Eur. Phys. J. B **16**, 397–402 (2000)

THE EUROPEAN PHYSICAL JOURNAL B

Absence of dynamical crossover in the vortex creep near by the second peak effect in superconducting Hg-1201 single crystals

A. Daignere, T. Aouaroun, and C. Simon[a]

Laboratoire CRISMAT[b], ISMRA et Université de Caen, 6 boulevard du Maréchal Juin, 14050 Caen Cedex, France

Received 11 January 2000

Abstract. DC magnetic relaxation measurements in $HgBa_2CuO_4$ single crystals are analyzed nearby the fishtail line. It is found that in this case, it is not necessary to introduce any crossover from plastic creep to elastic creep models at the fishtail line. This type of fishtail effect comes only from a competition between a critical current at low temperature which increases *versus* field and the activation energy, which decreases *versus* field. According to the doping level of the compound, the fishtail effect can be observed or not, without any correlation with a vortex phase transition. Moreover, in this type of fishtail effect, there is no history effects as recently observed in $YBaCu_2O_3$ by the partial magnetization loop technique, suggesting that the transition from plastic to elastic flow is here hidden by the disorder of these materials.

PACS. 74.60.Ge Flux pinning and creep, and flux-line lattice dynamics – 74.72.Gr Hg-based cuprates

1 Introduction

The dissipation due to vortex movements in high T_c's superconductors has been extensively described in terms of elasticity of the vortex lattice in presence of randomly distributed pinning centers ("collective creep"), characterized by energy barriers U diverging at vanishing current density and increasing with the magnetic field B [1]:

$$U(J,B) \propto B^{\nu} J^{-\mu} \tag{1}$$

where ν and μ are positive coefficients. Such a model was claimed to be verified in various high T_c's materials such as $YBa_2Cu_3O_7$ [2,3], ($Tl_{2/3}$, $Bi_{1/3}$)$Sr_2BaCu_2O_x$ [4] or $Nd_{1.85}Ce_{0.15}CuO_4$ [5] for magnetic fields smaller than B_{SP} (the field of the second peak in magnetization, the so-called "second peak field"). In these materials, it appears a crossover at B_{SP} and ν becomes negative above B_{SP}, suggesting a plastic behavior with no diverging barrier at vanishing current densities [6]. Sometimes, a crossover in μ is also observed at B_{SP} [2]. No model exists giving the exact $U(J)$ shape in this case. In $YBa_2Cu_3O_7$ (Y-123), Abulafia *et al.* [2] have proposed a phenomenological model, based on an analogy with dislocations in solids:

$$U(J) = U_0\left(1 - \sqrt{\frac{J}{J_0}}\right)\cdot \tag{2}$$

This model was recently used with success to analyze $HgBa_2CuO_4$ (Hg-1201) [7,8], ($Tl_{2/3}$, $Bi_{1/3}$)$Sr_2BaCu_2O_x$ ((Tl, Bi)-1212) [4], and $Tl_2Ba_2Ca_2Cu_3O_{10}$ (Tl-2223) above B_{SP} [9]. More generally, it is usually proposed to interpolate between the short and long time limits by a unique formula [1]:

$$U(J) = \mathrm{sign}(\mu) U_0 \left(\left(\frac{J}{J_0}\right)^{-\mu} - 1\right). \tag{3}$$

This formula describes a plastic behavior if μ is negative and an elastic behavior if μ is positive.

Recently, this crossover was observed in pure Y-123 crystals by the mean of the partial magnetization loop technique [10]. It was also reported [11] that this effect disappears in heavily twinned samples, or in presence of enough of columnar defects, suggesting that the crossover and the related history effects can be hidden by a too strong pinning. These recent results suggest that the data of Abulafia *et al.* in heavily twinned Y-123 samples were misinterpreted. In a previous paper [12], we have already suggested that it can be the case also in (Tl, Bi)-1212. Analyzing AC susceptibility and DC relaxation measurements on (Tl, Bi)-1212, we have proposed that it is possible to account for the second peak effect without introducing any change in the vortex dynamics at B_{SP}. We have proposed that the plasticity governs the vortex dynamics below and above B_{SP}.

In this work, we have chosen the study of a mercury based copper oxide superconductor, Hg-1201. The advantage of Hg-1201 compared to other compounds is the presence of a large fishtail feature [7,8,13,14] over a wide range of temperature from 2 K to 60 K (T_c = 96 K). The other advantage is its moderate anisotropy ($\gamma = 30$ [15–17]) which induces a fishtail position very convenient

[a] e-mail: charles.simon@ismra.fr
[b] UMR 6508 associée au CNRS

Table 1. T_c, size and argon annealing treatment for the different single crystals mentioned in the text.

	T_c (K) onset	Name	Size (μm^3)
As grown	96	A	790 × 500 × 100
As grown	92	D	1000 × 750 × 80
(Ar) 400 °C 18 h	84	B	540 × 425 × 40
(Ar) 500 °C 12 h	75	C	900 × 630 × 65

for SQUID measurements, with the field B_{SP} much larger than the complete penetration field. This allows to study both sides of the fishtail line without any problem with the field inhomogeneity in the sample [12].

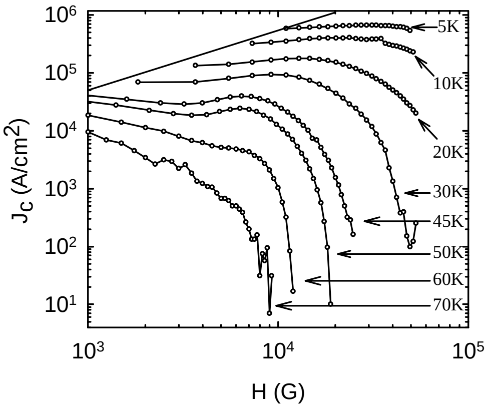

Fig. 1. Field dependence of the persistent current at different temperatures in sample A. The waiting time from that the field is applied to that the measurement is recorded is 1 minute. Straight lines are only guide for the eye.

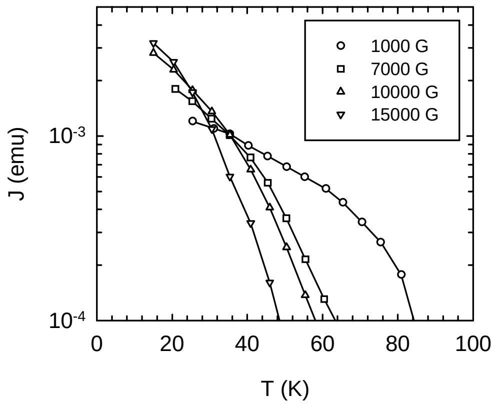

Fig. 2. The persistent current J after 1 minute of sample A, as a function of temperature at various magnetic fields. Note that, at a given temperature the crossing of the different curves is at the origin of the existence B_{SP} in Figure 1. Straight lines are only guide for the eye.

2 Experimental details

The crystals synthesis and properties are given in reference [15]. The experimental details were given elsewhere [4]. However, we summarize here the main points of the procedure: DC magnetic measurements were performed by SQUID magnetometry on the single crystals. The current density is calculated from the width of the hysteresis cycle as done in reference [4]. Very reproducible results were found among crystals. The crystals used here display different critical temperatures T_c according to the doping level of each crystal. Sample C doping level (the most underdoped in this study) has been obtained by an argon flux annealing. Size, T_c, and annealing treatments are summarized in Table 1. The c-axis is always aligned with the applied magnetic field B.

Relaxation measurements were done at many different temperatures and fields on both branches of the hysteresis cycles. In order to extract $U(J)$ from the time dependence of the width of the cycle $\Delta m(t)$, we have used

$$J = \frac{\Delta m}{\alpha} \tag{4}$$

and

$$\frac{U}{T} = -\ln\left(\frac{\mathrm{d}J}{\mathrm{d}t}\right) + K \tag{5}$$

where $\alpha = \frac{\pi}{3}R^3 d$ and K is a constant which depends on the field and is independent on the temperature. This method was first introduced by Maley *et al.* [18].

3 Experimental results and discussion

Let us first study sample A, the crystal with the optimum doping (T_c = 96 K). The critical current density was extracted from hysteresis loops with a waiting time of 60 seconds between the end of the field stabilization and the measurement. The data can be presented as a function of the magnetic field for different temperatures (Fig. 1), showing the existence of the second peak over a very broad range of temperature (5 to 60 K). But it can also be presented as function of the temperature at different magnetic fields (Fig. 2), showing that in this case, there is no anomaly at the second peak line (the second peak appears in this plot as a crossing of the different curves instead of as a maximum on a given curve as it is in Figure 1. The fishtail effect seems to be only a competition between the increase – as the magnetic field increases – of the critical current at low temperature $J(0)$ and the decrease of the irreversibility temperature T_{irr}. The interpretation of these magnetic field dependencies of $J(0)$ and of T_{irr} was given previously in term of plastic behavior [12].

In this framework, the second peak line has a dynamical origin. In order to study this dynamical aspect, the corresponding activation energies U were extracted from the relaxation of the magnetization following the procedure described in the experimental part. In Figure 3, the data at four different fields are reported for various temperatures. As it is proposed in the Maley's procedure, the choice of the constant K makes the curves temperature

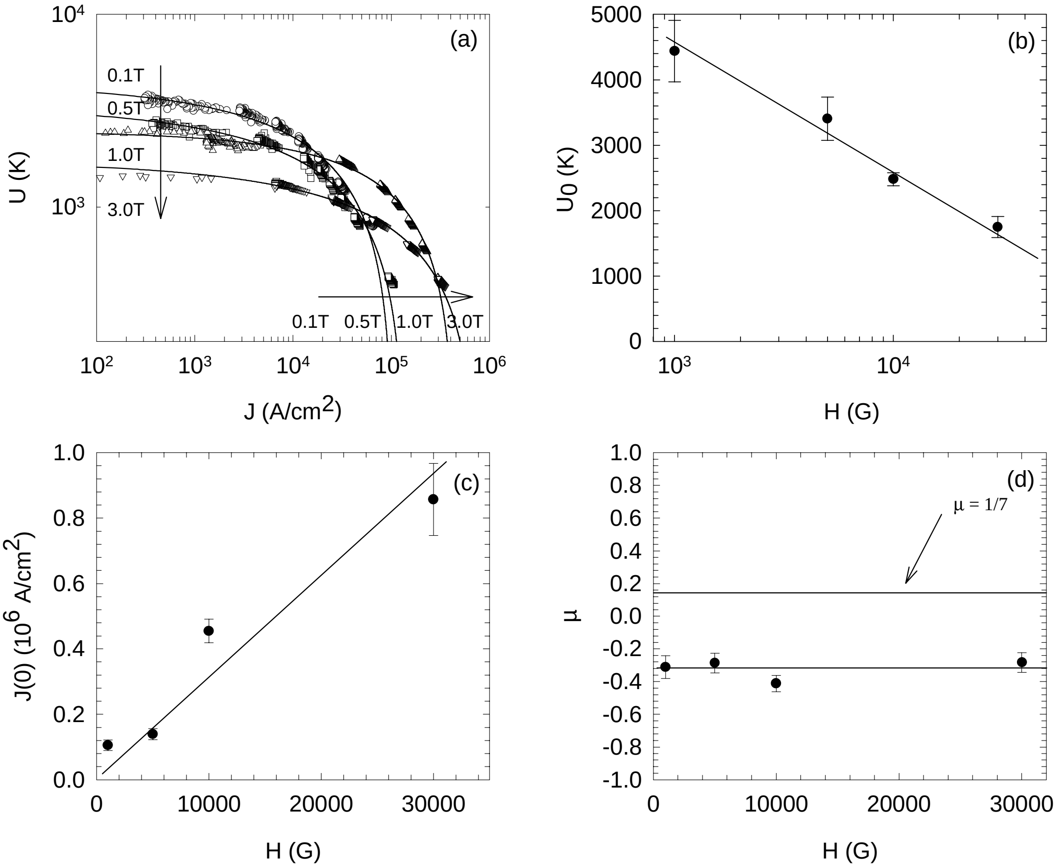

Fig. 3. (a) The current dependence of the activation energy U of sample A at four different magnetic fields. The solid lines are the fits by equation (3) of the text. The three corresponding parameters are presented in (b), (c), and (d) as functions of magnetic field. Straight lines are only guide for the eye.

independent. The low current extrapolation is clearly a finite value that we call U_0 in the following. This is strongly in favor of a plastic relaxation (indeed, an elastic model predicts a divergence at $J = 0$). Let us call $J(0)$ the extrapolation of the curves at $U(J) = 0$. The second peak origin is clearly due to the fact that U_0 decreases with the field whereas $J(0)$ increases. In Figure 3, the magnetic field dependencies of the different parameters of the fit are presented. U_0 decreases with B, whereas $J(0)$ increases. The parameter μ is always negative and roughly constant at about -0.3. In any collective creep model, μ should be positive, the value being $1/7$ at least, showing once again that the vortex movement corresponds always to a plastic creep.

We have investigated the effect of different doping in Hg-1201 crystals. In Figure 4, the current dependence of the activation energy is presented at different magnetic fields, as well as the three parameters U_0, $J(0)$ and μ sample B with $T_c = 84$ K. The results are very similar to that of the optimally doped sample. μ is always negative, U_0 is decreasing and $J(0)$ is increasing with magnetic field. There is a second peak effect which is reported in Figure 5 and compared to that of other doping states. On the contrary, sample C ($T_c = 75$ K) does not present any second peak effect (Fig. 6), though the magnetic field dependencies are very similar to that of the two previous ones (samples A and B). This is due to the fact that for the values of the parameters, there is no crossing of the curves $U(J)$ in the range of time which is studied here (from 1 to 10000 s). To look for the existence of the fishtail effect in this case, one should probably achieve measurements at very short times, at it is suggested in Figure 6a. The disappearance of the fishtail effect at the working time window is probably due to the fast time relaxation in this case. Yeshurun *et al.* have already pointed out on such an effect in Bi-2212 [20].

The temperature dependence as well as the time relaxation of the persistent current is then in favor of a plastic creep vortex relaxation in the whole range of the phase diagram that we have studied. The second peak phenomenon appears as a competition of the opposite field dependence of U_0 and $J(0)$, and not as a crossover or a phase transition as it was sometimes proposed. The question is at this point of the discussion: “what is the generality of this observation?”. In Tl-2212, the same behavior was observed [12]. In this case, we have also published a different interpretation of the same data [4], in term of a possible crossover between plastic and elastic creep. We believe that this interpretation, first proposed in heavily twinned Y-123 by Abulafia *et al.* [2] is not correct and is only a misunderstanding of the details of the model, as we have explained it already in [12]. So, after twinned

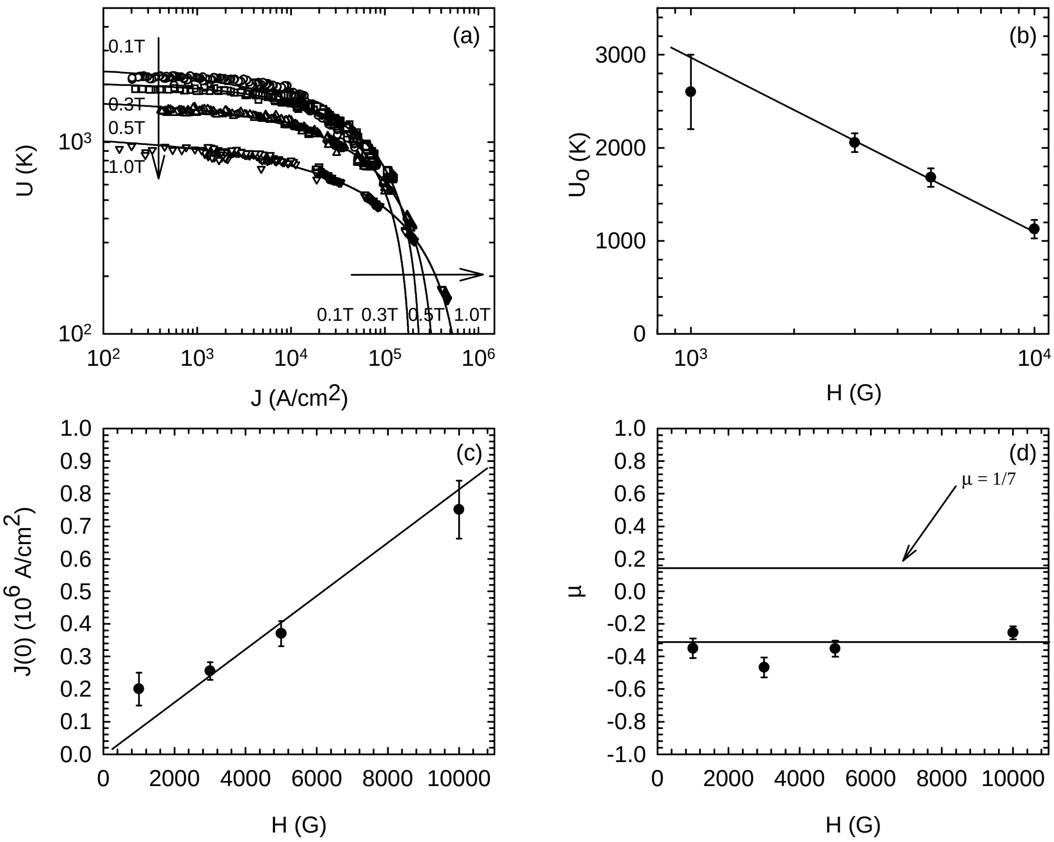

Fig. 4. (a) The current dependence of the activation energy U of sample B at four different magnetic fields. The solid lines are the fits by equation (3) of the text. The three corresponding parameters are presented in (b), (c), and (d) as functions of magnetic field. Straight lines are only guide for the eye.

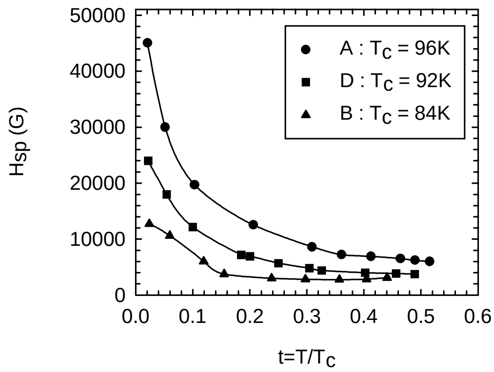

Fig. 5. The magnetic field of the second peak as a function of the reduced temperature for three different doping level. Sample C does not present any second peak. Straight lines are only guide for the eye. Sample D underlines the second peak doping dependence.

Y-123 [4], which can be reinterpreted as in [12], Tl-1212 [12], we have here a new compound which belongs to this class of second peak. Bi-2212 is clearly different [19]. Clean untwinned Y-123 is also very different. Deligiannis *et al.* [21] clearly demonstrated the influence of the purity of the Y-123 single crystals on the second peak effect, restricting the validity of the conclusion of reference [2].

As it was recently shown through the method of the partial magnetization cycles, the fishtail corresponds to a real crossover in the properties of the vortex matter [10,11]. In the same paper, the authors have shown that a large enough amount of extended defects (twins or columnar defects) can hide this crossover and we think that in this case, the second peak enters in our class of compounds, that of the "dirty" samples. Though this word ("dirty") is a little negative, this means mainly that the critical current is so large that the plastic creep dominates the relaxation properties, and hence, the critical currents values over the whole phase diagram (or nearly). In order to check this idea on the Hg-1201 compounds, we have performed the method of the partial magnetization loops (Fig. 7). In this figure, it is clear that the critical current extracted from the hysteresis loops is the same, whatever the history of the sample is. Along with this observation, the temperature dependence of the peak effect and the extended field width of the peak (over the biggest part of the magnetization loop (Fig. 7)), that are both similar to dirty or deoxygenated Y-123 samples, confirm that these samples belong the class of the dirty samples.

Quite surprisingly, high resolution electron microscopy on Hg-1201 samples has shown that there is no extended defects on the nanoscale length in these crystals [15].

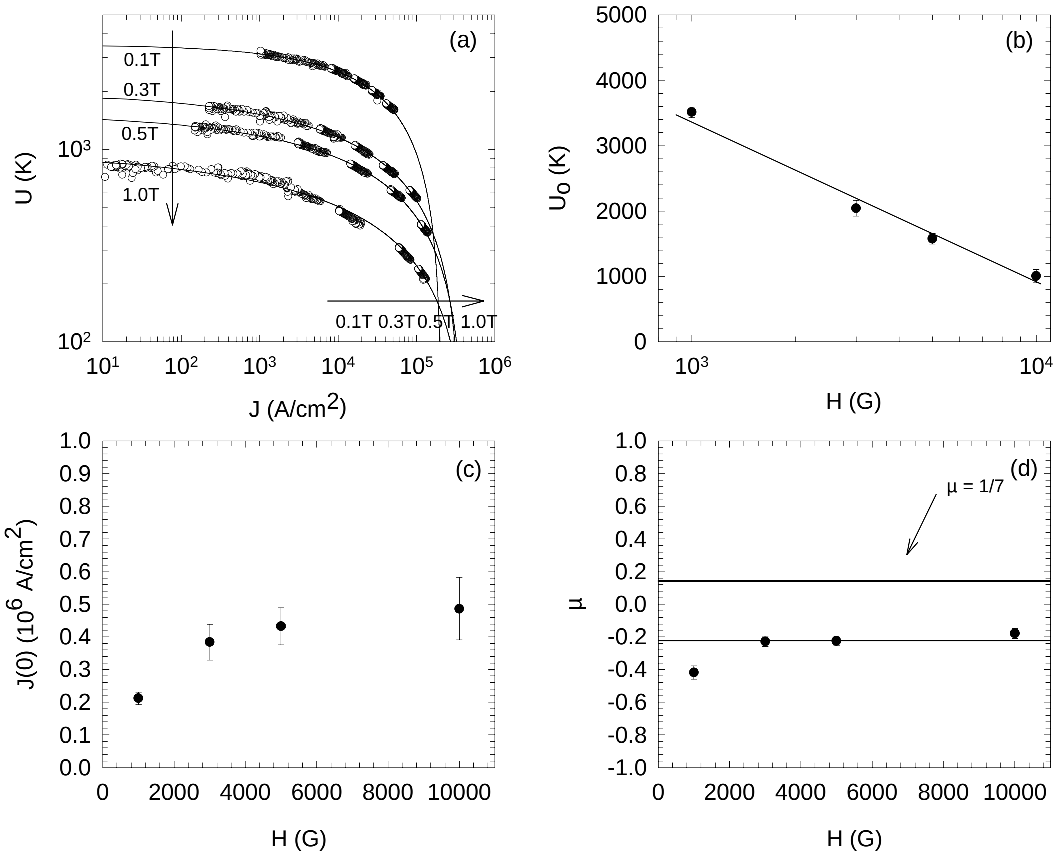

Fig. 6. (a) The current dependence of the activation energy U of sample C at four different magnetic fields. The solid lines are the fits by equation (3) of the text. The three corresponding parameters are presented in (b), (c), and (d) as functions of magnetic field. Straight lines are only guide for the eye.

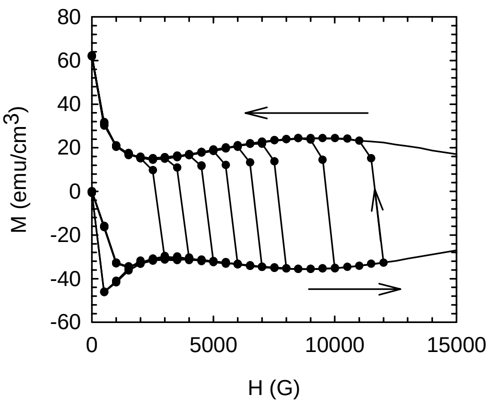

Fig. 7. Partial magnetizations loops for sample A, showing the absence of any history effects. Arrows show the magnetic field application path. Straight lines are only guide for the eye.

The origin of the pinning should be rather found in micro-defects (size of microns) which are presently investigated.

4 Conclusion

In conclusion, Hg-1201 crystals belong to the class of dirty materials, in the meaning that the second peak does not correspond to any crossover or phase transition of the vortex matter, but to a competition between two opposite variation *versus* magnetic field of the two parameters U_0 and $J(0)$. This effect, which should occur as soon as the plastic creep phenomenon dominates the relaxation of the vortex state can be observed or not, depending on the precise values of the parameters, as it is shown by studying the effect of the doping level in these crystals.

We thank V. Hardy, D. Feinberg and T. Klein for many valuable discussions.

References

1. Y. Yeshurun, A.P. Malozemoff, A. Shaulov, Rev. Mod. Phys. **68**, 3 (1996).
2. Y. Abulafia, A. Shaulov, Y. Wolfus, R. Prozorov, R. Burlachkov, Y. Yeshurun, D. Majer, A. Shaulov, V.M. Vinokur, Phys. Rev. Lett. **77**, 1596 (1996).
3. T. Klein, W. Harneit, L. Baril, C. Escribe-Filippini, D. Feinberg, Phys. Rev. Lett. **79**, 3795 (1997).
4. T. Aouaroun, V. Hardy, Ch. Simon, Physica C **294**, 42 (1998).
5. D. Giller, A. Shaulov, R. Prozorov, Y. Abulafia, Y. Wolfus, L. Burlachkov, Y. Yeshurun, E. Zeldov, V.M. Vinokur, J.L. Peng, R.L. Greene, Phys. Rev. Lett. **79**, 2542 (1997).

6. V. Geshkenbein, A. Larkin, M. Feigel'man, V.M. Vinokur, Physica C **162**, 239 (1989).
7. M. Pissas, D. Stamopoulos, E. Moraitakis, G. Kallias, D. Niarchos, M. Charalambous, Phys. Rev. B **59**, 12121 (1999).
8. D. Stamopoulos, M. Pissas, E. Moraitakis, G. Kallias, D. Niarchos, M. Charalambous, Physica C **317**, 658 (1999).
9. T. Aouaroun, Ch. Simon, Physica C **306**, 238 (1998).
10. S. Kokkaliaris, P.A. de Groot, S.N. Gordeev, A.A. Zhukov, R. Gagnon, L. Taillefer, Phys. Rev. Lett. **82**, 5116 (1999).
11. S. Kokkaliaris, A.A. Zhukov, P.A. de Groot, R. Gagnon, L. Taillefer, T. Wolf, Phys. Rev. B (in press).
12. T. Aouaroun, Ch. Simon, Phys. Rev. B **58**, 11692 (1998).
13. G. Villard, A. Daignere, D. Pelloquin, A. Maignan, Physica C **314**, 196 (1999).
14. G.K. Perkins, L.F. Cohen, A.A. Zhukov, A.D. Caplin, Phys. Rev. B **55**, 8110 (1997).
15. D. Pelloquin, V. Hardy, A. Maignan, B. Raveau, Physica C **273**, 205 (1997).
16. G. Le Bras, L. Frutcher, V. Vulcanescu, V. Viallet, A. Bertinotti, A. Forget, J. Hammann, J.F. Marucco, D. Colson, Physica C **271**, 205 (1996).
17. J. Hofer, J. Karpinski, M. Villemin, G.I. Meijer, E.M. Kopnin, R. Molinski, H. Schwer, C. Rossel, H. Keller, Physica C **297**, 103 (1998).
18. M. Maley, J.O. Willis, H. Lessure, M.E. Mchenry, Phys. Rev. B **42**, 2639 (1990).
19. E. Zeldov, D. Mjer, M. Konczykowski, V.B. Geshkenbein, V. Vinokur, H. Shtrickman, Nature **375**, 373 (1993).
20. Y. Yeshurun, N. Bontemps, L. Burlachkov, A. Kapitulnik, Phys. Rev. B **49**, 1548 (1994).
21. K. Deligiannis, P.A.J. de Groot, M. Ouessena, S. Pinfold, R. Langan, R. Gagnon, L. Taillefer, Phys. Rev. Lett. **79**, 2121 (1997).