also influence the flux jumping behavior. Both these effects stabilize the sample against flux instabilities, and this stabilizing effect increases with decreasing magnetic-field sweep rate. Demagnetizing effects are also shown to have a significant influence on flux jumping.

DOI: 10.1103/PhysRevB.67.024518 PACS number(s): 74.25.Qt, 74.72.Hs

I. INTRODUCTION

Magnetic flux jumps are one of the peculiar phenomena of interest in both conventional, hard type-II superconductors and in high-temperature superconductors (HTS's). Studies of flux instabilities in superconducting materials are of interest both from a basic point of view and also in light of their potential applications. In addition, the investigation of flux jumps in HTS's are relevant to understanding the complexity of the vortex matter in the mixed phase of these materials. It is known that under appropriate conditions, the critical state of a superconductor may become unstable, leading to an avalanchelike process, initiated by a small fluctuation of the temperature or external magnetic field. This process is associated with the sudden puncture of magnetic flux into the volume of the superconductor with a corresponding increase in the material's temperature. During this process, the screening current is appreciably reduced, perhaps even to zero. From the point of view of the applications, magnetic flux jumps are problematic as they may drive the superconductor into a normal or resistive state. Flux jumps cause also abrupt changes to the sample dimensions, which may be observed via magnetostriction measurements.[1] Flux jumps phenomenon have been studied primarily by magnetization measurements, screening experiments, and torque magnetometry (see Ref. 2 for a review).

The basic theory appropriate to magnetic flux jumping was developed in the late 1960s by Swartz, Bean, and Wipf.[3–5] Theoretical analysis usually assumes the fulfillment of the local adiabatic conditions for the sample, which in turn depends upon the relation between the thermal (D_t) and the magnetic (D_m) diffusivity of the material. If $D_t \ll D_m$, the local adiabatic conditions for the occurrence of the flux jump process are assumed to be satisfied. Flux jumps are associated with the diffusion of magnetic flux into the superconductor. The diffusion time τ_m of magnetic flux is inversely proportional to magnetic diffusivity, i.e., $\tau_m \sim 1/D_m$. Similarly, the thermal diffusion time τ_t is inversely proportional to thermal diffusivity, $\tau_t \sim 1/D_t$. If the thermal diffusion time is significantly longer than the characteristic time for the process, the conditions of this process are considered to be locally adiabatic. In the case of magnetic flux jumps, these conditions are satisfied when $\tau_t \gg \tau_m$ or $D_t \ll D_m$.

The stability criteria of the critical state of hard type-II superconductors may be obtained by analysis of a loop of several interconnected processes, as was discussed for example by Wipf[2] (see also Fig. 2 in Ref. 2). A small thermal fluctuation ΔT_1 causes an appropriate decrease in the critical current density. This in turn decreases the screening current of the superconductor, allowing some additional magnetic flux to enter the volume of the sample. The additional flux causes heat dissipation, which generates an additional increase of the temperature of the superconductor by the amount of ΔT_2. If $\Delta T_2 > \Delta T_1$ an avalanchelike process in form of a flux jump is induced. The range of temperature and magnetic field for which flux jumps occur is determined by two parameters. The first one is the instability field B_{fj}. In the adiabatic approximation, and for an infinite slab geometry sample, the instability field for the first flux jump (after cooling the sample in zero magnetic field) is given by the formula

$$B_{fj1} = \sqrt{\frac{2\mu_0 c J_c}{-dJ_c/dT}}, \qquad (1)$$

where c is specific heat, J_c is critical current density, and μ_0 and T are the magnetic permeability of vacuum and temperature, respectively. This theory assumes that J_c is independent on the magnetic field, and B_{fj1} are measured after cooling the sample in zero magnetic field.

At sufficiently low temperatures, both the specific heat of the superconductor and the instability field for the first flux jump B_{fj1} increase with temperature. At some higher temperature, the $B_{fj1}(T)$ curve reaches a maximum and then drops to zero at the critical temperature of the superconductor (T_c), because at this temperature the critical current of the superconductor vanishes. At 4.2 K typical values of B_{fj1} predicted by Eq. (1) are of the order of 0.1 T. Thus flux jumping is expected to be an important problem from the point of view of applications of type-II superconductors, as it limits the performance of these materials in a low-temperature regime.

The second parameter affecting the appearance of flux jumps is the critical dimension of the superconductor, i.e., the minimum sample dimension for which flux jumps occur. The critical dimension of the sample depends on the sample's shape, its orientation relative to the external magnetic field, and on the relation between B_{fj1} and the value of the field of full penetration (B^*) of the superconductor. For the case of infinite slab geometry sample, or for an infinitely long cylindrical sample with an external magnetic field aligned parallel to its surface (slab sample) or axis (cylindrical sample), the role of the critical dimension is played by the sample diameter. The parameter B^* depends on the sample shape, the sample's orientation in the magnetic field and the field dependence of the critical current density. To the good approximation B^* is proportional to the critical current density (J_c) and sample dimensions.

For the case of an infinite slab or cylinder and under the assumption that $J_c(B)=\mathrm{const}$ (the so-called Bean model[6]), the field of full penetration can be calculated using the relation $B^*=\mu_0 J_c d$, where d is a half of the diameter of the infinite slab or the cylinder. At sufficiently low temperatures B_{fj1} increases with increasing temperature, whereas B^* decreases. At some temperature (T_1), $B^*(T_1)=B_{fj1}(T_1)$ and at higher temperatures $B^*<B_{fj1}$. Assuming that $J_c(B)=\mathrm{const}$, the critical diameter of the slab or cylinder sample for which $\Phi_{crit}=2d_{crit}$, may be determined from the equation $B^*(T_1)=\mu_0 J_c(T_1) d_{crit}$. For a slab (or cylinder) with diameter smaller than the critical one, no flux jumps occur at any temperature for any external magnetic field, independent of whether the measurements are made during the virgin magnetization curve (taken after cooling the sample in zero external magnetic field) or for other parts of magnetization hysteresis loop. However, when the critical current density depends on magnetic field, the situation becomes more complex. In this case, even if there are no jumps in the virgin magnetization curve, some jumps (so-called "solitary jumps"[7]) may appear after reversal of external magnetic-field direction. When the critical current density is a non-monotonic function of the magnetic field (the so-called "fish tail" or "butterfly" effect), then under appropriate conditions so-called "island jumps" may also be found.[8] All these phenomena result from the changes in magnetic-field profile in a superconducting sample caused by the field dependence of the critical current density as well as by magnetic history. In all cases, however, some critical dimension of the sample exists and for samples with dimensions smaller than the critical one, no jumps occur at any temperature or magnetic field. Thus by reducing the diameter of the superconductor it is possible to avoid flux jumping. This approach is commonly used in producing multifilament superconducting wires. Flux jumping in conventional superconductors, including the extension of the basic flux jumping theory to nonadiabatic conditions, has been thoroughly reviewed in Ref. 9.

Magnetic flux jumps have also been observed in high-temperature superconductors.[2] Because of the existence of a critical dimension, flux jumping in HTS's was observed only in relatively large single crystals or well-textured polycrystalline samples with high values of the critical current. No such effect has been observed in ceramics, because the critical dimension in these materials is limited by the grain size, which is typically very small, of the order of several microns. Most of the studies of flux jumps in HTS's that have been reported to date have been carried out on $YBa_2Cu_3O_{6+\delta}$ (Ref. 2) or $La_{2-x}Sr_xCuO_4$ (Refs. 1, 10, and 11) single crystals, or on highly textured polycrystalline materials. In contrast, there are only a few reports of magnetic flux jumping in the $Bi_2Sr_2CaCu_2O_{8+x}$ system.

Early experiments by Guillot and co-workers[12] observed flux jumps in an assembly of preferentially oriented $Bi_2Sr_2CaCu_2O_{8+x}$ single crystals. Unfortunately, no systematic studies of this phenomenon were reported. Magnetic flux jumps were also found in a large polycrystalline $Bi_2Sr_2CaCu_2O_{8+x}$ flux tube.[13] More systematic observations of flux jumping in BiSCCO system have been reported by Gerber and co-workers.[14] This work reports flux jumps in a $Bi_2Sr_2CaCu_2O_8$ sample consisting of a pile of *c*-oriented single-crystalline slabs, but only at relatively high magnetic-field sweep rates, above 1 T/s.[14] Among HTS materials $Bi_2Sr_2CaCu_2O_{8+x}$ is characterized by a strong anisotropy, much stronger than is the case in $La_{2-x}Sr_xCuO_4$ or $YBa_2Cu_3O_{6+\delta}$. Hence flux jumps studies of $Bi_2Sr_2CaCu_2O_{8+x}$ may be useful in understanding the development of the instability process in strongly anisotropic superconductors. A detailed understanding of the instability process in $Bi_2Sr_2CaCu_2O_{8+x}$ is also important from the viewpoint of potential applications of Bi-based compounds in Ag/BiPbSrCaCuO composites.

Many aspects of magnetic flux instabilities in HTS's as well as in conventional superconductors require further investigation to both elucidate the intrinsic dynamics of magnetic flux in superconductors, and to enable future applications.

II. OBJECTIVES

Despite the large literature on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals or textured polycrystals, flux jump instabilities have rarely been reported on. Thus no systematic studies of the critical state stability in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals or textured materials have been reported and there is little understanding as to how different parameters affect flux jumping in this system. The limited literature does suggest that $Bi_2Sr_2CaCu_2O_{8+\delta}$ is less susceptible to flux jumps than other known type-II superconductors.

The present paper deals with systematic studies of magnetic flux jumping phenomena in *c*-oriented, textured $Bi_2Sr_2CaCu_2O_{8+\delta}$ samples at magnetic-field sweep rates between 0.06 and 0.2 T/min. Specifically, we investigate the temperature and magnetic-field sweep rate dependence of flux jumping, as well as the influence of magnetic flux creep on the phenomenon.

We will first compare the flux jumps in our textured $Bi_2Sr_2CaCu_2O_{8+\delta}$ sample with that in other type-II superconductors. We go on to estimate the basic parameters relevant to the critical state stability in this material. We then study the influence of the flux creep on the flux jumps. As flux creep is relatively strong in our sample, one may expect it to have a significant influence on the critical state stability. Several theoretical models describing the influence of the flux creep on the critical state stability have been developed.[10,15] However, the quantitative comparison of these models with experimental data is lacking.

Finally, the present work also deals with analysis of the influence of demagnetizing effects on the critical state stability. To the best of our knowledge, no investigation of this phenomenon has been performed to date. As the demagnetizing factor of our sample is large, it is important to take this effect into account in the analysis of the flux jumps events. The influence of demagnetizing effects on flux jumping is discussed in the framework of the Brand, Indenbom, and Forkl model of the critical state of an infinitely long and thin superconducting strip in an external magnetic field perpendicular to its surface.[16]

III. EXPERIMENTAL DETAILS

A $Bi_2Sr_2CaCu_2O_{8+\delta}$ polycrystalline boule sample with a circular cross section of about 6 mm in diameter was grown by the floating zone technique in a four mirror optical furnace. The critical temperature of the as-grown material was about 92 K, very close to optimal for this HTS. From the as-grown boule, a sample of approximate dimensions $4.2 \times 2.2 \times 0.2$ mm^3 was detached by cleaving, such that the shortest edge of the detached sample was parallel to the *c* axis.

X-ray-diffraction studies of the cleaved sample show it to consist of a mosaic of several well-aligned single crystals. The rocking curve showed that the total misalignment of the *c* axes of this mosaic of single crystals was about 5°. This sample was used for all further studies of magnetic flux jumps reported here. Magnetization measurements were carried out using a Quantum Design PPMS-9 system with the maximum external attainable field of 9 T. The measurements were performed using the extraction magnetometer option. In this option the sample is moved between two pickup coils with constant velocity, whereas the signal from the pickup coils is integrated to calculate the magnetic moment of the sample under study. During experiment the sample was surrounded by a low-pressure helium gas (around 0.5 Tr) thus similar heat sinking conditions were maintained by crossing from 1.95 K to above 4.2 K. In all the magnetization measurements reported here, the temperature was varied between 1.95 K and T_c and the external magnetic field was changed in sweep mode. The temperature dependence of magnetization hysteresis loops was measured with a constant sweep rate of 0.3 T/min. In addition, the magnetic-field sweep rate dependence of the flux jumping was studied systematically at a single temperature of 4.2 K. The sweep rates were adjustable between the maximum and the minimum rates attainable in our system, i.e., between 0.06 and 1.2 T/min, respectively.

IV. RESULTS

Figure 1 shows magnetization hysteresis loops for our sample, with the external magnetic field parallel to its *c* axis. These data were obtained for temperatures between 1.95 and 6.5 K. All the measurements presented here were performed after cooling the sample in zero magnetic field. The external magnetic field was then swept from 0 to 9 T, back to −9 T, and again back to 0 T. The magnetic flux jumps are observed in the temperature range from 1.95 up to 6 K and they are not evident at 6.5 K, as Fig. 1 shows. Such magnetization hysteresis loops were also measured above 6.5 K, to temperatures up to T_c, but these measurements showed no magnetic flux jumping in the investigated sample. Similar measurements, carried out with magnetic field parallel to the sample surface, i.e., perpendicular to the *c* axis and at the same sweep rate of 0.3 T/min, showed no magnetic flux jumps in the whole temperature range studied, i.e., between 1.95 K and T_c.

As can be seen in Fig. 1, the number of observed jumps decreases with increasing temperature. Increasing the temperature increases both the value of the field at the first flux jump, B_{fj1} (see also Fig. 4), as well as an increase in the field spacing between subsequent jumps. At temperatures above 3

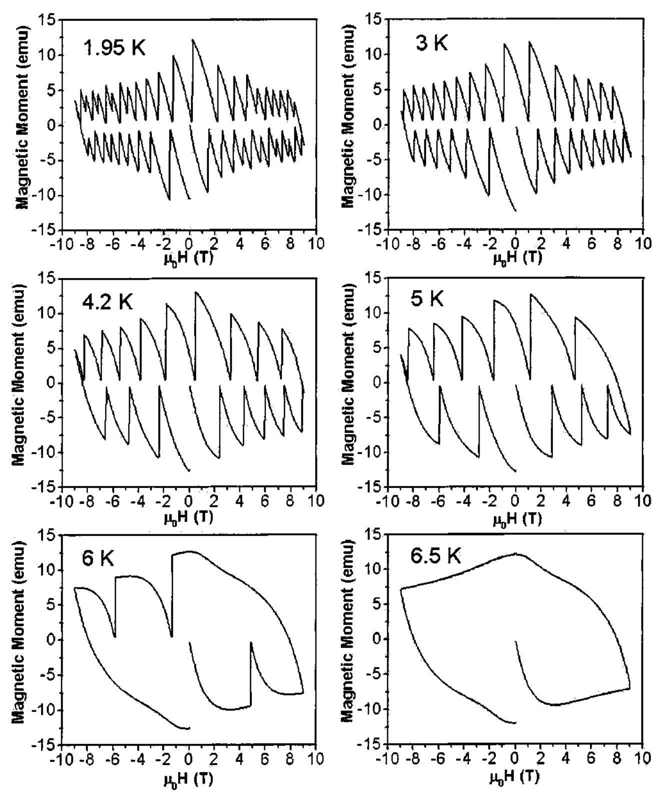

FIG. 1. Magnetization hysteresis loops taken of the $4.2 \times 2.2 \times 0.2$ mm^3 $Bi_2Sr_2CaCu_2O_{8+\delta}$ textured sample in the temperature range 1.9–6.5 K are shown. The *c* axis was parallel to the external magnetic field and the magnetic-field sweep rate was 0.3 T/min.

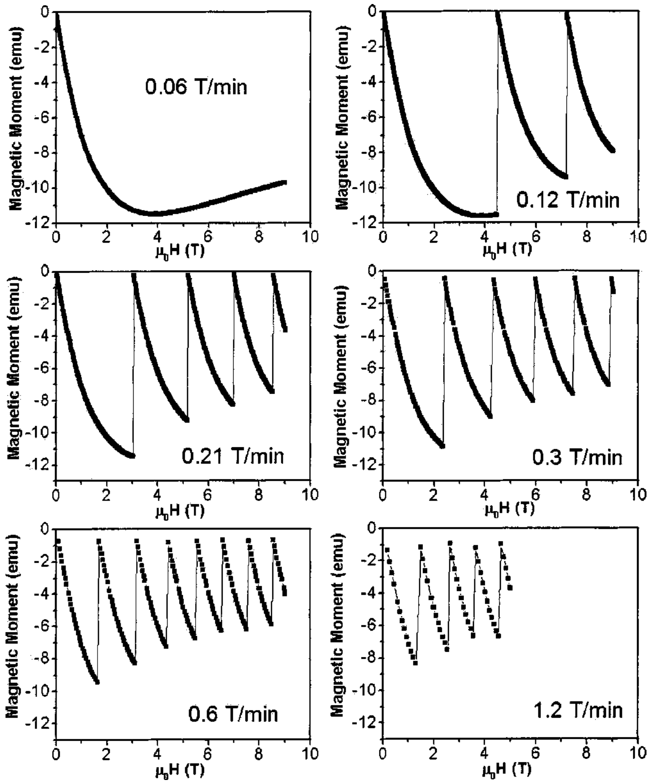

FIG. 2. The dependence of flux jumping versus the external magnetic-field sweep rate at the temperature 4.2 K is shown. The measurements were taken after cooling the sample in zero magnetic field with sweep rates 0.12, 0.21, 0.3, 0.6, 1.2 T/min, respectively. The *c* axis of the sample was parallel to the external magnetic field.

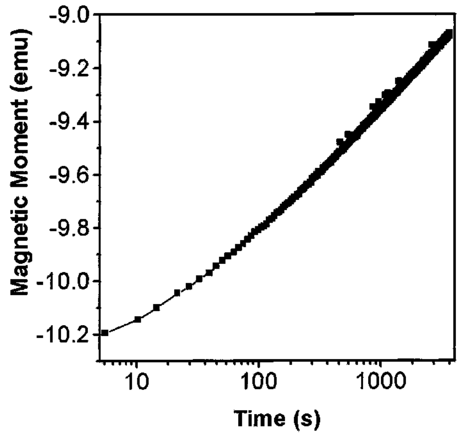

FIG. 3. The relaxation of the magnetic moment at 4.2 K in an external magnetic field 2 T is shown. The sample was first cooled in zero magnetic field, followed by an increase of the magnetic field to 2 T at a rate of 0.3 T/min. Subsequent to this, the relaxation of the sample was followed for 1 h.

K, all of the observed jumps are complete, meaning that the magnetization of the sample during a jump drops to zero. Figure 1 shows also the influence of the magnetic history on flux jumping. This influence is most clearly seen in the hysteresis loop measured at relatively high temperatures such as 6 K. Here one can see that only a single jump occurs within the first quadrant of the $M(H)$ plot, i.e., while the external magnetic field increases from 0 to 9 T. There are no jumps observed in the second quadrant of the $M(H)$ curve, when the magnetic field is decreased from 9 to 0 T. Subsequently there are two jumps present when the external magnetic field is changed from 0 to -9 T (within the third quadrant).

The magnetic-field sweep rate dependence on flux jumping has been studied at the temperature of 4.2 K and these results are shown in Fig. 2. These measurements were carried out in the first quadrant of the $M(H)$ hysteresis loop. With increasing sweep rate, and external magnetic field in the range from 0 to 9 T, the number of observed flux jumps increases, whereas the value of B_{fj1} decreases (see also Fig. 6). We emphasize that, at the lowest attainable sweep rate of 0.06 T/min and the same temperature of 4.2 K, no flux jumps occurred in our sample. Figure 2 shows all experimental points recorded. One can see that the observed jumps occur in a time interval shorter than that between the subsequent experimental points. The minimum time interval between experimental points is limited in our system to about 5 s.

In order to analyze the influence of flux creep on flux jumps we have measured the magnetic relaxation of our sample. The following procedure was adopted during the measurement. The sample was cooled in zero magnetic field to the temperature of 4.2 K, at which time the external magnetic field was increased from zero to 2 T at a rate of 0.3 T/min. This value of the field, 2 T, was chosen to prevent appearance of flux jumps, which first occur at this temperature at slightly higher magnetic fields i.e. at 2.38 T (see Figs. 1, 2, 4, 6). Measurements of magnetic moment were then performed over a period of 1 h and these results are shown in Fig. 3. The relaxation of the magnetic moment is approximately logarithmic in time. After 1 h, about a 10% decrease from the initial value of magnetic moment is observed in the sample.

V. ANALYSIS

The behavior of the magnetization jumps displayed by our $Bi_2Sr_2CaCu_2O_{8+\delta}$ sample and shown in Fig. 1 is typical for thermally activated flux jumps in type II-superconductors.[1–5,7–14] These data allow one to construct a relation between the field of the first flux jump, B_{fj1} and temperature, as shown in Fig. 4. The fact that B_{fj1} increases with increasing temperature is consisitent with the adiabatic theory of flux jumping,[3–5] discussed earlier.

The present results show that all flux jumps we observe at temperatures higher than 3 K are complete. This indicates that the energy released during the jump is sufficient to drive the superconductor into the resistive state, which means that this energy is sufficient to increase the temperature of the sample to the value at which the critical current density of the superconductor vanishes. It is important to note that to reduce critical current density to zero in the case of HTSs, it is not necessary to heat the superconductor above T_c but just above the vortex melting temperature, where the vortices become virtually unpinned. At lower temperatures more energy is required to drive the superconductor into the resistive state as compared to higher temperatures. The temperature in-

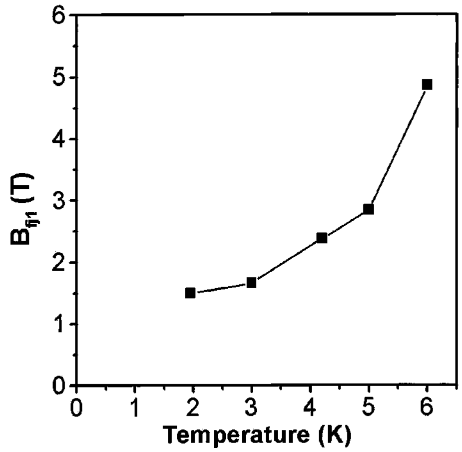

FIG. 4. The temperature dependence of B_{fj1}, determined on the basis of the data presented in Fig. 1 is shown.

crease during a jump depends on the quantity of energy released during the jump, and on the specific heat of the sample. At 1.95 K the magnetic-field interval between the successive jumps is less than at higher temperatures. Thus the magnetic energy stored in the superconductor between two successive jumps at 1.95 K is smaller than it is at higher temperatures. It may be that this magnetic energy is insufficient to drive the superconductor into the resistive state. Therefore for a number of jumps observed at 1.95 K, the magnetization of the sample does not drop to zero, as one can see in Fig. 1.

The magnetic history dependence on flux jumping, shown in Fig. 1, can also be accounted for by the theory presented in Refs. 7 and 8. In these references, the temperatures and magnetic-field range for which flux jumps occur was studied in the framework of the adiabatic theory, assuming different dependences of the critical current density as a function of the magnetic field. It was found that, if the critical current density decreases with increasing magnetic field, flux jumps first appear in the third quadrant of the $M(H)$ plot. Therefore this quadrant of the $M(H)$ plot is least stable from the point of view of appearance of flux jumping. Comparison of the magnetization hysteresis loops at different temperatures shows that as the temperature is lowered flux jumps appear in the first quadrant and also at the end in the second quadrant of the $M(H)$ plot. Thus the second quadrant of the $M(H)$ plot is the most stable from the point of view of appearance of flux jumping. This behavior of the flux jumps has been also observed in our sample, as shown in Fig. 1 (e.g., temperature 6 K).

In order to quantitatively compare the present experimental results with the predictions of the adiabatic theory, we have estimated the value of B_{fj1} at 4.2 K. This requires an estimate of the specific heat as well as temperature dependence of the critical current density. Determination of the critical current densities on the basis of magnetization hysteresis loop measurements as well as the stability of the critical state depends strongly on the distribution of the screening currents in a superconducting sample. This problem is important in the case of polycrystalline HTSs, where the grain boundaries may act as the weak links, reducing the critical current density even by several orders of magnitude. However, the texture of the polycrystalline samples is of great importance for limiting the critical current. If the polycrystalline sample consists of a set of well aligned grains, a large current may be shunt by the substantial common areas between adjacent grains, bypassing the weak links. This phenomenon is described in terms of the so-called "brick wall" model[17] and it is commonly observed in superconducting thin films as well as in Ag/BiPbSrCaCuO tapes, which despite their polycrystalline structure are characterized by high critical current densities. Similar is applicable in the case of our sample, when an external magnetic field is parallel to the c axes of the grains. In this case, screening currents flow within the ab planes of the grains and they have very large areas with which to bypass the weak links. Hence in our further analysis the whole sample will be treated as a single grain and the effect of the weak links will not be taken into account. It is also worth noting that after finishing our measurements the sample was cleaved again into several smaller pieces, each of which possessed almost the same surface area as the original sample. This suggests that the original sample had a sandwichlike structure of the weak links, which would not limit the screening currents in ab planes, when the external magnetic field is parallel to the c axes of the grains.

The temperature dependence of the critical current density in the direction parallel to the ab plane is estimated based on the magnetization data and these results are shown in Fig. 5. The widths of the magnetization hysteresis loops were measured at different temperatures at the zero external magnetic field, and subsequently, a value of the critical current density was estimated using a formula appropriate to a sample whose cross section in the plane perpendicular to an external magnetic field is in the shape of a rectangle, as discussed in Ref. 18. As the flux jumps occur primarily at low temperatures, this procedure cannot be effectively used in this range, below 6 K. Thus the temperature dependence of the critical current density was estimated only for temperatures above 6 K. Figure 5 shows this result between 6 and 38 K.

As one can see in Fig. 5 at zero external magnetic field and at 6 K critical current densities of the order of 10^6 A/cm^2 were found. These values of the critical current density are close to the upper limit of the critical current densities usually observed in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system. This fact is probably connected with the presence of a large number of structural defects acting as pinning centers. The temperature dependence of the critical current density at zero magnetic field is roughly exponential. However, it is difficult to fit a unique exponential formula to the whole range of experimental data [see Fig. 5(a)]. An exponential temperature (as well as magnetic-field) dependence of the critical current density in superconductors with weak pinning is expected from flux creep.[19] A precise analysis of these dependencies must also reflect the scaling of fundamental pinning related parameters on temperature, as well as on magnetic field.[20] To take into account the dependence of these parameters on temperature we have rescaled the temperature axis by a function $g(T)=1-(T/T_c)^2$ [see Fig. 5(b)]. This function is consistent with Ginzburg-Landau theory and is discussed in Refs. 19 and 20. In the case of HTS's the $g(T)$

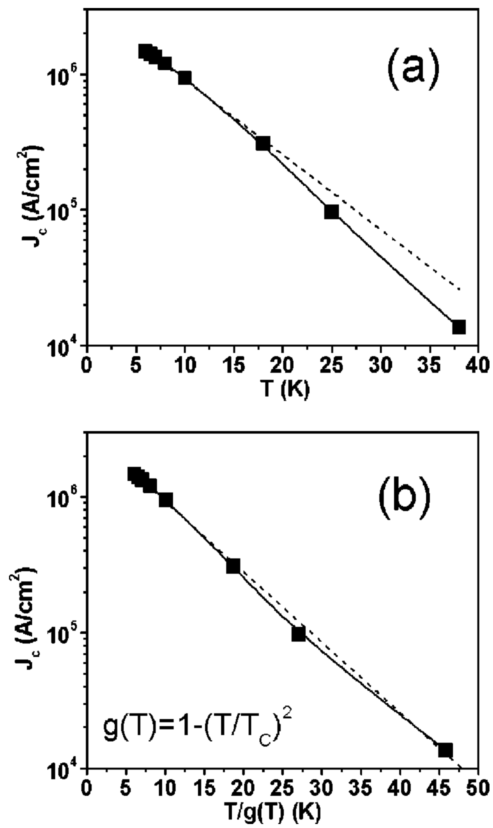

FIG. 5. (a) The temperature dependence of the critical current density in the direction parallel to the ab plane for zero external magnetic field in logarithmic scale is shown. The data was obtained on the basis of magnetization hysteresis loops measurements with an external magnetic field parallel to the c axis of the sample. (b) The same data in a normalized $T/g(T)$ scale, where $g(T)=1-(T/T_c)^2$ and $T_c=92$ K. Dotted lines show fit according to the exponential formula $J_c(T^*)=J_{c0}\exp(-T^*/T_0)$; see the text for details.

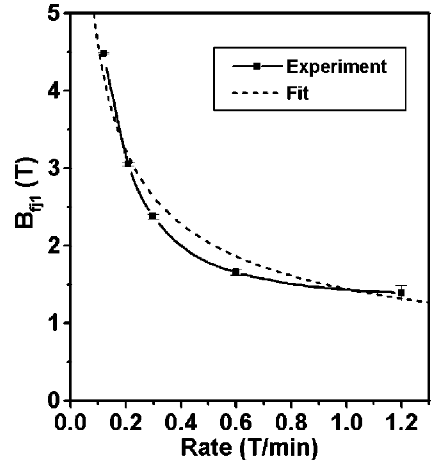

FIG. 6. The dependence of B_{fj1} on the sweep rate at a temperature of 4.2 K is shown. This was determined on the basis of data presented in Fig. 2. Experimental data are connected by spline (solid curve). The dotted line shows fit according to formula (32) from Ref. 15.

function is usually assumed in the form $g(T)=1-(T/T_{irr})^2$, where T_{irr} is the irreversibility temperature. At zero external magnetic field we have assumed $T_{irr}=T_c$. As one can see in Fig. 5, after application of this procedure, very good fitting of the available experimental data is obtained by using exponential formula $J_c(T^*)=J_{c0}\exp(-T^*/T_0)$ where $T^*=T/g(T)$, $J_{c0}=3\times10^6$ A/cm^2, and $T_0=8.4$ K.

The specific heat of $Bi_2Sr_2CaCu_2O_{8+\delta}$ at 4.2 K was estimated using $c(T)=\beta T^3$ with $\beta=2$ mJ/K^4 mol,[21,22] from which we get $c(4.2\ \mathrm{K})=11\times10^2$ J/Km^3. Using this value of specific heat, the above temperature dependence of the critical current density, and formula (1), we estimate $B_{fj1}(4.2\ \mathrm{K})\approx0.15$ T, a value roughly one order of magnitude lower than that observed in our experiment. Similar discrepancies between experimentally observed values of B_{fj1} and those calculated within the framework of the adiabatic theory have been reported for other HTS systems.[1,2,7,10–12,14] In these studies, the experimentally observed values of B_{fj1} at 4.2 K are of an order of 1 T or higher.

In order to account for why our sample appears more stable against flux jumping than would be expected from adiabatic theory, two phenomena need be considered. First, it is possible that adiabatic conditions may simply not be fulfilled in our experiment. Were this to be the case, we would expect the thermal anchoring of the sample to the cold finger of the cryostat to strongly influence flux jumping. The second possibility is flux creep. As was shown by McHenry *et al.*,[10] flux creep stabilizes the critical state of the superconductor against the flux jumps. Both possibilities may imply a dependence of the flux jumping on the sweep rate, as in fact is observed experimentally. This means that decreasing the sweep rate may stabilize the superconducting sample against flux jumping; thus the observed values of B_{fj1} would be higher than those predicted by adiabatic theory.

Figure 6 shows the dependence of the field of the first flux jump B_{fj1} on the magnetic-field sweep rate. As the sweep rate decreases the value of B_{fj1} increases rapidly and at a sweep rate of 0.12 T/min it approaches a value of about 4.5 T (Fig. 6). From Fig. 6, one sees that B_{fj1} tends to saturate at higher sweep rates. The exact value of the B_{fj1} field at the saturation cannot be determined, as the maximum sweep rate attainable in our system is 1.2 T/min. However, we estimate it to be around 1 T, several times higher than the value predicted by adiabatic theory. Similar strong sweep rate dependence on B_{fj1} was observed in other HTS systems.[10,11,14,23]

To check whether the adiabatic conditions are satisfied in our experiment we need to determine the relation between thermal (D_t) and magnetic (D_m) diffusivity. These parameters are estimated by applying standard procedure presented in Ref. 10 from the formulas $D_t\approx\kappa/c$ and $D_m\approx\rho/\mu_0$, where κ is the thermal conductivity, c is the specific heat, and ρ is the resistivity. The estimation of these parameters in $Bi_2Sr_2CaCu_2O_{8+\delta}$ is difficult for several reasons. First, the transport properties of this system are extremely anisotropic. The value of the in-plane thermal conductivity for $Bi_2Sr_2CaCu_2O_{8+\delta}$ is estimated to be $\kappa(4.2\ \mathrm{K})\approx1$ W/K m,[24] which gives $D_t(4.2\ \mathrm{K})\approx9\times10^{-4}$ m^2/s. However, the value of the thermal conductivity along the c axis of $Bi_2Sr_2CaCu_2O_{8+\delta}$ is difficult to determine experimentally, although one expects this value, as well as that for the thermal diffusivity, to be significantly lower than in ab plane, due to the planar nature of the material.

The estimate of the magnetic diffusivity in superconductors is also difficult. In nonsuperconducting materials the coefficient of the magnetic diffusivity is proportional to their resistivity. The normal-state resistivity in $Bi_2Sr_2CaCu_2O_{8+\delta}$ is extremely anisotropic.[25] The in-plane resistivity ρ_{ab} varies linearly with temperature with $d\rho_{ab}/dT = 0.46\ \mu\Omega$ cm/K, whereas resistivity along the c direction ρ_c is about five orders of magnitude higher.[25] In the configuration appropriate to our experiment, the flux front moves in the direction parallel to the ab plane. Hence, for the magnetic diffusivity, the estimation of ρ_{ab} is the appropriate one. Assuming a linear temperture dependence to ρ_{ab} below T_c, one obtains $\rho_{ab}(4.2\ K) \approx 1.9\times10^{-8}\ \Omega$m and therefore $D_m^{\text{ab-normal}}(4.2\ K) \approx 1.5\times10^{-2}\ m^2/s$ for the normal-state diffusivity. This value of magnetic diffusivity is more than one order of magnitude higher than the in-plane thermal diffusivity. However, since our sample is not in a normal state but in a superconducting mixed state, the flux flow resistivity ($\rho_f = \rho_n(B/B_{c2})$, where ρ_n is the normal-state resistivity, and B_{c2} is the upper critical field of the superconductor) must be used to estimate the magnetic diffusivity. On the basis of our magnetization data and above expressions, we estimate $\rho_f \approx \frac{1}{30}\rho_n$ just before appearance of the first flux jump, which gives $D_m^{ab}(4.2\ K) \approx 5\times10^{-4}\ m^2/s$. This value of magnetic diffusivity is the same order of magnitude as the in-plane thermal diffusivity. Therefore adiabatic conditions may be not fulfilled in our experiment at 4.2 K and this may be one reason for enhanced stability of our sample against flux jumping at this temperature. We may also expect an influence of the heat exchange conditions on flux jumping in our system as well. We should bear in mind, however, that our sample's geometry is that of a relatively thin pellet with its flat surface parallel to the ab planes. Such a geometry minimizes heat exchange by transport within the ab plane, and heat transport along the c axis is expected to be significantly lower than that in the ab plane. On the other hand, the estimation of the magnetic diffusivity on the basis of flux flow resistivity alone may be questionable. Recently, it was suggested by Mints[15] that the presence of flux creep may cause $D_m \ll D_t$ and as a result the local heat exchange conditions to be strongly nonadiabatic.

Flux creep is a phenomenon which may stabilize our sample against flux jumping, as well as imply a sweep rate dependence on flux jumps. $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals are characterized by relatively strong magnetic relaxation caused by flux creep.[26,27] At low temperatures and for a relatively small time window, this magnetic relaxation is logarithmic in time. Similar magnetic relaxation was found in our sample (see Fig. 3). On the basis of our results we have estimated the effective pinning potential (U_{eff}) to be $U_{eff}/k \approx 210$ K at $T = 4.2$ K and $H = 2$ T, where k is the Boltzmann constant. This value of U_{eff} is typical for the given temperature and magnetic-field range in the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system.

Another system characterized by relatively strong flux creep and magnetic relaxation is $La_{1-x}Sr_xCuO_4$.[20] Similarly, a strong influence of the external magnetic-field sweep rate on flux jumping was found in $La_{1.86}Sr_{0.14}CuO_4$ crystals.[10] The presence of flux creep changes the magnetic flux profile in a superconducting sample during a sweep of an external magnetic field. It was shown by McHenry *et al.*[10] that in the presence of flux creep, heat generated in the superconducting sample by a fluctuation of an external magnetic field is relatively small compared to the case when flux creep is absent. This fact influences the stability conditions of the critical state. As a result we expect an increase of the value of B_{fj1} relative to that predicted by the theory, in which flux creep phenomenon is not taken into account. Flux creep phenomenon can fully stabilize the superconducting sample against flux jumping as the rate of magnetic-field changes decreases. Related behavior was indeed observed in our experiment (see Fig. 2).

The influence of flux creep on flux jumping was also analyzed theoretically by Mints.[15] In this model a logarithmic dependence of the screening current density on the electric field (induced by external magnetic-field changes) was assumed, whereas the thermal conditions were assumed to be extremely nonadiabatic. (i.e., $\tau_t \ll \tau_m$ or $D_t \gg D_m$). As a result the predicted values of the B_{fj1} depend strongly on the heat transfer coefficient. Assuming the Bean model[6] [i.e., $J_c(B) = \text{const}$] this theory predicts $B_{fj1} \sim (dH_e/dt)^{-1/2}$, where dH_e/dt is the external magnetic sweep rate. A fit of this formula to our experimental data is shown in Fig. 6 by the dotted line. Comparison of the experimental and the fitted curve show that while the experimental curve tends to saturate at higher sweep rates around the value of $B_{fj1} \approx 1$ T the formula predicts that it approaches zero. It was shown in Ref. 15 that taking into account a decrease of the critical current density with magnetic field slows down the decrease of B_{fj1} with increasing dH_e/dt. Nevertheless, the theoretical curve still approaches zero at sufficiently high sweep rates. For more accurate comparison of the theoretical formula (from Ref. 15) with experiment, investigations at higher sweep rates would be necessary. A quantitative comparison of this formula with our experimental results was impossible, because neither the electric-field dependence of the screening current nor the heat-transfer coefficient in our experimental setup were known.

Finally, let us discuss the influence of demagnetizing effects on flux jumping. As our sample is in a form of a thin pellet and the external magnetic field is aligned perpendicular to its surface, one may expect a relatively strong influence of such effects on the flux instabilities. The easiest way to analyze the influence of demagnetizing effects on a magnetic material is to introduce a demagnetizing factor D. In the case of superconductors this factor is often estimated from the initial slope of the magnetization curve. Such procedure gives $D \approx 0.82$ in our case. However, the application of the demagnetizing factor is not fully appropriate in the case of superconductors, due to the fact that the magnetization of superconductor is caused by macroscopic screening currents. The self-component of the magnetic field significantly alters the distribution of these currents in a superconducting sample. This fact was confirmed by a number of experiments performed on both conventional[28] and high-temperature superconductors.[29,30] The experiments were performed by magneto-optic technique[29] or by using scanning Hall probes[28,30] on thin conventional superconducting discs,[28] HTS films,[29] or thin single crystals,[30] in the external magnetic field perpendicular to their surfaces. Until now, many attempts have been undertaken to solve the problem of the magnetic field and screening current distribution in superconductors with nonzero demagnetizing factors.[31] In most cases this problem cannot be solved analytically and numerical calculations are necessary. However, the problem of the distribution of the screening currents and magnetic field was solved analytically for superconducting samples with large (close to 1) demagnetizing factors, i.e., for samples in shape of infinitely long and thin strips[16] or infinitely thin disks.[32]

Since the demagnetizing factor of our sample is large, let us discuss some features of the model presented in Ref. 16 pertinent to the present studies of flux jumping. In the above-mentioned model, the magnetization of an infinitely long and thin strip in an external magnetic field perpendicular to its surface as a function of this field (after cooling the sample in zero field) is given by

$$M=-\frac{1}{2}J_c a \tanh\left(\pi\frac{\mu_0 H_e}{B^{**}}\right), \tag{2}$$

where J_c is the critical current density, a is half of the width of the strip, H_e is the external magnetic field, $B^{**}=\mu_0 J_c d^*$, and d^* is the thickness of the strip. This model assumes that $d^* \ll a$ and $J_c(B)=\text{const}$.

On the basis of Eq. (2) one can conclude that the magnetization of the infinitely long and thin strip never saturates. The model implies that the center of the strip is fully screened even for extremely large external magnetic fields. Hence one cannot use the concept of the field of full penetration the same way one would for the well-known case of a sample with zero demagnetizing factor (for example an infinitely long slab or cylinder). However, to some extent the role of the field of full penetration in the case of a strip is assumed by the B^{**} parameter. It is important to note that in this case d^* is the thickness of the sample, i.e., the dimension of the sample measured in the direction parallel to the external magnetic field. In the case of our sample, $d \approx 0.2$ mm and it is significantly smaller than other sample dimensions. Using the critical current density we estimated earlier, we may estimate $B^{**}(2\text{ K}) \approx 5$ T and $B^{**}(6\text{ K}) \approx 3.5$ T. These values are indeed quite close to the maximum value of B_{fj1} found in our experiment, i.e., 4.86 T at 6 K (Fig. 1). Thus one may conclude that in the case of very thin samples, such as single crystals or textured samples of the $Bi_2Sr_2CaCu_2O_{8+\delta}$ system, with an external magnetic field perpendicular to their surfaces, the role of the critical dimension from the point of view of appearance of flux jumps is played by the thickness of the sample.

VI. SUMMARY

Flux jumps phenomena in a thin $Bi_2Sr_2CaCu_2O_{8+\delta}$ textured sample with an external magnetic field parallel to the c axis have been systematically studied. The values of the experimentally observed instability fields depend strongly on the external magnetic-field sweep rates. Both flux creep and the heat exchange conditions between the sample and its environment must be taken into account in a quantitative analysis of this phenomenon. For thin samples in an external magnetic field perpendicular to their surfaces, the role of the critical dimension from the point of view of appearance of flux jumps is played by their thickness.

We conclude that the necessary requirements for the avoiding flux jumping in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals are following: (i) The sample thickness has to be lower than its critical dimension, of the order of 0.1 mm, when J_c at the relevant field strengths and temperatures is of the order of 10^6 A/cm^2. (ii) The magnetic sweep rates have to be low enough to allow for the stabilizing influence of flux creep to operate effectively and to allow for the effective heat exchange between the sample and the experimental environment.

Most experiments performed so far on $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals reported in the literature have been carried out on superconducting quantum interference device systems with very low magnetic sweep rates and on very thin (of the order of 0.1 mm) samples. It is thus not surprising that flux jumps have not been reported in these experiments.

Several questions concerning flux jumps in the high-temperature superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ system remain open. In the present studies we saw no evidence for flux jumps when the orientation of the sample within the external magnetic field was such that the ab plane was parallel to the external magnetic field. Thus one concludes that this system exhibits a very strong anisotropy with regard to flux jumps. The absence of flux jumps in the orientation of the ab plane parallel to the magnetic field may be caused by a reduced density of the critical current flowing in the c direction, as compared to the critical current density in ab planes. To study this effect in greater detail, better quality single crystals, which are much thicker in the c direction, are necessary and currently unavailable. Such experiments are beyond the scope of the present work.

The present work also did not answer definitively the question about how the local adiabatic conditions in our sample are fulfilled, as strong flux creep characterizes our sample. We believe that the comprehensive understanding of the phenomenon of the flux creep on flux jumps will be accomplished by studies of flux jump dynamics, which are currently in progress.

ACKNOWLEDGMENTS

We acknowledge financial support from the Natural Sciences and Engineering Research Council of Canada and Polish Government Agency KBN, Contract No. 8T11B03817. One of us (A.N.) would like to acknowledge a NATO Science Fellowship.

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