Fluctuation conductivity and possible pseudogap state in FeAs-based superconductor $EuFeAsO_{0.85}F_{0.15}$

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Abstract

The study of excess conductivity $\sigma'(T)$ in the textured polycrystalline FeAs-based superconductor $EuFeAsO_{0.85}F_{0.15}$ ($T_c = 11$ K) prepared by the solid state synthesis is reported for the first time. The $\sigma'(T)$ analysis has been performed within the local pair (LP) model based on the assumption of the LPs formation in cuprate high-T_c superconductors (cuprates) below the pseudogap (PG) temperature $T^* \gg T_c$. Similarly to the cuprates, near T_c $\sigma'(T)$ is adequately described by the 3D term of the Aslamasov–Larkin (AL) theory but the range of the 3D-AL fluctuations, ΔT_{3D}, is relatively short. Above the crossover temperature $T_0 \approx 11.7$ K $\sigma'(T)$ is described by the 2D Maki–Thompson (MT) fluctuation term of the Hikami–Larkin theory. But enhanced 2D-MT fluctuation contribution being typical for the magnetic superconductors is observed. Within the LP model the PG parameter, $\Delta^*(T)$, was determined for the first time. It is shown that $\Delta^*(T)$ demonstrates the narrow maximum at $T_s \approx 160$ K followed by the descending linear length down to $T_{SDW} = T_{NFe} \approx 133$ K. Observed small ΔT_{3D}, enlarged 2D $\sigma'(T)$ and linear $\Delta^*(T)$ are considered to be the evidence of the enhanced magnetic interaction in $EuFeAsO_{0.85}F_{0.15}$. Importantly, the slop of the linear $\Delta^*(T)$ and its length are found to be the same as it is revealed for $SmFeAsO_{0.85}$. The results suggest both the similarity of the magnetic interaction processes in different Fe-pnictides and applicability of the LP model to the $\sigma'(T)$ analysis even in magnetic superconductors.

1. Introduction

The discovery of high-Tc superconductivity in FeAs-based compounds (Fe-pnictides or FePn's) [1] has stimulated a great burst of research activity (e.g. see [2–5] and references therein). Following the discovery in LaFeAs(O,F) with $T_c = 26$ K [1], superconductivity was found in many materials with related crystal structures, that commonly possess iron-pnictide or iron-chalcogenide layers. Actually the various members of the iron containing FePn's can be divided into three main family of materials, which show superconducting (SC) transition upon substitution by a dopant or upon applying external pressure. They are, (i) the quaternary 1111 compounds, RFeAsO, where R represents a lanthanide such as La, Ce, Sm, Eu etc [1, 6–8] with transition temperatures as high as 56 K in $SmFeAsO_{1-x}F_x$; (ii) the ternary AFe_2As_2 (A = Ca, Sr, Ba, Eu) [9–12] compounds, also known as 122 systems that exhibit superconductivity up to 38 K; and (iii) the binary chalcogenide 11 systems (e.g. FeSe) with the SC transition temperatures up to 14 K [13]. The common feature for the first two families is a structural transition from a tetragonal to an orthorhombic phase at $T_s = (150–190)$ K which is closely related to the formation of a spin-density-wave (SDW) type magnetic instability at $T = T_{SDW}$ due to antiferromagnetic (AF) ordering of the Fe spins [2]. For '1111' systems $T_{SDW} < T_S$ [2, 14] whereas for '122' compound, e.g for $EuFe_2As_2$ [15], $T_{SDW} \approx T_s$. Apparently, the superconductivity emerges from the FeAs or FeSe layers which are

the building blocks of the corresponding quasi two-dimensional crystal structures suggesting the analogy to the cuprate-based high-T_c superconductors (HTSC's or cuprates). Like in the cuprates and heavy fermion metals, superconductivity of the iron-based compounds has a direct relation to magnetism. The maximal T_c is found in the vicinity of the extrapolated point where SDW order of the Fe 3d magnetic moment is suppressed by doping or pressure.

However, also like in the cuprates, up to now the physical nature of the SC pairing mechanism in the new FeAs-based HTSC's remains uncertain [16]. There is a growing evidence that it is presumably of the magnetic type [5, 16], and all members of the iron arsenide $RFeAsO_{1-x}F_x$ family are characterized by the long-range (non-local) magnetic correlations [17], whereas the role of the common electron–phonon interaction [18] is still questionable. It is well known that upon electron or hole doping with F substitution at the O site [1, 19, 20] or with oxygen vacancies [21, 22], all properties of the parent RFeAsO compounds drastically change and evident AF order has to disappear [2]. However, recent results [23–27] point toward an important role of the low-energy spin magnetic fluctuations [28]. They emerge on doping away from the parent AF state which is of a SDW type [23, 24, 27] as mentioned above. Thus, below T_S the AF fluctuations, being likely of the spin wave type, are believed to noticeably affect the properties of doped $RFeAsO_{1-x}F_x$ systems [17, 23, 24]. As shown by many studies [23–26], the static magnetism persists well into the SC regime of FePn's. As a result, rather peculiar normal state behavior of the doped systems upon T diminution is expected in this case [19, 25, 26]. Besides, it was recently shown theoretically that antiferromagnetism and superconductivity can coexist in these materials only if Cooper pairs form an unconventional, sign-changing state [17, 26, 27].

The correlation between the SDW and SC order is a central topic in the current research on the FeAs-based high-T_c superconductors. However, the clear nature of the complex interplay between magnetism and superconductivity in the FeAs-based HTSC's is still rather controversial. As a result, rather complicated phase diagrams for different FePn's [20, 25–27] and especially for $SmFeAsO_{1-x}F_x$ [19, 29] are reported. For all these HTSC's rather wide temperature region is found in which superconductivity coexists with SDW regime.

In this paper we focus on the study of the fluctuation conductivity (FLC) and possible pseudogap (PG) in $EuFeAsO_{0.85}F_{15}$. Somewhat surprisingly, among the quaternary '1111' compounds $EuFeAsO_{1-x}F_x$ is not enough studied. It is likely due to the largest atomic radius of Eu, $r_{at} \approx 2.1$ Å, resulting in relatively low $T_c \approx 11$ K and $H_{c2} \approx 14$ T at 0.7 T_c [30]. In this case just the ternary Eu-based '122' compounds such as $Eu_{0.5}K_{0.5}Fe_2As_2$ ($T_c = 32$ K) [10], $EuFe_2(As_{1-x}P_x)_2$ ($T_c \approx 28$ K) [31] and $EuFe_{2-x}Co_xAs_2$ ($T_c \approx 21$ K) (see [32] and references therein) were widely studied. Special attention was devoted to $EuFe_2As_2$ because it is the only rare-Earth based member of the '122' family. Besides, in contrast to the AFe_2As_2 (A = Ca, Sr, Ba) compounds, where only the iron possesses a magnetic moment, in $EuFe_2As_2$ a large additional magnetic moment of about $7\mu_B$ is carried by Eu which is in the 2+ state. As a result, it exhibits a combined transition of structural and SDW order of Fe magnetic moments at the highest reported $T_S = T_{SDW} \approx 190$ K in the FePn's and subsequently Eu 4f moments order below $T_{NEu} \approx 20$ K into a canted AF state [10, 22, 23]. Thus, in Eu-based compounds it seems to be possible to study the interplay between the localized Eu^{2+} moments and the itinerant magnetism of the FeAs layers along with its influence on superconductivity at different doping. Besides, it was found that the AF ground state could easily be switched to a FM state in small in-plane fields of order 1 T [15]. These observations suggest that the Eu-based systems are close to a FM instability [15, 30]. Thus, many different properties of the parent as well as of the doped $EuFe_2As_2$, from relatively simple resistivity measurements [10] up to angle resolved photoemission spectroscopy (ARPES) studies which revealed the droplet-like Fermi surfaces in the AF phase of $EuFe_2As_2$ [34], were thoroughly analyzed. At the same time, the properties of $EuFeAsO_{1-x}F_x$ remain substantially uncertain [30, 35].

Moreover, despite of the number of papers devoted to the FePn's, in contrast to cuprates, there is an evident lack of the FLC and PG studies in FePn's [2]. Strictly speaking, apart from our investigation of the FLC and PG in $SmFeAsO_{0.85}$ [14] we have no information as for the similar experiments performed by another research groups. As a result, the possibility of a PG state in the FeAs-based HTSC's still remains controversial [36]. It is well known that the PG is a specific state of matter which is observed in underdoped cuprates and characterized by reduced density of states (DOS) at the Fermi level at temperatures well above T_c [36–39]. For $YBa_2Cu_3O_{7-\delta}$ (YBCO) the noticeable reduction of DOS, i.e PG, was observed below representative PG temperature $T^* \gg T_c$ in the study of the Knight shift measured by NMR technique [40]. Recently reduced DOS and PG were directly measured by ARPES for optimally doped Bi2201 [41]. Unfortunately, as far as we know, there is no information about such experiments performed on FePn's.

Nevertheless, electron spin resonance (ESR) of Eu^{2+} which successfully probes the local DOS of the conduction electrons in the normal state ($T > T_{SDW}$) have recently been measured on $EuFe_{2-x}Co_xAs_2$ ($0 \leqslant x \leqslant 0.4$) and $EuFe_2As_{2-y}P_y$ ($0 \leqslant y \leqslant 0.43$) iron pnictides [32]. It was shown that substitution of cobalt for iron or phosphorous for arsenic gradually suppresses the SDW phase and reduces the slope of the linear increase of the linewidth $\Delta H(T)$ above T_{SDW}, due to the Korringa relaxation, down to about $b = 3$ Oe/K. This indicates the reduction of the conduction-electron DOS at the Fermi energy on increasing Co

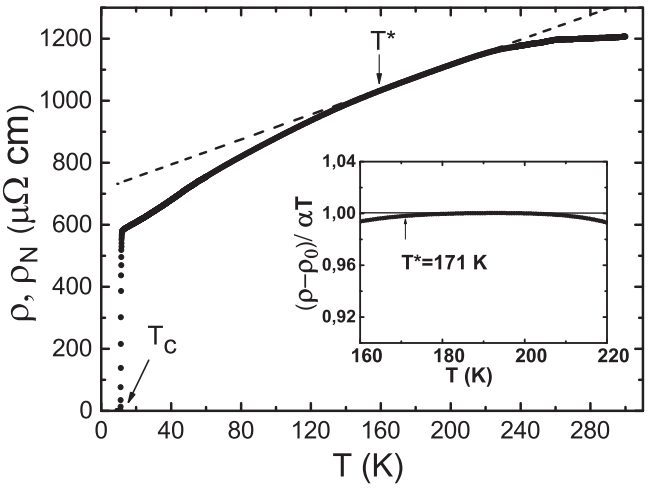

Figure 1. Temperature dependence of the in-plane resistivity ρ of $EuFeAsO_{0.85}F_{0.15}$ textured polycrystal (dots). Straight dashed line designates normal-state resistivity $\rho_N(T)$ extrapolated to the low T region. Insert displays the more precise way of $T^* = 171$ K determination using $(\rho - \rho_0)/aT$ versus T criterion (see the text).

or P substitution. The fact suggests the possibility of the PG state in doped FePn's, at least in the Eu-based compounds.

To clarify the issue, we have analyzed the excess (fluctuation) conductivity derived from the resistivity measurements on $EuFeAsO_{0.85}F_{0.15}$. The analysis has been performed within the LP model [42, 43], as mentioned above. The model is based on the assumption that in cuprate HTSC's the PG appears due to formation of the local pairs (LPs) below T^* [38, 44–46].

2. Experiment

Textured polycrystalline samples of $EuFeAsO_{0.85}F_{0.15}$ were synthesized by solid state reaction method as described elsewhere [10, 30]. Rectangular samples of about $5 \times 1 \times 1$ mm were cut out of the pressed pellets. A fully computerized setup on the bases of a physical properties measurement system (Quantum Design PPMS-9T) utilizing the four-point probe technique was used to measure the longitudinal resistivity, $\rho_{xx}(T)$, with sufficient accuracy. Silver epoxy contacts were glued to the extremities of the sample in order to produce a uniform current distribution in the central region where voltage probes in the form of parallel stripes were placed. Contact resistances below 1Ω were obtained.

3. Results and discussion

3.1. Resistivity

Temperature dependence of resistivity $\rho(T) = \rho_{xx}(T)$ for studied $EuFeAsO_{0.85}F_{0.15}$ with $T_c = 11$ K is shown in figure 1 (dots). The SC transition temperature T_c is determined by extrapolating the linear part of the resistive transition to $\rho(T_c) = 0$ [48, 49]. The comparatively small width of the SC transition rules out significant variation of the SC parameters over the sample volume. The whole resistivity curve (figure 1) is somewhat *S*-shaped with the feebly marked positive thermally activated buckling which is characteristic for the slightly doped cuprates [50, 51]. However, over the temperature range $T^* \approx 171$ K to $T \approx 210$ K $\rho(T)$ varies linearly with T at a rate $d\rho/dT = 2.0\ \mu\ \Omega$ cm K^{-1}. This linearity sorts well with the normal state of the HTSC's, as it was proved by the theory [52]. Above 210 K $\rho(T)$ deviates downwards from the linear dependence (figure 1) which is typical for the FePn's [1, 2, 14]. The linear dependence can be written as $\rho_N(T) = aT + \rho_0$, where $\rho_N(T)$ is the linear normal state resistivity and ρ_0 is its intercept with *y*-axis. Certainly, $(\rho(T) - \rho_0)/aT = 1$ above the PG temperature T^*, providing the more precise way of T^* determination with accuracy ±0.5 K [53, 54]. Insert in figure 1 demonstrates the result of this approach.

3.2. Fluctuation conductivity

With decrease of temperature, resistivity $\rho(T)$ expectedly deviates downwards from the normal state linear dependence at $T^* = (171 \pm 0.5)$ K $\gg T_c$ (figure 1). This results in appearance of the excess conductivity as a difference between measured $\rho(T)$ and the normal state resistivity $\rho_N(T)$ extrapolated to low T region [42, 52]:

Table 1. The parameters of the $YB_2Cu_3O_{7-\delta}$ (1), $SmFeAsO_{0.85}$ (2), $EuFeAsO_{0.85}F_{0.15}$ (3) and $Dy_{0.6}Y_{0.4}Rh_{3.85}Ru_{0.15}B_4$ (4).

Sample	T_c (K)	T_c^{mf} (K)	T^* (K)	ΔT_{3D} (K)	$\xi_c(0)$ (Å)	$\Delta(\ln\sigma')$	D^*
1	87.4	88.5	203	1.8	1.65 ± 0.01	0.2	5 ± 0.1
2	55	57	175	1.5	1.4 ± 0.02	0.5	5 ± 0.2
3	11	11.2	171	0.5	2.84 ± 0.02	1.4	4.4 ± 0.1
4	6.4	6.68	161	0.16	2.9 ± 0.03	1.7	—

$$\sigma'(T) = \sigma(T) - \sigma_N(T) = [1/\rho(T)] - [1/\rho_N(T)], \tag{1}$$

The procedure of the $\rho_N(T)$ definition by the linear dependence is widely used in the literature (see [42, 48, 54–56] and references therein).

In the case of cuprates, $\sigma'(T)$ is considered to be intimately connected with the PG [42, 43, 49] and is believed to appear due to formation of the LPs at $T \leqslant T^*$ regarded as a PG temperature [38, 44–47]. There are several experiments [40, 41], as mentioned above, in which the decrease of $\rho(T)$ below T^* is followed by the partial decrease of DOS at the Fermi level, which is just called a PG [36, 42, 44]. In the case of FePn's it is believed that magnetic subsystem also can be taken into account to explain the excess conductivity appearance. It is especially the case for $EuFeAsO_{0.85}F_{0.15}$ where the iron magnetic moment is added by the large magnetic moment carried by Eu atoms [37]. Thus, in FePn's the excess conductivity is expected to be due to both LPs formation and a specific interaction of the magnetic type which has to somehow govern the LPs behavior below T^*. To the best of our knowledge, in practice the excess conductivity in FePn's, and especially in $EuFeAsO_{0.85}F_{0.15}$, is poorly studied. Moreover, except for the mentioned above ESR experiments [32], there are no reliable measurements of the temperature dependence of DOS in Eu-based FePn's. As a result, it is not entirely clear does observed excess conductivity (1) appear due to the PG opening or not? Thus, the question as for the possibility of a PG state in FePn's still remains uncertain. Besides, up to now there is no rigorous theory to describe the excess conductivity in the whole temperature range from T^* down to T_c in the HTSC's. Taking above considerations into account, we have analyzed found $\sigma'(T)$ within our LP model paying more attention at the possible difference in revealed results in comparison with those obtained for YBCO films [42] and $SmFeAsO_{0.85}$ polycrystals [14, 42] regarded as the reference samples. Here we focus on the analysis of the FLC and possible PG derived from measured excess conductivity within the LP model [42, 43]. Determined from the analysis sample parameters are summarized in table 1.

The LP model approach consists of several logical steps [42]. First, the mean field critical temperature T_c^{mf} must be defined. It determines the reduced temperature [57]

$$\varepsilon = (T - T_c^{mf}) \,/\, T_c^{mf} \tag{2}$$

and, in that way, is of a primarily importance for the whole analysis. Here $T_c^{mf} > T_c$ is the critical temperature in the mean-field approximation, which separates the FLC region from the region of critical fluctuations or fluctuations of the SC order parameter Δ directly near T_c (where $\Delta < k_B T$) neglected in the Ginzburg–Landau theory [58]. As shown by many studies (see [42, 59] and references therein), FLC near T_c is always described by the standard equation of the Aslamasov–Larkin (AL) theory [60] with the critical exponent $\lambda = -1/2$ (figure 3, line 1) which determines the FLC in any 3D system

$$\sigma'_{AL3D} = C_{3D} \frac{e^2}{32\,\hbar\,\xi_c(0)} \varepsilon^{-1/2}. \tag{3}$$

Here C_{3D} is a numerical factor used to fit the data to the theory [55, 59] and $\xi_c(T)$ is a coherence length along the c-axis [57]. This means that the conventional 3D FLC is realized in HTSC's as $T \to T_c$ [59, 61]. Simple algebra yields $\sigma'^{-2} \sim (T - T_c^{mf})/\,T_c^{mf}$. Evidently, $\sigma'^{-2} = 0$ when $T = T_c^{mf}$. This way of T_c^{mf} determination was proposed in [62] and justified by different FLC experiments [42, 55, 59]. Moreover, when T_c^{mf} is properly chosen the data in the 3D fluctuation region near T_c is always fitted by equation (3) [42].

Figure 2 displays the σ'^{-2} versus T plot for studied $EuFeAsO_{0.85}F_{0.15}$ (dots). Because of the high accuracy of the resistivity measurements, the error bars on all curves, except figure 6, are less that the experimental points size. Extremely good linear $\sigma'^{-2}(T)$ dependence, which corresponds to the 3D AL fluctuation region, is observed near T_c. The intercept of the extrapolated linear $\sigma'^{-2}(T)$ with T-axis determines $T_c^{mf} = (11.2 \pm 0.01)$ K. Above the crossover temperature $T_0 \approx 11.73$ K the data deviates right from the line suggesting the presence of the 2D Maki–Thompson (MT) [63, 64] fluctuation contribution to $\sigma'(T)$ [59, 61]. At the crossover temperature $T_0 \sim \varepsilon_0$ the coherence length $\xi_c(T) = \xi_c(0)\varepsilon^{-1/2}$ is to amount to d, which is the distance between conducting layers in HTSC's [48, 55, 57]. This yields

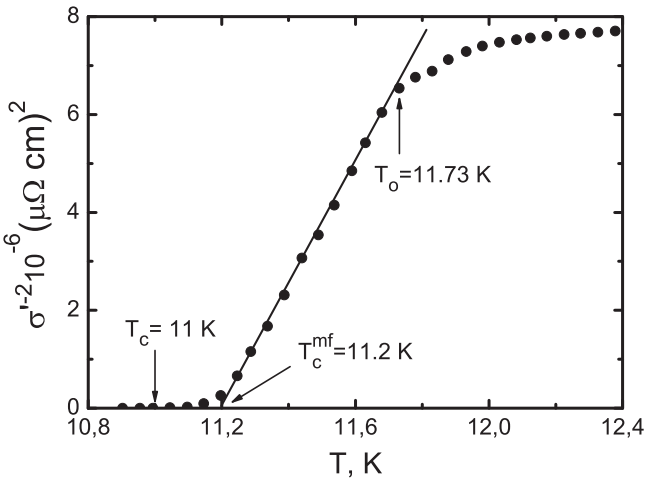

Figure 2. Inverted squared excess conductivity σ'^{-2} (dots) as a function of temperature plotted in the temperature range near T_c. The intercept of its linear extrapolation with the x-axis determines $T_c^{mf} = 11.2$ K [62]. The straight solid line is in keeping with the linear σ'^{-2} which actually corresponds to the 3D AL fluctuation region.

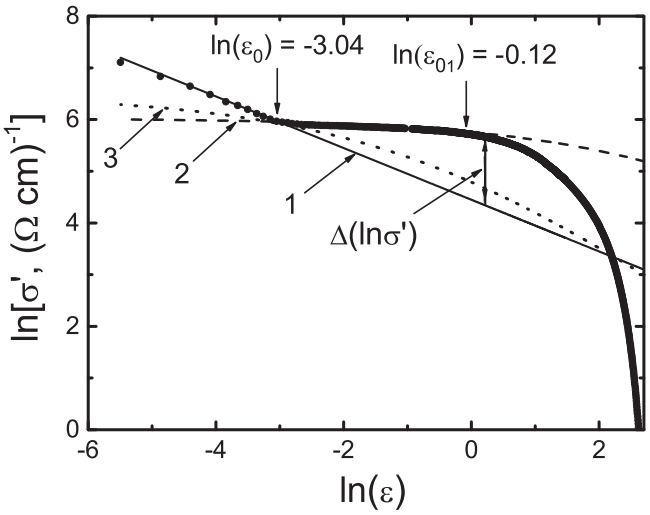

Figure 3. $\ln\sigma'$ as a function of $\ln\varepsilon$ (dots) compared with fluctuation theories: 1–3D AL; 2—MT with $d = d_{01}$; 3—MT with $d = 13$ Å. $\ln\varepsilon_0 = -3.04$ corresponds to the crossover temperature T_0 which allows the determination of $\xi_c(0) = d\sqrt{\varepsilon_0} = (2.84 \pm 0.02)$ Å. Accordingly, $\ln\varepsilon_{01} = -0.12$ corresponds to the representative temperature T_{01} which determines the range of the SC fluctuations where the Josephson interaction between the internal planes has to set in. $\Delta(\ln\sigma')$ indicates the increase of $\ln\sigma'$ likely due to enhanced magnetic interaction.

$$\xi_c(0) = d\sqrt{\varepsilon_0} \tag{4}$$

and allows the determination of $\xi_c(0)$ which is one of the important parameter of the LP model analysis.

The excess conductivity σ', derived from the resistivity measurements by means of equation (1), is plotted in figure 3 (dots) as a function of ε in customary double logarithmic scale. In complete agreement with the above considerations, from T_c^{mf} and up to $T_0 = 11.73$ K ($\ln\varepsilon_0 \approx -3.04$) $\ln\sigma'$ versus $\ln\epsilon$ is well fitted by the 3D fluctuation term (3) of the AL theory (figure 3, solid line 1) with $\xi_c(0) = (2.84 \pm 0.02)$ Å determined by equation (4) and $C_{3D} = 0.32$. By analogy with cuprates, to find $\xi_c(0)$ we make use of $d = c$ which is the c-axis lattice parameter [42, 48]. Unfortunately, it is not much known about the lattice parameters in $EuFeAsO_{0.85}F_{15}$. That is why, in contrast to cuprates where $d \approx 11.7$ Å [59], now we set $d = c = 13$Å being determined for $Eu_{0.5}K_{0.5}Fe_2As_2$ [10]. The found parameters are summarized in table 1.

Above T_0 measured $\sigma'(\epsilon)$ noticeably upturns from the linear 3D AL dependence (figure 3, dots) indicating the appearance of the 2D MT fluctuations, as mentioned above. Really, above T_0 and up to $T_{01} \approx 21$ K ($\ln\varepsilon_{01} \approx -0.12$) $\sigma'(T)$ is fitted by the MT fluctuation term (5) (figure 3, dashed curve 2) of the HL theory [57]

$$\sigma'_{\rm MT} = \frac{e^2}{8d\,\hbar}\frac{1}{1-\alpha/\delta}\ln\left((\delta/\alpha)\,\frac{1+\alpha+\sqrt{1+2\,\alpha}}{1+\delta+\sqrt{1+2\,\delta}}\right)\varepsilon^{-1}, \tag{5}$$

which dominates well above T_c in the 2D fluctuation region [57, 61, 65]. In equation (5)

$$\alpha = 2\left[\frac{\xi_c(0)}{d}\right]^2\varepsilon^{-1} \tag{6}$$

is a coupling parameter

$$\delta = \beta\frac{16}{\pi\,\hbar}\left[\frac{\xi_c(0)}{d}\right]^2 k_B\,T\,\tau_\phi \tag{7}$$

is the pair-breaking parameter, τ_ϕ that is defined by equation

$$\tau_\phi\beta\,T = \pi\hbar/8k_B\varepsilon = A/\varepsilon \tag{8}$$

is the phase relaxation time, and $A = 2.998\times10^{-12}$ sK. The factor $\beta = 1.203(l\,/\,\xi_{ab})$, where l is the mean-free path and ξ_{ab} is the coherence length in the ab plane, considering the clean limit approach ($l > \xi$) [42, 65]. Eventually, above T_{01} the data noticeably downturns from the theory.

The physics underlying this picture is determined by the extremely short coherence length $\xi_c(T)$ which rapidly decreases with increase of temperature [57, 58]. Near $T_c\,\xi_c(T) > d$ and connects the fluctuating Cooper pairs (FCP) by Josephson interaction in the whole sample volume, thus forming the 3D state described by the 3D AL term. Above T_0, where $d > \xi_c(T) > d_{01}$, the Josephson interaction between the pairs in the whole sample volume is lost. But up to $T_{01} > T_0$ the Josephson interaction between the internal planes, separated by d_{01}, is hold out, thus forming the 2D state [42, 61], in which $\sigma'(\varepsilon)$ is described by the 2D MT term (5) of the HL theory [57]. That is why, T_0 is considered as a crossover temperature corresponding to the 3D–2D and simultaneously to the AL–MT crossover [42, 61, 65]. Finally, above T_{01} (above $\ln\varepsilon_{01}$ (figure 3)), at which $\xi_c(T_{01}) = d_{01}$, the pairs are believed to be confined within As–Fe–As layers, or within CuO_2 planes in the case of cuprates, thus forming the quasi-2D conductivity [61]. In this case $\xi_c(T) < d_{01}$, and there is no direct interaction even between the internal planes now. As a result, $\sigma'(T)$ does not submit to any fluctuation theory. In FePn's $d_{01} \ll d$ is the distance between As atoms in the conducting As–Fe–As layers ([20, 66, 67] and references therein). In the studied sample $d_{01} \approx 3.02$ Å in good agreement with that found for $SmFeAsO_{0.85}$ [14].

Revealed $\xi_c(0) = (2.84 \pm 0.02)$ Å is about 1.7 and 2.0 times of that obtained for the YBCO film ($T_c = 87.4$ K) [42] and correspondingly for $SmFeAsO_{0.85}$ polycrystal ($T_c = 55$ K) [14] (table 1). It is not surprising seeing we assume that $\xi(0) \sim \hbar v_F/\pi\Delta(0)$ or $\xi(0) \sim 2\hbar v_F/5\pi k_B T_c$ [65]. Here we have taken into account the experimental [68] and theoretical [69, 70] fact that in YBCO HTSC's $2\Delta(0)/k_B T_c \sim 5$ which is the sign of the strong superconductivity in contrast to BCS weak coupling limit $2\Delta(0)/k_B T_c^{\rm BCS} \approx 4.28$ established for d-wave superconductors [71, 72]. Thus, the lower T_c the higher both $\xi_c(0)$ and correspondingly the in-plane coherence length $\xi_{ab}(0)$ in agreement with our results. Simultaneously, the temperature range of the 3D FLC turned out to be rather short: $\Delta T_{3D} = T_0 - T_c^{mf} \approx 0.5$ K (figures 2 and 3). Accordingly, $\Delta T_{3D} \approx 1.8$ K and $\Delta T_{3D} \approx 1.5$ K were obtained for the reference YBCO film [42] and $SmFeAsO_{0.85}$ polycrystal [14], respectively. The shortening of the ΔT_{3D} can likely be considered as a first sign of the enhanced magnetic interaction in $EuFeAsO_{0.85}F_{0.15}$. The conclusion comes from the fact that the shortest $\Delta T_{3D} \approx 0.16$ K was observed for the utterly magnetic superconductor $Dy_{0.6}Y_{0.4}Rh_{3.85}Ru_{0.15}B_4$ with $T_c = 6.4$ K [73] (see the table).

In the 2D fluctuation region $\sigma'(T)$ is noticeably enlarged in comparison to that obtained for the YBCO films [42, 65] (figure 3, curve 3). For the first time the enhancement of the excess conductivity above T_0, marked in figure 3 as a maximal distance $\Delta(\ln\sigma')$ between the data and extrapolated 3D AL term, was observed for $SmFeAsO_{0.85}$ [14]. But now the enhancement is even larger (refer to figure 3). The largest $\Delta(\ln\sigma')$ was again observed for the utterly magnetic superconductor $Dy_{0.6}Y_{0.4}Rh_{3.85}Ru_{0.15}B_4$ (table 1). In that case the $\ln\sigma'$ versus $\ln\varepsilon$ was found to be completely flat in the large temperature range above T_0 being evidently behind any fluctuation theory description [73]. In our case $\ln\sigma'$ versus $\ln\varepsilon$ is also somewhat close to be flat (figure 3, dots). The result allows us to conclude that observed increase of $\sigma'(T)$ above T_0 is most likely due to expected enhanced magnetic interaction in studied $EuFeAsO_{0.85}F_{0.15}$. Nevertheless, equation (5) is still of use to fit the data. Unfortunately neither l [65] nor ξ_{ab} [55] are measured in our experiment, and τ_ϕ remains uncertain. That is why we have to use somewhat another approach. First, we set $\delta = 2$, because in YBCO films it is always $\approx$2 when $\xi_c(0)$ is properly defined [42, 65]. Next, we have employed the following equality

$$\xi_c(0) = d\,\sqrt{\varepsilon}_0 = d_{01}\,\sqrt{\varepsilon}_{01}, \tag{9}$$

to rewrite equation (6) as

$$\alpha = 2\,\varepsilon_{01}/\varepsilon. \tag{10}$$

Thus, just the value of ε_{01} governs equation (5) now, and the MT fit is rather good (figure 3). If we make use of the common approach and take the coupling parameter α from equation (6) with $d = c = 13$ Å, it will result in the dashed curve (3) (figure 3), which is close to that found for reference YBCO film [42] but apparently does not meet the case.

Summarizing results one may conclude that T_{01} is a representative temperature which determines the range of SC fluctuations above T_c, in which $\sigma'(T)$ obeys conventional fluctuation theories (refer to figure 3). At $T \geqslant T_{01}$ the theories do not work, and the data rapidly deviates down from the theoretical MT curve (equation (5)) (figure 3, curve 2) in full agreement with above considerations. It is likely the consequence of the theoretical prediction [74], justified by experiment [76], that up to T_{01} the stiffness of the order parameter wave function of the high-Tc superconductor has to persist. It means, in turn, that below T_{01} the FCPs have to behave in a good many way like the conventional SC pairs, but without the long-range ordering (the so-called short-range phase correlations) [74, 76]. On the other hand, it is worth to repeat that $\xi_c(T)$, which increases along with decrease of temperature [58], becomes equal to d_{01} just at $T = T_{01}$ [14], finally connecting the internal layers by the Josephson interaction at $T < T_{01}$ [61]. As a result, just below T_{01} somewhat correlated 2D FLC, which obeys the HL fluctuation theory (MT term), appears in the FeAs-base superconductor (figure 3, curve 2), as mentioned above. Thus, there observes a definite correlation between the crystal structure and physical properties of the HTSC's, which becomes apparent owing to the extremely short coherence length of the HTSC's (table 1).

The LP model approach has provided a very good 2D MT fit in the case of $SmFeAsO_{0.85}$ [14]. In the case of $EuFeAsO_{0.85}F_{0.15}$, there are several peculiarities, mostly observed in the 2D fluctuation region, which allow one to conclude that the role of the magnetic interaction in studied $EuFeAsO_{0.85}F_{0.15}$ is expectedly larger than even in $SmFeAsO_{0.85}$. However, all these particularities do not affect the further considerations because to proceed with the analysis we only need the value of $\xi_c(0)$ which is strictly determined by the crossover temperature T_0.

3.3. PG analysis

From the above FLC analysis it is clear that in FePn's the FCPs have to persist at least up to T_{01}. To understand what will happen with the FCPs at the higher temperatures and to get information about the PG from the measured excess conductivity one evidently needs an equation which describes the whole experimental $\sigma'(T)$ curve from T^* down to T_c and contains the parameter Δ^* in the explicit form [42, 43]. In cuprates Δ^* is referred to as a PG which appears most likely due to the LPs formation [44–47], and $\Delta^*(T)$ has to reflect the peculiarities of the LPs behavior along with decrease of temperature below T^* [42, 78, 79]. In $EuFeAsO_{0.85}F_{0.15}$ the excess conductivity is assumed to appear due to both LPs formation and magnetic interaction, as mentioned above. Thus, the parameter $\Delta^*(T)$, extracted from the temperature dependence of $\sigma'(T)$ in this case, is expected to somehow reflect the complex interplay between the SC and magnetic fluctuations, which is of a primarily importance to comprehend the principles of the coupling mechanism in the FeAs-based HTSC's.

In vie of the absence of the rigorous theory, we have applied the LP model approach to perform the PG analysis. The equation for $\sigma'(\varepsilon)$ has been proposed in [78] with respect to the LPs

$$\sigma'(\varepsilon) = \frac{e^2 A_4 \left(1 - \frac{T}{T^*}\right)\left(\exp\left(-\frac{\Delta^*}{T}\right)\right)}{(16\,\hbar\,\xi_c(0))\sqrt{2\,\varepsilon^*_{c0}\sinh(2\,\varepsilon/\varepsilon^*_{c0})}}. \tag{11}$$

Here, $\Delta^* = \Delta^*(T_c) = \Delta^*(T_c^{mf})$ is assumed. Besides, the dynamics of pair-creation $(1 - T/T^*)$ and pair-breaking $\exp(-\Delta^*/T)$ below T^* has been taken into account in order to correctly describe the experiment [42, 78]. Solving equation (11) regarding $\Delta^*(T)$ one can readily obtain

$$\Delta^*(T) = T \ln \frac{e^2 A_4 \left(1 - \frac{T}{T^*}\right)}{\sigma'(T)\,16\,\hbar\,\xi_c(0)\,\sqrt{2\,\varepsilon^*_{c0}\sinh(2\,\varepsilon\,/\,\varepsilon^*_{c0})}}, \tag{12}$$

where A_4 is a scaling factor which has the same meaning as the C-factor in the FLC theory [42, 55, 78] and $\sigma'(T)$ is the excess conductivity measured over the whole temperature interval from T^* down to T_c^{mf}. Usually equation (11) fits the data rather good, suggesting conclusion that found by means of equation (12) $\Delta^*(T)$ has, in turn, to properly reflect the properties of the PG [42, 43, 78].

The next step of the LP model approach is to determine some additional unknown parameters needed for the further analysis. Apart from T^*, T_c^{mf} and $\xi_c(0)$ determined above, both equations (11) and (12) contain the theoretical parameter ε^*_{c0}, numerical factor A_4, and $\Delta^*(T_c)$, which is the PG value at T_c^{mf}. Within the LP model all the parameters can be easily determined from experiment. First, in the range of $\ln\varepsilon_{c01} < \ln\varepsilon < \ln\varepsilon_{c02}$ (figure 4) or accordingly $\varepsilon_{c01} < \varepsilon < \varepsilon_{c02}$ (13.2 K $< T <$ 24.6 K) (insert in figure 4), $\sigma'^{-1} \sim \exp(\varepsilon)$. This exponential dependence turns out to be the common feature of different HTSC's [42, 78, 80]. As a result, $\ln(\sigma'^{-1})$ is a linear function of ε with a slope $\alpha^* = 0.18$ which determines parameter $\varepsilon^*_{c0} = 1/\alpha^* = 5.54$ [78, 80].

To find A_4 one has to calculate $\ln\sigma'(\ln\varepsilon)$ using equation (11) in the whole temperature interval from T^* down to T_c fit it to experiment in the range of 3D AL fluctuations near T_c (figure 4), where $\ln\sigma'(\ln\varepsilon)$ is a linear

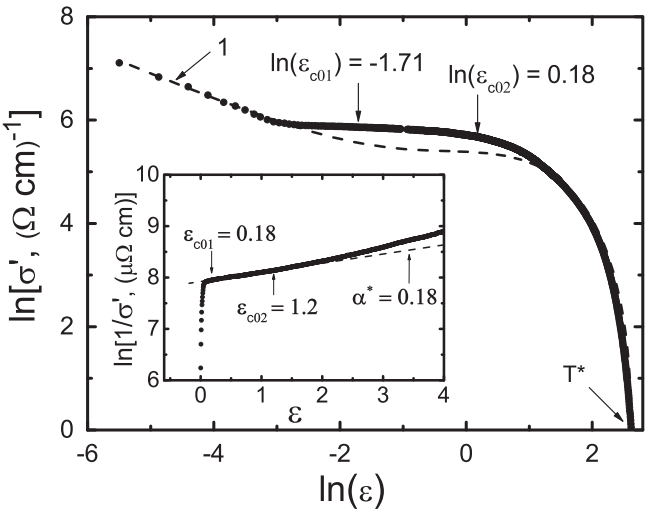

Figure 4. $\ln\sigma'$ versus ($\ln\varepsilon$) (dots) plotted over the whole temperature interval $T^* = 171$ K to $T_c^{mf} = 11.2$ K. The dashed curve (1) is fit to the data with equation (11). Insert: $\ln\sigma'^{-1}$ (dots) as a function of ε. Solid line indicates the linear part of the curve between $\varepsilon_{01}^* \sim 0.18$ and $\varepsilon_{02}^* \sim 1.2$. Corresponding $\ln\varepsilon_{01}^* \sim -1.71$ and $\ln\varepsilon_{02}^* \sim 0.18$ are marked by the arrows at the main panel. The slope $\alpha^* = 0.18$ determines the parameter $\varepsilon_{c0}^* = 1/\alpha^* = 5.56$ (see the text).

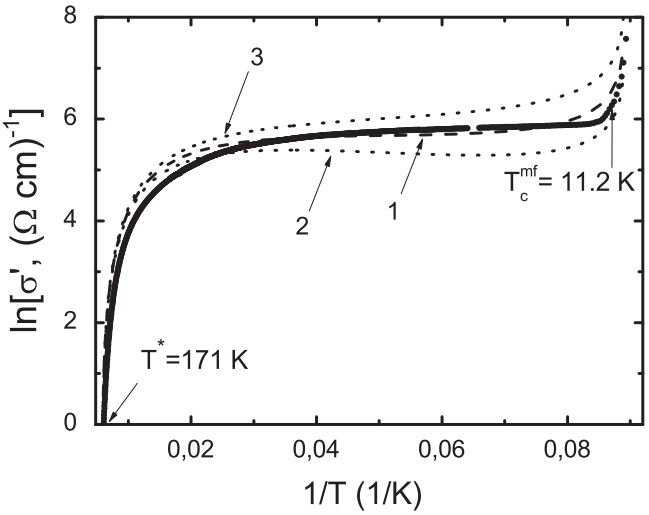

Figure 5. $\ln\sigma'$ as a function of $1/T$ (dots)) plotted over the whole temperature range T^* down to T_c^{mf}. The dashed and doted curves are fits to the data with equation (11). The best fit is obtained when equation (11) is computed with $\Delta^*(T_c) = 24,\ 2$ K ($D^* = 2\Delta^*(T_c)/k_B T_c = 4.4$) (dashed curve 1). Curves 2 and 3 correspond to $D^* = 5.6$ and 3.2, respectively, and shown for the comparison.

function of the reduced temperature ε with a slope $\lambda = -1/2$ [42, 78]. In contrast to YBCO films [42, 78] and BiSrCaCuO single crystals [43], in which the best fit is observed, the curve given by equation (11) (figure 4, dashed curve 1) deviates down from the data in the certain temperature range above T_0. The deviation is most likely the result of enhanced magnetic interaction in $EuFeAsO_{0.85}F_{0.15}$, as mentioned above. But it is of no importance for the further consideration since the value of A_4 can be strictly determined from the plot. As it is seen from the figure, the fit in the range of the 3D AL fluctuations near T_c is expectedly good resulting in $A_4 = 2.8$. Importantly, if we put found rather unusual $\Delta^*(T)$ (figure 6) into equation (11) instead of constant $\Delta^*(T_c)$, the resulting curve will describe the measured $\sigma'(T)$ perfectly.

However, to explore equation (11), one has to know the value of $\Delta^*(T_c)$ too. In our consideration $\Delta^*(T_c) = \Delta(0)$ is assumed [81, 82], where $\Delta(0)$ is the SC gap at $T = 0$. Thus, the equality $2\Delta^*(T_c)/k_B T_c = 2\Delta(0)/k_B T_c$ is to occur. Finally, to estimate $\Delta^*(T_c)$, we plot $\ln\sigma'$ as a function of $1/T$ (figure 5, dots) [42, 79] and fit it to equation (11). In this case the slope of the theoretical curves (figure 5, dashed and dotted curves 1–3) turns out to be very sensitive to the value of $\Delta^*(T_c)$ [78, 79]. The best fit is obtained when $2\Delta^*(T_c)/k_B T_c \approx 4.4$ (figure 5, dashed curve 1) which is close to but still larger than the mentioned above BCS coupling limit

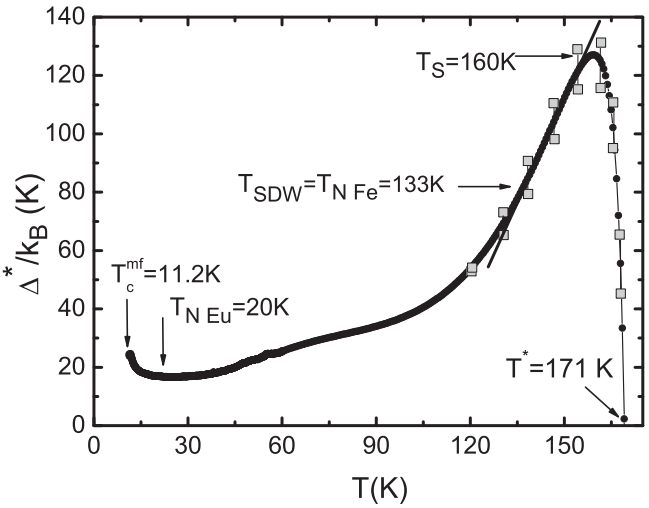

Figure 6. Temperature dependence of the PG parameter Δ^*/k_B of $EuFeAsO_{0.85}F_{0.15}$ (dots). Solid line designates the positive slope linear region between $T_S = 160$ K and $T_{SDW} = T_{NFe} = 133$ K, which is believed to be the direct sign of the magnetic interaction in HTSC's. Also shown are the representative temperatures $T^* = 171\ K$, $T_{NEu} \simeq T_{01} \approx 20$ K, and $T_c^{mf} = 11.2$ K. Thin solid curve is guidance for eye.

$2\Delta(0)/k_B\ T_c^{BCS} \approx 4.28$ [71, 72]. The result suggests that $\Delta^*(T_c)/k_B \approx 24.2$ K (≈2.1 meV). It seems to be reasonable seeing the measured $T_c = 11$ K is relatively low. Thus, all parameters needed to calculate $\Delta^*(T)$ are determined now. Figure 6 (dots) displays $\Delta^*(T)$ calculated using equation (12) with the following set of parameters derived from the experiment within the LP model: $T^* = 171$ K, $T_c^{mf} = 11.2$ K, $\xi_c(0) = 2.84$ Å, $\varepsilon_{c0}^* = 5.6$, $A_4 = 2.8$. Table 1, convincingly shows that all sample parameters change logically with increase of the magnetic interaction in the corresponding compounds. Because $\Delta^*(T) \propto 1/\sigma'(T)$ (equation (12)), whereas $\sigma'(T)$ is extremely small near T^*, the error bars are shown in figure 6. However, their size becomes less than the size of the experimental points below $T \sim 120$ K.

As can be seen from the figure, $\Delta^*(T)$ exhibits narrow maximum at $T_{max} \approx 160$ K followed by a positive slope linear region down to $T \approx 133$ K (figure 6, dots). The shape of the whole curve is completely different from that usually observed for YBCO and BiSCCO cuprates, in which Δ^* is the increasing function of temperature with the wide maximum at $T_{pair} \approx 130$ K and ≈150 K, respectively [42, 43]. However, the found $\Delta^*(T)$ dependence appears to be typical for the '1111' FePn's. For the first time such positive slop linear $\Delta^*(T)$ was observed for $SmFeAsO_{0.85}$ between $T_s = 150$ K and $T_{SDW} = 133$ K, and can be considered as the principal feature of the enhanced magnetic interaction in the HTSC's [14]. In SmFeAsO both representative temperatures $T_s = 150$ K and $T_{SDW} = T_{NFe} = 133$ K were independently determined from the resistivity [2, 83] and specific heat [84] experiments, respectively. By analogy with these results, one may conclude that $T_{max} = T_s \approx 160$ K is the structural transition temperature, and the next representative temperature is $T_{SDW} = T_{NFe} \approx 133$ K, which corresponds to the SDW transition followed most likely by the AF ordering of Fe spins in $EuFeAsO_{0.85}F_{0.15}$. Found $T_s \approx 160$ K is higher than that observed for SmFeAsO [22] and LaFeAsOF [1, 2]. It is likely because the Eu-based compounds (e.g. $EuFe_2As_2$) demonstrate the highest T_s [10, 22], as mentioned above. But the second representative temperature in $EuFeAsO_{0.85}F_{0.15}$, namely $T_{SDW} = T_{NFe} \approx 133$ K, is just the same as found for the *SmFeAsO*, and is distinctly observed for the first time. Below this temperature $\Delta^*(T)$ continues to decrease gradually down to $T_{NEu} \approx 20$ K, which is the temperature of Eu 4f moments ordering [10, 22]. After that $\Delta^*(T)$ starts to increase with the more pronounced rise just below T_{NEu}. And finally $\Delta^*(T)/k_B$ acquires the value of about 24 K at $T = T_c^{mf}$ in good agreement with the above calculations. It is worth to note, that $T_{NEu} \approx T_{01}$ (figure 6), below which the system undergoes transition into the range of the SC fluctuations, where LPs behave in a good many way like the incoherent FCPs (short-range phase correlations) [39, 74, 76], as mentioned above. Thus, one may conclude that the FCPs can appear in the FeAs-based superconductor only after the ordering of all magnetic moments has happened in the sample. Nevertheless, despite of the strong influence of magnetism, the LP model approach has allowed us to obtain rather reasonable and self-consistent results.

To be more sure, we have compared results (figure 7, curve 1) with those obtained for $SmFeAsO_{0.85}$ [14] (figure 7, curve 2). As it is seen in figure 7, both samples demonstrate just the same positive slope linear descending $\Delta^*(T)$ just between T_s and T_{SDW}, which is designated by the straight line in the figure. Moreover, the length of the both linear regions turns out to be also the same suggesting the similar mechanism of the magnetic interaction in both superconductors above T_{SDW}. In the case of $SmFeAsO_{0.85}$ the linear descending $\Delta^*(T)$ region was qualitatively explained within the Machida–Nokura–Matsubara (MNM) theory developed for the

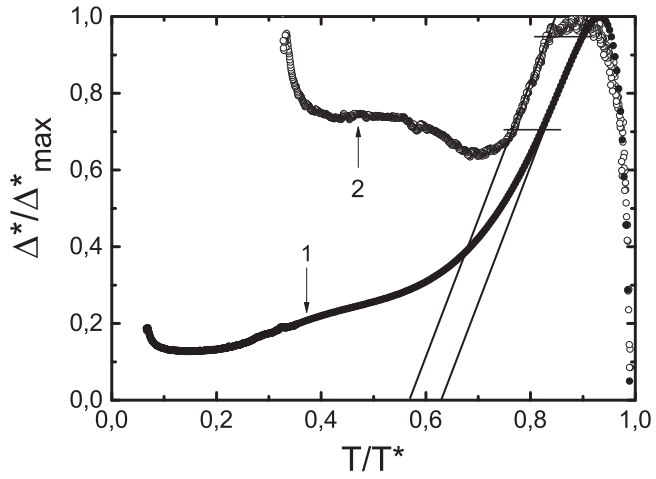

Figure 7. $\Delta^*(T)/\Delta_{max}$ as a function of T/T^* for studied $EuFeAsO_{1-x}F_x$ (curve 1, dots) and reference $SmFeAsO_{0.85}$ [14] (curve 2, circles). Solid lines with equal positive slope designate the linear $\Delta^*(T)$ regions for both samples. Horizontal lines designate its equal length. The result suggests the generality of the interaction mechanism for the superconductors in which the AF ordering may coexist with superconductivity.

superconductors in which the AF ordering may coexist with the superconductivity, such as e.g. RMo_6S_8 (R = Gd, Tb, and Dy) [85]. In accordance with the MNM theory, in such compounds $\Delta(T)$ drops linearly below $T_N < T_c$ due to formation of the energy gap of SDW on the Fermi surface which partially suppresses the SC gap. As AF gap saturates at lower temperatures, $\Delta(T)$ gradually recovers its value with increasing the SC condensation energy.

The shape of the $\Delta^*(T)$ curve observed for $SmFeAsO_{0.85}$ [14] was found to be rather close to that predicted by the MNM theory for the intermediate value of the AF gap [85]. Consequently, one may conclude that observation of the similar $\Delta^*(T)$ behavior in $SmFeAsO_{0.85}$ but above T_c (figure 7, curve 2) can be considered as an additional evidence for the LPs existence in the FeAs-based superconductor [14, 42]. Really, it was assumed that, in accordance with the MNM theory, the order parameter of the LPs, Δ^*, is suppressed below T_s by the low-energy magnetic fluctuations [23–27] resulting in observed positive slope linear drop of $\Delta^*(T)$ followed by the SDW transition [14, 42]. As far as the magnetic ordering has already happened in the sample, the Δ^* versus T behavior at $T < T_{SDW}$ is believed to be determined predominantly by the formation of the incoherent FCPs, assuming the effect of magnetic fluctuations to be relatively small [14, 42].

Compare results (figure 7), we may conclude that obtained for $EuFeAsO_{0.85}F_{0.15}$ $\Delta^*(T)$ also can be qualitatively explained within the MNM theory probably with the similar value of the SDW gap. However, in contrast with $SmFeAsO_{0.85}$, in $EuFeAsO_{0.85}F_{0.15}$ $\Delta^*(T)$ continues to decrease even below T_{SDW} pointing out the more strong influence of magnetism most likely due to rather large and still disordered intrinsic magnetic moments of the Eu atoms [10, 22, 31]. Thus, in contrast with results of [33, 34], we may conclude that in $EuFeAsO_{0.85}F_{0.15}$ influence of the electron scattering due to Eu^{2+} local moments also have to be taken into account to explain unusual $\Delta^*(T)$ behavior. Nevertheless, the question: 'Can revealed $\Delta^*(T)$ be completely attributed to the PG formed by the LPs at $T < T^*$, as happens with cuprates?' still remains open. The comparison with our recent results obtained on FeSe compounds [86] allows us to conclude that over wide temperature range below T^* the value and temperature dependence of Δ^* in $EuFeAsO_{0.85}F_{0.15}$ are mainly governed by the magnetic fluctuations [23–27]. Only below $T_{01} \approx T_{NEu}$ the role of the LPs in formation of the excess conductivity, which are believed to transform into FCPs (short-range phase correlations) near T_c, becomes predominant. By the way, the FeSe compounds demonstrate the very similar $\Delta^*(T)$ behavior, with the same linear slope at high temperatures, thus suggesting conclusion that mechanism of the SC state formation in different FePn should be basically the same.

4. Conclusion

For the first time the excess conductivity $\sigma'(T)$ in the FeAs-based superconductor $EuFeAsO_{0.85}F_{0.15}$ was analyzed over the whole temperature range from $T^* = 171$ K down to $T_c^{mf} = 11.2$ K. $EuFeAsO_{0.85}F_{0.15}$ is characterized by the enhanced magnetic interaction mostly owing to the large additional magnetic moment of about $7\mu_B$ carried by Eu [10, 22]. Nevertheless, the analysis was performed within the LP model developed for the cuprate HTSC's [42, 43, 78] and based on the assumption of the LP formation below $T^* \gg T_c$ [44–46],

which is believed to be responsible for the appearance of the excess conductivity $\sigma'(T)$ [38, 39, 42, 74, 76]. In magnetic superconductors, such as $EuFeAsO_{0.85}F_{0.15}$, the temperature dependence of σ' has to reflect the complex interplay between the SC fluctuations and magnetism which is of a primarily importance to comprehend the principles of the coupling mechanism in HTSC's.

It is shown that over the temperature range T_c^{mf} =11.2 K to T_0 = 11.7 K $\ln\sigma'$ versus $\ln\epsilon$ is perfectly fitted by the 3D AL theory (refer to figure 3, solid line 1). Above T_0 up to $T_{01} \approx 21$ K $\sigma'(T)$ can be described by the 2D MT fluctuation term (5) (figure 3, solid curve 2) of the HL theory [57]. Thus, below T_{01} there is a range of the SC fluctuations where local pairs have to exist in the form of the FCPs (short-range phase correlations) [37–39]. In other words, the stiffness of the SC wave function [74] has to persist up to $T_{01} \approx 21$ K [76]. However, the range of the 3D AL fluctuations $\Delta T_{3D} = 0.5$ K is relatively short (figures 2 and 3), and enhanced $\sigma'(T)$ is observed above T_0. The shortest $\Delta T_{3D} \approx 0.16$ and the largest $\Delta \ln\sigma' \approx 1.7$ in the 2D fluctuation region were observed for the utterly magnetic superconductor $Dy_{0.6}Y_{0.4}Rh_{3.85}Ru_{0.15}B_4$ with $T_c = 6.4$ K [73] (table 1). Thus, the shortening of the ΔT_{3D} and increase of the σ'_{2D} can be considered as an evidence of the enhanced magnetic interaction in the FePn's. Nevertheless, the strictly designated in the experiment crossover temperature T_0 allows us to determine $\xi_c(0) = (2.84 \pm 0.02)$ Å being of the essential importance for the whole analysis.

Making use of equations (11) and (12) to analyze the $\sigma'(T)$, temperature dependence of the parameter Δ^* was calculated over the whole temperature range $T^* > T > T_c^{mf}$ (figure 6). In cuprates $\Delta^*(T)$ is referred to as a PG which is most likely due to the LPs formation at $T < T^*$ and has to reflect the peculiarities of the LPs transformation along with decrease of temperature [42, 78, 79]. In $EuFeAsO_{0.85}F_{0.15}$ the more peculiar character of $\Delta^*(T)$ is revealed (figure 6, dots) suggesting the enhanced role of the magnetic interaction in FePn's. Found $\Delta^*(T)$ exhibits narrow maximum at $T_s \approx 160$ K, which corresponds to the structural transition in the sample, followed by the positive slope linear region down to $T_{SDW} = T_{NFe} \approx 133$ K (figure 6, dots). For the first time such positive slope linear $\Delta^*(T)$ dependence was observed for $SmFeAsO_{0.85}$ between $T_s = 150$ K and $T_{SDW} = 133$ K and is believed to be the more noticeable feature of the magnetic influence in the high-T_c superconductors [14, 42]. Found $T_s \approx 160$ K is higher than that observed for SmFeAsO [22] and LaFeAsOF [1, 2]. It is likely because the Eu-based compounds (e.g. $EuFe_2As_2$) demonstrate the highest T_s [10, 22]. But the SDW temperature $T_{SDW} = T_{NFe} \approx 133$ K is the same as in SmFeAsO, and distinctly revealed for the first time. Below this temperature $\Delta^*(T)$ continues decrease gradually down to $T_{NEu} \simeq T_{01} \approx 20$ K, which is the temperature of Eu 4f moments ordering [10, 22]. After that $\Delta^*(T)$ starts to increase with the more pronounced rise just below T_{NEu}. And finally $\Delta^*(T)/k_B$ acquires the value of about 24 K at T_c^{mf} in good agreement with our calculations. Thus, we may conclude that, despite the strong influence of magnetism, our LP model approach has allowed us to obtain rather reasonable and self-consistent results. This experimental fact points out the possibility of the LP existence even in magnetic superconductors.

To be more sure, we have compared results with those obtained for $SmFeAsO_{0.85}$ (figure 7). Importantly, both samples demonstrate just the same positive slope linear drop of $\Delta^*(T)$ just between T_s and T_{SDW}. Moreover, the length of the positive slope regions turned out to be also the same suggesting the same mechanism of the magnetic interaction in both superconductors. However, in $EuFeAsO_{0.85}F_{0.15}$ $\Delta^*(T)$ continues to decrease even below T_{SDW} pointing out the more strong influence of magnetism in this case most likely due to rather large and still disordered intrinsic magnetic moments of the Eu atoms [10, 22, 31]. In $SmFeAsO_{0.85}$ [14] such unusual $\Delta^*(T)$ behavior was qualitatively explained within the MNM theory [85] in which the $\Delta^*(T)$ drop was assumed to be due to formation of the energy gap of SDW on the Fermi surface which partially suppresses SC gap. The observation of the linear $\Delta^*(T)$ behavior in $SmFeAsO_{0.85}$ above T_c (figure 7, curve 2) was considered as an additional evidence for the LPs existence in the FePn's [14, 42]. It was assumed that, in accordance with the MNM theory, the order parameter of the LPs, Δ^*, is suppressed below T_s by the low-energy magnetic fluctuations resulting in observed linear drop of $\Delta^*(T)$ followed by the SDW transition [14, 23–27]. By analogy we may conclude that in $EuFeAsO_{0.85}F_{0.15}$ the LPs also have to be taken into account at $T < T^*$, and found $\Delta^*(T)$ also can be qualitatively explained within the MNM theory likely with the same value of the SDW gap. Thus, in FePn's the temperature dependence of $\Delta^*(T)$ is believed to reflect the complex interplay between SC and magnetic fluctuations, as it is distinctly observed in our experiments.

Recently the similar $\Delta^*(T)$ dependence was observed both in $HoBa_2Cu_3O_{7-\delta}$ slightly doped single crystals [59] and FeSe compounds [86] suggesting the generality of the interaction mechanisms for the superconductors in which the AF ordering may coexist with superconductivity.

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