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2015 Supercond. Sci. Technol. 28 055017

(http://iopscience.iop.org/0953-2048/28/5/055017)

IOP Publishing | Superconductor Science and Technology
Supercond. Sci. Technol. **28** (2015) 055017 (5pp) | doi:10.1088/0953-2048/28/5/055017

Observation of an anomalous peak in isofield $M(T)$ curves in $BaFe_2(As_{0.68}P_{0.32})_2$ suggesting a phase transition in the irreversible regime

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Received 22 January 2015, revised 18 March 2015
Accepted for publication 19 March 2015
Published 14 April 2015

Abstract

We measure magnetization as a function of temperature, magnetic field, and time in a $BaFe_2(As_{0.68}P_{0.32})_2$ single crystal with $T_c = 27.6$ K. The fish tail observed in many $M(H)$ curves is used to construct isofield $M(T)$ curves which show an anomalous peak at some temperature T_t, suggesting a possible phase transition in the irreversible regime. A vortex dynamics study performed along the peaks evidences a minimum in the relaxation rate occurring at the same position T_t of the minimum value of M in these peaks. A vortex dynamics study performed on $M(H)$ curves shows two distinct minima in the relaxation rate: a first minimum (H_1) for a lower field correlated with T_t and a second (H_2) correlated with the peak in the fish tail. A phase diagram is constructed, and the line corresponding to the T_t and H_1 points obeys an expression developed in the literature for a structural rhombic to square lattice phase transition, further supporting this view.

Keywords: $BaFe_2(As_{1-x}P_x)_2$, second magnetization peak, flux creep relaxation rate

(Some figures may appear in colour only in the online journal)

1. Introduction

Since the discovery of superconductivity in iron-pnictide systems [1–3], vortex dynamics has been the object of intensive study because many different compounds belonging to this system show potential for applications mainly due to the considerably high-superconducting critical temperature, T_c; high upper critical field, H_{c2}; high critical current; and considerably low anisotropy [4–6]. Additionally, iron pnictides also exhibit considerable flux creep, making it possible to study in detail different pinning mechanisms. Among these studies, special attention has been given to the study of the second magnetization peak (SMP), or fish tail, which in pnictides shows similarities to those observed and studied in high-T_c superconductors [7–10]. It is worth mentioning that the SMP was previously observed and studied in low-T_c superconductors, such as Nb [11]. The SMP is associated with a peak in the critical current that is of great interest for applications from the technological point of view. The SMP, or fish tail, appears in most single-crystal pnictides, such as in the 122 family, $BaFe_2(As,P)_2$ [12], $Ba(Fe,Co)_2As_2$ [13–15], $(Ba,K)Fe_2As_2$ [16, 17], $Ba(Fe,Ni)_2As_2$ [18, 19], $Ba(Fe,Ru)_2As_2$ [20] and $(Ba,Na)Fe_2As_2$ [21]; in the 111 LiFeAs [22]; in the oxi-pnictides SmFeAs(O,F) [23, 24], CeFeAsO [25],

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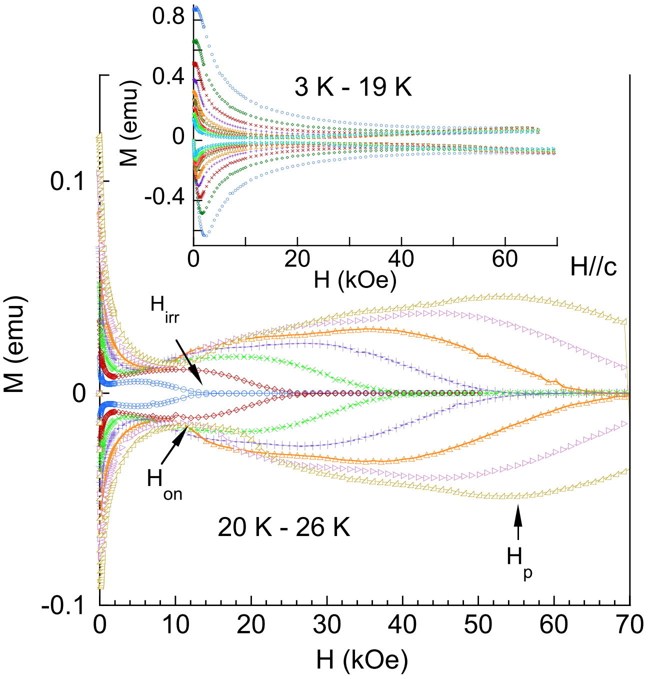

Figure 1. Isothermal $M(H)$ curves as a function of temperature. Main: 20–26 K in steps of 1 K. Inset: 3–19 K in steps of 2 K.

CeFeAs(O,F) [26], $NdFeAsO_{0.85}$ [27]; and $PrFeAsO_{0.60}F_{0.12}$ [28, 29]; and in the chalcogenide Fe(Se,Te) [30–32] among others. As a result of the low anisotropy, the SMP is observed for magnetic fields applied parallel, perpendicular, or forming an angle with the c-axis of the sample [19]. The rich variety of explanations for the SMP, which for instance include vortex lattice phase transition [13, 22], pinning crossover [14, 16], and order–disorder transition [31], and a lack of evidence for pinning crossover or softness of the vortex lattice [18, 19] suggests that the mechanism responsible for the effect is sample dependent [16, 29]. It is worth mentioning the important role that the multi-band character [33, 34], along with anisotropy and pinning, may play in the vortex dynamics of pnictides [35]. Another important feature in pnictides is the existence of nanoscale variations in the gap, as observed in gap maps obtained through scanning tunneling microscopy (STM) in Ba(Fe, $Co)_2As_2$ samples [36–38]. In that case, as a magnetic field is applied, one may expect that regions with a lower carrier density may become normal, thus affecting the entire vortex distribution.

Among the explanations found for the SMP it is worth mentioning the phase transition of the vortex lattice, whose fingerprint appears to be a minimum in the isofield relaxation rate $-R$ versus T [13, 22, 31]. This minimum refers to a softness of the vortex lattice which, due to energy considerations, gives rise to a structural phase transition which leads to an increase in the relaxation rate as the temperature increases, thereby explaining the fish-tail form of the SMP [13, 39, 40]. This well-founded explanation appears not to contradict the elastic to plastic pinning crossover observed near the peak field of the SMP, H_p [13].

In this work, we report on isothermic and isofield magnetization data obtained for a single crystal of $BaFe_2(As_{0.68}P_{0.32})_2$ with T_c = 27.6 K and $\delta T_c \approx 1$ K for $H\|$ c-axis. Isothermal $M(H)$ curves obtained after zero-field cooling (zfc) show a pronounced second magnetization peak which is apparent for temperatures from 3 K to 26 K. As a result of the pronounced fish tail form of the curves, a plot of many $M(H)$ curves shows several crossings occurring for many different magnetic fields, suggesting the existence of some anomaly in the isofield $M(T)$ curves in the irreversible regime. Isofield $M(T)$ curves are then obtained by extracting the magnetization values from the $M(H)$ curves and are compared with zfc $M(T)$ curves obtained by zero-field cooling to a certain temperature T at which the magnetic field is applied, and data are collected as the temperature increases. Whereas this last procedure gives rise to a smooth $M(T)$ curve, the curve obtained from $M(H)$ measurements presents an anomalous peak, suggesting some sort of transition in the magnetization. Reproducibility of the anomalous peaks is verified by performing additional magnetization measurements $M(H,T)$ for temperatures along the peaks, where each set of data is obtained after a zfc procedure. To study the vortex dynamics along the anomalous $M(T)$ peaks, we measured the magnetization as a function of time for each of these $M(H,T)$ measurements. The resulting isofield relaxation rates $-R(T)$ versus T plots show a minimum at approximately the same position at which the corresponding $M(T)$ data reaches a minimum, suggesting that the anomalous peak is related to a vortex lattice phase transition. Magnetization as a function of time is also obtained for fields along the SMP of several $M(H)$ curves, enabling the study of different relaxation rate regimes. The resulting plots of R versus H further corroborate the vortex lattice phase transition scenarios occurring below the SMP peak, H_p, whereas a pinning crossover is suggested to occur above H_p. To our knowledge, the existence of an anomalous peak in the irreversible regime of $M(T)$ curves has not been observed before.

2. Experimental setup

The high-quality $BaFe_2(As_{0.68}P_{0.32})_2$ single crystal used in this work (with the approximate dimensions $4 \times 4 \times 0.03$ mm^3 and mass m = 3.582 mg) was grown by the BaAs/BaP flux method [41]. The sample exhibits a sharp T_c = 27.6 K with $\delta T_c < 1$ K. Magnetic measurements were performed using an MPMS-XL system from Quantum Design (equipped with a magnetic shield) in two modes: the reciprocating sample option (RSO) mode was used for $M(H)$ measurements, and DC scanning was used for $M(T)$ measurements. The sample, as usual, was attached to a plastic straw, enabling measurements with $H \|$ c-axis. All measurements were obtained with a zfc procedure: before the temperature is lowered, the magnetic shield was demagnetized and then the superconducting coil was quenched, after which the remanent field was about 0.1 Oe. After cooling from above T_c to the desired temperature, the magnetic field was applied without overshooting,

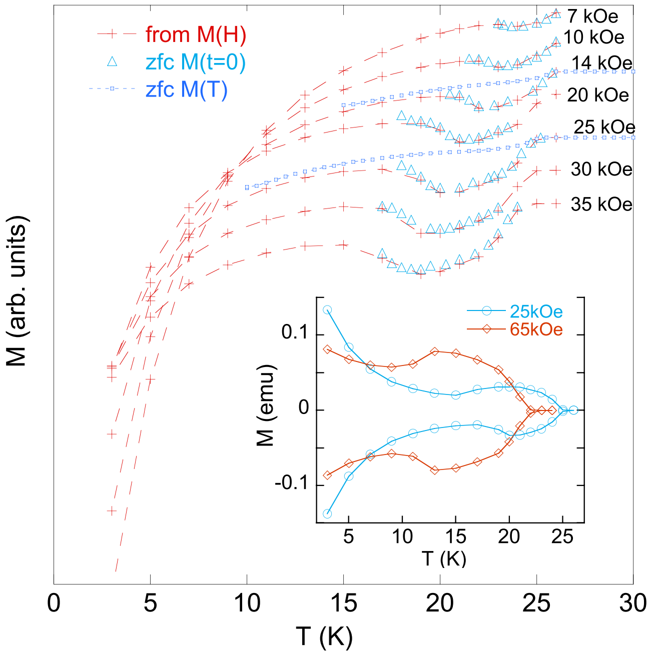

Figure 2. Isofield $M(T)$ curves as obtained from 7 to 35 kOe in three different ways: red crosses—from $M(H)$ curves; solid blue—corresponding to zfc $M(T)$ curves; and blue triangles—corresponding to zfc $M(t=0)$ data, each set of data obtained in the same way as the $M(H)$ curves. The curves are dislocated along the y-axis for a better presentation. Inset: selected $M(T)$ curves obtained from both branches of the $M(H)$ curves.

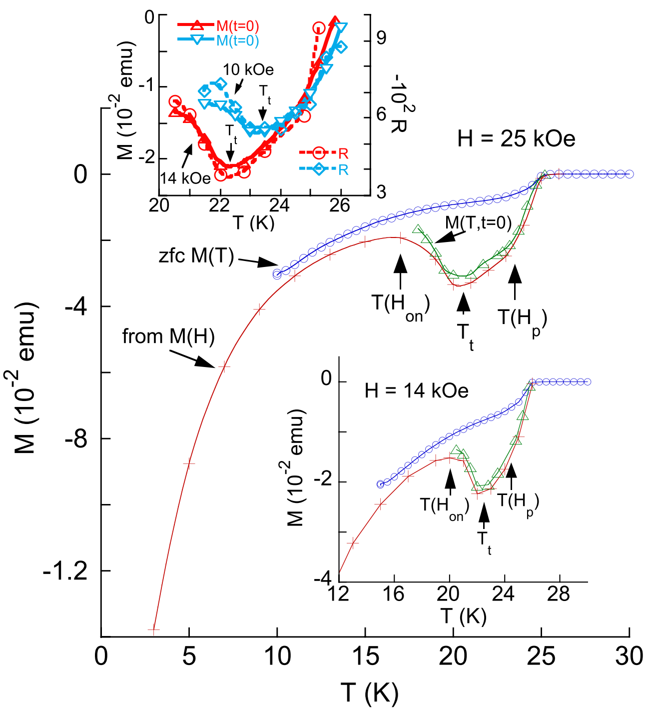

Figure 3. Details of the $M(T)$ curve for H = 25 kOe. Lower inset: details of the $M(T)$ curve for H = 14 kOe. Upper inset: double plots of $M(t=0)$ versus T (open triangles in the figure 3) and $-R$ versus T for H = 10 and 14 kOe. The $-R$ versus T curves are shifted along the y-axis for better presentation.

and data was collected after the field was declared stable. In the case of isothermal $M(H)$ hysteresis curves, data were collected with field increasing (or decreasing after a maximum field was reached) at fixed δH increments. In that case we also obtained magnetic relaxation curves (over a period of 1 to 1.5 h) for magnetic fields along the SMP of the increasing field branch of selected $M(H)$ curves. In the case of $M(T,\text{time})$ data for fixed fields, the magnetization as a function of time (over a period of 2 h) was collected for each temperature after a zfc procedure. In the case of zfc isofield $M(T)$ curves, data were collected with the T increasing at fixed δT increments. Most of the magnetic relaxation curves (not shown) presented an initial transient stage with a comparatively low relaxation rate (observed before in a $Ba(Fe,Ni)_2As_2$ system [18, 19]) holding for the first 10 to 15 min, after which the usual $\log(t)$ behavior was achieved, making it possible to extract the relaxation rate, defined as $R = d\ln(M)/d\ln(t)$.

3. Results and discussion

Figure 1 shows isothermal $M(H)$ curves obtained for $H\parallel c$-axis with temperatures ranging from 3 K to 26 K. The SMP is clearly visible for the curves above 20 K, and from this it is possible to identify the fields H_{on}, corresponding to the onset of the SMP; H_p, corresponding to the maximum of the SMP; and the irreversible field, H_{irr}. It is possible to see that a much broader SMP takes place below 24 K, and as a consequence, it is difficult to precisely identify the position of H_{on} below 20 K. An interesting fact that can be visualized from the plots of figure 1 is the crossing of different $M(H)$ curves, which for a fixed H leads to a maximum in $|M|$ upon increasing T.

To verify this effect we obtained isofield $M(T)$ curves by extracting values of M for fixed selected magnetic fields from the zfc $M(H)$ curves, which corresponds to an $M(T)$ curve with each point obtained after a zfc procedure. The resultant curves for selected magnetic fields obtained from the increasing field branch of the $M(H)$ curves are shown in figure 2, where the inset shows two selected curves with values of M also extracted from the decreasing field branch of $M(H)$ curves, where the resultant curve interestingly resembles the fish-tail effect observed in $M(H)$ curves. It is interesting to see the existence of an anomalous peak in each curve of figure 2, with a minimum occurring at a temperature T_t. Since the anomalous peak develops for a fixed magnetic field (which may discard a pinning crossover), one may associate the peak with a possible phase transition occurring in the irreversible regime. To check for the reproducibility of the peaks we measured the zfc magnetization for temperatures along each of these peaks, where each set of data was taken after a zfc to the desired temperature, setting the magnetic field, and measuring magnetization. To further study vortex dynamics, each of these data was measured as a function of time. The resultant zfc $M(t=0)$ values are represented as open triangles in figure 2 and, as shown, consistently reproduce peaks in more detail. We also measured two isofield zfc $M(T)$ curves for H = 14 and 25 kOe, which are plotted in figure 2. One can understand the absence of the peak in these zfc $M(T)$

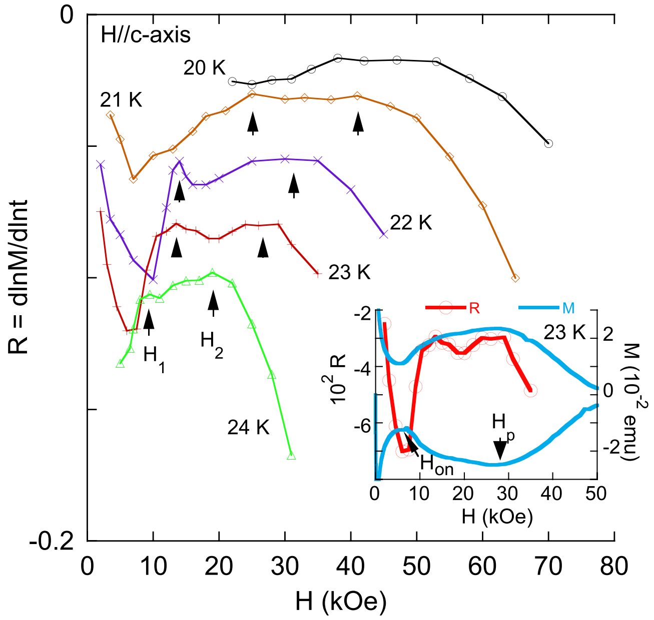

Figure 4. Plots of R versus H for $T = 20$–24 K, where the curves are dislocated along the y-axis for a better presentation (note that $|R|$ increases from top to bottom). The inset shows a double plot of R and M versus H for $T = 23$ K.

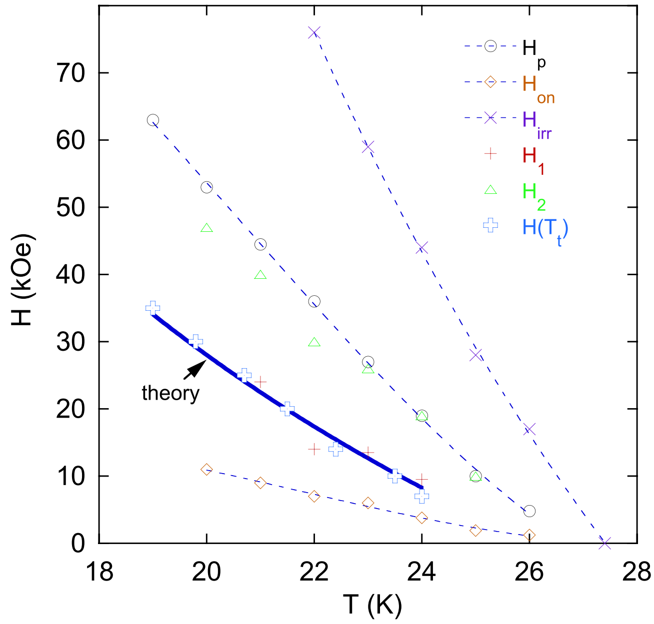

Figure 5. Vortex phase diagram. The solid line is a fit to the theory (equation (1)). Dotted lines are only guides for the eyes.

curves because the M values in this case do not correspond to the maximum allowed value in the irreversible regime. This fact is a possible reason why this anomalous peak in $M(T)$ curves has apparently not been observed before, as the usual way to measure isofield zfc $M(T)$ curves is by continuously increasing the temperature.

Figure 3 shows the $M(T)$ curves obtained for $H = 25$ kOe in the main figure and for 14 kOe in the lower inset, where the open triangles correspond to zfc $M(t = 0)$ data obtained along the peaks for $t = 0$ as previously discussed. The plots in figure 3 make it possible to better visualize how the anomalous peak develops. Vortex dynamics along the anomalous peaks were studied by obtaining the relaxation rate R of each M(time) data obtained along the peaks (open triangles). The upper inset of figure 3 shows $-R$ versus T plotted along with the corresponding $M(t = 0)$ versus T data for two selected magnetic fields, where it is possible to see that $-R$ shows a minimum at a temperature at which it virtually coincides with the position of the minimum in $M(t = 0)$ at T_t. This trend was observed for all $-R$ versus T curves. It is important to mention that the minimum in $-R$ occurring near T_t in this inset may represent a softness of the vortex lattice, which is followed by a steep increase in $-R$ as the temperature increases above T_t. According to [13], this steep increase in $-R$ explains the SMP, which suggests that the anomalous peak is intrinsically related to the SMP observed in the $M(H)$ curves. To better exemplify the analogy between the anomalous peak and the SMP, we indicate in figure 3 with arrows the temperatures for which H_{on} and H_p are equal to the field in each plot.

Figure 4 shows the results of R versus H as obtained from magnetic relaxation data collected along the SMP of selected $M(H)$ curves. Interestingly, it is possible to identify a kind of double maximum (or minimum if one considers $|R|$) within the SMP for four $M(H)$ curves. The maximum occurring between the fields H_{on} and H_p, called H_1, appears to correlate with the peak in $-R$ versus T; and the second maximum, called H_2, appears to be associated with H_p. This suggests that the decrease in magnetization occurring above H_p is associated with a change in the pinning mechanism, probably elastic to plastic, which, as pointed out in reference [13], does not contradict a vortex phase transition occurring below H_p. The inset of figure 4 shows a selected isothermal R versus H curve plotted along with the corresponding $M(H)$ curve, where it is possible to visualize the positions of the double maximum with respect to the fields H_{on} and H_p.

To summarize the results, we plot the fields H_{on}, H_p, H_{irr}, H_1, H_2, and T_t in a phase diagram in figure 5, where it is easy to visualize that H_2 is probably correlated with H_p, and H_1 with T_t, further suggesting that T_t represents a phase transition of the vortex lattice in the irreversible regime. It is worth mentioning that a similar correlation between a minimum in $-R$ versus H and a minimum in $-R$ versus T, was observed in reference [13] for $BaFe_{2-x}Co_xAs_2$ and the matching was associated with a vortex lattice phase transition, as predicted and discussed in references [39, 40]. This fact motivated us to fit the line formed by the points T_t and H_1 in figure 5 to the expression presented in reference [13] for a structural rhombic to square lattice phase transition,

$$H_{spt} = A\frac{T_0 - T}{C^{\nu-1}T^{\nu}}, \qquad (1)$$

where $C = \frac{4\pi^3\lambda^2}{L_z\phi_0^2}$, λ is the London penetration depth, L_z represents an effective superconducting layer width for thermal fluctuations [13], and ϕ_0 is the flux quantum. We used the values $\lambda = 108$ nm, which is appropriate for our sample [42], and $L_z \approx 10^{-4}$ cm as in reference [39]. The fitting was conducted by assuming A, T_0 and ν as free parameters.

The resultant fitting, shown as a solid line in figure 5, produces the values $A = 0.98T_c$, $T_0 = 26.1$ K, and $\nu = 0.85$. The values of the parameters A and T_0 appear to be in reasonable agreement with the values found for $Ba(Fe,Co)_2As_2$ [13] and $La_{2-x}Sr_xCuO$ [39], whereas a slightly smaller value was found here for the exponent ν, which might be related to the smaller value of $\kappa = 47$ for our sample [42] whereas $\kappa \approx 75$ for the samples in references [13, 39]. As previously mentioned, there is an apparent absence of works in the literature showing a similar anomalous peak in $M(T)$ curves in the irreversible regime, which may indicate that the effect is observed only for the system studied. On the other hand, one month after this work was submitted, an interesting work was published in the arxiv.org data base [43], where the authors observed a similar anomalous peak in the low-T_c superconductor $Yb_3Rh_4Sn_{13}$, evidencing that the effect could be of a more general nature.

4. Conclusions

We observed an anomalous peak in isofield $M(T)$ curves in the irreversible regime of the studied sample, which suggests a possible phase transition. To our knowledge, this anomalous peak was observed for the first time in the present study. It was shown that the anomalous peaks with minimum M value occurring at T_t were associated with the SMP observed in $M(H)$ curves. Vortex dynamics studies performed along the peaks of the $M(T)$ curves and along the SMP of the $M(H)$ curves suggest that the anomalous peaks are related to a vortex lattice phase transition. The line formed by the points H_1 and T_t (extracted from the anomalous peaks) was successfully fitted by a theory developed for a structural rhombic to square lattice phase transition, further supporting this view.

Acknowledgments

SSS and ADA are grateful for support from the Brazilian agencies CNPq and FAPERJ. JM and DS acknowledge support from the Xunta de Galicia (Grant No. GPC2014/038). The work at IOP, CAS, was supported by MOST (973 project: 2011CBA00110), NSFC (11374011 and 91221303), and CAS (SPRP-B: XDB07020300).

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