Chapter 7

Pseudogap and Local Pairs in High-T_c Superconductors

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Additional information is available at the end of the chapter

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1. Introduction

The discovery of superconductivity in copper oxides with an active CuO_2 plane [1] at temperatures of the order of 100 K is undoubtedly one of the most important achievements of the modern solid state physics. However, even more than twenty six years later since the discovery the physics of the electronic processes and interactions in high-temperature superconductors (HTS's) and, in particular, the superconducting (SC) pairing mechanism, resulting in such high T_c's, where T_c is the superconducting transition (critical) temperature, still remain controversial [2]. This state of affairs is due to the extreme complexity of the electronic configuration of HTS's, where quasi-two-dimensionality is combined with strong charge and spin correlations [3, 4, 6–12].

Gradually it became clear that the physics of superconductivity in HTS's can be understood, first and foremost, by studying their properties in the normal state, which are well known to be very peculiar [4, 6–12]. It is believed at present that the HTS's possess at least five specific properties [2, 7, 8, 11–13]. First of all it is the high T_c itself which is of the order of 91 K in optimally doped (OD, oxygen index $(7-\delta) \approx 6.93$) $YBa_2Cu_3O_{7-\delta}$ (YBCO, or Y123), of the order of 115 K in OD $Bi_2Sr_2Ca_2Cu_3O_{8+\delta}$ (Bi2223) and in corresponding Tl2223 [8, 9, 12], and arises up to $T_c \approx 135K$ in OD $HgBa_2Ca_2Cu_3O_{8+\delta}$ (Hg1223) cuprates [14]. The next and the most intrigueing property is a pseudogap (PG) observed mostly in underdoped cuprates below any representative temperature $T^* \gg T_c$ [2, 8]. As T decreases below T^*, these HTS's develop into the PG state which is characterized by many unusual features [2, 8, 12, 13, 15, 16]. The other property is the strong electron correlations observed in the underdoped cuprates too [3, 5, 12, 16]. However, existence of the such correlations in, e.g., FeAs-based superconductors still remains controversial [17–21]. The next property is pronounced anisotropy [6–9, 11, 12] observed both in cuprates [2, 9, 12] and FeAs-based superconductors (see Refs. [17–19] and references therein). As a result, the inplane resistivity, $\rho_{ab}(T)$ is much smaller than $\rho_c(T)$, and the coherence length in the ab plane, $\xi_{ab}(T)$, is about ten times of the coherence length along the c-axis, $\xi_c(T)$. The last but not least property is a reduced density of charge carriers n_f. n_f is zero in the antiferromagnetic (AFM) parent state of HTS's and gradually increases with

doping [2, 8, 9, 11, 12]. But even in an optimally doped YBCO it is an order of magnitude less than in conventional superconductors [2, 8, 9, 11, 12, 15]. There is growing evidence that just the reduced density of charge carriers may be a key feature to account for all other properties of HTS's [2, 6, 7, 13, 22–26].

The Chapter addresses the problem of the PG which is believed to appear most likely due to the ability of a part of conduction electrons to form paired fermions (so-called local pairs) in a high-T_c superconductor at $T \leq T^*$ [6, 13, 22–27]

2. Theoretical background

There are two different approaches to the question of the mechanisms for SC pairing of charge carriers in cuprates and therefore the physical nature of the PG [2, 27]. In the first approach, pairing of charge carriers in HTS's is of a predominantly electronic character, and the influence of phonons is inessential [3–5, 28, 29]. In the second approach, pairing in HTS's can be explained within the framework of the Bardeen-Cooper Shieffer (BCS) theory, if its conclusions are extended to the case of strong coupling [12, 30–32]. However, it gradually became clear that aside from the well-known electron-phonon mechanism of superconductivity, due to the inter-electronic attraction by means of phonon exchange [33, 34], other mechanisms associated with the inter-electronic Coulomb interaction can also exist in HTS's [3–8, 10, 12, 35, 36]. That is why it is not surprising that the systems of quasiparticle electronic excitations, where factors other than phonons and excitons resulting in inter-electronic attraction and pairing are considered, are studied in a considerable number of theoretical investigations of HTS's. Some examples are charge-density waves [7, 37, 38], spin fluctuations [3, 11, 39–41], "spin bag" formation [42, 43], and the specific nature of the band structure - "nesting" [44]. The main distinguishing feature of these investigations compared to the conventional superconductors is the more detailed study of the models based on the existence of strong interelectronic repulsion in the Hubbard model which can result in anisotropic d-pairing [35, 45]. Attempts have also been made to construct anisotropic models of high-temperature superconducting (HTS) systems with different mechanisms of interelectronic attraction [12, 46, 47]. Unfortunately, the consensus between both approaches has not been found. As a result, up to now there is still no completed fundamental theory to describe high-T_c superconductivity as a whole and to clarify finally the PG phenomenon [2].

2.1. Pseudogap in HTS's

Gradually it became evident that a high critical temperature is by no means the only property that distinguishes HTS's from conventional low-temperature superconductors. Another, property of cuprates, which attracts much attention, is the PG state [2, 8, 15, 26, 36]. All experiments convincingly show [8] that as the charge-carrier density decreases relative to its value in OD samples, a completely unusual state, where the properties of the normal and superconducting phases appear together [48], arises in HTS systems in a sizable temperature interval above T_c [8, 15, 26, 27, 49–54]. From the very discovery of the PG state some authors called this state a "pseudogap phase". However, for example, as Abrikosov notes [55], this state actually cannot be interpreted as some new phase state of matter, since the PG is not separated from the normal state by a phase transition. At the same time it can be said that HTS system undergoes a crossover at $T \leq T^*$ [56]. Below $T^* >> T_c$, for reasons which have

still not been finally established, the density of quasiparticle states at the Fermi level starts to decrease [57–59]. That is why the phenomenon has been named a "pseudogap"

The number of papers devoted to the problem of the pseudogap in HTS's is extraordinarily large (see Refs. [6–8, 12, 15, 84] and [40, 49, 50, 53, 54, 56, 59] and references therein) and new papers are constantly appearing [38, 41, 47, 60–63]. It seems to be reasonable as it is completely clear that a correct understanding of this phenomenon can also provide an answer to the question of the nature of high-temperature superconductivity as a whole. Among many other papers it is worth to mention the most radical model as for the nature of high-temperature superconductivity and a PG in cuprates. It is the Resonating Valence Bonds (RVB) model proposed by Anderson [64, 65], which describes a spin liquid of singlet electronic pairs. In this model, largely relies on the results obtained using one-dimensional models of interacting electrons, the low-temperature behavior of electrons differs sharply from the standard behavior in ordinary three-dimensional (3D) systems. An electron possessing charge and spin is no longer a well-defined excitation. So-called charge and spin separation occurs. It is supposed that spin is transferred by an uncharged fermion, called a spinon and charge - a spinless excitation - by a holon. In the RVB model both types of excitations - spinons and holons - contribute to the resistivity. However, the holon contribution is considered to be determining, while spinons, which are effectively coupled with a magnetic field **H**, must determine the temperature dependence of the Hall effect. Even though the RVB model led to a series of successes [65, 66], it is dificult to think up the physics behind the processes which could lead to the charge and spin separation especially in quasi-two-dimensional systems, which cuprate HTS's are. Nevertheless, the RVB model contains at lest one rational idea, namely, it is supposed that two kinds of quasi-particles with different properties have to exist in the high-temperature superconducting (HTS) system at T below T^*. In the RVB model such particles are spinons and holons.

However, even though researchers have made great efforts in this direction, the physics of the PG phenomenon is still not entirely understood (see Ref. [2] and references therein). That is why, we have eventually to propose our own Local Pair (LP) model [13, 27] developed to study a pseudogap $\Delta^*(T)$ in high-temperature superconductors and based on analysis of the excess conductivity derived from resistivity experiments. We share the idea of the RVB model as for existence of two kinds of quasi-particles with different properties in HTS's below T^*. But in our LP model these are normal electrons and local pairs, respectively. I will frame our discussion in terms of the local pairs, and try to show that this approach allows us to get a set of reasonable and self-consistent results and clarify many of the above questions.

2.2. The main considerations as for local pair existence in HTS's

There are several considerations leading to the understanding of the possibility of paired fermions existence in HTS's at temperatures well above T_c which I am going to discuss now. It is well known, that a pseudogap in HTS's is manifested in resistivity measurements as a downturn of the longitudinal resistivity $\rho_{xx}(T)$ at $T \leq T^*$ from its linear behaviour above T^* (Fig.1). This results in the excess conductivity $\sigma'(T) = \sigma(T) - \sigma_N(T)$, which can be written as

$$\sigma'(T) = [\rho_N(T) - \rho(T)]/[\rho(T)\rho_N(T)]. \quad (1)$$

Here $\rho(T) = \rho_{xx}(T)$ and ρ_N(T)=αT+b determines the resistivity of a sample in the normal state extrapolated toward low temperatures.

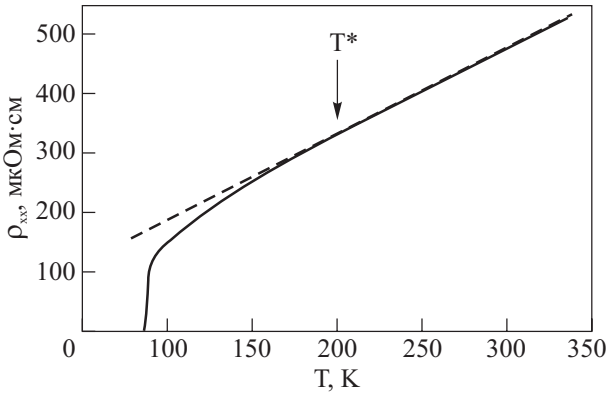

Figure 1. Resistivity ρ versus temperature T (•) for YBCO film F1 (Table I); dashed line represents $\rho_N(T)$.

This way of determining $\rho_N(T)$, which is widely used for calculation $\sigma'(T)$ in HTS's [2], has found validation in the Nearly Antiferromagnetic Fermi Liquid (NAFL) model [11]. The question of whether the appearance of excess conductivity $\sigma'(T)$ in cuprates can be wholly attributed to fluctuating Cooper pairing or whether there are other physical mechanisms responsible for the decrease of $\rho_{xx}(T)$ at $T < T^*$ is one of the central questions in the modern physics of HTS's. To clarify the issue it seems reasonable to probe the PG by studying the fluctuation (induced) conductivity (FLC). The study of FLC provides the relatively easy but rather effective method which directly examines the possibility of paired fermions arising at temperatures preceding their transition into the SC state [67, 68].

Both Aslamasov-Larkin (AL) [69] and Maki-Thompson (MT) [70, 71] coventional FLC theories have been modified for the HTS's by Hikami and Larkin (HL) [72]. In the absence of a magnetic field the AL contribution to the FLC is given by the expression

$$\sigma'_{AL} = \frac{e^2}{16\hbar d}(1+2\alpha)^{-1/2}\varepsilon^{-1}, \tag{2}$$

Correspondingly, the HL theory gives for the MT fluctuation contribution the equation

$$\sigma'_{MT} = \frac{e^2}{8d\hbar}\frac{1}{1-\alpha/\delta}\,ln\left((\delta/\alpha)\,\frac{1+\alpha+\sqrt{1+2\alpha}}{1+\delta+\sqrt{1+2\delta}}\right)\varepsilon^{-1}. \tag{3}$$

In both equations

$$\alpha = 2\,[\xi_c^2(T)\,/\,d^2] = 2\,[\xi_c(0)\,/\,d]^2\,\varepsilon^{-1} \tag{4}$$

is the coupling parameter, d≃11.7 Å in YBCO, is the distance between conducting layers,

$$\delta = 1,203\frac{l}{\xi_{ab}}\frac{16}{\pi\hbar}\left[\frac{\xi_c(0)}{d}\right]^2 k_B\,T\,\tau_\phi \tag{5}$$

is the pair-breaking parameter, and ξ_c is the coherence length along the c-axis, i.e. perpendicular to the CuO_2 conducting planes. The factor $\beta = 1.203(l\,/\,\xi_{ab})$, where l is the electron mean-free path, and ξ_{ab} is the coherence length in the *ab* plane, takes account of the

approach to the clean limit introduced in the Bierei, Maki, and Thompson (BMT) theory [73]. Correspondingly,

$$\varepsilon = ln(T/T_c^m f) \approx (T - T_c^{mf}) \,/\, T_c^{mf} \tag{6}$$

is the reduced temperature in HTS's. 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 order parameter Δ directly near T_c, neglected in the Ginzburg-Landau (GL) theory [74, 75]. Hence it is evident that the correct determination of T_c^{mf} is decisive in FLC calculations.

Equation (3) actually reproduces the result of the Lawrence-Doniach (LD) model [76], which examines the behavior of the FLC in layered superconductors, which cuprates and FeAs-based superconductors actually are. In the LD model, and hence in the HL theory, it is proposed that a Josephson interaction is present between the conducting layers. This occurs in the 3D temperature region, i.e., near T_c, where $\xi_c(T) > d$. Thus, according to the HL theory the AL fluctuation contribution predominates near T_c. Correspondingly, the MT mechanism predominates for $k(T - T_c^{mf}) >> \hbar/\tau_\phi$, where two-particle tunnelling between conducting layers is impossible, since $\xi_c(T) < d$ (2D fluctuation region) [77]. Thus, the HL theory predicts the alteration of the electronic dimensionality of the HTS sample leading to a 2D-3D crossover, as T approaches T_c. Simultaneously the physical mechanism of superconducting fluctuations changes too resulting in MT-LD crossover. In accordance with the HL theory, the 2D-3D crossover occurs at

$$T_0 = T_c\{1 + 2[\xi_c(0)/d]^2\} \tag{7}$$

where it is assumed that α=1/2, i.e.

$$\xi_c(0) = (d/2)\,\sqrt{\varepsilon}_0. \tag{8}$$

Thus, now $\xi_c(0)$ can be determined, since ε_0 is a measured reduced crossover temperature. Correspondingly, the MT-LD crossover occurs at a temperature at which $\delta \simeq \alpha$ [72], which gives

$$\varepsilon_0 = (\pi\hbar)/[1.203(l/\xi_{ab})(8\,k_B\,T\,\tau_\phi)] \tag{9}$$

In accordance with our results [67], it should be the same temperature T_0. It makes it possible to determine τ_ϕ which is the phase relaxation time (lifetime) of fluctuating pairs. The evaluation of τ_ϕ in comparison with transport relaxation time τ of charge carriers measured by electrical conductivity, is a principal contribution to understanding the physics of transport properties. Whether $\tau_\phi > \tau$ or $\tau_\phi \approx \tau$ is important in view of the controversy over the Fermi-liquid or non-Fermi-liquid nature of the electronic state in HTS's [9, 64, 77]. Thus, the study of FLC can yield information about the scattering and fluctuating pairing mechanisms in HTS's as T draws near T_c.

As it was shown in our study of FLC [2, 67, 68], for optimally doped YBCO the interval $T_c < T < T_{c0} = (110 \pm 5)\,K$ is precisely that temperature region in which the temperature dependence of the resistivity, and consequently of the excess conductivity, is governed by the superconducting fluctuations leading to the onset of fluctuation conductivity which is described by the conventional fluctuation theories [69–72], as mentioned above. It means that fluctuating Cooper pairs have to exist in cooprates up to very high temperatures, namely, up to $\sim$ 130 K in YBCO [27, 67, 68, 78] and up to $\sim (140 - 150)$ K in Bi compounds [16, 52, 53].

The conclusion has subsequently been shown to be consistent with results of several other research groups which will be briefly discussed now. 1. Kawabata et al. [78] has made a number of small ($D \sim 3\mu km$) holes in the slightly underdoped YBCO film by means of photolithography and then applied a magnetic field. Expected magnetic flux quantization was observed up to $T_{pair} \sim 130\,K$. The important point here is that period of oscillations corresponds to the charge of $Q = 2e$ evidently suggesting the electronic pairing in this temperature range. 2. In tunneling experiments by, e.g., Renner et al. [79], the peculiarities of measured differential conductivity dI/dV observed in the SC part of the PG in Bi2212 compounds [13] were found to persist up to temperatures well above T_c, and disappeared only at $T = T_{pair} \approx 140\,K$. But the wide maximum corresponding to the non-SC part of the PG was observed up to $T^* \approx 210\,K$. 3. It has subsequently been shown to be consistent with results of other groups dealing with the tunneling measurements [50–54]. Thus, in tunneling experiments by Yamada et al. performed on Bi compounds too [52], the temperature dependencies of the SC gap and PG, equal to the positions of the tunnel conductivity peaks, similar to that obtained in Ref [79], were studied for the three Bi2223 samples with different doping level. The noticeable increase of the PG in temperature interval from T_c up to $T_{pair} \approx 150\,K$ (SC part of the PG), similar to that obtained in our experiments with YBCO films [27], was found for all three samples [52]. However, in accordance with the LP model [13, 27], the peaks, which have the SC nature, as well as corresponding PG values, are smeared out above T_{pair}, suggesting expected transition into non-SC part of the PG.

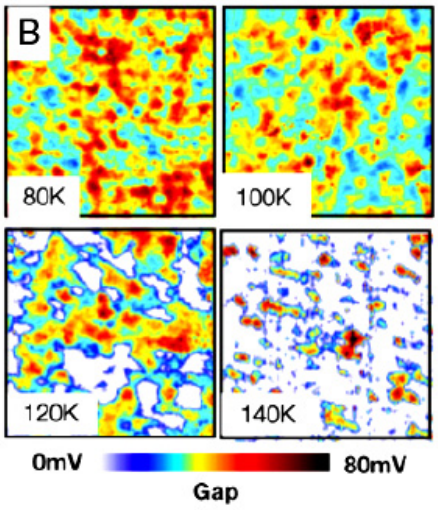

Figure 2. STM image of Bi2212 with T_c =93 K at different temperatures [[16]].

4. Eventually, Yazdani [16] was able to get the direct image of the local pair SC clusters in Bi compounds up to approximately $140\,K$ using the novel STM technique (Fig. 2). As it is clearly seen in the figure obtained for an optimally doped Bi2212 sample (T_c = 93 K), the state of the system at 100 K is almost the same as that below T_c. At 120 K the picture evidently changes, but the local pairs still form the SC cluster which determines the collective (superconducting-like) behavior of the system in this SC part of the PG. Even at 140 K the

SC nuclei are distinctly seen in the figure. But there are no closed clusters now. As a result, no collective behavior of the system is observed above $T_{pair} \geq 140\,K$, as it was shown in the tunneling experiments [52]. In accordance with the LP model, it is a non-SC part of a PG above T_{pair} [13]. Taking all these experimental results into account, the existence of paired fermions (local pairs) in the SC part of the PG, i.e, in the temperature interval from T_c up to T_{pair}, is believed to be well established now [13]. Additionally, T_{pair} is found to amount to $\simeq$ 130, 140 and 150 K for Y123, Bi2212, and Bi2223, respectively [13, 80].

2.2.1. Properties of the systems with low and reduced current-carrier density

Before to proceed with a question what would happen with the local pairs in the non-SC part of the PG above T_{pair} [13], let us have a look once again at the resistivity curve (Fig.1) obtained for our slightly underdoped YBCO film (sample F1, Table I). Three representative temperatures, at which $\rho(T)$ noticeably changes it slop, are distinctly seen on the plot. The first temperature is $T^* = 203\,K$ at which the local pairs are believed to appear [2, 27]. The second one is $T_{on} \approx 89,4\,K$ corresponding to the onset of the superconducting transition. The last one is $T_c = 87.4\,K$ at which the local pairs have to condense [6, 23, 24]. One basic question is whether any particularities affect the slop of the experimental curve around $T_{pair} \sim 130\,K$. The answer is completely negative. Indeed, the resistivity smoothly evolves with temperature and shows no peculiarities up to T^*. The fact suggests that nothing happens with the pairs at T_{pair}. Thus, one may draw a conclusion that if there are paired fermions in the sample below T_{pair} they also have to exist at $T > T_{pair}$, i.e., up to the very T^*. The point of view where the appearance of a PG in HTS's is due to the paired fermions formation at $T_c < T < T^*$ gradually gaining predominance [15, 27, 47, 81–84]. The possibility of the long-lived pair states formation in HTS's in the PG temperature range was justified theoretically in Refs. [26, 85, 86]. Nevertheless, the question of whether or not paired fermions can form in HTS's in the whole PG temperature range still remains very controversial. Indeed, it seems unlikely that conventional fluctuating Cooper pairs [33] are formed at temperatures $T^* > 200\,\mathrm{K}$ [13, 27] especially considering the fact that the coherence length in HTS's is extremely short ($\xi_{ab}(T \leq T^*) \simeq (10 \div 15)$ Å) [2, 6, 8, 11, 12, 15].

We have, however, to keep in mind that we are dealing with the systems with low and reduced charge-carrier density n_f, as mentioned above. It has been shown theoretically [6, 23–26, 85] that such systems acquire some unusual properties compared to conventional superconductors. In conventional superconductors it is assumed that the chemical potential $\mu = \varepsilon_F$, where $\varepsilon_F = E_F$ is the Fermi energy, and their relation actually depends on nothing. In the systems with low and reduced n_f the chemical potential μ becomes a function of n_f, T and the energy of a bound state of two fermions, $\varepsilon_b = -(m\,\xi_b^2)^{-1}$ [23–26]. Here ξ_b is the scattering length in the s channel, and m is the mass of fermions with a quadratic dispersion law $\varepsilon(k) \sim k^2$ [23–25]. In the case of HTS's it is believed that $\xi_b(T)$ equals to the coherence length of a superconductor in the *ab* plane, $\xi_{ab}(T)$, and $m = m^*$ which is an effective mass of quasi-particles [11, 47]. ($m^* \sim 4.7m_0$ in nearly optimally doped (OD) YBCO [9, 11, 67, 68]. Thus, the ε_b becomes an important physical parameter of a Fermi liquid and determines a quantitative criterion for dense ($\varepsilon_F \gg |\varepsilon_b|$) or dilute ($\varepsilon_F \ll |\varepsilon_b|$) Fermi liquid. Accordingly, $k_F\varepsilon_b \gg 1$ and $\mu = \varepsilon_F$ in the first case, and $k_F\varepsilon_b \ll 1$ and $\mu = -|\varepsilon_b|/2$ ($\neq \varepsilon_F$) in the second one which correspond to the strong coupling [61, 84, 86]. Consequently, in the strong-coupling limit μ is to be equal to approximately $\varepsilon_b/2$. It should be also noted, that in this case the paired fermions have to appear in the form of so-called strongly bound bosons (SBB) which satisfy

Bose-Einstein condensation (BEC) theory [6, 23–26, 84–89]. In accordance with the theory, the SBB are extremely short but very tightly coupled pairs. As a result, the SBB have to be local (i.e. not interacting with one another) objects since the pair size is much less than the distance between the pairs. Besides, they cannot be destroyed by thermal fluctuations, and consequently may form at very high temperatures.

It is clear that some other parameters, including the mean-field critical temperature T_c^{mf} and temperature dependence of the SC order parameter $\Delta(T)$ have to change too. Analysis shows that in conventional superconductors with a high fermion density $T_c^{mf} \approx T_c$, i.e. it is identical to the BCS theory value [6, 23, 24, 33]. Moreover, $T_c^{mf} << \varepsilon_F$ in this case. For the systems with low density $T_c^{mf} \sim |\varepsilon_b|$, whence $T_c^{mf} >> \varepsilon_F$ [6, 24, 25]. The latter relation means that in this case T_c^{mf} characterizes not the condensation temperature T_c but rather the temperature at which the fermions start to bind into pairs, i.e., T^*. An equation for $\Delta(T)$ in a form convenient for comparing with experiment was obtained in Ref [87]. In this case the temperature dependence $\Delta(T)$ was calculated on the basis of the crossover from BCS to BEC limit for different values of the parameter $\mu/\Delta(0) = x_0$, where $\Delta(0)$ is the value of the SC order parameter at T=0:

$$\Delta(T) = \Delta(0) - \left((8\sqrt{\pi}) \sqrt{-x_0(\Delta(0)/T)^{3/2}} \right) exp\left[-(\mu^2 + \Delta^2(0))^{1/2}/T \right] \qquad (10)$$

Equation (2) determines how the character of $\Delta(T)$ changes when the parameter x_0 changes from 10 (BCS limit) to -10 (BEC limit) (Fig. 12). As it is shown in Ref. [88] the character of the pseudogap temperature dependence $\Delta^*(T)$ in HTS's has to change in the same manner as the charge-carrier density decreases.

2.2.2. The model of the local pairs (Local Pair model)

For obvious reasons, the question of which density should be regarded as low or high has not been posed for ordinary metals, and for a long time the question of a supposed BCS-BEC transition with decreasing n_f [74] was only of theoretical interest. The situation changed dramatically after the discovery of HTS's [1], where the charge-carrier density n_f is much lower than in conventional superconductors [8, 9, 11, 12, 15, 27], as discussed above. It means that in HTS's the mentioned above strongly bound bosons have to exist. Besides, the coherence length in the *ab* plane, $\xi_{ab}(T)$ is extremely short in HTS's, especially at high temperatures [2, 6, 8, 11, 12, 15] ($\xi_{ab}(T \leq T^*) \simeq 13$Å in YBCO [67, 68]). It leads to the very strong bonding energy ε_b in the pair [23–25] which is an additional requirement for the formation of the SBB [6, 24–26]. Taking all above considerations into account, one may draw a conclusion that at high temperatures ($T \leq T^*$) the local pairs in HTS's, which are believed to generate a pseudogap [2, 6, 13, 26, 89], have to be in the form of the SBB [2, 6, 13, 26, 27, 47, 81, 85–89]. *This is the first basic assumption of the LP model [2, 27].* This condition is realized just in the underdoped cuprates (see Ref. [2] and references therein) and new FeAs-based superconductors [17, 20]. But, strictly speaking, the presence or absence of a PG in FeAs-based HTS's still remain controversial [17, 21].

This assumption is supported by the fact that in accordance with the theory [6, 23, 24, 26] fermions start to bind into pairs at T^*, whereas the local pairs (or SBB) formed in the process may condense only for $T_c << T^*$, which at first glance seems to be in complete agreement

with experimental observations [2, 12, 80, 90, 91]. But, the non-interacting SBB cannot be condensed at all [6, 23, 24, 85, 86], and this is a point. Eventually, just the value of $\xi_{ab}(T) = \xi_{ab}(0)\,(T/T_c - 1)^{-1/2}$ will determine the system behavior below T^* [2, 6, 24, 25, 86–89]. As temperature lowers, $\xi_{ab}(T)$ has to noticeably increase whereas the bonding energy ε_b in the pair has to decrease. As a result, the paired fermions have to change their state from the SBB into fluctuating Cooper pairs which behave in a good many ways like those of conventional superconductor [2, 6, 13, 26, 85, 89]. It is just that we call the local pairs. Thus, with decrease of temperature there must be a transition from BEC to BCS state, which is a consequence of a very short ξ_{ab} at high temperatures and its noticeable temperature dependence. *The possibility of a such transition is the main assumption of the LP model [2, 13, 27].* Precisely how this happens is one of the challenging questions in strongly correlated electron systems. Nevertheless, the transition was predicted theoretically in Refs. [23–25, 89] and approved in our experimental studies [2, 27].

Within the LP model a new approach to the analysis of the FLC and PG in HTS's was developed [2, 13, 27, 67]. First, it was convincingly shown that FLC measured for all without exception HTS's always demonstrates a transition from 2D ($\xi_c(T) < d$) into 3D ($\xi_c(T) > d$) state, as T draws near T_c. The result is most likely a consequence of Gaussian fluctuations of the order parameter in 2D metals [6, 23–25, 84], which HTS compounds with pronounced quasi-two-dimensional anisotropy of conducting properties actually are [2, 6, 9]. The Gaussian fluctuations were found to prevent any phase coherency organization in 2D compounds. As a result, the critical temperature of an ideal 2D metal is found to be zero (Mermin-Wagner-Hoenberg theorem), and a finite value is obtained only when three-dimensional effects are taken into account [6, 23, 24, 85, 87]. That is why, the FLC in the 3D state is always extrapolated by the standard 3D equation of the AL theory, which determines the FLC in any 3D system:

$$\sigma'_{AL3D} = \frac{e^2}{32\,\hbar\,\xi_c(0)}\varepsilon^{-1/2}, \tag{11}$$

This means that the conventional 3D FLC is realized in HTS's as $T \to T_c$ [67, 77]. Above the crossover temperature T_0 (Eq. (7)) the FLC in well-structured YBCO films was found to be of the MT FLC type [2, 67], in a good agreement with the HL theory [72]. The LD model was found to describe the experimental FLC only in the case of HTS compounds with pronounced structural defects [92, 93]. Therefore, we denote the observed 2D-3D crossover also as MT-AL [2, 67], unlike the MT-LD one predicted by the HL theory. It is clear on physical grounds that with increasing temperature the 3D fluctuation regime will persist until $\xi_c > d$ [77]. Thus, in this case the crossover should occur at $\xi_c \cong d$, i.e., at

$$\xi_c(0) = d\,\sqrt{\varepsilon_0}, \tag{12}$$

which is larger by a factor of two than is predicted by the LD and HL theories. $\xi_c(0)$ is one of the important parameters of the PG analysis.

Second, observation of the 2D-3D (MT-AL) crossover allows us to determine ε_0 quite accurately and, using Eq.(12), to obtain reliable values of $\xi_c(0)$ [2, 67, 68]. However, τ_ϕ [(see Eq.(9)] still remains unknown, since neither l nor $\xi_{ab}(0)$ is measured experimentally in a study of FLC. To find τ_ϕ we proceed as follows: we denote

$$\beta = [1.203\,(l/\xi_{ab})]; \tag{13}$$

we assume as before that $\tau_\phi(T) \propto 1/T$ [11, 67], and for our subsequent estimate of $\tau_\phi(100\,K)$ we assume that $\tau_\phi\, T$ =const. Finally, equation (9) can be rewritten as

$$\tau_\phi\, \beta\, T = (\pi\hbar)/(8\, k_B\, T\, \varepsilon_0) = A\, \varepsilon_0, \tag{14}$$

where $A = (\pi\hbar)/(8\, k_B) = 2.988 \times 10^{-12}$. Now the parameter $\tau_\phi(100\, k)\, \beta$ is also clearly determined by the measured value of ε_0 and eventually enables us to determine $\tau_\phi(100\, k)$ [2, 67, 68].

Third, now as a PG analysis is concern. It is clear, to get information about the PG we need an equation which describes the whole experimental curve from T_c up to T^* and contains PG in the explicit form. Besides, the dynamics of pair-creation and pair-breaking above T_c must be taken into account [2, 32, 45, 72, 84]. However, the conventional fluctuation theories [72] well fit the experiment up to approximately 110 K only, whereas $T^* \simeq 200\,K$ even in slightly underdoped cooprates [2, 27, 67], as discussed above. Unfortunately, so far there is no completed fundamental theory to describe the high-T_c superconductivity as a whole and in particular the pseudogap phenomenon. For lack of the theory, such equation for $\sigma'(\varepsilon)$ has been proposed in Ref. [27] with respect to the local pairs:

$$\sigma'(\varepsilon) = \frac{e^2\, A_4\, \left(1 - \frac{T}{T^*}\right)\, \left(exp\left(-\frac{\Delta^*}{T}\right)\right)}{(16\,\hbar\,\xi_c(0)\, \sqrt{2\,\varepsilon^*_{c0}\, \sinh(2\,\varepsilon\,/\,\varepsilon^*_{c0})}}, \tag{15}$$

where ε is a reduced temperature given by Eq. (6), and $T_c^{mf} > T_c$ is the mean-field critical temperature, as discussed above. Besides, the dynamics of pair-creation ($(1 - T/T^*)$) and pair-breaking ($exp(-\Delta^*/T)$) above T_c have been taken into account in order to correctly describe the experiment [2, 13, 27]. Here A_4 is a numerical factor which has the meaning of the C-factor in the FLC theory [2, 92]. All other parameters, including the coherence length along the c-axis, $\xi_c(0)$, and the theoretical parameter ε^*_{c0} [2, 27], directly come from the experiment. The way of ε^*_{c0} determination is shown in the insert to Fig. 4 and explained below. Thus, the only adjustable parameter remains the coefficient A_4. To find A_4 we calculate $\sigma'(\varepsilon)$ using Eq. (15) and fit the experiment in a range of 3D AL fluctuations near T_c where $ln\sigma'(ln\varepsilon)$ is the linear function of ε with a slope $\lambda = -1/2$ (Eq. (11)). Solving Eq. (15) for the pseudogap $\Delta^*(T)$ one can readily obtain [27]

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

where σ'(T) is the experimentally measured excess conductivity over the whole temperature interval from T^* down to T_c^{mf}.

3. Experimental results with respect to the Local Pair model

3.1. YBCO films with different oxygen concentration

Within proposed LP model the FLC and PG in YPrBCO films [94], in slightly doped $HoBa_2Cu_3O_{7-\delta}$ single-crystals [95], and evev in FeAs-based superconductor $SmFeAsO_{0.85}$ with T_c =55 K [20] (see division 3.4 below) were successfully studied for the first time. As

a result, convincing set of self-consistent and reproducible results was obtained which has to corroborate the LP model approach. But the basic results have been obtained from the analysis of the resistivity data for the set of four YBCO films with different oxygen concentration [2, 27, 67, 68]. The films were fabricated at Max Plank Institute (MPI) in Stuttgart by pulse laser deposition technique [96]. All samples were the well structured *c*-oriented epitaxial YBCO films, as it was confirmed by studying the correspondent x-ray and Raman spectra [93]. The sample F1 (T_c=87.4 K) close to optimally doped systems, the sample F6 (T_c=54.2 K) which represents weakly doped HTS systems, and the samples F3 and F4 with T_c near 80 K were investigated to obtain the required information. Fig. 3 displays the temperature dependencies of the longitudinal resistivity $\rho_{xx}(T) = \rho(T)$ of the experimental films with parameters shown in Table I, where d_0 is the sample thickness.

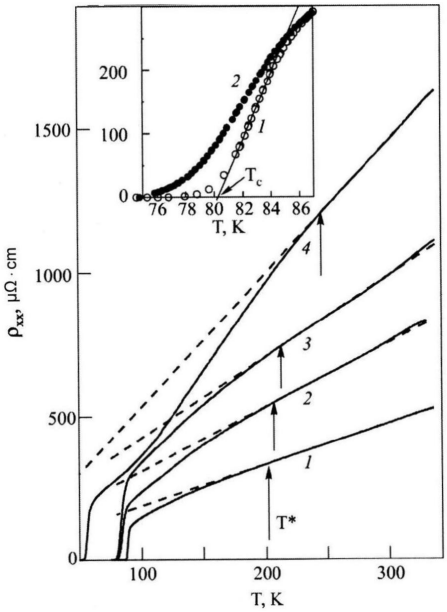

Figure 3. Temperature dependencies of ρ_{xx} for the samples F1(1), F3 (2), F4 (3), and F6 (4). Inset: ρ_{xx}(T) for sample F4 (T_c=80.3 K) in zero magnetic field (1) and for **H** = 0.6 T (2).

The inset shows $\rho(T)$ for the sample F4 (T_c=80.3 K) in zero magnetic field **H**=0 (curve 1), showing how T_c was determined, and at $\mathbf{H} = 0.6T$ (curve 2), confirming the phase uniformity of the samples. Comparing the results with similar dependencies obtained for single crystals [97], the oxygen index of our samples can be estimated as follows: $\Delta y = (7 - y) \cong 6.85$ (F1), $\Delta y \cong 6.8$ (F3), $\Delta y \cong 6.78$ (F4), and $\Delta y \cong 6.5$ (F6). The resistivity parameters of the films are listed in Table I.

To simplify our discussion a little bit, I will consider only the sample F1, as an example. The similar results were obtained for all other YBCO films being studied and compared with those obtained for $HoBa_2Cu_3O_{7-\delta}$ [95] and $SmFeAsO_{0.85}$ [20]. Besides, I will consider mainly the basic aspects of the PG analysis only and touch on the FLC results as far as is necessary. To look for more details, one can see Refs.[2, 13, 20, 27, 67, 68, 94, 95].

Sample	d_0 ()	T_c (K)	T_c^{mf} (K)	$\rho(100K)$ $(\mu\Omega cm)$	$\rho(300K)$ $(\mu\Omega cm)$	T* (K)	$\xi_c(0)$ ()
F1	1050	87.4	88.46	148	476	203	1.65
F3	850	81.4	84.55	237	760	213	1.75
F4	850	80.3	83.4	386	1125	218	1.78
F6	650	54.2	55.88	364	1460	245	2.64

Table 1. The parameters of the YBCO films with different oxygen concentration (sample F1−F6).

3.2. Pseudogap in YBCO films with different oxygen concentration

We proceed from the fact that the excess conductivity $\sigma'(T)$ arises as a result of the formation of paired fermions (local pairs) at temperatures $T_c < T < T^*$ [2, 6, 13, 23, 26, 47]. It is believed that formation of such pairs gives rise to their real binding energy, ε_b, which the quantity Δ^* characterizes [27]. As a result, the density of states of the normal excitations in this energy range decreases [57], which is referred to as the appearance of a pseudogap in the excitation spectrum [59, 61, 84, 98].

Since the PG is not measured directly in our experiments, the problem reduces to determining $\Delta^*(T)$ from the experimental dependence $\sigma'(T)$ and comparing it with those obtained from Eq. (10). To perform the analysis, the excess conductivity of every studied YBCO film, measured in the whole temperature interval from T^* down to T_c, was treated in the framework of the LP model using Eq. (15) and Eq. (16) [2, 13, 27]. Aside from the parameters, which directly come from experiment (Tables I), we substitute into Eq. (15) the values of $\Delta^*(T_c)$. Here, by analogy to the superconducting state, $\Delta^*(T_c)$ is the value of the PG in the limit $T \to T_c$. As it was shown in Ref. [15], $\Delta^*(T_c) \cong \Delta(0)$ and, correspondingly, Δ^* satisfies the condition $2\Delta^* \sim k_B\, T_c$, as it was demonstrated in Ref's. [99–101]. The conclusion has subsequently been confirmed by the tunneling experiments in Bi compounds [52]. To justify the values of $\Delta^*(T_c)$ used in our analysis we applied an approach proposed in Ref. [88] in which, however, the fluctuation contributions into $\sigma'(T)$ are neglected. But a definite advantage of their representation of the experimental data in the coordinates $ln\sigma'$ versus (1/T) is the fact that the rectilinear part of the resulting plot has turned out to be very sensitive to the value of $\Delta^*(T_c)$, which makes it possible to adjust the value chosen for this parameter. As expected, matching is achieved for values of $\Delta^*(T_c)$ which are determined by the relation $2\Delta^*(T_c)/k_B\, T_c \cong 5$ [99–101]. For the sample F4 $\Delta^*(T_c) \approx 190K$, i.e., $2\Delta^*(T_c)/(k_B\, T_c) \simeq 4.75$ [2, 27].

The curve constructed for F1 using Eq. (15) with the parameters ξ_{c0}^* =0.233, $\xi_c(0)$ = 1.65 Å, T_c^{mf} =88.46 K, T^*=203 K, $\Delta^*(T_c)$=218 K, and A_4 = 20 is labeled with the number 4 in Fig. 4. As one can see from the figure, the equation (15) describes well the experimental curve (thick solid line marked by **I**) over the whole temperature interval from T^* down to T_c. Similar results were obtained for the all other films studied.

Curve numbered 3 in the figure reproduces result of Ref. [102] in which, however, both the dynamics of pair-creation and pair-breaking above T_c were neglected. But, in accordance to our knowledge, the authors of the Ref. [102] were the first who have paid attention to the experimental fact that in YBCO compounds the reciprocal of the excess conductivity $\sigma'^{-1}(T)$ is an exponential function of ε in a certain temperature range above T_{c0} . Correspondingly, the adjustable coefficient A_3 [102] is chosen so that the computed curve matches experiment in the

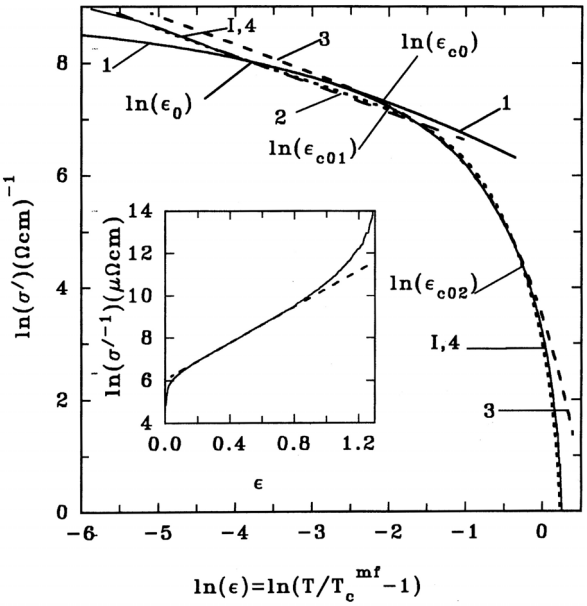

Figure 4. $\sigma'(T)$ in the coordinates $ln\sigma'$ versus $ln\varepsilon$ (solid curve **I**) for sample F1 for T from T_c to T^* in comparison with theory: curve 1-Maki-Thompsom contribution; 2-Aslamasov-Larkin contribution; 3 - theory [102]; 4 - Eq. (15) (short dashed segment). Inset: ln σ'^{-1} versus ε (solid line); dashed line - extrapolation of the rectilinear section [2, 27].

region of exponential behavior of $\sigma'^{-1}(T)$ (usually from $T_{c01} \approx 100\,K$ up to $T_{c02} \approx 150\,K$). It is clear that $ln\sigma'^{-1}$ is to be the linear function of ε, as shown in the insert of Fig. 4. The advantage of this approach is that it enables us to determine the parameter ε^*_{c0} which is reciprocal of the slope α of this linear function: $\varepsilon^*_{c0} = 1/\alpha$ [2, 102].

The same experimental dependencies of $\sigma'(T)$, as shown in Fig. 4, were obtained for all studied compounds, including $HoBa_2Cu_3O_{7-\delta}$ [95] and $SmFeAsO_{0.85}$ [20], suggesting the similar local pairs behavior in different HTS's. The fact enabled us to analyze the FLC and PG in $HoBa_2Cu_3O_{7-\delta}$ single crystals [95] and in $SmFeAsO_{0.85}$ FeAs-based superconductor [20] also in terms of the LP model, as will be discussed in the next divisions. Note, the complete coincidence of the given by Eq. (15) theoretical curve and the data (Fig. 4) is not necessary. We fit experiment by the theory to determine mostly the coefficient A_4 [2, 27], and coincidence in the 3D fluctuation region near T_c is only important, as discussed above. Nevertheless, the good coincidence of both theoretical and experimental curves obtained for all studied compounds [20, 67, 94, 95] means, in turn, that substituting into Eq. (16) the experimentally measured values of the $\sigma'(T)$ with the corresponding set of parameters, we should obtain a result which reflects the real behavior of $\Delta^*(T)$ quite closely in the experimental samples. The values of $\Delta^*(T)$ calculated using Eq. (16) for all YBCO films with the similar sets of parameters, as designated above for the film F1, are shown in Fig. 5 which actually displays our principal result. Indeed, despite the rather different $\Delta^*(T_c)$ and all other parameters, very similar $\Delta^*(T)$ behavior is observed for all studied films. The main common feature of every plot is a maximum of $\Delta^*(T)$ observed at the same $T_{max} \approx 130$ K. The important point here is

that the coherence length $\xi_{ab}(T_{max})$ was found to be the same for every studied film, namely, $\xi_{ab}(T_{max}) \approx 18$Å [2, 27].

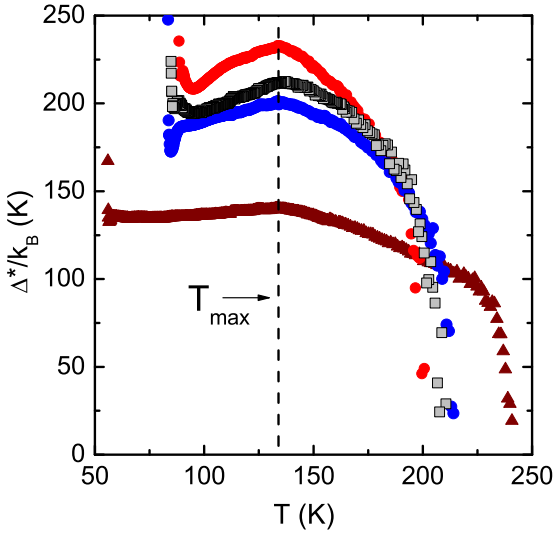

Figure 5. Dependencies of Δ^*/k_B on T calculated by Eq. (16) for samples F1 (upper curve, circles), F3 (squares), F4 (dots) and F6 (low curve, triangles). $T_{max} = T_{pair} \approx 130\,K$.

Let us discuss the obtained results (Fig. 5) now. Above 130 K ξ_{ab}(T) is very small ($\xi_{ab}(T^*) \approx 13$ Å), whereas the coupling energy ε_b is very strong. It is just the condition for the formation of the SBB [6, 24–26]. It was found [27] that over the temperature interval $T_{max} = T_{pair} < T < T^*$ every experimental $\Delta^*(T)/\Delta^*(T_{max})$ curve shown in Fig. 5 can be fitted by the Babaev-Kleinert (BK) theory [87] in the BEC limit (low n_f) in which the SBB have to form [6, 24–26, 85, 87]. (See also Fig. 13 as an example). The finding has to confirm the presence of the local pairs in the films at $T \leq T^*$ which are supposed to exist at these temperatures just in the form of SBB. As SBB do not interact with one another, the local pairs demonstrate no SC (collective) behavior in this temperature interval. It has subsequently been shown to be consistent with the tunneling experiments in Bi compounds [52] in which the SC tunneling features are smeared out above T_{pair}. Thus, above T_{max} (Fig. 5), which is also called T_{pair} in accordance with, e.g., Ref. [80], it is the so-called non-superconducting part of the PG.

But the pairs have already formed and exist in the sample even in this temperature range, this is a point. There a few evidences as for paired fermions existence in temperature interval from T^* down to T_{pair} [2]. Firstly, from studying the nuclear magnetic resonance (NMR) in weakly doped Y123 systems [57], the anomalous decrease of the Knight shift K(T) was observed on cooling just at $T \leq T^*$ (Fig. 6). In Landau theory [75] $K \sim \rho_n(\varepsilon) \equiv \rho_F$, where $\rho_n(\varepsilon)$ is the energy dependence of the density of Fermi states in the normal phase, which in classical superconductors actually remains constant in the whole temperature range of the normal phase existence, i.e., approximately down to T_c. Thus, the decrease of K(T) directly

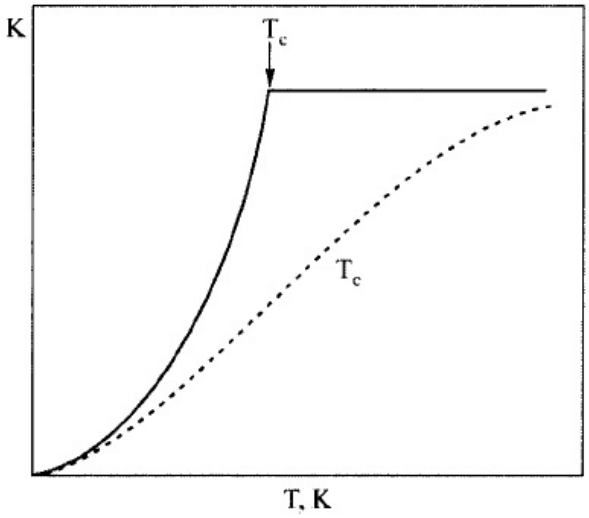

Figure 6. Temperature dependence of the Knight shift K(T) in classical superconductors (solid line) and in HTS's (dashed line) [[57]].

points out at the decrease of density of states most likely because of the local pair formation. Secondly, in measurements of the Hall effect noticeable enhancement of the Hall coefficient $R_H(T) \sim 1/e\,n_f$ was found on cooling just below T^* [2, 81, 97]. Obviously, the increase of R_H directly points out at the decrease of the normal charge-carrier density n_f. It is believed that it is because of the fact that any part of electrons transform into the local pairs. Thirdly, studying the behavior of the Nb-YBCO point contacts in high-frequency fields, we observed the pair-breaking effect of the microwave power up to $T^* \approx 230\,K$ [103]. It is clear, the observation of the pair-breaking effect naturally implies the existence of the paired fermions in the sample at such high temperatures. And, finally, very recently the polar Kerr effect (PKE) in Bi2212 was reported which also appears just below $T^* \approx 130\,K$ [90]. To be observable the PKE evidently acquires the presence of two different kinds of the quasi-particles in the sample. It is believed that such particles are most likely the normal electrons and local pairs.

Let us turn back to Fig. 5. With decreasing temperature below T_{max}, $\xi_{ab}(T)$ continues to increase whereas $\varepsilon_b(T)$ becomes smaller. Ultimately, at $T \leq T_{max} = T_{pair} \approx 130\,K$, where $\xi_{ab}(T) > 18$Å, the local pairs begin to overlap and acquire the possibility to interact. Besides, they do can be destroyed by the thermal fluctuations now, i.e. transform into fluctuating Cooper pairs, as mentioned above. The SC (collective) behavior of the local pairs in this temperature region is distinctly observed in many experiments [52, 67, 78–80], as discussed in details in div. 2.2. Eventually, the direct imaging of the local pair SC clusters persistence up to approximately $140\,K$ in Bi compounds is recently reported in Ref. [16] (Fig.2). Thus, below T_{max} it is the SC part of the pseudogap. Moreover, we consider $\xi_{ab}(T_{max}) \approx 18$Å to be the critical size of the local pair, at least in the YBCO [2, 27]. In fact, the local pairs behave like SBB when $\xi_{ab}(T) < 18$Å, and transform into fluctuating Cooper pairs when $\xi_{ab}(T) > 18$Å below T_{max}, thus resulting in the BEC-BCS transition [2, 27]. That is why, I will call T_{max} as T_{pair} now, as it becomes of common occurrence in the literature [80].

3.3. Fluctuation conductivity and pseudogap in $HoBa_2Cu_3O_{7-\delta}$ single crystals under pressure

To proceed with further understanding of physical nature of HTS's, it seemed to be rather interesting to compare above results for YBCO films, where no noticeable magnetism is expected, with any other HTS's in which magnetic subsystem could play significant role. One of a such system is $HoBa_2Cu_3O_{7-\delta}$ which has magnetic moment $\mu_{eff} \approx 9{,}7\mu_B$, due to magnetic moment of pure Ho which is $\mu_{eff} \approx 10.6\mu_B$ [95]. Thus, when Y is substituted by Ho a qualitatively another behavior of the system is expected because of Ho magnetic properties. Besides, in HTS compounds of the $ReBa_2Cu_3O_{7=\delta}$ (Re = Y, Ho, $Dy\cdots$) type with reduced n_f the specific non-equilibrium state can be realized under change of temperature [104] or pressure [105]. In our experiments effect of hydrostatic pressure up to 5 kbar on the fluctuation conductivity σ'(T) and pseudogap Δ^*(T) of weakly doped high-T_c single crystals $HoBa_2Cu_3O_{7-\delta}$ (HoBCO) with $T_c \approx 62$ K and oxygen index 7-$\delta \approx 6{,}65$ was studied [95]. The comparison of results with those obtained for $YBa_2Cu_3O_{7-\delta}$ (div. 3.2) and FeAs-based superconductor $SmFeAsO_{0.85}$ (div. 3.4) is to shed more light on the role of magnetic subsystem in the HTS's.

Measurements were carried out with current flowing in parallel to the twin boundaries when their influence on the charge carriers scattering is minimized [95]. Obtained results are analyzed within the Local Pair model [27]. The FLC and PG analysis of the sample under pressure is mainly discussed, and all results are summarized in the end. As usual, below the PG temperature $T^* \gg T_c$ resistivity of HoBCO, ρ(T), deviates down from linearity resulting in the appearance of the excess conductivity $\sigma'(T) = \sigma(T) - \sigma_N(T)$ (Eq.(1)). Resulting $\ln\sigma'$ as a function of $\ln\varepsilon$ near T_c is displayed in Fig. 7.

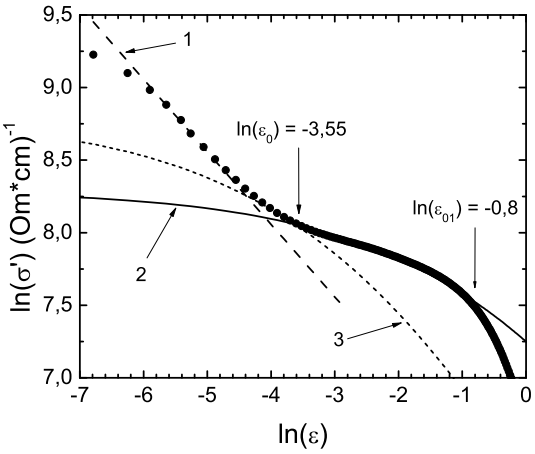

Figure 7. $\ln\sigma'$ vs $\ln\epsilon$ for $P = 4.8$ kbar (dots). Curve 1 - AL term; 2 - MT term with $d_1 = 2.95$Å; 3 - MT term with $d = 11.68$Å. Arrows designate T_0 and T_{01}.

As expected in the LP model, above the mean field critical temperature $T_c^{mf} \approx 65.4$ K and up to $T_0 \approx 67.3$ K ($\ln\varepsilon_0 \approx -3.55$), experimental $ln\sigma'(ln\varepsilon)$ can be well extrapolated by the

3D fluctuation term of the AL theory (Eq.(11)) (Fig. 7, dashed line 1). Above T_0, up to $T_{01} \approx 95\,\mathrm{K}$ ($\ln\varepsilon_{01} \approx -0.8$), the experimental data are well extrapolated by the MT fluctuation contribution (Eq. (3)) (Fig. 7, curve2) of the HL theory [72]

Here I would like to emphasize that curve 2 in Fig. 7 is plotted with $d_1 = 2.95$Å, where d_1 is the distance between conducting CuO_2 planes in HoBaCuO [106], and with $\tau_\phi(100\mathrm{K})\,\beta = (0.665 \pm 0.002)\times 10^{-13}$s which is defined by a formula $\tau_\phi\,\beta\,\mathrm{T} = \mathrm{A}\varepsilon_{01}$ (Eq. (14)). Accordingly, d_1 corresponds to $T_{01} \approx 95$ K ($\ln\varepsilon_{01} \approx -0.8$) marked by the right arrow in the figure. At $T \le T_{01}$, $\xi_c(T) \ge d_1$ is believed to couple the CuO_2 planes by Josephson interaction, and 2D FLC has to appear [67, 77]. This scenario of the FLC appearance reminds that observed for the $SmFeAsO_{0.85}$ sample (see div. 3.4), and found $ln\sigma'(ln\varepsilon)$ is close to that shown in Fig. 10. If we choose $d \approx 11.7$Å $= c$, which is a dimension of the unit sell along the c-axis, as in the case of YBCO films [67], the theory noticeably deviates from experiment (curve 3). Strictly speaking, this curve reflects the temperature dependence of the FLC being close to that obtained for the YBCO film F1 shown in Fig. 4.

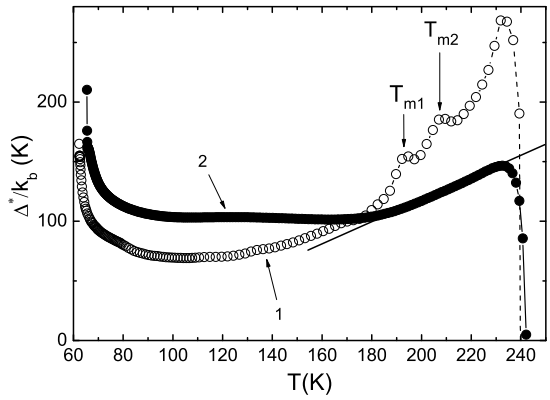

Figure 8. Δ^*/k_B as a function of T. Curve 1 - P = 0; 2 - P = 4.8 kbar. Arrows designate maxima temperatures at P = 0: T_{m1} and T_{m2}.

Thus, compare results one may conclude that HoBaCuO obviously demonstrates the enhanced 2D fluctuation contribution, compared to YBCO, and behaves in a good many ways like the $SmFeAsO_{0.85}$ (Fig. 10), most likely due to influence of its magnetic subsystem. Nevertheless, at $T = T_0 \approx 67.3$ K ($\ln\varepsilon_0 \approx -3.55$), at which $\xi_c(T) = d$, the habitual dimensional 2D-3D (AL - MT) crossover is distinctly seen on the plot. Below T_0 $\xi_c(T) > c$, and 3D fluctuation behavior is realized in which the fluctuating pairs interact in the whole volume of the sample [67]. It should be emphasized that, as well as it was found for the $SmFeAsO_{0.85}$ [20], at both T_{01} and T_0 (arrows in Fig. 7) $\xi_c(0) = d_1\varepsilon_{01}^{1/2} = d\varepsilon_0^{1/2} = (1.98 \pm 0.005)$Å. The finding is believed to confirm the validity of our analysis.

The similar $\ln\sigma'$ vs $\ln\varepsilon$ was also obtained for $P = 0$ ($T_c = 61.4$ K, $\rho(100\mathrm{K}) = 200\mu\Omega$cm, $T_0 = 63.4$ K, $T_{01} = 79.4$ K, $\tau_\phi(100\mathrm{K})\beta = 1.13 \cdot 10^{-13}$s and $d_1 = 3.2$Å). Thus, the pressure leads to increase in T_0 and T_{01}, i.e. increases the interval of 3D and especially 2D fluctuations. Most likely, it is due to decrease of the phase stratification of the single crystal under pressure

[104, 105]. The value of the C-factor also points out at this effect: $C_{3D} = 1.1$ and $= 0.53$ at $P = 4.8$ kbar and $P = 0$ kbar, respectively. The closer C_{3D} to 1.0, the more homogeneous is the sample structure [2, 67].

The experimental dependence of $\sigma'(T)$ in the whole temperature interval from T^* and down to T_c^{mf} turned out to be very close to that, shown in Fig. 4. The finding enables us to calculate $\Delta^*(T)$ using Eqs. (15) and (16). Resulting temperature dependence of the PG is shown in Fig. 8. In the figure curve 1 is plotted for $P = 0$ using Eq.(16) with the following parameters derived from experiment: $\varepsilon_{c0}^* = 0.88$, $\xi_{c(0)} = 1.57$Å, $T_c^{mf} = 62.3$ K, $T^* = 242$ K, $A_4 = 4.95$ and $\Delta^*(T)/k = 155$ K. Curve 2 is plotted for $P = 4.8$ kbar with $\varepsilon_{c0}^* = 0.67$, $\xi_c(0) = 1.98$Å, $T_c^{mf} = 65.4$ K, $T^* = 243$ K, and $A_4 = 18$, $\Delta^*(T)/k = 160$ K, respectively. In this case $T_c = 64$ K and $\rho(100)\text{K} = 172\mu\Omega$cm.

When $P = 0$, $\Delta^*(T)$ exhibits two unexpected maxima at $T_{m1} \approx 195$ K and at $T_{m2} \approx 210$ K (Fig. 8, curve 1), most likely because of two-phase stratification of the single crystal [104, 105]. Pressure-induced enhancement of the rising diffusion processes is assumed to cause a redistribution of labile oxygen from the low-temperature phase poor in charge carriers to the high-temperature one [105]. It results in the disappearance of both peaks and linear $\Delta^*(T)$ dependence with a positive slope at high T (Fig. 8, curve 2). Simultaneously, the sample resistivity, ρ, noticeably decreases, whereas T_c and $\xi_c(0)$ somewhat increase. Note that the maxima of $\Delta^*(T)$ and initial values of ρ, T_c and $\xi_c(0)$ are restored when the pressure is removed suggesting the assumption. Thus, both $\sigma'(T)$ and $\Delta^*(T)$ are markedly different from those obtained for the YBCO films [27, 67]. They resemble similar curves obtained for FeAs-based superconductor $SmFeAsO_{0.85}$ [20] (see div. 3.4). The result can be explained by the influence of paramagnetism in $HoBa_2Cu_3O_{7-\delta}$ [95, 104, 105]. Additionally, the linear drop of the PG, found for both $HoBa_2Cu_3O_{7-\delta}$ [95] and $SmFeAsO_{0.85}$ [20], is believed to reflect the influence of weak magnetic fluctuations in such compounds [21, 107, 108], as will be discussed in more details in the next division.

3.4. Fluctuation conductivity and pseudogap in $SmFeASO_{0.85}$

Despite of a huge amount of papers devoted to FeAs-based superconductors, there is an evident lack of the FLC and PG studies in these compounds [20]. This state of affairs is most likely due to the extreme complexity of the electronic configuration of the FeAs-based compounds, where the strong influence of magnetism, being changed with doping, is observed [17–19]. It is well known that upon electron or hole doping with F substitution at the O site [17, 113], or with oxygen vacancies [17, 18] all properties of parent RFeAsO compounds drastically change and evident antiferromagnetic (AFM) order has to disappear [17–19]. However, recent results [107–110] point toward an important role of low-energy spin fluctuations which emerge on doping away from the parent antiferromagnetic state which is of a spin-density wave (SDW) type [107, 108, 110]. Thus, below $T_S \sim 150K$ the AFM fluctuations, being likely of spin wave type, are believed to noticeably affect the properties of doped $RFeAsO_{1-x}F_x$ systems (Fig. 9). As shown by many studies [108–110] the static magnetism persists well into the SC regime of ferropnictides. In $SmFeAsO_{1-x}$ strongly disordered but static magnetism and superconductivity both are found to coexist in the wide range of doping, and prominent low-energy spin fluctuations are observed up to the highest achievable doping levels where T_c is maximal [21, 107, 108].

The interplay between superconductivity and magnetism has been a long-standing fascinating problem [111, 112], and relation 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 FeAs-based HTS's is still rather controversial [112]. As a result, rather complicated phase diagrams for different FeAs-based high-T_c systems [17, 109, 110], and especially for $SmFeAsO_{1-x}$ [113–116] (Fig. 9) are reported.

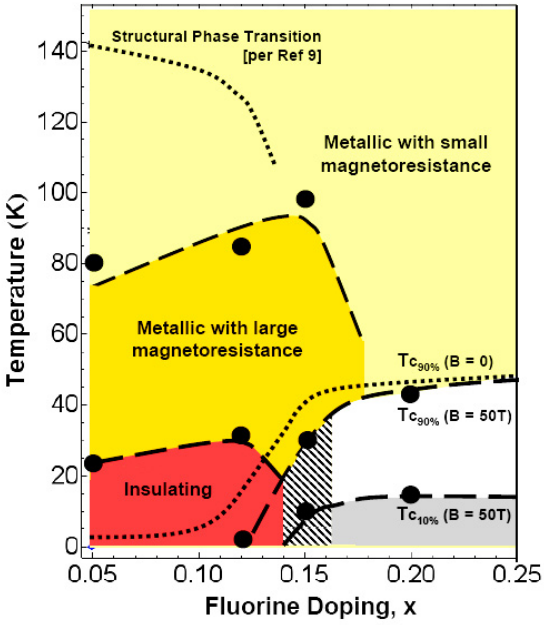

Figure 9. Phase diagram of $SmFeAsO_{1-x}F_x$ [[113]].

Naturally, rather peculiar normal state behavior of the system upon T diminution is expected in this case [109, 110, 113], when x is of the order of 0.15, as it is in our sample [20].

3.4.1. Experimental details

To shed more light on the problem, analysis of the FLC and PG was carried out within the LP model using results of resistivity measurements of $SmFeAsO_{0.85}$ polycrystal (T_c = 55 K) performed on fully computerized set up [20]. The width of the resistive transition into superconducting (SC) state is $\Delta T \leq 2K$ suggesting good phase and structural uniformity of the sample. In accordance with the LP model approach the resistivity curve above $T^* \sim 170K$ is extrapolated by the straight line to get $\sigma'(T) = \sigma(T) - \sigma_N(T)$ using Eq.(1).

The crossing of measured $\sigma'^{-2}(T)$ with T-axis denotes the mean-field critical temperature $T_c^{mf} \cong 57K$. This is the usual way of T_c^{mf} determination within the LP model [2, 67]. Resulting $\ln\sigma'$ versus $\ln\varepsilon$ is displayed in Fig. 10 in the temperature interval relatively close to T_c (dots) and compared with the HL theory [72] in the clean limit (curves 1-3). As expected, up to $T_0 \approx$

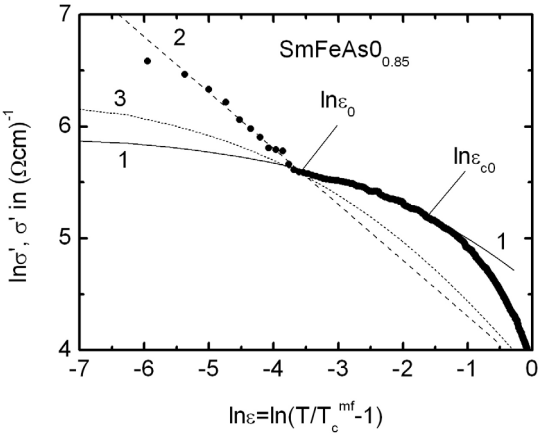

Figure 10. $ln\sigma'$ as a function of $ln\varepsilon$ near T_c (dots) in comparison with the HL theory: 1-MT contribution (d = 3.05Å); 2 - 3D AL contribution; 3-MT contribution (d = 8.495Å).

58.5 K ($ln\varepsilon_0$ =-3.6) the data are well extrapolated by the AL fluctuation contribution (Eq. 11) for any 3D system (straight line 2 in the figure). As mentioned above, this 3D fluctuation behavior was found to be typical for all without exception HTS compounds [2, 20, 67, 80, 95]. Accordingly, above T_0, up to $T_{c0} \approx 69K$ ($\ln\varepsilon_{c0} \cong -1.55$), this is 2D MT term (Eq. (3)) of the HL theory (Fig. 10, curve 1) which dominates well above T_c in the 2D fluctuation region [2, 67], as discussed in details in div. 2.2. As before, $\xi_c(0) = d\,\varepsilon_0^{1/2}$ is the coherence length along the *c*-axis, i.e. perpendicular to the conducting planes, and d is the distance between conducting layers in $SmFeAsO_{1-x}$. Thus, expected MT-AL (2D-3D) crossover is clearly seen in Fig. 10 at $ln\varepsilon_0$ =-3.6. The fact enables us to determine T_0 (Eq. (7)) and therefore the ε_0 (Eq. (7, 9)) with adequate accuracy. Now, proceeding in the usual way, i.e., using Eqs. (12, 14), and set d = 8.495Å, which is a dimension of the $SmFeAsO_{0.85}$ unit sell along the *c*-axis [114], $\xi_c(0) = (1.4 \pm 0.005)$Å, and $\tau_\phi(100K)\,\beta = (11 \pm 0.03) \times 10^{-13}$ s are derived from the experiment. As it is seen from the figure, Eq. (11) with measured value of $\xi_c(0)$ and the scaling factor C_3D = 0.083 describes the data fairly well just above T_c^{mf} (Fig. 10, dashed line 2) suggesting 3D fluctuation behavior of $SmFeAsO_{0.85}$ near T_c.

Till now the FeAs-based superconductor behaves like the YBCO films. However, the discrepancy appears when MT contribution is analyzed (Fig. 10, curve 3). Indeed, substituting the measured values of $\xi_c(0)$ and $\tau_\phi(100K)\,\beta$ into Eq. (3) we obtain curve 3 which looks like that found for YBCO films but apparently does not match the data. The finding suggests that our choice of d is very likely wrong in this case. To proceed with the analysis we have to suppose that $SmFeAsO_{1-x}$ becomes quasi-two-dimensional just when $\xi_c(T)$, getting rise with temperature diminution, becomes equal to d_1 = 3.05 Å at $T = T_{co} \approx 69K$ ($ln\varepsilon_{c0} \cong -1.55$). It is worth to emphasize that $(3.1 \div 3.0)$Å is the distance between *As* layers in conducting $As - Fe - As$ planes in $SmFeAsO_{1-x}$ [18, 114]. Below this temperature $\xi_c(T)$ is believed to couple the *As* layers in the planes by Josephson interaction [95]. This approach gives the

same value of $\xi_c(0) = d\,\varepsilon_{c0}^{1/2} = (1.4 \pm 0.005)$Å as calculated above using the usual crossover temperature T_0. We think this fact is to confirm the supposition. At the same time the phase relaxation time changes noticeably and amounts $\tau_\phi(100K)\,\beta = (1.41 \pm 0.03) \times 10^{-13}$s in this case. Substitution of measured values of $\xi_c(0)$ and this new $\tau_\phi(100K)\,\beta$ into Eq. (3) enables us to fit the experimental data by the MT term just up to T_{c0} which is about 15 K above T_c (Fig. 10, curve 1). The result suggests enhanced 2D MT fluctuations in $SmFeAsO_{1-}$ compared to YBCO films. Recall, the similar enhanced 2D MT fluctuations are found for $HoBa_2Cu_3O_{7-\delta}$ [95] (div. 3.3)

3.4.2. Pseudogap analysis

Somehow surprisingly, $ln\sigma'$ versus $ln\varepsilon$ measured for the $SmFeAsO_{0.85}$ in the whole temperature range from T^* down to T_c^{mf} was found to be very close to that of YBCO films (Fig. 4). Even the exponential dependence of the reciprocal of the excess conductivity $\sigma'^{-1}(T)$ still occurs between $ln\varepsilon_{c0}$ and $ln\varepsilon_{c02}$ ((69 - 100)K). As a result, the function $ln\sigma'^{-1}$ versus ε appears to be linear in this temperature range (similar to that shown in insert in Fig. 4), and its slope $1/\alpha$ still determines the parameter ε_{c0}^* used in the PG analysis [20, 27]. Taking obtained results into account, one can draw a conclusion that the LP model approach can be applied to analyze the temperature dependence of the PG. To proceed with the PG analysis the value of the coefficient A_4 must be found. As before, to determine A_4 we fit the experimental $\sigma'(\varepsilon)$ by the theoretical curve (Eq. (15)) in the region of 3D fluctuations near T_c [20, 27]. All other parameters directly come from experiment, as discussed above. The theoretical $\sigma'(\varepsilon)$ curve is constructed using Eq. (15) with the reasonable set of experimentally measured parameters: ξ_{c0}^* = 0.616, $\xi(0)$ = 1.4Å, T_c^{mf} = 56.99 K, $T^* = 175K$, A_4 = 1.98 and optionally chosen $\Delta^*(T_c)/k_B$ = 160 K and found to describe the experimental data well in the whole temperature interval from T^* down to T_c^{mf} [95]. The only exception is the 2D MT region where relatively small deviation down from experiment, negligible in the case of YBCO films [67], is observed. It is due to enhanced MT fluctuation contribution in the 2D fluctuation region, as mentioned above. Compare results with those obtained for magnetic superconductor $Dy_{0.6}Y_{0.4}Rh_{3.85}Ru_{0.15}B_4$ [117] we assume this enhancement to be the consequence of weak magnetic fluctuations in $SaFeAsO_{1-x}$ [107–110], as will be discussed below.

Now we have almost all parameters to calculate the temperature dependence of PG using Eq.(16) except the value of $\Delta^*(T_c)$ which actually is responsible for the A_4. The problem is, the value of $\Delta^*(T_c)$ and in turn the ratio $2\Delta^*(T_c)/k_B\,T_c$ in Fe-based superconductors remain uncertain. Reported in the literature values for $\Delta(0)$ and $2\Delta(0)/T_c$ in $SmFeAsO_{1-x}$ range from $2\Delta(0) \approx 37$ meV ($2\Delta/T_c \sim 8$, strong-coupling limit) obtained in measurements of far-infrared permittivity [17], down to Δ = (8 - 8.5) meV ($2\Delta/T_c \sim$ (3.55 - 3.8)) measured by a scanning tunneling spectroscopy [118, 119] which is very close to standard value 3.52 of the BCS theory (weak-coupling limit). It is believed at present that $SmFeAsO_{1-x}$ has two superconducting gaps $\Delta_1(0) \approx 6.7$ meV and $\Delta_2(0)$ which ranges from $\approx 15\,meV$ up to $\approx 21\,meV$ [120]. Besides we still think that $\Delta^*(T_c) \approx \Delta(0)$ [20], as is was justified in Ref. [15]. To feel more flexible, four curves are finally plotted in Fig. 11 with $\Delta^*(T_c)/k_B$ = 160 K ($2\Delta^*(T_c)/T_c \cong 5.82$), = 140 K ($2\Delta^*(T_c)/T_c \cong 5.0$), 120 K ($2\Delta^*(T_c)/T_c \cong 4.36$) and = 100 K ($2\Delta^*(T_c)/T_c \cong 3.63$) from top to bottom, respectively. Naturally, different values of coefficients A_4 correspond to each curve, whereas the other above parameters remain unchangeable.

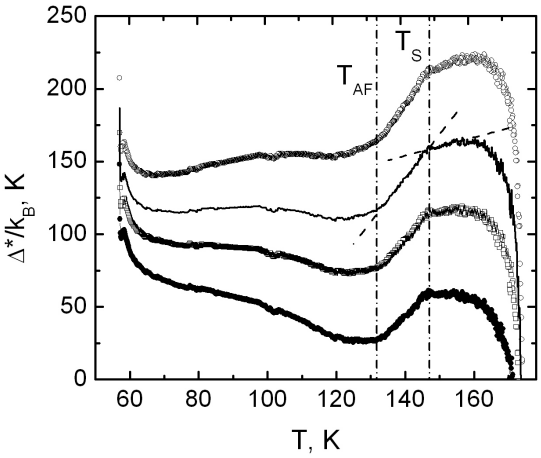

Figure 11. Δ^*/k_B versus T dependencies for $SmFeAsO_{0.85}$ with four different values of $\Delta^*(T_c)/k_B$ (see the text).

Very unexpected $\Delta^*(T)$ behavior is observed (Fig. 11). The most striking result is a sharp drop of $\Delta^*(T)$ at $T_s \approx 147$ K, as clearly illustrates the curve with $\Delta^*(T_c)/k_B$ =140 K plotted without symbols. Usually T_s is treated as a temperature at which a structural tetragonal-orthorhombic transition occurs in parent SmFeAsO. In the undoped FeAs compounds it is also expected to be a transition to SDW ordering regime [17–19]. Below T_S the pseudogap $\Delta^*(T)$ drops linearly down to $T_{AFM} \approx 133$ K (Fig. 11), which is attributed to the AFM ordering of the Fe spins in a parent SmFeAsO compounds [17, 121]. Below T_{AFM} the slop of the $\Delta^*(T)$ curves apparently depends on the value of $\Delta^*(T_c)$ [20]. Strictly speaking it is difficult to say at present is $T_{AFM} = T_N$ of the whole system or not because the AFM ordering of Sm spins occurs at $\approx 5K$ only [17, 121].

Found $\Delta^*(T)$ behavior is believed to be explained in terms of the theory by Machida, Nokura and Matsubara (MNM) [111] developed for AFM superconductors in which the AFM ordering with a wave vector Q may coexist with the superconductivity. This assumption was supported in, eg., the theory by Chi and Nagi [122]. In the MNM theory the effect of the AFM molecular field $h_Q(T)$ ($|h_Q| \ll \varepsilon_F$) on the Cooper pairing was studied. It was shown, that below T_N the BCS coupling parameter $\Delta(T)$ is reduced by a factor $[1 - const \cdot |h_Q(T)|/\varepsilon_F]$ due to the formation of energy gaps of SDW on the Fermi surface along Q. As a result the effective attractive interaction $\breve{g}\,N(0)$ or, equivalently, the density of states at the Fermi energy ε_F is diminished by the periodic molecular field that is

$$\breve{g}\,N(0) = g\,N(0)\,[1 - \alpha\,m(T)]. \tag{17}$$

Here $m(T)$ is the normalized sublattice magnetization of the antiferromagnetic state and α is a changeable parameter of the theory. Between T_c and T_N ($T_c > T_N$ is assumed) the order parameter is that of the BCS theory. Since below T_N the magnetization $m(T)$ becomes nonvanishing, $\breve{g}\,N(0)$ is weakened that results in turn in a sudden linear drop of $\Delta(T)$

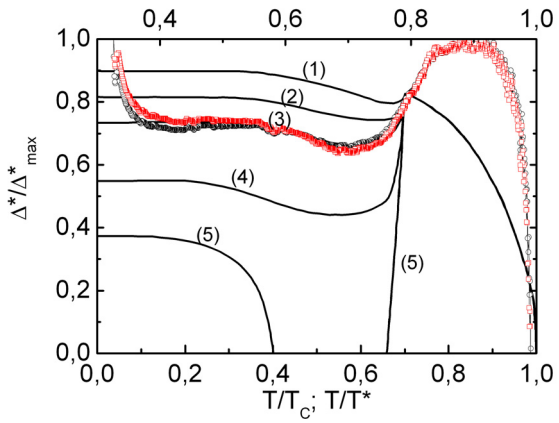

Figure 12. $\Delta^*(T)/\Delta_{max}$ in $SmFeAsO_{0.85}$: (red ○) - $\Delta^*(T_c)/k_B$=130 K; (○) - 135 K. Solid curves $\Delta(T)/\Delta_{max}$ correspond to MNM theory with the different $\alpha \sim 1/[\breve{g}\,N(0)]$: (1) - α = 0.1, (2) - α = 0.2, (3) - α = 0.3, (4) - α = 0.6 , (5) - α = 1.0; T_N/T_c = 0.7 [[111]].

immediately below T_N. As $m(T)$ saturates at lower temperatures, $\Delta(T)$ gradually recovers its value with increasing the superconducting condensation energy (Fig. 12, solid curves). This additional magnetization $m(T)$ was also shown to explain the anomaly in the upper critical field H_{c2} just below T_N observed in studying of RMo_6S_8 (R = Gd, Tb, and Dy) [111]. However, predicted by the theory decrease of $\Delta(T)$ at $T \leq T_N$ was only recently observed in AFM superconductor $ErNi_2B_2C$ with $T_c \approx 11$ K and $T_N \approx 6$ K, below which the SDW ordering is believed to occur in the system [123]. The result evidently supports the prediction of the MNM theory. Our results are found to be in a qualitatively agreement with the MNM theory as shown in Fig. 12, where the data for $\Delta^*(T_c)/k_B$ = 130 K (red ○) and $\Delta^*(T_c)/k_B$ = 135 K (○) are compared with the MNM theory (solid lines).

The curves are scaled at T/T_c = 0.7 and demonstrate rather good agreement with the theory below T/T_c = 0.7. Note, that the upper scale is T/T^*. Both shown $\Delta^*(T)$ dependencies suggest the issue that just $\Delta^*(T_c)/k_B$ = 133 K, which is just T_{AFM}, would provide the best fit with the theory. Above T/T_c = 0.7 the data evidently deviate from the BCS theory. It seems to be reasonable seeing $SmFeAsO_{0.15}$ as well as any other ferropnictides is not a BCS superconductor.

It is important to emphasize that in our case we observe the particularities of $\Delta^*(T)$ in the PG state, i. e. well above T_c but just at $T \approx T_s$, below which the SDW ordering in parent SmFeAsO should occur. However, it seems to be somehow surprising as no SDW ordering in optimally doped $SmFeAsO_{0.15}$ is expected. The found very specific $\Delta^*(T)$ can be understood taking mentioned above weak AFM fluctuations (low-energy spin fluctuations), which should exist in the system, into account. At the singular temperature T_s these fluctuations are believed to enhance AFM in the system likely in the form of SDW. After that, in accordance with the MNM theory scenario, the SDW has to suppress the order parameter of the local pairs as shown by our results. Thus, the results support the existence both weak AFM fluctuations and the paired fermions (local pairs) in the PG region, which order parameter is apparently suppressed by these fluctuations [20].

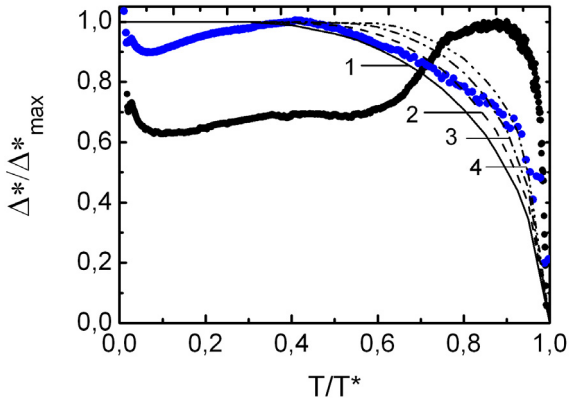

Figure 13. $\Delta^*(T)/\Delta^*_{max}$ in $SmFeAsO_{0.85}$ with $\Delta^*(T_c)/k_B$ = 160 K (•) and in YBCO film with T_c = 87.4 K (blue •) [27] as a function of T/T^* (T/T_c in the case of the theory). Curves $1 \cdots 4$ correspond to BK theory with different $x_0 = \mu/\Delta(0)$: 1 - x_0 = 10.0 (BSC limit), 2 - x_0 = -2.0, 3- x_0 = -5.0, 4 - x_0 = -10.0 (BEC limit) [[87]].

To confirm the conclusion, relation $\Delta^*(T)/\Delta^*_{max}$ as a function of T/T^* (T/T_c in the case of the theory) is plotted in Fig. 13. Black dots represent the studied $SmFeAsO_{0.85}$ with $\Delta^*(Tc)/k_B$ = 160 K, which corresponds to the strongly coupled limit ($2\Delta^*(T_c)/T_c \cong 5.82$). Blue dots display the data for YBCO film F1 [27]. The solid and dashed curves display the results of the Babaev-Kleinert (BK) theory [87] developed for the SC systems with different charge carrier density n_f . For the different curves the different theoretical parameter $x_0 = \mu/\Delta(0)$ is used, where μ is the chemical potential. Curve 1, with x_0 = +10, gives the BCS limit. Curve 4 with x_0 = -10 represents the strongly coupled BEC limit, which corresponds to the systems with low n_f in which the SBB must exist [23, 25, 85, 87]. As well as in the YBCO film, the $\Delta^*(T)/\Delta^*_{max}$ in $SmFeAsO_{0.85}$ evidently corresponds to the BEC limit (Fig. 13) suggesting the local pairs presence in the FeAs-based superconductor. Below $T/T^* \approx 0.4$ both experimental curves demonstrate the very similar temperature behavior suggesting the BEC-BCS transition from local pairs to the fluctuating Cooper pairs to be also present in FeAS-based superconductors [20]. But, naturally, no drop of $\Delta^*(T)$ is observed for the YBCO film (Fig. 13, blue dots) at high temperatures, as no antiferromagnetism is expected in this case. This fact can be considered as an additional evidence of the AFM nature of the $\Delta^*(T)$ linear reduction below T_s in $SmFeAsO_{0.85}$ found in our experiment.

It has to be emphasized that recently reported phase diagrams [113–116] (Fig. 9) apparently take into account a complexity of magnetic subsystem in $SmFeAsO_{1-x}F_x$ and are in much more better agreement with our experimental results. But it has to be also noted that we study the $SmFeAsO_{1-x}$ system whereas the phase diagrams are mainly reported for the $SmFeAsO_{1-x}F_x$ compounds. Is there any substantial difference between the both compounds has yet to be determined. Evidently more experimental results are required to clarify the question.

3.5. Angle-resolved photoemission measurements of the energy pseudogap of high-T_c $(Bi,Pb)_2(Sr,La)_2CuO_{6+\delta}$ superconductors: A model evidence of local pairs

Taking all above consideration into account, it can be concluded that the FLC and PG description in terms of local pairs gives a set of reasonable and self-consistent results. However, to justify the conclusion it would be appropriate to test the LP model approah using independent results of other research groups who have measured straightforwardly the PG or any other related effects. But for a long time there was a lack of indispensable data.

Fortunately, analysis of the pseudogap in $(Bi,Pb)_2(Sr,La)_2CuO_{6+\delta}$ (Bi2201) single-crystals with various T_c's by means of ARPES spectra study was recently reported [80]. The study of Bi2201 allows avoid the complications resulting from the bilayer splitting and strong antinodal bosonic mode coupling inherent to Bi2212 and Bi2223 [90, 91]. Symmetrized energy distribution curves (EDCs) were found to demonstrate the opening of the pseudogap on cooling below T^*. It was shown that T^*, obtained from the resistivity measurements, agrees well with one determined from the ARPES data using a single spectral peak criterion [80]. Finally, from the ARPES experiments information about the temperature dependence of the loss of the spectral weight close to the Fermi level, $W(E_F)$, was derived [80]. $W(E_F)$ versus T measured for optimally doped OP35K Bi2201 (T_c=35 K, T^* = 160 K) turned out to be rather unexpected, as shown in Fig. 14a taken from Ref. [80]. Above T^* the $W(E_F)$ is nonlinear function of T. But below T^*, over the temperature range from T^* to $T_{pair} = (110 \pm 5)$ K (Fig. 14a), the $W(E_F)(T)$ decreases linearly which is considered as a characteristic behavior of the "proper" PG state [80]. However, no assumption as for physical nature of this linearity as well as for existence of the paired fermions in the PG region is proposed. Below T_{pair} the $W(E_F)$ vs T noticeably deviates down from the linearity (Fig. 14a). The deviation suggests the onset of another state of the system, which likely arises from the pairing of electrons, since the $W(E_F)(T)$ associated with this state smoothly evolves through T_c (Fig. 14a).

To compare results and justify our Local Pair model, the ρ_{ab} vs T of the OP35K Bi2201, reported in Ref. [80], was studied within the LP model [13]. The $\Delta^*(T)$ was calculated by Eq. (16) with the following reasonable set of parameters: T_c = 35 K, T_c^{mf} = 36,9 K, T^* =160 K, $\xi_c(0)$= 2.0Å, ε_{c0}^* = 0.89, and A_4 = 59. $\sigma'(T)$ is the experimentally measured excess conductivity derived from the resistivity data using Eq. (1). Resulting $\Delta^*(T)/\Delta_{max}^*$ is plotted in Fig. 14b (green dots). As expected, the shape of the $\Delta^*(T)$ curve is similar to that found for YBCO films (Fig. 5). Besides, the maximum of $\Delta^*(T)/\Delta_{max}^*$ at $T_{max} \approx 100K$ actually coincides with the change of the $W(E_F)(T)$ slop at T_{pair}, measured by ARPES, which seems to be reasonable. In fact, in accordance with our logic, T_{max} is just the temperature which divides the PG region on SC and non-SC parts depending on the local pair state, as described above. Recall, that above T_{max} the local pairs are expected to be in the form of SBB. Most likely just the specific properties of SBB cause the linear $W(E_F)(T)$ over this temperature region (Fig. 14a). The two following facts are believed to confirm the conclusion. Firstly, when SBB disappear above T^*, the linearity disappears too. Secondly, below T_{max}, or below T_{pair} in terms of Ref. [80], the SBB have to transform into fluctuating Cooper pairs giving rise to the SC (collective) properties of the system. This argumentation coincides with the conclusion of Ref. [80] as for SC part of the pseudogap below T_{pair}. As SBB are now also absent, the linearity of $W(E_F)(T)$ again disappears. Thus, we consider the $\Delta^*(T)$, calculated within our Local Pair model (Fig. 14b), to be in a good agreement with the temperature dependence of the loss of the spectral weight

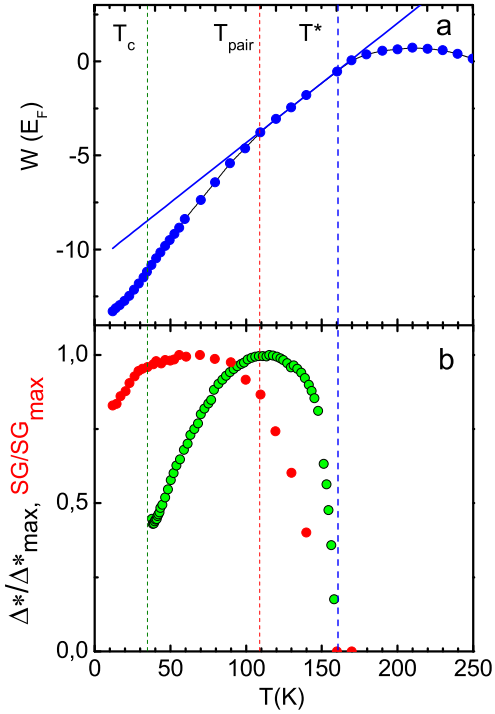

Figure 14. a. Spectral weight W(E_F) vs T (blue dots) for OP35K Bi2201. The solid line is the guidance for eyes only [[80]]. b. Pseudogap $\Delta^*(T)/\Delta^*_{max}$ (green dots) and spectral gap SG/SG_{max} (red dots) [[80]] as the functions of temperature for the same sample.

W(E_F) (Fig. 14a) obtained from the ARPES experiments performed on the same sample. In this way, the results of ARPES experiments reported in Ref. [80] are believed to confirm our conclusion as for existence of the local pairs in HTS's, at least in Bi2201 compounds.

Also plotted in Fig 14b is the normalized spectral gap ($SG(T)$) (red dots) equals to the energy of the spectral peaks of EDCs measured by ARPES [80]. Important in this case is that $SG(T)$ smoothly evolves through both T_{pair} and T_c. The fact is believed to confirm assumed in the LP model the local pair existence above T_{pair}. Despite the evident similarity there are, however, at least two differences between the curves shown in Fig. 14b. First, there is no direct correlation between the $SG(T)$ and the $W(E_F)(T)$ (Fig. 14 a, b). Why the maximum of $SG(T)$ is shifted toward low temperatures compared to T_{pair}, has yet to be understood. The second difference is the absolute value of the SG compared to the pseudogap. The spectral gap has $SG_{max} \approx$ 40 meV and $SG(T_c) \approx 38$ meV [80]. It gives $2SG(T_c)/k_BT_c \approx 26$ which is apparently too high. The PG values are $\Delta^*_{max} \approx 16.5$ meV and $\Delta^*(T_c) \approx 6.96$ meV, respectively. It gives $2\Delta^*(T_c)/k_BT_c \approx 6.4$ which is a common value for the Bi compounds [124] with respect to

relatively low T_c in this case. Thus, there is an unexpected lack of coincidence between the SG and PG.

4. Conclusion

The Chapter presents a detailed consideration of the LP model developed to study the PG in HTS's. In accordance with the model the local pairs have to be the most likely candidate for the PG formation. At high temperatures ($T_{pair} < T \leq T^*$) we believe the local pairs to be in the form of SBB which satisfy the BEC theory (non-SC part of a PG). Below T_{pair} the local pairs have to change their state from the SBB into fluctuating Cooper pairs which satisfy the BCS theory (SC part of a PG). Thus, with decrease of temperature there must be a transition from BEC to BCS state [2, 27]. The possibility of such a transition is considered to be one of the basic physical principals of the high-T_c superconductivity. The transition was predicted theoretically in Ref. [23, 24, 74] and experimentally observed in our experiments [2, 20, 27, 95].

A key test for our consideration is the comparison of the $\Delta^*(T)$, calculated within the LP model, with the temperature dependence of the loss of the spectral weight close to the Fermi level $W(E_F)(T)$, measured by ARPES for the same sample [80]. The resulting $\Delta^*(T)$ is found to be in a good agreement with the $W(E_F)(T)$ obtained for OP35K Bi2201 (Fig. 14). It allows us to explain reasonably the $W(E_F)(T)$ dependence, both above and below T_{pair}, in terms of local pairs.

The obtained results are also in agreement with the conclusions of Ref's. [16, 90, 91] as for SC and non-SC parts of the PG in Bi systems. Besides, formation of the local pairs is also believed to explain the rise of the polar Kerr effect and response of the time-resolved reflectivity, both observed for Bi systems just below T^* [90]. While, the Nernst effect [16], which is likely due to the SC properties of the local pairs, is observed only below T_{pair}, or below T_{max} in terms of our model. All the facts have to support the local pair existence in HTS's at $T \leq T^*$, Thus, we may conclude, that on the basis of the developed LP model the self-consistent picture of the PG formation in HTS's is obtained. At the same time the issue concerning the pairing mechanism in HTS's still remains controversial [22].

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5. References

[1] J. G. Bednorz , K. A. Mueller. "Possible High - T_c Superconductivity in the Ba-La-Cu-O System", *Z. Phys. B. - Condensed Matter*, vol. 64, pp. 189-193, 1986.

[2] A. L. Solovjov, V. M. Dmitriev, "Fluctuation Conductivity and Pseudogap in YBCO High-Temperature Superconductors", *Low Temp. Phys.* vol. 35, pp. 169-197, 2009.
[3] C. P. Slichter, " Experimental Evidence for Spin Fluctuations in High Temperature Superconductors", *Strongly Correlated Electronic Materials*, K. S. Bedell, Z. Wang, D. Meltzer, A. Balatsky, and E. Abrahams, Ed., Redwood City: Addison-Wesley, 1994, p. 427-479.
[4] Yu. A. Izyumov, "Strongly Correlated Electrons: t-J-Model", *Physics Uspekhi*, vol. 167, pp. 465-497, 1997.
[5] J. M. Tranquada, G. D. Gu, M. Hücker et al. (13 auth.), "Evidence for Unusual Superconducting Correlations Coexisting with Stripe Order in $La_{1.875}Ba_{0.125}CuO_4$", *Phys. Rev. B*, vol. 78, pp. 174529(1-4), 2008.
[6] V. M. Loktev, "Particularities of Superconductivity in 2D Metals: Transition from Cooper Pairing to the Local One", *Low Temp. Phys.*, vol. 22, pp. 488-491, 1996.
[7] A. A. Pashitskii, "Low-frequency Fluctuations of the Charge Density and High-Temperature Superconductivity in Metallic-Oxides Compounds", *Low Temp. Phys.* vol. 21, pp. 763-777, 1995; and *Low Temp. Phys.*, vol. 21, pp. 837-883, 1995.
[8] T. Timusk and B. Statt, "The Pseudogap in High-Temperature Superconductors: an Experimental Survey", *Rep. Prog. Phys.*, vol. 62, pp. 161-222, 1999.
[9] Y. Iye, *Phys. Properties of High-Temperature Superconductors*, D. M. Ginsberg, Ed., vol.3, Singapore: World Scientfic, 1992, pp. 285-361.
[10] V. V. Eremenko, V. N. Samovarov, V. N. Svishchev, V. L. Vakula, M. Yu. Libin, and S. A. Uyutnov, "Observation of the Habbard and Covalent Correlations in Spectral Characteristics of $YBa_2Cu_3O_{6+x}$ Films", *Low Temp. Phys.*, vol. 26, pp. 541-556, 2000.
[11] B. P. Stojkovic, D. Pines, "Theory of the Longitudinal and Hall Conductivities of the Cuprate Superconductors", *Phys. Rev. B*, vol. 55, pp. 8576-8595, 1997.
[12] E. G. Maksimov, "The Problem of High-Temperature Superconductivity. The Update Situation", *Physics Uspekhi*, vol. 43, pp. 965-993, 2000.
[13] A. L. Solovjov, M. A. Tkachenko, "Pseudogap and Local Pairs in High-T_c Cuprate Superconductors", *arXiv:1112.3812v1 [cond-mat.supr-con]*.
[14] C.W. Chu, L. Gao, F. Chen, Z. J. Huang, R. L. Meng,and Y. Y. Xue, "Superconductivity Above 150 K in $HgBa_2Ca_2Cu_3O_{8+\delta}$ at High Presures", *Nature*, vol. 365, pp. 323-324, 1993.
[15] J. Stajic, A. Iyengar, K. Levin, B. R. Boyce, and T. R. Lemberger," Cuprate Pseudogap: Competing Oder Parameters or Precursor Superconductivity", *Phys. Rev. B*, vol. 68, pp. 024520-024529, 2003.
[16] A. Yazdani, "Visualizing Pair Formation on the Atomic Scale and the Search for the Mchanism of Superconductivity in high-T_c cuprates", *J. Phys.: Condens. Matter*, vol. 21, pp. 164214-164219, 2009.
[17] M V. Sadovskii, *Physics Uspekhi*, "High-Temperature Superconductivity in Layered Iron Compounds", vol. 51, pp. 1201-1271, 2008.
[18] A. L. Ivanonskii, "New High-Temperature Superconductors Based on Rare Earth and Transition Metal Oxyarsenides and Related Phases: Synthesis, Properties and Simulation", *Physics Uspekhi*, vol 51, pp. 1229- 1306, 2008.
[19] Y. A. Izyumov and E. Z. Kurmaev, *Physics Uspekhi*, vol. 51, pp. 1261- 2008.
[20] A. L. Solovjov, V. N. Svetlov, V. B. Stepanov, S. L. Sidorov, V. Yu. Tarenkov, A. I. D'yachenko, and A.B.Agafonov, "Possibility of Local Pair Existence in Optimally Doped

$SmFeAsO_{1-x}$ in Pseudogap Regime", *arXiv:1012.1252v [cond-mat, supr-con]*, 2010; *Low Temp. Phys.*, vol. 37, pp. 557-601, 2011.
[21] I. I. Mazin, "Superconductivity gets an iron boost", *Nature*, vol. 464, pp. 11-13, 2010.
[22] V.M. Loktev, V.M. Turkowsky, "On the Theory of a Pseudogap State in Low Dimensional Superconductors with Anisotropic Order Parameter", *Rep. National Academ. Sci. Ukr.*, vol. 1, pp. 70-75, 2012.
[23] Ñ.A.R. Sa de Melo, M. Randeria, and J. R. Engelbrecht, "Crossover from BCS to Bose Superconductivity: Transition Temperature and Time-Dependent Ginzburg-Landau Theory", *Phys. Rev. Lett.*, vol. 71, pp. 3202-3205, 1993.
[24] R. Haussmann, "Properties of a Fermi Liquid at the Superfluid Transition in the Crossover Region Between BCS Superconductivity and Bose-Einstein Condensation", *Phys. Rev. B*, vol. 49, pp. 12975-12983, 1994.
[25] J. R. Engelbrecht, M. Randeria, and C. A. R. Sa de Melo,"BCS to Bose Crossover: Broken Symmetry State", *Phys. Rev. B*, vol. 55, pp. 15153-15156, 1997.
[26] O. Tchernyshyov, "Noninteracting Cooper Pairs Inside a Pseudogap", *Phys. Rev. B*, vol. 56, pp. 3372-3380, 1997.
[27] A. L. Solovjov and V. M. Dmitriev, "Resistive studies of the pseudogap in YBaCuO films with consideration of the transition from BCS to Bose-Einstein condensation", *Low Temp. Phys.*, vol. 32, pp. 99-108, 2006.
[28] V. J. Emery and S. A. Kivelson, "Importance of Phase Fluctuations in Superconductors with Small Superfluid Density", *Nature*, vol. 374, pp.434-437, 1995.
[29] P. W. Anderson, "The Theory of Superconductivity in High-T_c Cuprates", *Phys. Rev. Lett.*, vol. 67, pp. 2092, 1991.
[30] A. S. Alexandrov and N. F. Mott, *High Temperature Superconductors and Other Superfluids*, London: Taylor and Francis, 1994.
[31] J. T. Devreese, *Polarons*, (Encyclopedia of Applied Physics), G.L. Trigg, Ed., vol. 14, Dordrecht: VCH Publishers, 1996, pp. 383-414.
[32] J. Bonča and S. A. Trugman, " Bipolarons in the Extended Holstein Hubburd Model", *Phys. Rev. B*, vol. 64, pp. 094507(1-4), 2001.
[33] J. Bardeen, L. N. Cooper, and J. R. Schrieffer, "Theory of Superconductivity", *Phys. Rev.*, vol. 108, pp. 1175-1204, 1957.
[34] Ponomarev Ya. G., Tsokur E. B., Sudakova M. V., S. N. Tchesnokov et.al., "Evidence for Strong ElectronŰPhonon Interaction from Inelastic Tunneling of Cooper Pairs in c-Direction in $Bi_2Sr_2CaCu_2O_8$ Break Junctions", Solid State Commun. Vol. 111, pp. 513-518, 1999.
[35] K. H. Bennemann and J. B. Katterson, Ed.,*The Physics of Superconductors. Conventional and High-T_c Superconductors*, vol. 1, New York: Springer, 2003.
[36] P. W. Anderson, *The Theory of Superconductivity in the High T_c Cuprates*, Princeton: Princeton University Press, 1997.
[37] L. Benfatto and S. G. Sharapov, "Optical-Conductivity Sum Rule in Cuprates and Unconventional Charge Density Waves: a Short Review", *Low Temp. Phys.*, vol. 32, pp. 533-547, 2006.
[38] A. M. Gabovich, A. I. Voitenko, T. Ekino, Mai Suan Li, H. Szymczak, and M Pękała, "Competition of Superconductivity and Charge Density Waves in Cuprates: Recent Evidence and Interpretation", *Advances in Condensed Matter Physics*, vol. 2010, ID 681070, 40 pp. 2010.

[39] A. Mills and H. Monien, "Antiferromagnetic Correlations and Nuclear Magnetic Relaxation in High-T_c Superconductors: A Critical Reexamination", *Phys. Rev. B*, vol. 45, pp. 5059-5076, 1992.

[40] T. Sakai and Y. Takahashi, "Pseudogap Induced by Antiferromagnetic Spin Correlation in High-Temperature Superconductors", *J. Phys. Soc. Jpn.*, vol. 70, pp. 272-277, 2001.

[41] I. Eremin and D. Manske, " Excitations in Layered Cuprates: a Fermi-Liquid Approach", *Low Temp. Phys.*, vol. 32, pp. 519-532, 2006.

[42] J. R. Schrieffer, X. G. Wen, and S. C. Zhang, "Dynamic Spin Fluctuations and the Bag Mechanism of High-T_c Superconductivity", *Phys. Rev. B*, vol. 39, pp. 11663-11679, 1990.

[43] A. Kampf and J. R. Schrieffier, "Pseudogaps and the Spin-Bag Approach to High-T_c Superconductivity", *Phys. Rev. B*, vol. 41, pp. 6399-6408, 1990.

[44] J. Ruvalds, "Theoretical Prospects for High-Temperature Superconductors", *Semicond. Sci. Technol.*, vol. 9, pp. 905-926, 1996.

[45] J. F. Annet, N. Goldenfeld, A. J. Leggett, "Transport Properties of High-Tc Cuprates", D.M. Ginsberg, Ed., *Physics Properties of High-Temperature Superconductors*, vol. 5, Singapore: World Scientific, 1995. pp. 375-462.

[46] R. Zeyher and M. L. Kulič,"Renormalization of the Electron-Phonon Interaction by Strong Electronic Correlations in High-T_c superconductors", *Phys. Rev. B*, vol. 53, 2850-2862, 1996.

[47] A. V. Chubukov and J. Schmalian, "Superconductivity due to Massless Boson Exchange in the Strong-Coupling Limit". *Phys. Rev. B.*, vol. 72, pp. 174520 (1-14), 2006.

[48] V. M. Krasnov, A. Yurgens, D. Winkler, P. Delsing, and T Claeson, "Evidence for Coexistence of the Superconducting Gap and the Pseudogap in Bi-2212 from Intrinsic Tunneling Spectroscopy", *Phys. Rev. Letters*, vol. 84, p. 5860-5863, 2000.

[49] R. A. Klemm, "Striking similarities between the pseudogap phenomena in cuprates and in layered organic and dichalcogenide superconductors", *Physica C*, Vol. 341-348, pp. 839-847, 2000.

[50] T. Ekino, Y. Sezaki, H. Fujii, "Features of the Energy Gap Above T_c in $Bi_2Sr_2CaCu_2O_{8+\delta}$ as Seen by Break-Junction Tunneling", *Phys. Rev. B*, vol. 60, pp. 6916-6919, 1999.

[51] M. Suzuki and T. Watanabe, "Discriminating the Superconducting Gap from the Pseudogap in $Bi_2Sr_2CaCu_2O_{8+\delta}$ by Interlayer Tunneling Spectroscopy", *Phys. Rev. Lett.*, vol. 85, pp. 4787-4790, 2000.

[52] Y. Yamada, K. Anagawa, T. Shibauchi, T. Fujii, T. Watanabe, A. Matsuda, Sand M. Suzuki, "Interlayer Tunneling Spectroscopy and Doping Dependent Energy-Gap Structure of the Trilayer Superconductor $Bi_2Sr_2Ca_2Cu_3O_{10+\delta}$. *Phys. Rev. B*, vol. 68, pp. 054533(1-11), 2003.

[53] T. Ekino, A. M. Gabovich, Mai Suan Li, M. Pękała, H. Szymczak, and A. I. Voitenko, "Analysis of the Pseudogap-Related Structure in Tunneling Spectra of Superconducting $Bi_2Sr_2CaCu_2O_{8+\delta}$ Revealed by the Break-Junction Technique",*Phys. Rev. B*, vol. 76, pp180503(R)(1-4), 2007.

[54] M. C. Boyer, W. D. Wise, K. Chatterjee et al. (8 auth.), "Imaging the Two Gaps of the High-Temperature Superconductor $Bi_2Sr_2CuO_{6+x}$, *Nature Physics*, vol. 3, pp. 802-806, (2007)

[55] A. A. Abrikosov,"Properties of the Pseudogap Phase in High-T_c Superconductors", *Phys. Rev. B*, vol. 64, pp. 104521(1-10, 2001.

[56] J. L. Tallon and J. W. Loram, "The Doping Dependence of T^* what is the Real High-T_c Phase Diagram?", *Physica C*, vol. 349, pp. 53-68, 2001.

[57] H. Alloul, T. Ohno, and P. Mendels,"89Y NMR Evidence for a Fermi-Liquid Behavior in $YBa_2Cu_3O_{6+x}$". *Phys. Rev. Lett.*. vol. 63, pp. 1700-1703, 1989.
[58] H. Yasuoka, T. Imai, and T. Shimizu, *NMR and NQR in Highly Correlated Metallic and Superconducting Cu Oxides*, H. Fukuyama, S. Maekawa, and A. P. Malozemoff, Ed., (Strong Correlation and Superconductivity), Berlin: Springer, 1989, p. 254-261.
[59] B. Bucher, P. Steiner, J. Karpinski, E. Kaldis, and P. Wachter, "Influence of the Spin Gap on the Normal State Transport in $YBa_2Cu_3O_4$", *Phys. Rev. Lett.*, vol. 76, pp. 2012-2015, 1993.
[60] E. A. Pashitski and V. I. Pentegov, " To the Mechanism of SC and PG State Appearance in High-T_c Superconductors", *Ukr. Fiz. Zh.*, vol.50, pp. A77-A81, 2005.
[61] G. Deutscher, "Superconducting Gap and Pseudogap", *Low Temp. Phys.*, vol. 32, pp. 566-571, 2006.
[62] A. M. Gabovich and A. I. Voitenko, "Model for the Coexistence of d-Wave Superconducting and Charge-Density-Wave Order Parameters in High-Temperature Cuprate Superconductors", *Phys. Rev. B*, vol. 80, 224501 (1-9), 2009.
[63] T. Ekino, A. M. Gabovich, Mai Suan Li, M. Pękała, H. Szymczak and A. I. Voitenko, "d-Wave Superconductivity and s-Wave Charge Density Waves: Coexistence between Order Parameters of Different Origin and Symmetry", *Symmetry*, vol. 3, pp. 699-749, 2011.
[64] P. W. Anderson, "The Resonating Valence Bond State in La_2CuO_4 and Superconductivity", *Science*, vol. 233, pp. 1196-1198, 1987.
[65] P. W. Anderson and Z. Zou, "Normal" Tunneling and "Normal" Transport: Diagnostics for the Resonating-Valence-Bond State". *Phys. Rev. Lett.*, vol.60, pp. 132-135, 1988.
[66] R. K. Nkum and W. R. Datars, "Fluctuation-Enhanced Conductivity in the Sb-Doped Bi-Pb-Sr-Ca-Cu-O Superconducting Systems", *Phys. Rev. B*, vol. 44, pp. 12516-12520, 1991.
[67] A. L. Solovjov, H.-U. Habermeier, and T. Haage,"Fluctuation Conductivity in $YBa_2Cu_3O_{7-y}$ films with Different Oxygen Content. I. Optimally and Lightly Doped YBCO Films", *Low Temp. Phys.*, vol. 28, pp. 17-24, 2002.
[68] A. L. Solovjov, H.-U. Habermeier, and T. Haage, "Fluctuation Conductivity in $YBa_2Cu_3O_{7-y}$ Films with Different Oxygen Content. II. YBCO Films with $T_c \approx 80\,K$", *Low Temp. Phys.*, vol. 28, pp. 99-108, 2002.
[69] L. G. Aslamazov and A. L. Larkin, "The Influence of Fluctuation Pairing of Electrons on the Conductivity of the Normal Metal", *Phys. Lett.*, vol. 26A, pp. 238-239, 1968.
[70] K. Maki, "The Critical Fluctuation of the Order Parameter in Type-II Superconductors", *Prog. Theor. Phys.*, vol.39, pp. 897-906, 1968.
[71] R. S. Thompson, "Microwave Flux Flow and Fluctuation Resistance of Dirty Type-II Superconductors", *Phys. Rev. B.*, vol. 1, pp. 327-333, 1970.
[72] S. Hikami, A.I. Larkin, "Magnetoresistance of High Temperature Superconductors", *Mod. Phys. Lett. B*, vol.2, pp. 693-698, 1988.
[73] J. B. Bieri, K. Maki and R. S. Thompson, "Nonlocal Effect in Magneto-Conductivity of High-Tc Superconductors", *Phys. Rev. B*, vol. 44, pp. 4709 - 4711, 1991.
[74] V. L. Ginzburg, L. D. Landau, " On the Theory of Superconductivity", *JETP*, vol. 20, pp. 1064-1082, 1950.
[75] E. M. Lifshitz and L. P. Pitaevski, *Statistical Physics*, vol. 2, Moscow: Nauka, 1978.

[76] W. E. Lawrence and S. Doniach, "Theory of Layer Structure Superconductors", in *Proceedings of the 12-th International Conference on Low Temperature Physics*, Kioto, 1971, pp. 361-362.

[77] Y. B. Xie, "Superconducting Fluctuations in the High-Temperature Superconductors: Theory of the dc Resistivity in the Normal State", *Phys. Rev. B*, vol. 46, pp. 13997-14000, 1992.

[78] K. Kawabata, S. Tsukui, Y. Shono, O. Mishikami et al., "Detection of a Coherent Boson Current in the Normal State of a High-Temperature Superconductor $YBa_2Cu_3O_y$ Film Patterned to Micrometer-Size Rings", *Phys. Rev. B*, vol. 58, pp. 2458- 2461, 1998.

[79] Ch. Renner, B. Revaz, J.-Y. Genoud, K. Kadowaki, and Q. Fischer, "Pseudogap Precursor of the Superconducting Gap in Under- and Overdoped $Bi_2Sr_2CaCu_2O_{8+\delta}$", *Phys. Rev. Lett.*, vol. 80, pp. 149-152, 1998.

[80] T. Kondo, Y. Hamaya, A. D. Palczewski1, T. Takeuchi, J. S.Wen, Z. J. Xu, G. Gu, J. Schmalian and A. Kaminski, "Disentangling Cooper-pair Formation Above the Transition Temperature from the Pseudogap State in the Cuprates", *Nature Phys.*, vol. 7, pp. 21-25, 2011.

[81] A. S. Alexandrov, V. N. Zavaritsky, and S. Dzhumanov, "Hall Effect and Resistivity in Underdoped Cuprates", *Phys. Rev. B*, vol. 69, 052505(1-4), 2004.

[82] A. C. Bódi, R. Laiho, E. Lähderanta, "Boson-Fermion Fluctuation Dominated Model of the Superconducting Transition in Hole-Underdoped Cuprates", *Physica C*, Vol. 411, pp. 107-113, 2004.

[83] K. Morawetz, B. Schmidt, M. Schreiber, and P. Lipavsky, "Enhancement of Fermion Pairing due to the Presence of Resonant Cavities", *Phys. Rev. B*, vol. 72, pp. 174504 (1-5), 2005.

[84] V. M. Loktev, "Spectra and Pseudogap Phenomena in High-Temperature Superconductors", *Ukr. Fiz. Zh. Oglyadi*, vol. 1, pp. 10-48, 2004.

[85] V. N. Bogomolov, " Superconductivity of High- and Low-Temperature Superconductors as Bose-Einstein Condensation. (Diluted Metals)", *Lett. JETF*. vol, 33, p. 30-37, 2007.

[86] V. M. Loktev and V. M. Turkowski, "Doping-Dependent Superconducting Properties of Two-Dimensional Metals with Different Types of Interparticle Coupling", *Low Temp. Phys.*, vol. 30, pp. 179-191, 2004.

[87] E. Babaev, H. Kleinert, "Nonperturbative XY-model Approach to Strong Coupling Superconductivity in Two and Three Dimensions", *Phys. Rev. B*, vol. 59, pp. 12083-12089, 1999.

[88] D. D. Prokof'ev, M. P. Volkov, and Yu. A. Bojkov,"The Amount and Temperature Dependence of Pseudogap in YBCO Obtained from Resistivity Measurements", *Fiz. Tverd. Tela*, vol. 45, pp. 1168-1176, 2003.

[89] V. P. Gusynin, V. M. Loktev, and S. G. Sharapov, Phase Diagram of 2D Metal System with Variable Number of Charge Carriers", *Lett. JETF*, vol. 65, pp. 170-175, 1997.

[90] Rui-Hua He, M. Hashimoto, H. Karapetyan et al. (19 auht.), "From a Single-Band Metal to a High-Temperature Superconductor via Two Thermal Phase Transitions", *Science*, vol. 331, pp. 1579-1583, 2011.

[91] K. Nakayama, T. Sato, Y.-M. Xu, Z.-H. Pan et al. "Two Pseudogaps with Dfferent Energy Scales at the Antinode of the High-temperature $Bi_2Sr_2CuO_6$ Superconductor Using Angle-resolved Photoemission Spectroscopy", *arXiv:1105.5865v [cond-mat, supr-con]* pp. 1-5, 2011.

[92] B. Oh, K. Char, A. D. Kent, M. Naito, M. R. Beasley et al., "Upper Critical Field, Fluctuation Conductivity, and Dimensionality in $YBa + 2Cu_3O_{7-x}$", *Phys. Rev. B*, vol. 37, pp. 7861-7864, 1988.

[93] T. Haage, J. Q. Li, B. Leibold, M. Cardona, J. Zegenhagen, H.-U. Habermeier, "Substrate-Mediated Anisotropy of Transport Properties in $YBa_2Cu_3O_{7-\delta}$", *Solid State Comm.*, Vol.99, pp. 553-557, 1996.

[94] A. L. Solovjov, V. M. Dmitriev, "FLuctuation Conductivity and Pseudogap in $Y_{1-}PrBa_2Cu_3O_{7-y}$ films", *Low Temp. Phys.*, vol. 32, pp. 753-760, 2006.

[95] A. L. Solovjov, M. A. Tkachenko, R. V. Vovk, Z. F. Nazyrov, and M. A. Obolenskii, "Fluctuation Conductivity and Pseudogap in Slightly Doped $HoBa_2Cu_3O_{7-\delta}$ Single Crystals under Pressure", *Low Temp. Phys.*, vol. 37, pp. 1053-1056, 2011.

[96] H.-U. Habermeier, "Pulsed Laser Deposition - a Versatile Technique Only for High-temperature Superconductor Thin-film Deposition?", *Applied Surface Science*, Vol. 69.Ű pp. 204-211, 1993.

[97] T. Ito, K. Takenaka, and S. Uchida, "Systematic Deviation from T-Linear Behavior in the In-Plane Resistivity of $YBa_2Cu_3O_{7-y}$: Evidence for Dominant Spin Scattering", *Phys. Rev. Lett.*, vol. 78, pp. 3995-3998, 1993.

[98] K. Maki, H. Won, "Pseudogap Phenomenon in High-T_c Cuprates", *J. Magnetic Mat.*, Vol. 226-230. pp. 350-352, 2001.

[99] K. W. Wang, W. Y. Ching, "A Structural-Based Microscopic Theory on High-Temperature Cuprate Superconductors", *Physica C*, 2004.vol. 416, pp. 47-67, 2004.

[100] R. O. Zaitsev, "To the Peculiareties of the Electronic Mechanism of the Superconductivity", *Zh. Eksp. Teor. Fiz.*, vol. 125, pp. 891-905 2004.

[101] V. M. Dmitriev and A. L. Solovjov, "Energy Gap and Features of HTS's Conductivity", *Fiz. Nizk. Temp. (Low.Temp.Phys.)*, vol.16, pp. 650-653, 1990.

[102] 201B. Leridon, A. Defossez, J. Dumont, J. Lesueur, and J. P. Contour, ". Conductivity of Underdoped $YBa_2Cu_3O_{7-\delta}$: Evidence for Incoherent Pair Correlations in the Pseudogap Regime", *Phys. Rev. Lett.*, vol. 87, pp. 197007 (1-4), 2001.

[103] V.M. Dmitriev, A. L. Solovjov, A. I. Dmitrenko, L. A. Ischenko, "Nonlinear Properties of $YBa_2Cu_3O_x$ under Microwave Irradiation in the Temperature Range 4.2 - 270 Ê", *Fiz. Nizk. Temp. (Low Temp. Phys.)*, vol. 15, pp. 1223-1225, 1989.

[104] R. V. Vovk, M. A. Obolenskii, A. A. Zavgorodniy, I. L. Goulatis, V. I. Beletskii, A. Chroneos, "Structural Relaxation, Metal-to-Insulator Transition and Pseudo-Gap in Oxygen Deficient $Ba_2Cu_3O_{7-\delta}$ Single Crystals", *Physica C*, vol. 469, pp. 203-206, 2009.

[105] R. V. Vovk, Z. F. Nazyrov, M. A. Obolenskii, I. L. Goulatis, A. Chroneos, S. V. Pinto, "Phase Separation in Oxygen Deficient $Ba_2Cu_3O_{7-\delta}$ Single Crystals: Effect of High Pressure and Twin Boundaries", *Phil. Mag.*, vol. 91, pp. 2291-2302, 2011.

[106] G. D. Chryssikos, E. I. Kamitsos, J. A. Kapoutsis et al. (8 auth.), "X-ray Diffraction and Infrared Investigation of $RBa_2Cu_3O_7$ and $R_{0.5}Pr_{0.5}Ba_2Cu_3O_7$ Compounds (R, Y and Lanthanides)", *Physica C*, vol. 254, pp. 44-62, 1995.

[107] A. J. Drew, Ch. Niedermayer, P. J. Baker, F. L. Pratt, S. J. Blundell et al. (16 auth.), "Coexistence of Static Magnetism and Superconductivity in $SmFeAsO_{1-x}F_x$ as Revealed by Muon Spin Rotation", *Nature materials*, vol. 8, pp. 310-317, 2009.

[108] S. Sanna, R. De Renzi, G. Lamura et al. (8 auth.), "Magnetic-Superconducting Phase Boundary of SmFeAsO1-xFx Studied via Muon Spin Rotation: Unified Behavior in a Pnictide Family", *Phys. Rev. B*, vol, 80, pp. 052503 (1-4), (2009).

[109] L.F. Zhu and B.G. Liu, "Striped Antiferromagnetism and Electronic Structures of SrFeAsF and Their Implications", *EPL*, vol. 85, pp 67009-67013, 2009.
[110] R. M. Fernandes, D. K. Pratt, W. Tian et al (13 auth), "Unconventional pairing in the iron arsenide superconductors", *Phys. Rev. B*, vol. 81, 140501(R1-R4), 2010.
[111] K. Machida, "Coexistence Problem of Magnetism and Superconductivity" *Appl. Phys. A*, vol. 35, 193-215, 1984.
[112] W. Jiao, Q. Tao, J. Bao, et al. (8 auth), "Anisotropic Superconductivity in $Eu(Fe_{0.75}Ru_{0.25})_2As_2$ Ferromagnetic Superconductor", EPL, vol. 95, pp. 67007(1-6), 2011.
[113] S. C. Riggs, J. B. Kemper, Y. Jo, Z. Stegen, L. Balicas, G. S. Boebinger, F. F. Balakirev et al. (11 auth), "Log-T Divergence and Insulator-to-Metal Crossover in the Normal State Resistivity of Fluorine Doped $SmFeAsO_{1-x}F_x$ *arXiv: Cond-mat/0806.4011.*, 2008.
[114] S. Margadonna, Y. Takabayashi, M. T. McDonald et al. (8 auth.), "Crystal Structure and Phase Transitions Across the Metal-Superconductor Boundary in the $SmFeAsO_{1-x}F_x$ $(0 \leq x \leq 0.20)$ Family *Phys. Rev. B*, vol. 79, pp, 014503(1-7), 2009.
[115] Y. Kamihara, T. Nomura, M. Hirano et al. (9 auth.) "Electronic and Magnetic Phase Diagram of Superconductors, SmFeAsO1-xFx", *New Journal of Physics*, vol.12, pp 033005(1-14), (2010).
[116] M. Tropeano, C. Fanciulli et al. (15 auth.), "Transport and Infrared Properties of SmFeAs(O1-xFx): From SDW to Superconducting Ordering", *Supercond. Sci. Technol.*, vol. 22, pp. 034004(1-7), 2009.
[117] A. V. Terekhov, M. A. Tkachenko, E. P. Khlybov, A. Zaleski, and A. L. Solovjov, "Fluctuation Conductivity, Pseudogap, Magnetic and Transport Properties of a Magnetic Superconductor $Dy_0.6Y_0.4Rh_3.85Ru_0.15B_4$", unpublished.
[118] O. Millo, I. Asulin, O. Yuli, et al. (8 auth.), "Scanning Tunneling Spectroscopy of $SmFeAsO_{0.85}$: Possible Evidence for d-Wave Order-Parameter Symmetry", *Phys. Rev. B*, vol. 78, pp. 092505(1-3), 2008.
[119] T. Y. Chen, Z. Tesanovic, R. H. Liu, X. H. Chen, C. L. Chien, "A BCS-like Gap in the Superconductor $SmFeAsO_{0.85}F_{0.15}$", *Nature*, vol. 453, pp. 1224-1228, 2008.
[120] D. Daghero, M. Tortello, R. S. Gonnelli, V. A. Stepanov, N. D. Zhigadlo, and J.Karpinski, "Evidence for Two-Gap Nodeless Superconductivity in $SmFeAsO_{0.8}F_{0.2}$ from Point-Contact Andreev-Reflection Spectroscopy", *arXiv:0812.1141v1 [cond-mat.supr-con]*, 2008.
[121] L. Ding, C. He, J. K. Dong, T.Wu, R. H. Liu, X. H. Chen, and S. Y. Li, "Specific Heat of the Iron-Based High-Tc Superconductor $SmO_{1-x}F_xFeAs$", *Phys. Rev. B*, vol. 77, pp. 180510R(1-4), 2008.
[122] Hongguang Chi and A. D. S. Nagi, "Transport Properties of Antiferromagnetic Superconductors", *Journal of Low Temperature Physics*, vol. 86, pp. 139-160, 1992
[123] N. L. Bobrov, V. N. Chernobay, Yu. G. Naidyuk et al. (9 auth.), "Competition of Multiband Superconducting and Magnetic Order in $ErNi_2B_2C$ Observed by Andreev Reflection", *EPL*, vol. 83, pp. 37003p (1-5), 2008.
[124] Ya. Ponomarev, M. Mikheev, M. Sudakova, S. Tchesnokov, and S. Kuzmichev, "Extended van Hove Singularity, Strong ElectronŰPhonon Interaction and Superconducting Gap in Doped Bi-2212 Single Crystals", *Phys. Status Solidi C*, vol. 6, pp. 2072-2075, 2009.