PHYSICAL REVIEW B **69**, 180510(R) (2004)

Vortex solid-liquid transition in $Bi_2Sr_2CaCu_2O_{8+\delta}$ with a high density of strong pins

S. Colson, C. J. van der Beek, and M. Konczykowski
Laboratoire des Solides Irradiés, CNRS-UMR 7642 & CEA/DSM/DRECAM, Ecole Polytechnique, 91128 Palaiseau, France

M. B. Gaifullin and Y. Matsuda
Institute for Solid State Physics, University of Tokyo, Kashiwanoha, Kashiwa, Chiba 277-8581, Japan

P. Gierłowski
Institute of Physics, Polish Academy of Sciences, Al. Lotnikow 32/46, 02-668 Warsaw, Poland

Ming Li and P. H. Kes
Kamerlingh Onnes Laboratorium, Leiden University, P.O. Box 9506, 2300 RA Leiden, The Netherlands
(Received 16 January 2004; revised manuscript received 18 March 2004; published 20 May 2004)

The introduction of a large density of columnar defects in $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals does not, at sufficiently low vortex densities, increase the irreversibility line beyond the first order transition (FOT) field of pristine crystals. At such low fields, the flux line wandering length r_w behaves as in pristine crystals. Next, vortex positional correlations along the *c* axis in the vortex Bose glass at fields above the FOT are smaller than in the low-field vortex solid. Third, the Bose-glass-to-vortex liquid transition is signaled by a rapid decrease in *c*-axis phase correlations. These observations are understood in terms of the ''discrete superconductor'' model.

DOI: 10.1103/PhysRevB.69.180510 PACS number(s): 74.25.Qt, 74.25.Op, 74.25.Nf

Heavy-ion irradiation of the layered high temperature superconductor $Bi_2Sr_2CaCu_2O_{8+\delta}$ induces the formation of amorphous latent tracks in the material, that act as strong pinning centers for vortices. Vortex localization on these ''columnar defects'' (CD's) leads to the superconducting Bose-glass phase at low field and temperature.[1] In single crystalline $Bi_2Sr_2CaCu_2O_{8+\delta}$, the irreversibility line (IRL) $B_{irr}(T)$ [or $T_{irr}(B)$], below which the $I(V)$ characteristic is no longer linear because of vortex pinning by CD's, can be identified with the Bose-glass transition line.[2] It was proposed[2] that when the defect density n_d is much larger than the vortex density B/Φ_0 (with $\Phi_0 = h/2e$ the flux quantum), vortex lines will behave qualitatively as in unirradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, even though the two-dimensional pancake vortices of which they are constituted are always located on the tracks. This ''discrete superconductor'' description[2] can be applied when $B, B_\Lambda < \frac{1}{6} B_\phi$, where $B_\phi = \Phi_0 n_d$ and $B_\Lambda = \Phi_0(\lambda_J^{-1} + \lambda_{ab}^{-1})^2$.[2] The Josephson length $\Lambda_J = \gamma s$, $\gamma = \lambda_c/\lambda_{ab}$ is the ratio of the London penetration depths $\lambda_{ab,c}$ for currents parallel to the material *ab* plane and *c* axis, respectively, and $s = 1.5$ nm is the separation between superconducting layers.

Here, we present measurements of vortex fluctuations in heavy-ion irradiated (HII) $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, near the IRL, that corroborate the ''discrete superconductor'' model. The first order vortex solid to liquid transition (FOT) in pristine $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals[3] has a very different dependence on oxygen content δ than the second order Bose glass to flux liquid transition after HII. The modification of the relative position of the two transitions in the vortex phase diagram by oxygen doping exposes two regimes. At high temperatures and low fields, the vortex solid-to-liquid transition in HII $Bi_2Sr_2CaCu_2O_{8+\delta}$ coincides with the FOT before irradiation. Moreover, the vortex wandering length r_w obeys the same temperature and field dependence as in the pristine material,[4] suggesting an identical mechanism of the transition. At higher vortex densities and lower temperature, vortex lines in the Bose glass are surprisingly *less* correlated along the *c* axis than in the vortex solid before HII. Nevertheless, the Bose glass-to-flux liquid transition is also marked by a rapid decrease of *c*-axis correlations.

We have used underdoped ($T_c = 69.4 \pm 0.6$ K) $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals, grown by the traveling solvent floating zone method at the FOM-ALMOS center, the Netherlands, in 25 mbar O_2 partial pressure.[5] The crystals were annealed for one week in flowing N_2 gas, and irradiated with 5.8 GeV Pb^{56+} ions at GANIL (Caen, France). Crystal A (dimensions $610 \times 420 \times 30$ μm^3, $B_\phi = 2$ T) was irradiated at $T = 80$ K to avoid self-doping;[6] indeed, T_c was unchanged following irradiation. The T_c of crystals B and C (dimensions $980 \times 600 \times 40$ and $1160 \times 660 \times 40$ μm^3, $B_\phi = 1$ T), irradiated at 293 K, increased to 75.6 ± 0.3 K.[6] Crystals A and C were mounted with the *c* axis parallel to the ion beam during irradiation, whereas sample B was rocked at incommensurate frequencies, around two orthogonal axes, resulting in homogeneously splayed CD's with angles between 0 and 15° with respect to the *c* axis.

The IRL's of different crystals (Fig. 1) were obtained as the onset temperature of the nonlinear ac transmittivity using a local Hall probe magnetometer in ac mode, operated at a frequency of 21 Hz and an ac field amplitude of 0.5 Oe.[7,8] The differential magneto-optical technique (DMO)[9–11] was used to determine the IRLs of samples A, B, and C [inset of Fig. 4(a)]. DMO reveals that B_{irr} depends on the position on the crystal surface;[10,11] the range of B_{irr} is denoted by the error bars.

Figure 1 shows the dependence of $B_{irr}(T)$ after HII for $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals with different oxygen content. The oxygenation can be characterized by the number of holes n_h per Cu.[6,12] For the as-grown ($n_h = 0.18$) and over-

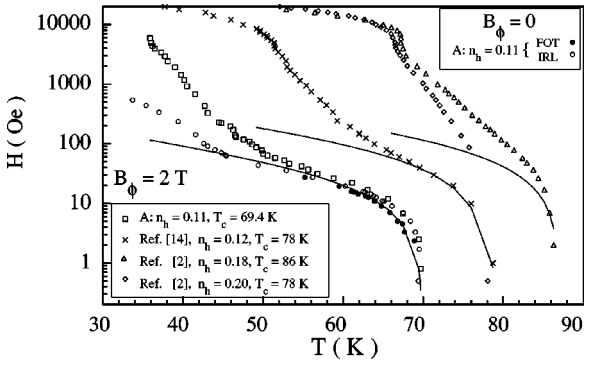

FIG. 1. IRL (open symbols) and FOT lines (closed symbols, drawn lines) in $Bi_2Sr_2CaCu_2O_{8+\delta}$ single crystals with different oxygen content, before and after irradiation with 1×10^{11} cm^{-2} 6 GeV Pb^{56+} ions (B_ϕ=2 T). (●, ○) Pristine underdoped crystal A, n_h=0.11,T_c=69.4 K; (□) crystal A, two days after irradiation at 80 K. (×, △, ◇) Different doping levels n_h, from Refs. 2 and 14. The FOT lines of the pristine material (drawn lines) are well described by Eq. (2), with parameter values $(\varepsilon_0 s/k_B, B_\Lambda)$ =(360 K, 35 G) (n_h=0.11), (475 K, 55 G) (n_h=0.12), (1000 K, 45 G) (n_h=0.18).

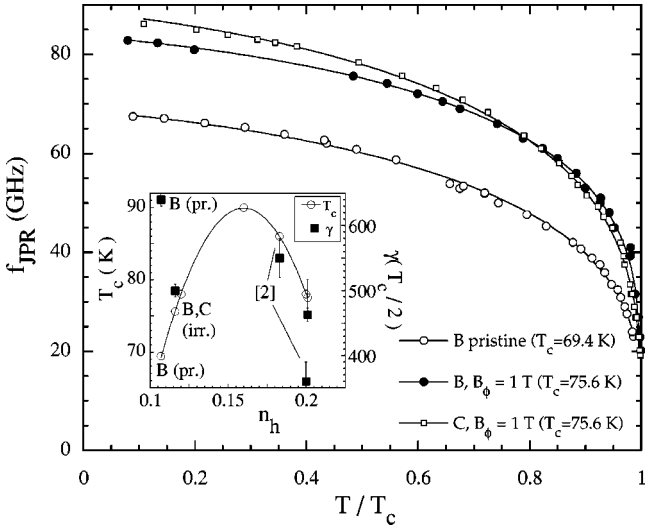

FIG. 2. Josephson plasma frequency f_{JPR} in zero field vs T/T_c for crystal B before irradiation, and for crystals B and C after irradiation. The increase in f_{JPR} is due to oxygen self-doping (Ref. 6). Solid lines are guides to the eye. Inset: T_c and γ at $\frac{1}{2}T_c$ vs the hole density per Cu n_h, for pristine (pr) and irradiated crystals B and C, and for the crystals of Ref. 2.

doped (n_h=0.2) crystals of Ref. 2, that have a transition width ΔT_c=0.3 K, the IRL coincides with the FOT of pristine $Bi_2Sr_2CaCu_2O_{8+\delta}$ with the same T_c over a temperature range of less than 1 K below T_c; for lower temperature, one observes the usual dramatic increase of B_{irr} following HII.[13] For moderate underdoping, n_h=0.12,[14] the IRL's prior to and after irradiation coincide over a span of nearly 10 K. Finally, for crystal A (as well as for crystals B and C, not shown in Fig. 1) an increase of B_{irr} after irradiation is observed only for $T<57\pm2$ K. In the temperature regime in which an irradiation-induced enhancement is observed, B_{irr} follows an exponential temperature dependence for all doping levels. The IRL always lies below the upper limit[2,14]

$$B_{irr}^{max}(T)=B_\Lambda\left(\frac{\varepsilon_0(T)s}{k_BT}\right)\exp\left(\frac{\varepsilon_0(T)s}{k_BT}\right)\quad(B,B_\Lambda\ll B_\phi). \tag{1}$$

This represents a ''mobility threshold'' or ''delocalization line'' above which two-dimensional pancake vortices can diffuse from their equilibrium site in the vortex solid. The IRL can be compared to the FOT line of the pristine crystal. The latter is well described by[15]

$$B_{FOT}=0.5B_\Lambda\varepsilon_0(T)s/k_BT, \tag{2}$$

drawn in Fig. 1 using values of λ_{ab} and γ determined from independent experiments.[4,6] Note that $B_{irr}^{max}(T)$ and the FOT line depend only on the vortex line energy per unit length, $\varepsilon_0(T)=\Phi_0^2/4\pi\mu_0\lambda_{ab}^2(T)$, and on B_Λ.

The evolution of the vortex phase diagram with changing oxygen content results from the different dependence of the Bose-glass delocalization line and the FOT line on $\varepsilon_0(T)$. As one goes from optimally doped to underdoped $Bi_2Sr_2CaCu_2O_8$, the decrease of $\varepsilon_0(T)$ leads to a downward shift of the exponential Bose-glass line that is much larger than the roughly linear shift of the FOT,[16] uncovering a substantial temperature range over which the FOT line survives the irradiation (Fig. 1). In optimally doped and overdoped crystals the relative shift is much smaller, but, nevertheless, one can identify a temperature range near T_c in which HII does *not* increase the IRL beyond the FOT line of the pristine material.

In order to characterize vortex fluctuations in this high temperature regime, we have determined the vortex wandering length in the vortex solid[17,18] in the presence of CD's using Josephson Plasma Resonance (JPR).[4,19] In $Bi_2Sr_2CaCu_2O_{8+\delta}$, thermal fluctuations may shift two pancake vortices belonging to the same flux line, and located in consecutive superconducting layers n and $n+1$, by a vector $\mathbf{u}_{n,n+1}$ with respect to one another. The wandering length r_w is defined as the thermal and disorder average $r_w=\langle\mathbf{u}_{n,n+1}\rangle$, and can be extracted from JPR experiments. Following the procedure of Ref. 4, valid in the regime $B<B_\Lambda\sim30-40$ G,

$$r_w^2=\frac{2\Phi_0}{\pi B}\left[1-\frac{f_{JPR}^2(B,T)}{f_{JPR}^2(0,T)}\right], \tag{3}$$

with $f_{JPR}(B,T)$ and $f_{JPR}(0,T)$ the JPR frequencies in field B and in zero field, respectively. The ratio $f_{JPR}^2(B,T)/f_{JPR}^2(0,T)\equiv\langle\cos(\phi_{n,n+1})\rangle$ corresponds to the average cosine of the gauge-invariant difference of the superconducting order parameter phase between layers n and $n+1$.[20]

The JPR frequency in zero field was measured using the bolometric method[21] on crystal B both before and after irradiation, and on crystal C after irradiation (Fig. 2). We observe an increase in f_{JPR} after room temperature irradiation, implying a decrease in the London penetration depth $\lambda_c=2\pi/\sqrt{\mu_0\epsilon}f_{JPR}(0,T)$. Here $\epsilon=11.5\epsilon_0$ is the dielectric permittivity, ϵ_0 is the permittivity of the vacuum,[22] and μ_0

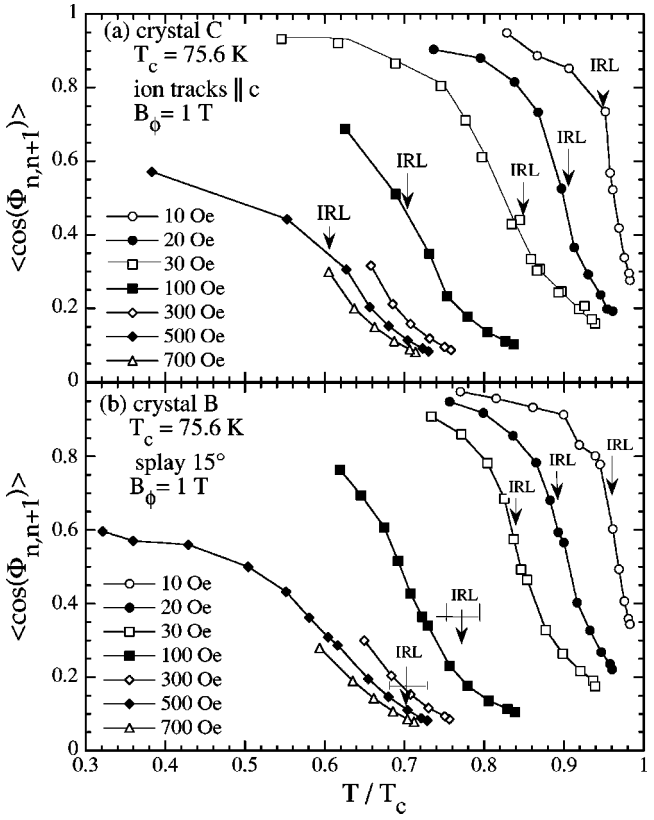

FIG. 3. $\langle\cos\phi_{n,n+1}\rangle$ vs reduced temperature in irradiated samples C (a) and B (b), for different fields 10 Oe$<H<$700 Oe. Arrows show T_{irr} obtained by DMO.

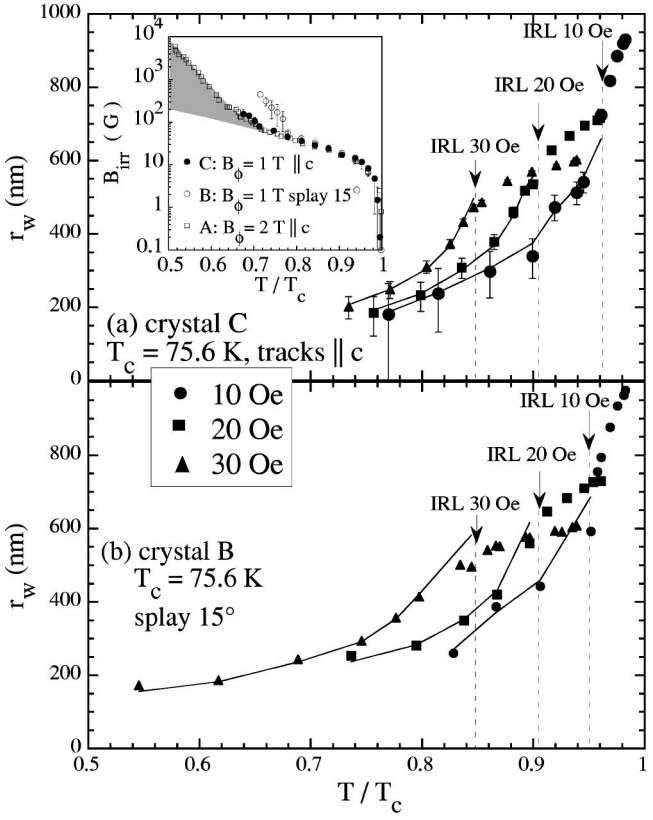

FIG. 4. Experimental r_w vs T/T_c for irradiated samples B and C, for low field values: $H=10$, 20, and 30 Oe. Solid lines are fits to Eq. (4), while dashed lines denote T_{irr} for the different fields. The (B_{irr},T) diagram for crystals A, B (from DMO, see the text) and C is shown in the inset.

$=4\pi\times10^{-7}$ H m^{-1}. The decrease of λ_c can be understood as stemming from the oxygen self-doping induced by the irradiation,[6] if one assumes that oxygen ions are expelled from the tracks not only to the CuO_2 planes but also to the BiO planes. This would lead to a decrease of the *c* axis parameter,[23] an increase of the interlayer coupling, and a concomitant decrease of λ_c.

Both the bolometric method and the cavity perturbation technique[4] were used to measure $\langle\cos(\phi_{n,n+1})\rangle$ on crystals B and C, in fields up to 700 Oe (Fig. 3). For $B\leqslant30$ G, the IRL roughly coincides with the inflection point of $\langle\cos(\phi_{n,n+1})\rangle$ as function of *T*, as does the FOT in unirradiated samples.[4,24] From $\langle\cos(\phi_{n,n+1})\rangle$, we obtain r_w using Eq. (3). The field and temperature dependence of r_w, plotted in Fig. 4, is similar to that observed in pristine $Bi_2Sr_2CaCu_2O_{8+\delta}$,[4] at least for $T<T_{irr}(B)$. Thus, it is tempting to fit the experimental r_w to the formula that describes vortex fluctuations in the *vortex solid* in pristine crystals,[4]

$$r_w^2\approx\alpha s^2\frac{k_BT\gamma^2}{\varepsilon_0 s}\left[\frac{4}{\pi(\alpha x^2+\frac{1}{4})}+\frac{1}{2}\ln(0.66x^2)+\frac{2}{\pi^2}\left(\frac{a_0}{\lambda_{ab}}\right)^2\ln\left(1+\frac{x^2}{21.3}\right)\right]^{-1}. \quad (4)$$

Here, $x=a_0/r_w$, $a_0\approx(\Phi_0/B)^{1/2}$ is the intervortex spacing, and $\alpha\sim1$; $\lambda_{ab}(0)=358$ nm is obtained from λ_{ab} of pristine underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ ($T_c=69.4$ K)[4] and the Uemura relation,[25] and λ_c from $f_{JPR}(0)$. Using Eq. (4), we obtain a very good description of r_w in the regime $T<T_{irr}(B)$ (Fig. 4). As in unirradiated $Bi_2Sr_2CaCu_2O_{8+\delta}$ crystals, the whole expression (4) is used to fit the data at the lowest field $H=10$ Oe (with $\alpha=0.6$–0.75). At $H=20$ and 30 Oe, Eq. (4) also well describes the data, but, as in pristine $Bi_2Sr_2CaCu_2O_{8+\delta}$, better fits (with $\alpha=0.35$–0.5) are obtained if the first term in the denominator is omitted. We have shown previously that pancake vortices are always located on the defects,[14,26] which outnumber the flux lines by a factor 300 to 1000. Nevertheless, in the temperature range in which the IRL is described by Eq. (2), thermal vortex excursions in HII $Bi_2Sr_2CaCu_2O_{8+\delta}$ are indistinguishable from those in the pristine material. A similar conclusion may well hold true at lower temperature and higher fields, as follows from the recent observation in HII underdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$ of an abrupt change in vortex dynamics *below* the exponential Bose-glass line, at the FOT field prior to irradiation.[27] In other words, vortex fluctuations in the vortex solid phase are not affected by the introduction of a high density of columnar pins.

On the contrary, in the part of the vortex liquid phase that is converted to Bose glass by the irradiation [hatched area in the inset to Fig. 4(a)], vortex fluctuations are profoundly affected by the CD's. In pristine $Bi_2Sr_2CaCu_2O_{8+\delta}$, order pa-

rameter phase correlations in the liquid are described by the high-temperature expansion result $\langle\cos(\phi_{n,n+1})\rangle \propto 1/TB$.[16,24] After irradiation, $\langle\cos(\phi_{n,n+1})\rangle$ in this field region no longer follows this behavior, but rather follows a convex temperature dependence, saturating at a low temperature value of approximately 0.6 (Fig. 3). The low-temperature saturation means that between the FOT and the Bose glass line, vortex lines (pancake stacks) are *less* ordered along the *c* axis than in the vortex solid, but *more* ordered than in the flux liquid before irradiation. Presumably, this is because the pancakes belonging to the same flux line occupy many different columns even in the Bose glass phase.[2,26] Nevertheless, pancakes stay confined to the same ''site,'' or vortex line, which leads to an enhancement of *c*-axis correlations. A possible mechanism for this enhancement is that the columnar defects play the role of a ''substrate potential,'' supplementary to the electromagnetic and Josephson coupling between pancakes.[28] It can be seen from Fig. 3 that the *c*-axis phase coherence induced by the CD's is now destroyed at the IRL rather than at the FOT: At T_{irr}, $\langle\cos(\phi_{n,n+1})\rangle$ shows the inflexion point characteristic of the crossover from a state with long-range order of the superconducting phase.[24] This result confirms that of Doyle *et al.* that the IRL in HII layered superconductors corresponds to a loss of *c* axis phase coherence.[29]

To conclude, we have shown that the introduction of a large density of amorphous columnar defects does not change thermal vortex excursions in the vortex solid state of a layered superconductor. At temperatures sufficiently close to T_c, at which the defects are ineffective, this has the consequence that the irreversibility line in the presence of CD's coincides with that of the pristine superconductor. The situation is radically different in the flux liquid: CD's increase pancake alignment and phase correlations along the *c* axis with respect to the situation in the flux liquid, but cannot enhance them beyond the correlations in the vortex solid.

[1] D.R. Nelson and V.M. Vinokur, Phys. Rev. Lett. **68**, 2398 (1992); Phys. Rev. B **48**, 13060 (1993).
[2] C.J. van der Beek, M. Konczykowski, A.V. Samoilov, N. Chikumoto, S. Bouffard, and M.V. Feigel'man, Phys. Rev. Lett. **86**, 5136 (2001).
[3] E. Zeldov, D. Majer, M. Konczykowski, V.B. Geshkenbein, V.M. Vinokur, and H. Shtrikman, Nature (London) **375**, 373 (1995).
[4] S. Colson, M. Konczykowski, M.B. Gaifullin, Y. Matsuda, P. Gierłowski, M. Li, P.H. Kes, and C.J. van der Beek, Phys. Rev. Lett. **90**, 137002 (2003).
[5] M. Li, C.J. van der Beek, M. Konczykowski, A.A. Menovsky, and P.H. Kes, Phys. Rev. B **66**, 024502 (2002).
[6] M. Li, C.J. van der Beek, M. Konczykowski, H.W. Zandbergen, and P.H. Kes, Phys. Rev. B **66**, 014535 (2002).
[7] J. Gilchrist and M. Konczykowski, Physica C **212**, 43 (1993).
[8] C.J. van der Beek, M. Konczykowski, V.M. Vinokur, T.W. Li, P.H. Kes, and G.W. Crabtree, Phys. Rev. Lett. **74**, 1214 (1995).
[9] A. Soibel, E. Zeldov, M. Rappaport, Y. Myasoedov, T. Tamegai, S. Ooi, M. Konczykowski, and V.B. Geshkenbein, Nature (London) **406**, 282 (2000).
[10] A. Soibel, Y. Myasoedov, M.L. Rappaport, T. Tamegai, S.S. Banerjee, and E. Zeldov, Phys. Rev. Lett. **87**, 167001 (2001).
[11] C.J. van der Beek, I. Abalosheva, M. Konczykowski, M. Li, P.H. Kes, and M.V. Indenbom, cond-mat/0309653 (unpublished).
[12] M.R. Presland, J.L. Tallon, R.G. Buckley, R.S. Liu, and N.E. Flower, Physica C **176**, 95 (1991).
[13] M. Konczykowski, N. Chikumoto, V.M. Vinokur, and M.V. Feigel'man, Phys. Rev. B **51**, 3957 (1995).
[14] M. Li, C.J. van der Beek, M. Konczykowski, and P.H. Kes, Physica C **369**, 278 (2002).
[15] L.I. Glazman and A.E. Koshelev, Phys. Rev. B **43**, 2835 (1991); Physica C **173**, 180 (1991).
[16] A.E. Koshelev, Phys. Rev. B **56**, 11201 (1997).
[17] L.N. Bulaevskii, A.E. Koshelev, V.M. Vinokur, and M.P. Maley, Phys. Rev. B **61**, R3819 (2000).
[18] A.E. Koshelev and L.N. Bulaevskii, Physica C **341-348**, 1503 (2000).
[19] Y. Matsuda, M.B. Gaifullin, K. Kumagai, K. Kadowaki, and T. Mochiku, Phys. Rev. Lett. **75**, 4512 (1995); Y. Matsuda, M.B. Gaifullin, K.I. Kumagai, M. Kosugi, and K. Hirata, *ibid.* **78**, 1972 (1997); T. Shibauchi, T. Nakano, M. Sato, T. Kisu, N. Kameda, N. Okuda, S. Ooi, and T. Tamegai, *ibid.* **83**, 1010 (1999).
[20] L.N. Bulaevskii, M.P. Maley, and M. Tachiki, Phys. Rev. Lett. **74**, 801 (1995).
[21] Y. Matsuda, N.P. Ong, Y.F. Yan, J.M. Harris, and J.B. Peterson, Phys. Rev. B **49**, 4380 (1994).
[22] M.B. Gaifullin, Y. Matsuda, N. Chikumoto, J. Shimoyama, K. Kishio, and R. Yoshizaki, Physica C **362**, 228 (2001).
[23] T.W. Li, A.A. Menovsky, J.J.M. Franse, and P.H. Kes, Physica C **257**, 179 (1996).
[24] M.B. Gaifullin, Y. Matsuda, N. Chikumoto, J. Shimoyama, and K. Kishio, Phys. Rev. Lett. **84**, 2945 (2000).
[25] Y.J. Uemura, G.M. Luke, B.J. Sternlieb, J.H. Brewer, J.F. Carolan, W.N. Hardy, R. Kadono, J.R. Kempton, R.F. Kiefl, S.R. Kreitzman, P. Mulhern, T.M. Riseman, D.Ll. Williams, B.X. Yang, S. Uchida, H. Takagi, J. Gopalakrishnan, A.W. Sleight, M.A. Subramanian, C.L. Chien, M.Z. Cieplak, G. Xiao, V.Y. Lee, B.W. Statt, C.E. Stronach, W.J. Kossler, and X.H. Yu, Phys. Rev. Lett. **62**, 2317 (1989).
[26] C.J. van der Beek, M. Konczykowski, R.J. Drost, P.H. Kes, N. Chikumoto, and S. Bouffard, Phys. Rev. B **61**, 4259 (2000).
[27] M. Konczykowski, C. J. van der Beek, E. Zeldov, M. Li, and P. H. Kes, Physica C (to be published).
[28] M.J.W. Dodgson, V.B. Geshkenbein, and G. Blatter, Phys. Rev. Lett. **83**, 5358 (1999).
[29] R.A. Doyle, W.S. Seow, Y. Yan, A.M. Campbell, T. Mochiku, K. Kadowaki, and G. Wirth, Phys. Rev. Lett. **77**, 1155 (1996).