Flux-dynamics associated with the Second Magnetisation Peak in iron-pnictide $Ba_{1-x}K_xFe_2As_2$

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(Dated: August 18, 2010)

We report on isofield magnetic relaxation data on a single crystal of $Ba_{1-x}K_xFe_2As_2$ with superconducting transition temperature $T_c=32.7$ K which exhibit the so called fish-tail effect. A surface map of the superconducting transition temperature shows that the superconducting properties are close to homogeneous across the sample. Magnetic relaxation data, $M(t)$, was used to obtain the activation energy $U(M)$ in order to study different vortex dynamics regimes. Results of this analysis along with time dependent measurements as a function of field and temperature extended to the reversible region of some $M(H)$ curves demonstrate that the irreversibility as well the second magnetization peak position, $H_p(T)$, are time dependent and controlled by plastic motion of the vortex state. In the region delimited by a characteristic field Hon (well below $H_p$) and $H_p$, the vortex dynamics is controlled by collective pinning. For fields below Hon the activation energy, $U_0$, increases with field as expected for collective pinning, but the pinning mechanism is likely to be in the single vortex limit.

PACS numbers: 74.70.Xa,74.25.Uv,74.25.Wx,74.25.Sv

I. INTRODUCTION

The recent discovery of the iron-pnictides superconductor systems1–3 with critical temperatures ranging from 20 to 55 K raised an intense interest on the study of their properties, such as pairing mechanism, thermodynamics and transport, normal-state band-structure, etc. Among these works, one can also find few studies dedicated to the vortex-dynamics, which due to their relatively high $T_c$ and upper critical field $H_{c2}$, are gaining interest for applications. Iron-pnictides materials, depending on each system and doping, exhibit the peak effect in the critical current, which is associated with a second magnetization peak appearing in the magnetization field $M(H)$ curves. Some of these systems also present a large magnetic relaxation which resembles for instance the giant-magnetic-relaxation observed in the cuprates.4–7

The study of the second magnetization peak also known as the "fish-tail" peak is of great interest, from both, academic as well technological view points.8–12 Fundamentally speaking, the mechanism and the origin of this effect is still much debated partly because it is system dependent with classification predominantly determined by superconducting anisotropy.4–7,9,10

So far, flux-dynamics studies of the second magnetization peak in iron-pnictides were performed on the systems, $SmFeAsO_{0.9}F_{0.1}$, with $T_c=55$ K where the authors inferred weak and collective pinning,11 and $Ba(Fe_{1-x}Co_x)_{2}As_2$, the most studied system, where the peak effect appears only for samples near optimally doping14–15 and weak and collective pinning are claimed in most of the works. The fish-tail has been also observed in $Ba_{0.6}K_{0.4}Fe_2As_2$ with $T_c=36.5$ K and studied from transport measurements.16–18 It is interesting to mention that the slightly underdoped samples of the $Ba_{1-x}K_xFe_2As_2$ system ($T_c \geq 30$K) presents a phase-separated co-existence of antiferromagnetism and superconductivity,19 which might be associated to the fact that samples with $T_c$ below 28 K do not show the second magnetization peak. Indeed it is likely that most forms of inhomogeneity ($T_c$ variation, doping variation, impurity phases, magnetic inclusions) will wash out the peak effect. Its observation is usually related to sample purity. Studies on $Ba(Fe_{1-x}Co_x)_{2}As_2$ includes; determination of the normalized flux-pinning force around the second magnetization peak,20 collective to plastic pinning crossover at the peak suggested by flux-creep data and relaxation rate analysis20; collective to plastic pinning crossover at the peak inferred by flux-creep data and the generalized-Inversion-Scheme analysis for the activation energy;21 fish-tail studied by magnetic measurements and magneto-optical imaging;21 observation of a highly disordered vortex-state from Bitter decoration and small-angle neutron scattering;22 vortex state structural phase transition at the peak from magnetization and flux-creep measurements within a thermodynamics analysis.23 The above studies are summarized in the table below, with comments of the type of measurement performed and the main conclusions of the study.

Importantly, the possibility that a first order phase transition instead of a vortex-dynamics crossover has been proposed to explain the second magnetization peak
in the pnictides demonstrates the need of more detailed and rigorous vortex-dynamics analysis. It is that motivated the present work. Another point not covered in the literature is the study of the crossover that should exist at the onset field of the fish-tail, also known as $H_{on}$. Phenomenologically speaking one should expect a crossover from single to collective pinning at $H_{on}$ because magnetization changes curvature at $H_{on}$, and it appears that this matter has not been studied in detail. In this work we address these above points by performing a detailed study of the vortex-dynamics as a function of magnetic field and temperature in an iron pnictide single crystal of $Ba_{1-x}K_xFe_2As_2$ with superconducting transition temperature $T_c = 32.7$ K which exhibits the fish-tail effect. The work addresses the existence of a change in the pinning mechanism (or crossover) associated with the anomalous second magnetization peak, as found in YBaCuO, and the pinning-crossover expected to exist at $H_{on}$. This work complements a previous study of the vortex phase diagram performed on the same system, and as above mentioned vortex-dynamics studies performed in other pnictides systems using different approaches. The experiment is conducted by obtaining magnetic relaxation data over selected isothermic M vs. H curves, $M(H)$, for magnetic fields values ranging from just above $H_{c1}$ (actually above the first penetration field peak appearing in isothermic magnetization $M(H)$ curves) up to field values close to the irreversible point $H_{irr}$. Magnetic relaxation curves are used to obtain the corresponding activation energies, allowing the study of the pinning mechanism for magnetic fields in the region of the anomalous second peak as treated in Ref[11] and below the field $H_{on}$. We have also measured isofield zero-field-cooled magnetization curves as a function of temperature, $M vs. T$ curves. All data, $M(H)$ and $M vs. T$ curves, were obtained for $H$ c-axis. The $M vs. T$ curves were used to obtain the near equilibrium irreversibility line, since $M(H)$ curves obtained at different fixed $dH/dt$ rates shown that the irreversible point is time dependent.

Results of this work show that the temperature dependence of the second magnetization peak position, $H_p$, and of the irreversibility field $H_{irr}$ are well explained in terms of a plastic motion of the vortex lattice. Results also demonstrate the existence of a crossover in the pinning mechanism at $H_{on}$, where apparently, this crossover occurs without a change in the behavior of the activation energy $U_0$ with field (increasing with field).

### II. EXPERIMENTAL

We measure a high quality crystal of $Ba_{1-x}K_xFe_2As_2$ with $T_c = 32.7$ K corresponding to a potassium content $x=0.28$ and with mass of approximately 0.05 mg. This is the same sample studied in our previous work and show a fully developed superconducting transition with width $\Delta T_c \approx 1K$. The crystal was grown by a flux method described elsewhere. Magnetization and magnetic relaxation data were taken after cooling the sample in zero applied magnetic field (but in the presence of the earth magnetic field). A commercial magnetometer, based on a superconducting quantum interference device (SQUID) was used for bulk magnetization measurements and a scanning Hall probe magnetometer (MHPM) was used to map the superconducting transition temperature distribution over the entire sample and to obtain few isothermal images of magnetic field profile in the sample, with a spatial resolution of 5 microns. Magnetization-vs-field, $M(H)$ curves were obtained at fixed temperatures ranging from 24 to 32 K, for fields up to 50 kOe. All $M(H)$ curves were obtained by extracting the data after the field was stabilized, in most cases the superconducting magnet was set in persistent mode. Additional curves were obtained with the magnet in the non-persistent (driven) mode, in order to obtain the hysteretic lines. Magnetic relaxation data, $M(t)$ curves, were obtained at $\Delta t \approx 1000$ s intervals over a period of $\approx 4000$ s for fields in the lower branch (increasing field) of selected isothermic hysteresis curves. We also measure long time magnetic relaxation curves over a period of 12 hours for selected values of $H_p$.

| Studied Samples | $T_c$ | measurements+results | conclusions |
|-----------------|------|----------------------|-------------|
| NdFeAsO0.85 poly-crystalline| $T_c = 46K$ | Fish-tail associated to a maximum in the creep rate with field at $T = 0.0,35 K$ | |
| SmFeAsO0.9FO.1 poly-crystalline H. Yang et al. Ref.12 | $T_c = 55K$ | M(H) curves - dynamic and traditional creep rates + activation energy analysis | Weak collective pinning |
| BaFe(1-x)CoAs2 single crystal Y. Nakajima et al. Ref.15 | $T_c = 25K$ | M(H) curves- Bean-like penetration of vortices by magneto optical images | |
| BaFeO.9CoO.1As2 single crystal A. Yamamoto et al. Ref.16 | $T_c = 22K$ | M(H) curves - normalised pinning force scaling independent of T around second peak | Dominant strong vortex pinning mechanism |
| BaFeO.9CoO.1As2 single crystal M.R. Eissfeldt et al. Ref.18 | $T_c = 22K$ | Low field Bitter decoration + small angle neutron scattering | |
| BaFeO.92CoO.07As2 single crystal R. Prozorov et al. Ref.17 | $T_c = 22K$ | M(H) curves - creep rate around second peak Activation energy comparison | Collective pinning for $H_p$ |
| BaFe(1-x)CoAs2 single crystals samples as a function of x B. Shen et al. Ref.14 | fish tail | M(H) curves-dynamic creep rate around second peak Generalised inversion scheme for activation energy | Collective pinning for $H_p$ |
| BaFeO.925CoO.05As2 single crystal R. Kopeliansky et al. Ref.19 | $T_c = 25K$ | M(H) curves - creep rate around second peak as function of T thermodynamics analysis | Phase transition of the vortex state near $H_p$ |
| BaO.6KO.4Fe2As2 single crystal H. Yang et al. Ref.20 | $T_c = 36K$ | M(H) curves - vortex pinning force around second peak | Pinning by small size normal cores |
| This work Ba1-xKxFe2As2 x=0.28 single crystal | $T_c = 32.7K$ | Map+M(H) curves+magnetic relaxation from $H_p$ to $H_{irr}$ Smoothing activation energy curves obtaining+creep rate analysis | Collective pinning at $H_p$-single to collective at $H_{irr}$ without change in the creep rate behavior |

**TABLE I:** Iron-pnictide systems which show the fish-tail effect.


magnetic field at $T = 29.5$ K and 28.9 K. Few magnetic relaxation data were measured on the upper branch (decreasing field) of the hysteresis curves to check for data symmetry, which confirm that bulk pinning is dominant for the studied isothermals. We also obtained isofield zero-field-cooled and field-cooled magnetization curves, $M_T$, with fields ranging from 0.05 to 30 kOe.

III. RESULTS AND DISCUSSION

Figure 1 shows a surface map of the superconducting transition temperature $T_c$ as obtained from the scanning Hall probe magnetometer with a 0.1 kOe field applied parallel to the c-axis after a zero-field-cooled procedure. It is possible to see from Fig. 1 that the sample is basically formed by two major regions, corresponding to more than 90% of the sample, one with $T_c = 31.8$ K that surrounds an inner region, the larger one, with $T_c = 32.3$ K. The sample also has a very small border or edge region with $T_c = 31.2$ K corresponding to about 5% of the sample, and an even smaller region with $T_c > 32.8$ K. The $T_c$ homogeneity of the sample can be considered in very good approximation to be within 0.5 K, showing that the sample is of high-quality and any effect due to sample inhomogeneity is expected to be negligible.

Figure 2 also shows magnetic relaxation data measured during 4000 sec for selected fields around the second magnetization peak which are plotted with the original $M(H)$ curve. Magnetic relaxation curves, $M(t)$, as shown in Fig. 2 allow to study the vortex-dynamics, and have been obtained on six isothermic $M(H)$ curves for fields going from below $H_{on}$ to above $H_p$. Magnetic relaxation curves, $M(t)$, were collected for a set of selected magnetic fields on $MvsH$ curves at $T=25.5$, 27.2, 28.9, 29.5, 30.1 and 30.7 K. All $M$ vs. log(t) curves obtained during 4000 seconds follow the typical linear curve observed in most flux creep experiments. This trend was also observed for 12 hours relaxation data obtained for fields below $H_{on}$, but not for fields below $H_{on}$, as will be discussed later.

We analyzed flux-creep data by following one of two different approaches. Either we obtained the relaxation rate $S = (1/M_0) dM(t)/d \ln t$ for each $M(t)$ curve and

![FIG. 1: Surface map of the superconducting transition temperature of the studied sample. The transition temperatures of the scanned surface are identified by colors labeled on the right.](image1)

![FIG. 2: Isothermic M(H) curves at $T=30.7$ K plotted with $M(t)$ data obtained for fixed fields. The upper inset show detail of data for fields near the reversible region. The lower inset show a plot of $U_{pol}$ vs. $H$ for $H \geq H_p$.](image2)
analyzed its behavior with $H > H_p$ or we analyze the activation energy $U(M)$ by fitting each curve to the expression predicted by the collective pinning theory, $U(H, M) = U_0(H)(M(t)/M_0)\nu$, which allow to study the behavior of the exponent $\nu$ with $H$. In the last expression $M(t)$ replaces $M(t) - M_0$ where $M_0$ is the equilibrium magnetization, obtained from the average magnetization of both branches in each $M(H)$ curve.

Several different approaches presented in the literature allow one to obtain the activation energy $U(M)$ from $M(t)$ curves. Here, the activation energy $U(M)$ is obtained for each $M(t)$ curve by applying an approach developed by Maley et al. where

$$U = -T \ln(dM(t)/dt) + CT$$

and $C$ is a constant which depends on the hoping distance of the vortex, the attempt frequency and the sample size. We should mention that similar $U(M)$ curves can also be obtained from $M(t)$ curves by following an approach developed in Ref.\textsuperscript{23}. The insets of Figures 3a and 3b show results of this approach with $C = 27$ (this value will be justified below) after application to selected $M(t)$ curves obtained for fixed magnetic fields at selected temperatures. The temperatures are selected in a way that each $M(t)$ curve for a given field is located below the field $H_p$ of its original $M(H)$ curve (but above $H_p$) as in Fig. 3a and above $H_p$ as in Fig. 3b. This condition is necessary since pinning mechanisms below and above $H_p$ might be of different nature. As shown in these figures, the $U(M)$ curves do not form a smooth curve with $M$, which is expected for temperatures very close to $T_c$. To obtain a smooth curve we have to scale the activation energy curves shown in the insets of Figs. 3a and 3b by a $g(T/T_c)$ scaling function.

Figures 3a and 3b show the results obtained by choosing $g(T/T_c) = (1 - T/T_c)^{1.5}$. This scaling function of $U(M)$ was suggested in Ref.\textsuperscript{23} and relies on pinning length scales for temperatures close to $T_c$. The interesting result of Fig. 3 is that below $H_p$ ($H_0 \leq H \leq H_p$), the smooth curves follow a power law with $M^{-1.4}$ as expect from the collective pinning theory, but a logM behavior is obtained for fields above $H_p$. The above analysis yield a constant $C = 27$ for our sample which is used to obtain the activation energy $U(M)$ for each $M(t)$ curve (we mention that this value of $C = 27$ is of the same order as values obtained for high-$T_c$ cuprates\textsuperscript{28}).

Figure 4 shows a selected $M(H)$ curve measured at $T = 29.5$ K. The $M(H)$ curve is plotted with magnetic re-

In Fig. 3: Activation energy $U(M,T)$ for fixed fields after scaled by the scaling function $g(T/T_c) = (1 - T/T_c)^{1.5}$; a) for fields $H \geq H_0$; b) for fields $H_0 \leq H \leq H_p$. Insets show $U(T)$ vs $M$ curves for selected fields prior scaling.

FIG. 4: Isothermal $M(H)$ curves at $T = 29.5$ K plotted with $M(t)$ data obtained for fixed fields. The lower inset show detail of data for low fields. The upper inset show a double plot of the exponent $\nu$ vs. $H$ (left y-axis) and $S = (1/M_0)dM/dln t$ vs. $H$ (right y-axis).
laxation data obtained over 1 hour (4000 sec) for fixed magnetic fields going from below $H_{on}$ to above $H_p$. The lower inset of Fig. 4 shows details of the low field data, providing evidence of the behavior before and after the field $H_{on}$. The upper inset show results of the relaxation rate $S$ (right $y$-axis) and exponent $\nu$ (left $y$-axis) plotted as a function of $H$. The values of $S$ and of the exponent $\nu$ were obtained as discussed above, by analyzing each $M(t)$ curve and the respective $U(M)$ curve. It is interesting to note that the behavior of $S$ and $\nu$ with $H$ are quite similar. The relaxation rate drops as field increases from below $H_{on}$ up to a field close to $H_p$ (the second peak position), increasing again as $H$ become larger than $H_p$. Similar curves for $S$ and $\nu$ as a function of $H$ were observed on all $M(H)$ curves over which we measured magnetic relaxation.

In addition to the fact that the exponent $\nu$ follows the inverse trend of the relaxation rate $S$ as a function of $H$, the absolute values of $\nu$ can provide relevant information about the pinning mechanism. As shown in the upper inset of Fig. 4, the region of fields between $H_{on}$ and $H_p$ corresponds to the region where $-\nu \approx 1$ for which the relation $U(H, M) = U_{0col}(H)(M(t)/M_0)^\nu$ predicted by the collective pinning theory might apply. Values of $-\nu \approx 1$ are expected from collective pinning theory, while values much smaller than 1, as observed on $M(t)$ curves below $H_{on}$ and above $H_p$, may be due to single vortex pinning regime for lower fields, or plastic pinning occurring above $H_p$, respectively.

Figures 5a and 5b show $U(M)$ curves as obtained from $M(t)$ curves appearing in Fig. 4. Figure 5a show a set of $U(M)$ curves for fields $H_{on} \leq H \leq H_p$ plotted with a set of $U(M)$ curves for $H_{on} < H < H_{on}$ and $H_{on}$. It is possible to see from these plots that the fields $H_{on}$ and $H_p$ are in fact characteristic fields separating regions with differences in the vortex dynamics. Following the results of Ref. 11 we fit $U(M)$ for fields above $H_p$ with the expression $U_{pl} = U_{0pl}(H)(1 - \sqrt{|M(t)/M_{opt}|})$. This is the appropriate description for plastic motion. Results of the fitting of $U(M)$ to the collective pinning expression of $U$ performed for $H_{on} \leq H \leq H_p$ and to the plastic expression of $U$ performed for fields $H_{on} \leq H \leq H_p$ produced values of $U_{0col}(H)$ and $U_{opt}(H)$ which show a power law behavior with $H$. As expected, $U_{0col}(H) \approx H^{0.4}$ increases with field while $U_{opt}(H) \approx H^{-0.7}$ decreases with field. The above exponents of $H$ are used to scale the correspondents $U(H, M)$ curves shown in Figures 5a and 5b turning them in-to smooth curves of $U(M)$ (in arbitrary units) plotted against $M(t)$. The results of this scaling are shown in Figure 5c. It is interesting to observe that each scaled curve follows a power law behavior with $M$ where each exponent value agrees with the averaged value of the exponent $\nu$ found in each corresponding field region as shown in the upper inset of Fig. 4. The smooth curves of Fig. 5c demonstrate the existence of a crossover in the pinning mechanism as field increases above $H_{on}$ as well demonstrate that the second magnetization peak in the studied sample is due to a pinning crossover mechanism, as was first demonstrated in Ref. 11 for $YBaCuO$. The second magnetization peak occurring at $H_p$ is formed by a crossover in the pinning mechanism, from collective to plastic pinning as the field increases. A visual inspection of $U(M)$ curves for $H_{on} < H < H_{p}$ in Fig. 5a suggests that these curves have the same behavior as the curves obtained for $H_{on} \leq H \leq H_p$ for which it is possible to infer that a plastic pinning dominates. However, this hypothesis is inconsistent with the fact that the activation energy $U_{opt}(H)$ (found by fitting $U(M)$ curves for $H_{on}$ to the correspondent expression for plastic pinning) for $H_{on}$ increases with field. On the other hand, the scaled $U(M)$ function appearing in Fig. 5c for $H_{on} < H < H_{p}$ was obtained assuming that $U(M)$ has a power law dependence with $H$ of the form $\approx H^{-0.2}$, an $H$ dependence with a negative exponent as found in the region $H \geq H_p$. These contradictory facts eliminate the possibility of plastic pinning in the region below $H_{on}$, as well as eliminate the possibility of collective pinning as observed for $H_{on} < H \leq H_p$. Figure 6 show plots of the relaxation rate $S = (1/M_0) dM(t)/d\nu t$ as obtained from magnetic relaxation data over three se-
lected isothermal M(H) curves for fields in the region of Hon. The same trend shown in Fig. 6 of S decreasing with field was observed in all M(H) isothermals, which means that, in fact, the correspondent activation energy $U_0 = kBT/S$ as defined by Beasley et al. increases with field in the region $H < Hon$. This is an interesting finding, because due to the positive inclination of M(H) for $H < Hon$ one would expect $U_0$ to decrease with field. Since above Hon, the activation energy $U_{0,cal}(H)$ (collective pinning region) also increases with field, the change in the pinning mechanism occurring at Hon has a different nature (probably single to collective pinning) than the pinning crossover occurring near $H_p$ (which is collective to plastic). The formation of the peak appears then to come from the existence of a pinning crossover, probably from single to collective pinning, as Hon is crossed. This is the field region ($H < Hon$) above which the fish-tail shape takes place.

We present in Fig. 7 the vortex-phase diagram obtained from the M(H) curves. An interesting finding is that the line defined by the values of $H_p(T)$ does not touch the irreversibility line, but ends at some temperature below $T_c$. This feature is shown in the inset of Fig. 7 which shows that the anomalous second peak in the magnetization is only well defined for temperatures below 32 K. A similar behavior for the $H_p(T)$ line was observed for a deoxygenated YBaCuO crystal. The crossover from collective to plastic pinning only exists below $T < 32$ K, since M(H) curves obtained above this temperature do not show the second magnetization peak. It is important to mention that both, $H_p(T)$ as well Hirr(T), are time dependent, and U(M) curves for fields close to both, $H_p(T)$ and Hirr(T), seems to be fitted by the plastic expression for the activation energy. To exemplify the time dependence of Hirr, values of Hirr obtained on M(H) curves by using different time windows, as for instance show in the upper inset of Fig. 2, are plotted with values of $T_{irr}$ obtained from isofield M vs. T curves (not shown). It is interesting to note that the values of $T_{irr}$ are close to the values of Hirr obtained 10 minutes after the field was stabilized. As shown in Ref.11, the fact that both, $H_p(T)$ and Hirr(T) are time dependent (with these values being shifted to the left with time) suggests that these fields are controlled by plastic pinning with expected temperature dependence of the form $H_p(T) \approx [1 - (T/T_c)^4]^{1.4}$. This expression was obtained in Ref.11 after considering that $U_{0,pl} \approx H^{-0.7}$. Since our fittings of U(M) in the region $H > H_p$, produced a similar behavior for $U_{0,pl}$ with H, with an exponent of H varying from -0.6 to -0.7 depending on the temperature of the M(H) curve, we also start our fittings of the $H_p(T)$ and $T_{irr}$ lines by assuming the temperature dependence $\approx [1 - (T/T_c)^4]^{1.4}$. However, the best fittings, as shown in Fig. 7, were obtained with a slightly different expression, $\approx [1 - (T/T_c)^4]^{1.7}$. For consistency we only fit values of $T_{irr}$. For the Hon(T) line we try the general expression $\approx (1 - T/T_c)^m$ where $m$ is a fitting parame-
the analysis performed in this work. The upper inset shows the original $\Delta M$ vs. $H$ curves. Since the $H_p$ vs. $T$ line in Fig. 7 follows a dependence with $(1 - (T/T_c))^4$, we find it natural to choose the same temperature dependence to scale the $x$-axis which is the magnetic field $H$. The scaling law used in the $y$-axis, $\Delta M$, was based on the fact that the strength of the critical current which is of the order of $\Delta M$, should follow the temperature dependence of the pinning length scale, which for temperatures close to $T_c$ has the form $g(T/T_c)^{1.5}$ (this is the same scaling function $g(T/T_c)$ used on the analysis of the activation energy presented in Fig. 2). The lower inset of Fig. 8 shows a plot of $\Delta M$ for $H = H_p$ vs. $T/T_c$, which shows a dependence with $(1 - T/T_c)^{1.7}$ instead $(1 - T/T_c)^{1.5}$. For this reason we choose to scale $\delta M$ with $(1 - T/T_c)^{1.7}$ instead $(1 - T/T_c)^{1.5}$ which produced a better scaling of the curves.

IV. CONCLUSIONS

In conclusion, our study of the vortex-dynamics in $Ba_{1-x}K_xFe_2As_2$ shows that the second magnetization peak occurring at $H_p$ is formed by a crossover in the pinning mechanism, from collective to plastic pinning as the field increases. This crossover only exists below a certain temperature $T < 32$ K, since $M(T)$ curves obtained above this temperature do not show the second magnetization peak. It is also shown the existence of a pinning crossover, probably from single to collective pinning, as $H_{on}$ is crossed. This is the field region ($H < H_{on}$) above which the fish-tail shape takes place. Results of this work show that both $H_p(T)$ as well Hirr(T) are time dependent and their temperature dependence are well explained by an expression predicted by assuming a plastic motion of the vortex state. We also show that the $g(T/T_c)$ scaling function of $U(M)$ curves (used in Fig. 3) and the temperature dependence expression used to fit the $H_p(T)$ and Hirr(T) lines, can be used to scale several $\Delta M(H)$ producing a reasonable collapse of the curves.

1. Y. Kamihara, T. Watanabe, M. Hirano, and H. Hosono, J. Am. Chem. Soc. 130, 3296 (2008).
2. M. Rotter, M. Tegel, and D. Johrendt, Phys. Rev. Let 101 107006 (2008).
3. H.Q. Luo, Z.S. Wang, H. Yang, P. Cheng, X. Zu, and Hai-Hu Wen, Supercond. Sci. Technol. 21, 125014 (2008).
4. Y. Yeshurun and A. P. Malozemoff, and A. Shaulov, Rev. Mod. Phys. 68, 911 (1996).
5. L.F. Cohen, G. Perkins, J. Laverty, W. Assmus and A.D. Caplin, Cryogenics 33, 356 (1993).
6. L.F. Cohen, H. Jensen, Reports on Progress in Physics 60, 1581 (1997).
7. B. Rosenstein, B.Ya. Shapiro, I. Shapiro, Y. Bruckental, A. Shaulov, and Y. Yeshurun, Phys. Rev.B 72, 144512 (2005).
8. Y. Yeshurun and A. P. Malozemoff, Phys. Rev. Lett. 60, 2202 (1988).
9. B. Rosenstein and V. Zhuravlev, Phys. Rev. B 76 (2007).
10. G. Perkins, L.F. Cohen, A.A. Zhukov and A.D. Caplin,
Y. Abulafia, A. Shaulov, Y. Wolfus, R. Prozorov, L. Burlachkov, Y. Yeshurun, D. Majer, E. Zeldov, H. Whi, V. B. Geshkenbein, and V. M. Vinokur, Phys. Rev. Lett 77, 1596 (1996). 014507 (2007).

H. Yang, C. Ren, L. Shan, and Hai-Hu Wen, Phys. Rev. 78, 092504 (2008).

J.D. Moore, L.F. Cohen, Y. Yeshurun, A.D. Caplin, K. Morrison, K.A. Yates, C.M. McGilvery, J.M. Perkins, D.W. McComb, C. Trautmann, Z.A. Ren, J. Yang, W. Lu, X.L. Dong, and Z.X. Zhao, Sup. Sci. Techn. 77, 1596 (1996). 014507 (2007).

H. Yang, C. Ren, L. Shan, and Hai-Hu Wen, Phys. Rev. Lett 102, 117006 (2009).

M. P. Maley, J. O. Willis, H. Lessure and M. E. McHenry, Phys. Rev. B 42, 2639 (1990).

S. Sengupta, D. Shi, S. Salem-Sugui, Jr., Z. Wang, P.J. McGinn, and K. DeMoranville, J. Appl. Phys. 72, 592 (1992).

R. Griessen, Wen Hai-hu, A. J. J. van Dalen, B. Dam, J. Rector, and H. G. Schnack, S. Libbrecht, E. Oszuqin, and Y. Bruynseraede Phys. Rev. Lett 72, 1910, (1994).

H. H. Wen, H. G. Schnack, R. Griessen, B. Dam and J. Rector, Physica C 241, 353 (1995).

M. E. McHenry, S. Simizu, H. Lessure, M. P. Maley and J. Y. Coulter, I. Tanaka and H. Kojima, Phys. Rev. B 44, 7614 (1991).

S. Salem-Sugui, Jr., L. Ghivelder, A. D. Alvarenga, J. L. Pimentel, Jr., Huiqian Luo, Zhaosheng Wang, and Hai-Hu Wen, Phys. Rev. B 80, 014518 (2009).

G K Perkin, J Moore, Y Bugsolavsky, L F Cohen, J Jun, S M Kazakov, J Karpinski, and A D Caplin, Supercond. Sci. Technol. 15, 1156 (2002).

M. R. Beasley, R. Labash, and W. W. Weeb, Phys. Rev. 181, 682 (1969).

D. Shi and S. Salem-Sugui, Jr., Phys. Rev. B 44, 7647 (1991).

S. Salem-Sugui, Jr., A. D. Alvarenga, M. Friesen, K. C. Goretta, O. F. Schilling, F. G. Gandra, B. W. Veal, and P. Paulikas, Phys. Rev. B 71 024503 (2005).

M. Tinkham, Phys. Rev. Lett. 61, 1658 (1988).

S. Salem-Sugui, Jr., L. Ghivelder, M. Friesen, K. Moloni, B. Veal and P. Paulikas, Phys. Rev. B 60 102 (1999).

L. Burlachkov, Phys. Rev. B 47, 8056 (1993).