Fishtail and vortex dynamics in the Ni-doped iron pnictide BaFe$_{1.82}$Ni$_{0.18}$As$_2$

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We study the vortex dynamics of a BaFe$_{1.82}$Ni$_{0.18}$As$_2$ crystal with $T_c = 8$ K by measuring flux creep over the second magnetization (or fishtail) peak for both $H \parallel c$ axis and $H \parallel ab$ planes. Magnetic relaxation data show an anomalously long initial stage of relaxation, lasting $\sim$10 min for the $H \parallel c$ axis and 2–3 min for $H \parallel ab$, resembling a transient effect with a lower relaxation rate, which is followed by the usual log(time) relaxation. Interestingly, study of the relaxation rate R vs H for both stages of relaxation and for both field directions are featureless over the field range associated with the fishtail. The same trend was confirmed by plotting R vs T obtained from flux-creep data measured as a function of temperature for a fixed field ($H \parallel c$ axis). A plot of the activation energy $U(M,T)$ calculated from the time of relaxation of the magnetization at a fixed field also shows a smooth behavior, further supporting the view that the fishtail peak is not associated with a crossover in a vortex pinning regime within the collective pinning scenario.

PACS number(s): 74.70.Xa, 74.25.Uv, 74.25.Wx, 74.25.Sv

The observation and study of the second magnetization or fishtail peak in pnictides[1] has attracted increasing attention by the scientific community. The relatively large flux creep observed in this material system allows detailed studies of the vortex dynamics and a comparison to a rich variety of models.[2] Until now, the fishtail effect has been studied in SmFeAsO$_{0.9}$F$_{0.1}$,[3] NdFeAsO$_{0.85}$,[4] Ba$_{1-x}$K$_x$Fe$_2$As$_2$,[5,6] BaFe$_{2-x}$Co$_x$As$_2$,[7–12] and more recently in LiFeAs (Ref. 13) and PrFeAsO$_{0.60}$F$_{0.12}$.[14] Different mechanisms have been claimed to account for the fishtail effect in these compounds (see, for instance, a table presented in Ref. 6), evidencing the need to build up a more comprehensive picture through additional studies, particularly on systems not yet investigated.

In this Brief Report, we present a vortex-dynamics study performed on the recent synthesized Ni doped iron-pnictide superconductor system BaFe$_{1.82}$Ni$_{0.18}$As$_2$.[15] We study an overdoped single crystal with $x = 0.18$, $T_c = 8$ K ($\delta T_c \approx 1$ K), $m = 78$ mg, and average dimensions $1.1 \times 0.4 \times 0.025$ cm, for magnetic fields applied along the ab-plane direction. In this geometry, a possible misalignment of the sample with respect to the direction of the applied magnetic field is estimated to be smaller than $2°$, which assures that any contribution of the c-axis component to the magnetization measured with $H \parallel ab$ planes is negligible. A small piece with $m = 23.4$ mg and average dimensions $04 \times 0.4 \times 0.02$ cm was broken from the large sample for the measurements with the $H \parallel c$ axis. Details on sample preparations and physical properties of the large high-quality single crystals can be found in Ref. 15. Isothermal $M(H)$ curves for the crystals for $H \parallel ab$ planes and the $H \parallel c$ axis exhibit the fishtail peak, the maximum occurring at an applied field H_p. The vortex-dynamics investigation was performed by measuring isofield and isothermic magnetic relaxation, M vs time curves, over a period of 1 h for magnetic field values lying below and above H_p on both branches of the $M(H)$ curves. All data were obtained after cooling the system from above T_c

to the desired temperature in zero applied magnetic field (but in the presence of the earth magnetic field), which is called the zero-field-cooled (ZFC) procedure. Magnetization data was obtained using commercial magnetometers based on a superconducting quantum interference device (SQUID) (MPMS-5T Quantum Design, and Criogenics-6T). The charge and discharge rate of the magnet were set equal to 100 Oe/s during the experiment.

Figure 1 shows isothermal $M(H)$ curves exhibiting the fishtail effect, as obtained for both geometries. $M(H)$ curves at 3 and 4 K for $H \parallel c$ and at 3 K for $H \parallel ab$ are plotted with correspondent magnetic relaxation data obtained on both branches. We refer to this as the isothermal method. The dotted line located at $H = 4.6$ kOe in Fig. 1(a) shows that once this field value is fixed, it is possible to go from below H_p to above it by increasing the temperature from 3 K. This second method, which we refer to as the isofield method, provides an independent check of the relaxation data taken using the isothermal route and allows the creation of an activation energy curve with temperature $U(T)$ as in Refs. 17 and 18. As depicted in Fig. 1, all $M(H)$ curves are quite symmetric relative to the x axis, evidencing that vortex dynamics is mostly due to bulk pinning. Also, since the equilibrium magnetization $M_{\text{eq}} = (M^+ + M^-)/2 \approx 0$, where M^+ and M^- refer to the magnetization in the upper and lower branches of the hysteresis curve, respectively, we use M instead $M - M_{\text{eq}}$ in all curves. The upper inset of Fig. 1 shows a plot of the critical current J_c vs H at 3 K for both geometries as estimated from the correspondent hysteresis curves shown in Fig. 1 by using the well-known expression $J_c = 20\Delta M(\text{emu/cm}^3)/[a(1 - a/3b)]$, where $b > a$.[19] The lower inset of Fig. 1 shows a plot of the fishtail peak field H_p as a function of temperature extracted from the curves of Fig. 1 for both field directions, where dotted lines are only a guide for the eyes. We observe from the inset figures that $J_c(H_p \parallel ab)/J_c(H_p \parallel c) \approx 3.3$ and $H_p(H \parallel ab)/H_p(H \parallel c) \approx 3.6$. Although neither of these
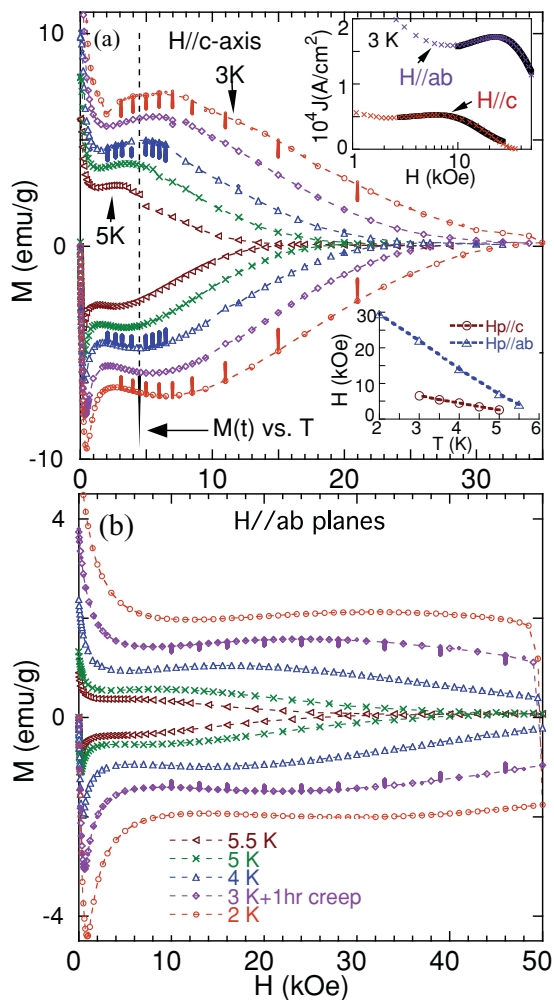
FIG. 1. (Color online) Isothermic $M(H)$ curves. (a) $H \parallel c$ axis, at 3, 3.5, 4, 4.5, and 5 K. The upper inset shows $J_c(T = 3$ K$)$ vs H in logarithmic scale for both field directions. Solid lines in the region of the peak represents a fit to an expression of Ref. 16. The lower inset shows H_p vs T extracted from $M(H)$ curves for both field directions; (b) $H \parallel ab$ planes.

FIG. 2. (Color online) Selected M vs time curves for $H \parallel c$: (a) lower branch of $M(H)$; (b) upper branch of $M(H)$. Solid lines are only a guide to the eyes, evidencing the increasing relaxation rate for $t > \tau_0$.

parameters is a fundamental measure of the superconducting anisotropy (for that we would have to extract the upper and lower critical fields), they clearly are consistent with each other and the fact that the anisotropy expected for this system is of the order of 3.[20]

Figure 2 shows selected magnetic relaxation data obtained on both branches of the $M(H)$ curve at 3 K for $H \parallel c$ axis. These curves exemplify the general behavior observed on all relaxation curves obtained in this Brief Report, namely, that all curves show first a slow relaxation rate, and then an increase in the relaxation rate after a time $\tau_0 \approx 10$ min after relaxation starts for $H \parallel c$, and $\tau_0 \approx 2$–3 min for $H \parallel ab$. This anomalous behavior showing two distinct linear behavior of M with $\log(t)$ or two distinct time windows cannot be explained in terms of a pinning crossover, since in that case the crossover always occurs from a higher rate of the initial stage of relaxation (corresponding to flux jumping over low activation energy pinning sites) to a lower rate (corresponding to flux jumping over higher activation energy pinning sites), as occurring
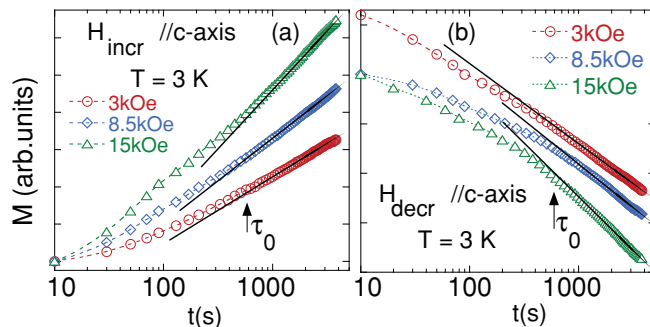
in the well-known surface-to-bulk-pinning crossover.[21] This scenario is the opposite of what is observed here. It should also be mentioned that the surface barriers' effects on relaxation are expected to be important only at temperatures near T_c.[22] Since the present experiments were conducted at temperatures much below T_c, it appears reasonable to exclude the importance of surface barriers on the relaxation curves. There are two other possible explanations for the nonlinearity of $M(t)$ vs $\log(t)$ curves. The first is due to an eddy current induced on the sample by the ramp rate dH/dt while charging the magnet.[23] After the magnet is charged and $dH/dt = 0$, the induced eddy current decays due to flux creep, producing a transient region which possesses a lower magnetic relaxation rate when compared to that due to the bulk pinning. The duration time of this transient relaxation is inversely proportional to the charge magnet rate dH/dt, and it is expected to last less than 1 min for a rate $dH/dt \approx 100$ Oe/s,[23] as used here. This effect, referred to as an initial settle time, is commonly observed in $M(t)$ curves and is inversely proportional do the ramp rate of the magnetic field,[23] and it is usually found to be of the order of 1 min. It should be mentioned that the ratio between the times $\tau_0(H \parallel c)/\tau_0(H \parallel ab) \approx 4$ for our data qualitatively agrees with the hypothesis that the anomalous initial decay of $M(t)$ is related to the transient relaxation associated with dH/dt, once $\tau_0 \approx J_1 a/(dB/dt)$,[23] where J_1 represents the eddy current [$J(H \parallel ab) \approx 3J(H \parallel c)$; see Fig. 1], a is the sample thickness perpendicular to H ($a = 0.025$ cm for $H \parallel ab$ and 0.4 cm for $H \parallel c$), and dB/dt is the rate of the magnetic induction field B. The other possible explanation is based on the existence of twin boundaries,[24] which may allow a continuous increase of vortices pinned between twin boundaries (appearing in the first time window). As a result, after the density of vortices pinned by twin boundaries increases above a certain value, the pressure overcomes the barrier, producing an increase in the rate of relaxation at the second time window.[24] This explanation would apply as well to our experiment, since the efficiency of twin boundaries, as pinning sites, changes and becomes less effective as the sample rotates from $H \parallel c$ to $H \parallel ab$ (this is because many *TB* aligned parallel to the field when $H \parallel c$ can become perpendicular to the field after a 90° rotation). However, after careful observation of the sample surfaces in a polarized light microscope, there are no visible twin boundaries, and up to
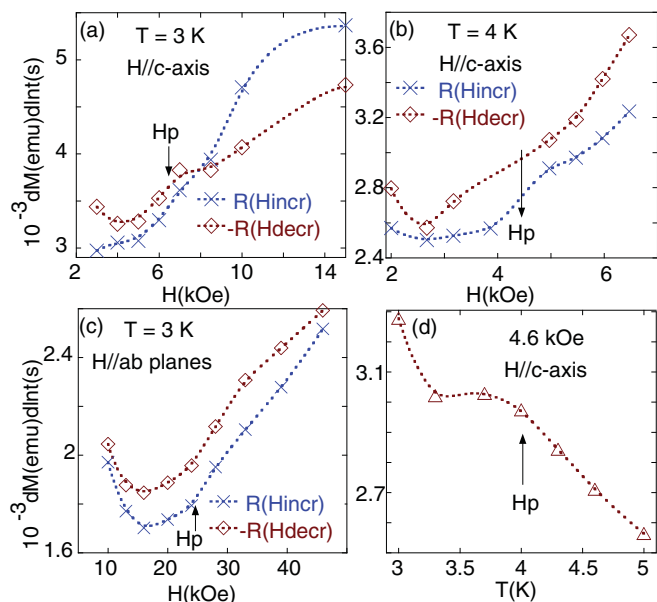
FIG. 3. (Color online) Plots of the relaxation rates; R vs H for both branches of $M(H)$ curves for (a) and (b) $H \parallel c$ axis, (c) $H \parallel ab$, and (d) R vs T for $H = 4.6$ kOe, $H \parallel c$.

FIG. 4. (Color online) The scaled activation energy $U(M,T)$ for $H = 4.6$ kOe are plotted against M. The solid line is a log M fit.

this point, twinning has only been observed in underdoped, not overdoped, crystals. Consequently, we assign the initial relaxation to a transient effect.

We analyze flux-creep data by obtaining the relaxation rate $R = dM/d \ln t$ of the second stage of relaxation (corresponding to the region $t > \tau_0$) for each $M(t)$ curve.[25–29] Figure 3 shows the results from relaxation obtained in the lower branch (H_{incr}) and in the upper branch (H_{decr}) of $M(H)$ curves for both geometries. We mention that we also obtained values of $R(t < \tau)$ for the first stage of relaxation, and observe that plots of $R(t < \tau)$ vs H approximately follow the same trend as the plots in Fig. 3. This fact may evidence that the same major bulk pinning mechanism is present in both stages of relaxation, supporting our hypothesis that the anomalous first stage of relaxation is related to a transient effect rather than to a twin-boundary-assisted effect. The main information one can extract from the many plots of Fig. 3 is the absence of any feature, minimum or maximum, located near the correspondent fishtail peak position represented by a vertical arrow in each figure. This fact strongly suggests that the fishtail peak observed in $M(H)$ curves for both field directions is not due to a pinning crossover.

We also obtain flux-creep data from the isofield method, with a path represented in Fig. 1(a) by a vertical dotted line for $H = 4.6$ kOe. $M(t)$ data were obtained by reaching the desired temperature in a ZFC procedure, followed by an increase of the field up to 4.6 kOe and measuring $M(t)$ for 60 min. Results of $R = dM/d \ln t$ obtained this way for all $M(t)$ data is presented in Fig. 3(d). As in other plots of R vs H shown in Fig. 3, the plot of Fig. 3(d) does not show any marked feature as H_p (located at $T = 4$ K) is crossed. The isofield activation energy curve $U(M,T)$, or $U(M,T)/g(T/T_c)$, where $g(T/T_c)$ is some scaling function, is believed to be a smooth function of M, where its behavior with M can provide information on the pinning mechanism.[17,18,25] Here we performed an analysis of
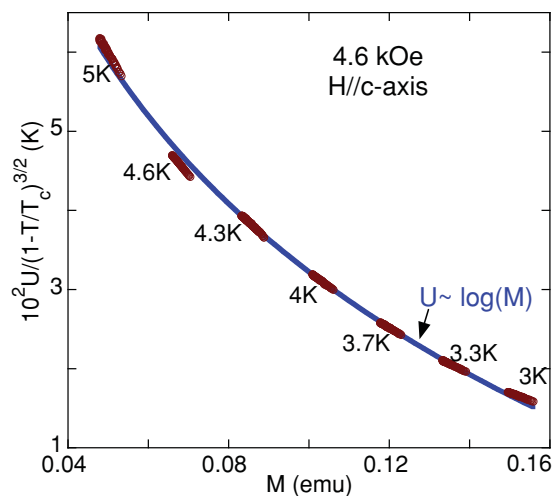
the activation energy as shown previously in Refs. 17 and 18 using the expression $U = -T \ln[dM(t)/dt] + CT$, where C is a constant which depends on the hopping distance of the vortex, the attempt frequency, and the sample size. The constant C is adjusted in a manner such that all $U(M,T)/g(T/T_c)$ curves plotted against M fall on a smooth curve. If all data does not fall on one smooth curve with a fixed value of C, it is an indication that the data does not fall into one pinning regime. Figure 4 show the results of the analysis. The appropriate scaling function for our case is $g(T/T_c) = (1 - T/T_c)^{3/2}$ (also used in Ref. 18) and the constant $C = 14$; similar values of the constant C have been found for high-T_c cuprates[17,18] and pnictides.[6] The plot of $U(T)$ shows an almost perfect logarithmic with M, indeed suggesting that a single pinning regime is operating in the temperature range studied at the fixed field of 4.6 kOe.

As a pinning regime crossover does not appear to be an appropriate explanation for the fishtail effect, it is interesting to explore whether the data can be understood within the model proposed for a vortex lattice phase transition,[16] using the expression $J_c(B) = A/[(B - B_p)^2 + (\Delta B)^2]^{5/4}$, where A is a fitting parameter and ΔB is the peak width. The M vs H curves have been fit to this expression, converting the magnetization data to critical current as described previously and using $B \approx H$. The good-quality fittings conducted on $J_c(T = 3$ K) for both field directions are shown as solid lines in the curves of the upper inset of Fig. 1(a). By considering $J_c = \Delta M$(emu/cm^3), the values of the fitting parameters are $A = 1.1 \times 10^4 G^{5/2}$ and $\Delta B = 14.2$ kOe for $H \parallel c$, and $A = 4.4 \times 10^4 G^{5/2}$ and $\Delta B = 46$ kOe for $H \parallel ab$. Note that the fittings produced larger values for the peak width compared to values obtained in Ref. 12. It is interesting that the data fits well to this expression, although we recognize that this in itself is not conclusive evidence of a phase transition in the vortex lattice. Moreover, we would expect a change in vortex dynamics as a signature that a phase transition has occurred, and we see no evidence for this.

In conclusion, our experiments show that the fishtail peak appearing on $M(H)$ curves for $H \parallel c$ and $H \parallel ab$ in

$BaFe_{1.82}Ni_{0.18}As_2$ does not appear to be associated with a softening in vortex pinning prior to melting, nor a change of pinning regime within a collective pinning model scenario. We observe an anomalously long relaxation period at the initial stage of relaxation lasting $\approx$10 min for $H \parallel c$, which is likely to be a transient effect due to the field rate dH/dt while charging (discharging) the magnet. This transient effect appears to be a feature intrinsic to the BaFeNiAs system we have studied, as we have also found it present in preliminary data obtained in a second crystal with $x = 0.1$ ($T_c \approx 20$ K) for $H \parallel ab$ planes.

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