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Increment of the collective pinning energy in $Na_{1-x}Ca_xFe_2As_2$ single crystals with random point defects introduced by proton irradiation

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Abstract

We study the influence of random point defects introduced by 3 MeV proton irradiation (doses 1×10^{16} and 2×10^{16} cm^2) on the vortex dynamics of $Na_xCa_{1-x}Fe_2As_2$ ($x = 0.5$ and $x = 0.75$) single crystals. Our results indicate that the irradiation produces an enhancement of the critical current density and a reduction of the creep rate in vortex relaxation. The plateau in the temperature dependence of vortex creep rate initially present in as-grown single crystals disappears after irradiation. This fact can be associated with a large increment of the collective pinning energy (from <100 to 350–400 K). On the other hand, Maley analysis indicates that after irradiation both samples present a glassy exponent μ close to the one expected in the so-called large bundle regime ($\mu \approx 7/9$) for random point defects.

Keywords: iron pnictides, vortex dynamics, proton irradiation

1. Introduction

The discovery of the AFe_2As_2 family (122 system, A: an alkaline-earth element) [1, 2] in 2008 provided a bridge to study the superconducting properties of systems in between conventional low-temperature (LTS) and unconventional high critical temperature superconductors (HTS) [3]. Among the properties of these materials, vortex dynamics is of particular relevance in both basic science and technological applications [3–5]. There are various methods to explore the vortex dynamics over a very broad range of vortex speeds [6]. These methods include ac susceptibility [7], transport measurements [8] and flux creep relaxation [9]. However only flux creep can be used deep into the vortex solid phase. Most theories which explain the vortex dynamics in superconductors with large thermal fluctuations were developed to understand the physics on anisotropic cuprates [10]. The microscopic basis of these models involves the collective interaction of flux lines. In this way the study of the vortex dynamics by performing relaxation (creep) measurements $S = -\partial \ln J_c / \partial \ln t$, with J_c the critical current density and t the time) is a key for developing methods to produce effective pinning enhancement. The relaxation in cuprates has been discussed considering the collective pinning theory $S = -\frac{T}{U_0 + \mu T \ln t/t_0}$ (equation (1)), where U_0 is the collective barrier in the absence of a driving force, μ is the glassy exponent and t_0 is an effective hopping attempt time. The nature of the vortex structure and the vortex pinning mechanisms can be inferred from μ, which scales the effective energy barrier and the persistent current density (J) as $U(J) \approx U_0 \left(\frac{J_c}{J}\right)^{\mu}$ (equation (2)), and depends on the creep

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regime. The estimation of the U_0 and μ in different types of superconductors and pinning landscapes is fundamental for a broader understanding of the resulting vortex phase diagrams. According to vortex-glass theory [7] and collective creep theory [11] the effective pinning energy is given by $U_{eff} = U_0(T)\left[\left(\frac{J_0}{J}\right)^{\mu} - 1\right]$ (equation (3)) where $U_0(T) = U_0 G(T)$ is the scale of the pinning energy with temperature dependence $G(T)$, and J_0/J is the current density scale for a particular pinning process (further on $J_0 \approx J_c$). The glassy exponent μ varies depending on the dimension and length scales for the vortex lattice in the collective-pinning model (random point defects in the three-dimensional case is $\mu = 1/7$, 3/2 or 5/2, and 7/9 for single vortex creep, small-bundle creep, and large-bundle creep, respectively). According to Maley *et al* [12] the effective activation energy $U_{eff}(J)$ can be experimentally obtained considering the approximation in which the current density decays as $\frac{dJ}{dt} = -\left(\frac{J_c}{\tau}\right)e^{-\frac{U_{eff}(J)}{T}}$. The final equation for the pinning energy is $U_{eff} = -T\left[ln\left|\frac{dJ}{dt}\right| - C\right]$ (equation (4)) where $C = ln(J_c/\tau)$ is a nominally constant factor. For an overall analysis it is necessary to consider the function $G(T)$, which results in $U_{eff}(J, T = 0) \approx U_{eff}(J, T)/G(T)$ (equation (5)) [13].

The magnetic field—temperature (H–T) vortex phase diagram depends on the nature and density of pinning centers [14–16]. Usually 122 single crystals present a complex pinning landscape which includes intrinsic pinning [17], small normal regions [18], chemical inhomogeneities [19], and twin boundaries [20]. Radiation damage is a controlled standard route to introduce defects into a material. The influence of proton [21, 22] and heavy ion irradiation [23] in the vortex dynamics of Co doped $BaFe_2As_2$ (Co-122) single crystals have been analyzed. In both cases, the irradiations produce an increase of the J_c. Proton irradiation modifies the vortex dynamics mainly at low and intermediate temperatures [22]. Heavy ion irradiation also modifies the creep rates even at temperatures close to the superconducting critical temperature (T_c) [23]. The difference in the pinning produced close to T_c was discussed in terms of temperature dependence of the coherence length $\xi(T)$ and the effectiveness of pinning produced by random point defects [15]. However, a more extensive comparison with other 122 systems (with different thermodynamic parameters and similar thermal fluctuations) is necessary for a broader understanding of the resulting pinning produced by similar type of irradiation. $Na_xCa_{1-x}Fe_2As_2$ single crystals [24] ($x = 0.5$ and $x = 0.75$) present the necessary characteristics for the above-mentioned comparison, since they present H_{c2} and T_c values both above and below those found in optimally doped Co-122 [25]. The main difference between $Na_xCa_{1-x}Fe_2As_2$ and Co-122 single crystals appears from defects which are initially present in the samples. In the former case, the pinning landscape is well described by a small amount of randomly distributed nanoparticles (strong pinning centers) and a denser distribution of smaller particles or point-like defects. In the latter, the crystals present a complex pinning landscape that includes a fish tail or second peak in the magnetization [22]. Thus, the simple pinning landscape initially present in these single crystals allows the analysis of the influence of proton irradiation in mixed pinning landscapes, as done in Co doped $BaFe_2As_2$ (Co-122) thin films [26].

The temperature dependence of vortex relaxation rate in optimally doped $Na_{0.25}Ca_{0.75}Fe_2As_2$ ($T_c \sim 33$ K) presents a plateau with an exponent μ value ($\mu \approx 0.7$), as predicted by the collective creep [27] theory developed to explain cuprates [4]. In addition, under-doped $Na_{0.5}Ca_{0.5}Fe_2As_2$ ($T_c \sim 19$ K) single crystals present a $S(T)$ plateau value smaller than that predicted by the collective creep models. As these compounds present a plateau with different $S(T)$ values (associated with $U_0 < 100$ K and different μ), they should be highly considered to expand the knowledge of the dynamics in superconductors with intermediate vortex fluctuations. The intrinsic superconducting properties in the $Na_xCa_{1-x}Fe_2As_2$ single crystals are as follows, $x = 0.5$AG: coherence length $\lambda_{ab}(0) = 260$ nm, $\xi_{ab}(0) = 3.6$ nm, $\gamma_{T\to T_c} = H_{c2}^c/H_{c2}^{ab} \approx 1.8$; [15, 28] and $x = 0.75$AG: $\lambda_{ab}(0) = 240$ nm, $\xi_{ab}(0) = 2.1$ nm, $\gamma_{T\to T_c} = H_{c2}^c/H_{c2}^{ab} \approx 1.8$ [15, 29]. The intrinsic thermal fluctuations can be parameterized by the Ginzburg number $\left(Gi = 1/2\left(\gamma T_c/H_c\xi^3\right)^2\right)$, which measures the relative size of the minimal ($T = 0$) condensation energy $H_c^2(0)\xi^3(0)/\gamma$ within a coherence volume and the thermal energy T. Here $H_c(0) = \phi_0/2\sqrt{2}\lambda(0)\xi(0)$ is the thermodynamic critical field, and λ is the penetration depth [10]. The Gi values for $x = 0.5$AG and $x = 0.75$AG are $\approx 1.3 \times 10^{-4}$ and $\approx 1 \times 10^{-3}$, respectively.

In this work the influence of random defects introduced by proton irradiation on J_c and vortex dynamics of $Na_xCa_{1-x}Fe_2As_2$ single crystals ($x = 0.5$ and $x = 0.75$) has been investigated. The irradiation produces an enhancement of the J_c in both samples. The 3 MeV protons are known for their capacity to create between one and a few tens of atomic displacements, producing mainly random point defects and some small nanoclusters [14]. Unlike YBCO single crystals, the plateau which is associated with glassy relaxation disappears after irradiating. This fact can be attributed to an increment in the collective pinning energy and the smaller T_c (according to equation (1), U_0 is never negligible in comparison with $\mu T \ln t/t_0$). Both irradiated single crystals show U_0 around 350 K and μ close to that expected for large bundles ($\approx 7/9$). The temperature range for the effectiveness of extra random point defects is different in each single crystal. The individual pinning force produced by random point defects (similar pinning landscape) is strongly dependent on the thermodynamic superconducting parameters and the vortex size/defect size ratio. In this way, the inclusion of random point defects modifies the scaling of the pinning force in $x = 0.75$ at temperatures close T_c (down to $T/T_c \approx 0.9$). On the other hand, the inclusion of extra random point defects in $x = 0.5$ does not modify the scaling of the pinning force at high temperatures ($T > 11$ K), a result that can be associated

Table 1. Summary of proton irradiation dose, displacements per atom (dpa), average distance between defects. Superconducting critical temperature (T_c) obtained from magnetization.

SC	3 MeV proton dose (cm^{-2})	Dpa	Inter defect distance (nm)	T_c (K) $x=0.75$	T_c (K) $x=0.5$
AG	—	0	—	33.4	17
F1	1×10^{16}	8.7×10^{-4}	3.6	32.7	15.4
F2	2×10^{16}	1.7×10^{-3}	2.8	—	14

with the nature of the pinning landscape initially present in the sample (vortex core size > defect radio).

2. Experimental

The $Na_xCa_{1-x}Fe_2As_2$ single crystals with $x=0.5$ and $x=0.75$ were grown by the self-flux technique previously described in [24]. Both AG samples are superconducting with T_c of 19.4 K ($x=0.5$AG) and 33.4 K ($x=0.75$AG) obtained from electrical transport [17]. The magnetization (**M**) measurements were performed by using a superconducting quantum interference device (SQUID) magnetometer with the applied magnetic field (**H**) parallel to the *c* axis ($\mathbf{H}\parallel c$). The T_c values used in this work (based on magnetization data) were determined from $M(T)$ at $H=1.5$ Oe applied after zero field cooling. As a consequence of the superconducting transition width in $x=0.5$ AG, a small difference in the T_c values (obtained either by magnetization or electrical transport) is observed. The J_c values were calculated from the magnetization data using the appropriate geometrical factor in the Bean Model [30], $J_c=\frac{20\Delta M}{w(l-w/3l)}$, where ΔM is the difference in magnetization between the top and bottom branches of the hysteresis loop, and l and w are the length and the width of the single crystal ($l>w$), respectively. The creep rate measurements were recorded for more than 1 h. In all cases, the initial time was adjusted considering the best correlation factor in the log–log fitting of the $\mathbf{J_c}(t)$ dependence. The initial critical state for each creep measurement was generated using $\Delta H\sim4H^*$, where H^* is the field for full-flux penetration [9].

Irradiation with 3 MeV protons produces mostly Frenkel pairs, i.e. random point defects [11]. Table 1 shows the cumulative amount of displacement damage (displacements per atom, DPA) after each dose, as estimated using the SRIM code [31], as well as the average distance between defects. The single crystals were irradiated with the same doses in [22, 26] (see table 1). The $x=0.5$ single crystal was irradiated twice ($x=0.5$F1 and $x=0.5$F2), whereas $x=0.75$ was irradiated only once ($x=0.75$F1). After irradiation the T_c fractional suppression $\left(\frac{T_c^{irr}-T_c^{unirradiated}}{T_c^{unirradiated}}\right)$ is larger in $x=0.5$ than in $x=0.75$ and in Co doped $BaFe_2As_2$ single crystals [22]. A discussion about these differences is out of the scope of this manuscript.

3. Results and discussion

3.1. Critical current density and pinning force scaling

Figure 1(a) shows $J_c(H)$ in $x=0.75$AG and $x=0.75$F1 at different temperatures (5 K, 20 and 25 K) [27]. The J_c(5 K, $H=0$) values present an increment due to the irradiation from 1.2 MA cm^{-2} (AG) to 3 MA cm^{-2} (F1), as previously observed in optimally doped Co-122 [22]. Furthermore, two evident differences appear in the comparison between the $J_c(H)$ dependence in the unirradiated and the irradiated single crystal. The first one is a change in the $J_c\propto H^{-\alpha}$ regime with $\alpha=0.55$ observed in the unirradiated sample and previously discussed in [24], associated with pinning dominated by nanoparticles [32]. The modification of the $J_c\propto H^{-\alpha}$ regime can be associated with a modification of the pinning landscape. After irradiating, the $J_c(H)$ dependences present the combination of two contributions: strong pinning centers (such as nanoparticles originally present in the as-grown single crystal), and a denser distribution of random point defects introduced by irradiation. Although a clear $J_c\propto H^{-\alpha}$ regime cannot be identified after the irradiation, the smoother $J_c(H)$ indicates that the relative strength of the vortex–vortex interaction as compared to the vortex–defects interactions is reduced as a consequence of the mixed pinning landscape. The second difference is an enhancement of J_c at high magnetic field, associated with the density of pinning centers. As discussed in [24], the $x=0.75$AG single crystal shows a $J_c(H)\approx$ *constant regime* at intermediate temperatures and high magnetic fields (see dashed lines in figure 1(a) for $x=0.75$AG at 20 and 25 K). This regime can be associated with single-vortex pinning due to a denser distribution of smaller particles, or point-like pinning. In $YBa_2Cu_3O_{7-\delta}$ (YBCO) single crystals a $J_c(H)\sim$ *constant* regime appears when defects like twin boundaries are removed and it can be associated with pinning by oxygen vacancies [33]. In clean YBCO single crystals the $J_c(H)\sim$ *constant* regime is extended to high magnetics fields (several Tesla), and the incorporation of pinning centers enhances the absolute J_c values changing the $J_c(H)$ dependence [33, 34]. Finally the vortex dynamics at high enough magnetic fields present a change in the vortex dynamics associated with plastic creep [35]. The comparison between clean YBCO and the $x=0.75$AG single crystals indicates that the enhancement $J_c(H)$ and the disappearance of the $J_c(H)\sim$ *constant* regime in $x=0.75$F1 can be understood in two different ways. On the one hand, it could be produced by an increment of random point defects due to proton irradiation. On the other, it can be attributed to the production of pinning centers (suppression of the superconductivity) different to those initially present in the sample (associated with intrinsic vacancies).

Figure 1(b) shows $J_c(H)$ in $x=0.5$AG [24] and $x=0.5$F1 at different temperatures. The $J_c(H)$ curves of $x=0.5$F2 (not shown) are similar to those found in $x=0.5$F1. The J_c(5 K, $H=0$) increases from 0.3 MA cm^{-2} (AG) to 0.58 (F1) and 0.64 MA cm^{-2} (F2). The $J_c(H)$ values at 11 K are smaller in the irradiated samples as a consequence of the T_c reduction (see table 1). However, it is important to remark that the

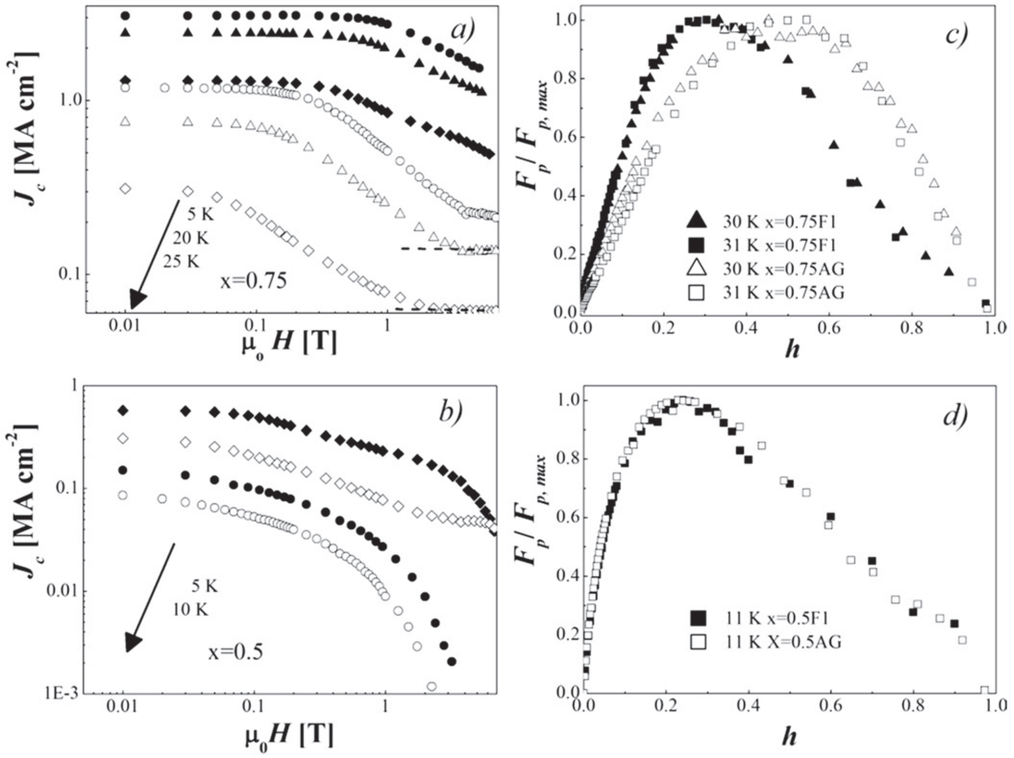

Figure 1. (a), (b) Critical current density (J_c) versus magnetic field (H) at different temperatures in $x = 0.75$AG (open symbol) and $x = 0.75$F1 (full symbol), and $x = 0.5$AG (open symbol) and $x = 0.5$F1 (full symbol). (c), (d) Normalized pinning force (F_p) versus normalized magnetic field ($h = H/H_{irr}(T)$) at high temperatures in $x = 0.75$ and $x = 0.5$, respectively.

irradiation modifies the $J_c(H)$ dependence features ($J_c \propto H^{-\alpha}$ regime) at 5 K, whereas the curves have similar H behavior at 11 K. As in $x = 0.75$F1, the $J_c(H)$ dependence at 5 K in $x = 0.5$ (F1 and F2) can be associated with a combination of a small amount of strong pinning centers (such as nanoparticles) and extra random point defects inducted by irradiation. In contrast, the similarity between the $J_c(H)$ dependence at 11 K for $x = 0.5$AG and $x = 0.5$F1 (also $x = 0.5$F2, not shown) indicates that the inclusion of extra random point defects does not modify the initial pinning mechanism present in $x = 0.5$AG at this temperature.

The pinning mechanism and the influence of the proton irradiation in the single crystals can be analyzed by the scaling of the pinning force ($F_P = J_c\, H$). The $F_p(H, T)$ can be scaled as $F_P/F_{P,\max} = Ah^m(1-h)^l$, where $F_{p,\max}$ is the maximum $F_p(H)$ at each temperature, A is a constant, m and l are exponents that depend on the pinning mechanism, and $h = H/H_{c2}(T)$ [36]. It is important to mention that the functional form of $F_p/F_{p,\max}$(h) to a microscopic pinning mechanism has been done for conventional superconductors, but such analysis is valid for h defined using $H_{c2}(T)$ rather than $H_{irr}(T)$, so it can not be directly applied here. Figures 1(c), (d) shows $F_P/F_{P,\max}$ versus h in ($x = 0.75$AG; $x = 0.75$F1) and ($x = 0.5$AG; $x = 0.5$F1), respectively. The selected temperatures correspond to those where H_{irr} was determined by magnetization, limited by the maximum field of the magnetometer. The pinning by random point defects affects the pinning force in $x = 0.75$F1, which is manifested as a change in $h_{\max}$ from ~0.5 ($x = 0.75$AG) to ~0.3 ($x = 0.75$F1). The data presented in figure 1(c) ($T/T_c > 0.9$) after irradiation can be fit by using $m = 1$ and $l = 2$, which in conventional superconductor can be associated with normal point defects [36]. Figure 1(d) shows the scaling in $x = 0.5$AG and in $x = 0.5$F1 at 11 K (similar behavior is expected at higher temperatures), remaining $h_{\max} \sim 0.25$. The same type of scaling indicates that the defects introduced by proton irradiation do not modify the pinning mechanisms at high temperatures in $x = 0.5$. The similitude in the scaling of the pinning force in $x = 0.5$AG and $x = 0.75$F1 indicates that the mechanism that dominate the pinning is due to random point defects (attributed to pinning by defects smaller than ξ). Previous studies in (Ba,K)Fe_2As_2 single crystals present $h_{\max}$ between 0.33 and 0.43 [37, 38], indicating the sensitivity of the vortex pinning to sample preparation conditions and the resulting pinning landscape.

3.2. Creep rate vortex relaxation and pinning energy

Figure 2(a) shows a comparison of the S (T/T_c) at $\mu_o H = 1$ T in $x = 0.75$AG and $x = 0.75$F1. The plateau initially presented in S (T) of $x = 0.75$AG at high magnetic fields [27] disappears as a consequence of irradiation. According to equation (1), this change in S (T) can be associated with an increment of the pinning energy. Figure 2(b) shows a Maley analysis for $x = 0.75$F1 at $\mu_o H = 1$ T. The experimental data can be adjusted by the equation (3) with $\mu = 0.90$ (0.03), $J_0 = 3.3$ (0.2) MA cm^{-2} and $U_0 = 400$ (40) K. We used $G(T) = (1 - (\frac{T}{T_c})^2)^{1.5}$ [13]. Although μ determines the

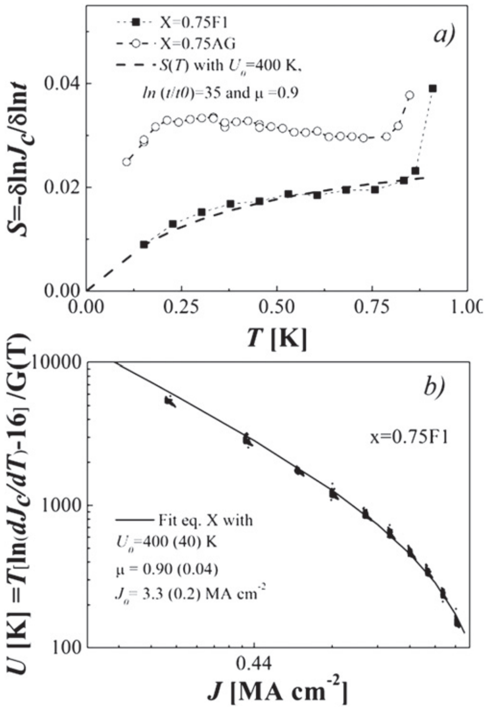

Figure 2. (a) Temperature dependence of the creep relaxation rate (S (T)) with $\mu_o H = 1$ T in $x = 0.75$AG and in $x = 0.75$F1. $S(T)$ dependence considering equation (1) is also included. (*b*) Maley analysis of $x = 0.75$F1 with $\mu_o H = 1$ T.

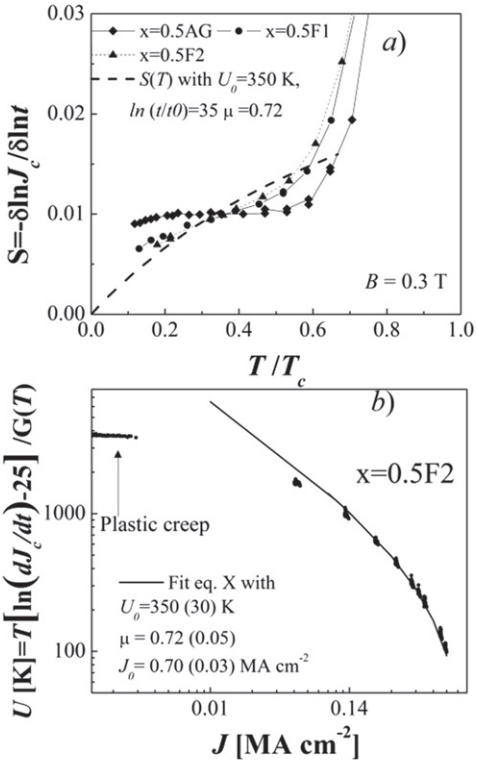

Figure 3. (a) Temperature dependence of the creep relaxation rate (S (T)) with $\mu_o H = 0.3$ T in $x = 0.5$AG, $x = 0.5$F1 and in $x = 0.5$F2. $S(T)$ dependence considering equation (1) is also included. (*b*) Maley analysis of $x = 0.5$F2 with $\mu_o H = 0.3$ T.

absolute value of the plateau, the large drop in the creep rates can be associated with a large increment in the U_0 value. An agreement between the experimental data and the expected S (T) dependence is obtained from equation (1) and $\mu = 0.9$ and $U_0 = 400$ K (see figure 2(a)). For adjusting the data ln (t/t_0) ~ 35 was considered. This value is close to that obtained in proton irradiated Co-122 single crystals [39].

Figure 3(a) shows the S (T/T_c) at $\mu_o H = 0.3$ T in $x = 0.5$AG, $x = 0.5$F1 and $x = 0.5$F2. Similarly with $x = 0.75$F1, the plateau in S (T) disappears after irradiating. Figure 3(b) shows a Maley analysis for $x = 0.5$F2 at $\mu_o H = 0.3$ T. The data can be adjusted by considering the equation (3) with $\mu = 0.72$ (0.03), $J_0 = 0.70$ (0.03) MA cm^{-2} and $U_0 = 350$ (30) K. An agreement between the experimental S (T/T_c) data and the estimation considering $\mu = 0.7$, ln (t/t_0) = 35 and $U_0 = 350$ K is obtained (see figure 3(a)). The concordance between the experimental and the expected creep rates in $x = 0.5$F2 is consistent with a large increment of the pinning energy due to proton irradiation. It is important to mention that the plateau initially present in $x = 0.5$AG considers $\mu \approx 3$, ln (t/t_0) ~ 30 and $U_0 \ll 100$ K. The notorious change in the value of μ, ranging from ≈3 (unirradiated, close to small bundles) to ≈0.7 (irradiated, close to large bundles) cannot be explained by the strong enhancement of the J_c values at low temperatures produced by the irradiation [7]. According to the collective creep theory a crossover from small to large bundles corresponds to a reduction in the $J_c/J_{depairing}$ ratio [10]. This fact indicates that μ values for pinning dominated by random nanoparticles or synergistic combinations of defects may be distant to those predicted by the collective pinning theory for random point defects.

Another aspect to be considered in figure 3(a) is the shift of the crossover to fast creep (associated with a change from elastic to plastic creep) to smaller T/T_c values [35]. This result is different than in $x = 0.75$F1 (the crossover shift to higher temperatures, see figure 2(a)) and in irradiated Co-122 (the crossover remain approximately at the same T/T_c) [22]. These differences can be associated with a balance between the effectiveness of the pinning produced by small defects in the different samples (random point), and with the increment of the vortex fluctuations produced by the irradiation. Experimental determination of λ in $x = 0.5$AG and $x = 0.5$F2, indicates that the irradiation produces an increment of $\lambda(0)$ from 260 nm to 420 nm [28], whereas H_{c2} values and $\gamma_{(T \to Tc)} \approx 1.8$ are not affected. The modification of the intrinsic superconductor parameters in $x = 0.5$ produces an increment in $Gi \approx 1 \times 10^{-4}$ ($x = 0.5$AG) to $Gi \approx 8 \times 10^{-4}$ ($x = 0.5$F2).

The results shown in this paper indicate that J_c in $Na_{1-x}Ca_xFe_2As_2$ single crystals can be enhanced by random point defects created by proton irradiation, as previously shown in other 122 systems [21, 22]. The Maley analysis indicates that U_0 is increased by the addition of random point defects. We found that the glassy μ exponent in both samples is close to that predicted in the so-called large bundle regime ($\mu = 7/9$) for random point defects at high magnetic fields [10]. The large increment in U_0 (evident from a drop in the S (T) values) can be understood by the concept of collective pinning (valid for small fraction of depairing critical current). This concept considers that the vortex interacts with several defects and its position is defined by the sum of interactions [10]. The force accumulated along a vortex segment L is $\Im_{\rm pin}(L) \approx (f_{\rm pin}^2 n_i \xi^2 L)^{1/2}$, where n_i is the density of pins acting with an individual force $f_{\rm pin}$. The typical distance where the vortex can be elastically self-readjusted is called the collective pinning length, $L_c \approx \xi\,(J_{\rm dep}/J_c)^{1/2}$. The resulting expression for the collective pinning energy (U_c) is given by $U_c \approx H_c^2 \xi^3/\gamma\,(J_c/J_0)^{1/2} \approx T_c\,(J_c(1-t)/J_0 G_i)^{1/2}$ (equation (6)), with $t = T/T_c$. Thus, by considering the intrinsic superconducting parameters of our crystals, U_c (0) ≈ 200 K (x = 0.75) and U_c (0) ≈ 500 K (x = 0.5) were obtained. These values are of the same order as those obtained from the Maley analysis. Some deviations between the values of U_0 obtained by the Maley analysis and the equation (6) can be expected due to the influence of the irradiation in the intrinsic superconducting parameters and the approximations included in the estimation. For instance, $\lambda_{ab}(0)$ in x = 0.5F2 increases from 260 nm to 430 nm as a consequence of the irradiation [28], which affects the estimation of U_c according to equation (4). No measurements of $\lambda_{ab}(0)$ in x = 0.75F1 have been performed.

Finally, the type of pinning produced by the irradiation in each single crystal can be understood from variations in T_c and in the electronic mean free path (δT_c and δl pinning, respectively). Pinning by extended defects such asrandom nanoparticles corresponds to δT_c, whereas δl pinning applies to point defects. The respective functions for each mechanism in the single vortex regime can be written as $J_c(t)/J_c(0) = (1-t^2)^{7/6}(1+t^2)^{5/6}$ and $J_c(t)/J_c(0) = (1-t^2)^{5/2}(1+t^2)^{-1/2}$, respectively [40]. Figures 4(a), (b) shows the results obtained for both single crystals before and after the irradiations at $\mu_o H$ = 0.001 T. In order to compare the effects of the δl and the δT_c pinning mechanisms, the P parameter was defined as $P_l = P_1 J_c^l(T)/J_c(T)$ and $P_{Tc} = \frac{P_2 J_c^{Tc}(T)}{J_c(T)}$, which represent the δl and the δT_c with $P_l + P_{Tc} = 1$ (see figure 4(c)) [41]. Before irradiating, the pinning in x = 0.75AG can be associated with a combination of δT_c and δl, whereas in x = 0.5AG it can be associated with δT_c at low temperatures, with a clear crossover (T^{cr}) to δl at intermediate temperaturas [27]. After irradiating, the pinning in x = 0.75F1 is dominated by δl, whereas the scenario in x = 0.5F2 is different. The low temperature range (approximately T < 10 K) initially dominated by δT_c presents a high contribution of δl. At high temperatures no changes are observed (δl pinning).

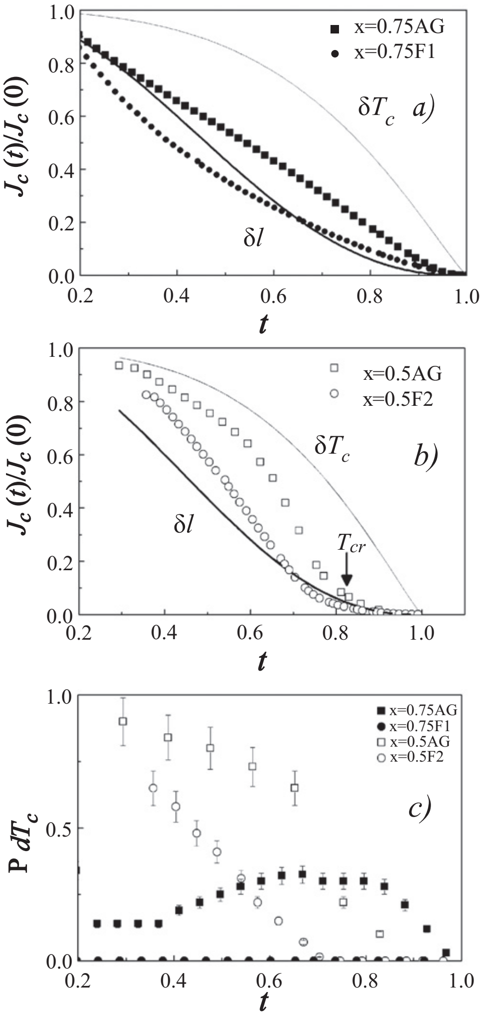

Figure 4. Reduced temperature (T/T_c) dependence of $J_c/J_c(0)$ experimental, and determined by δT_c and δl mechanism in (a) x = 0.5AG and x = 0.75F1. (b) x = 0.5AG and x = 0.5F2. In both cases the applied magnetic field is $\mu_0 H$ = 0.001 T. (c) Reduced temperature (T/T_c) dependence of the δT_c contribution for both single crystals before and after the irradiations (see details in the text).

4. Conclusions

We study the influence of random point defects produced by proton irradiation in the vortex dynamics of $Na_xCa_{1-x}Fe_2As_2$ single crystals with similar pinning landscape (intrinsic random point defects and strong pinning centers such as nanoparticles). The results show that the J_c values are enhanced by irradiation up to two (x = 0.5) and three (x = 0.75) times in comparison with as-grown single crystals. The plateau associated with glassy relaxation initially present in as-grown single crystals disappears after the irradiations as consequence of an increment in the collective pinning energy (U_c ≈ 350–400 K). Furthermore, the Maley analyses indicate that both samples present a glassy exponent μ close to that expected in the so-called large bundle regime ($\mu \approx 7/9$). The effectiveness of the pinning produced by random point defects depends on both, intrinsic superconducting properties and the interaction of the vortices with the pinning landscape. The proton irradiation in x = 0.75 (higher H_c smaller ξ), improves the pinning in all the temperature range. In addition, the effect becomes noticeable even at high temperatures (T/T_c > 0.9). On the other hand, in x = 0.5 (smaller H_c larger ξ), random point defects modify the vortex dynamics at low temperatures (manifested in an increment of J_c and a drop in S). Due to the increment in the vortex fluctuation at intermediate and high temperatures (up T/T_c > 0.65), the contribution of additional random point defects (with radius smaller than ξ) to the pinning mechanisms becomes negligible.

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