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Role of interelectron interaction in the pseudogap opening in high-T_c tunneling experiments

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The analysis of tunneling experiments showing the pseudogap-type behavior is carried out based on the idea of the renormalization of density of states due to the interelectron interaction in the Cooper channel (superconducting fluctuations contribution in tunneling current). It is demonstrated that the observed kink of the zero-bias conductance $G(0,T)$ of Y-Ba-Cu-O/Pb junctions in the vicinity of T_c can be explained in terms of fluctuation theory in a quite wide range of temperatures above T_c, using the values of microscopic parameters of the Y-Ba-Cu-O electron spectrum taken from independent experiments. The approach proposed also permits to explain qualitatively the shape of the tunneling anomalies in $G(V,T)$ and gives a correct estimate for the pseudogap position and amplitude observed in the experiments on Bi-Sr-Ca-Cu-O junctions.
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One of the most currently debated problems of the physics of high-temperature superconductors (HTS's) is the interpretation of pseudogap-type phenomena which have been observed in a wide range of oxygen concentrations and temperatures in the normal state of these materials.[1] In underdoped compounds such phenomena are well pronounced and have been investigated by various probes that include photoemission,[2] NMR,[3] transport,[4] neutron-scattering,[5] and optical[6] measurements. In addition to these, recently the observation of pseudogap structures in the conductance behavior of the Bi-Sr-Ca-Cu-O–based tunnel junctions in a wide range of temperature above T_c has been reported. These measurements were obtained by means of traditional electron-tunneling spectroscopy[7] as well as by scanning tunneling microscopy (STM) measurements[8,9] and interlayer tunneling spectroscopy.[10] The remarkable experiments of Ref. 8 also give evidence for pseudogap existence in the ''normal'' state of the overdoped (metallic) samples, which can be found quite surprising from the point of view of an ordinary Fermi-liquid approach.

To summarize these features, a model independent phase diagram has been proposed,[11] but there is still no consensus on the microscopic mechanism behind it. One common line of reasoning is that the normal state has pseudogap anomalies arising from pairing correlations in a state without phase coherence.[12] In the framework of this model, the pseudogap is a precursor to the superconducting gap as showed in angle-resolved photoemission spectroscopy (ARPES) data.[2] A different class of approaches to understand pseudogap phenomena is related to antiferromagnetic correlation scenarios,[13] where the pseudogap has no connection with the superconducting energy gap. Another point of view involves ''spin-charge separation.'' Here the pseudogap is associated with pairing of $S=\frac{1}{2}$ charge neutral fermions called spinons. This scenario has its origin in the resonating valence bond (RVB) ideas,[14] that were further developed[15] to understand not only the pseudogap phase, but the entire phase diagram from a Mott insulator to the overdoped regime.

The purpose of this article is to demonstrate that the account of the interelectron interaction (IEI) with small momentum transfer (Cooper channel) permits us to explain the main characteristic features of the pseudogap-type structures observed in the tunneling conductance of HTS's in the metallic part of the phase diagram (over-, optimally, or slightly underdoped compounds, where the Fermi surface is supposed to be well developed). The effect of the electron density-of-states (DOS) renormalization induced by IEI was studied in Refs. 16 and 17. It was provided that near the critical temperature this correction is singular in $\varepsilon = \ln(T/T_c)$, sign changing and manifesting itself in the very narrow range of energies $\delta E_c \sim \sqrt{T_c(T-T_c)}$ for clean, and $\delta E_d \sim T-T_c$ for dirty, systems. Nevertheless, it turns out that such DOS renormalization results in the appearance of the wide pseudogap-type structure in the tunneling conductance.[18] Actually, this effect was observed experimentally in conventional Al-I-Sn junctions.[19] We show below that this analysis can be extended to HTS tunnel junctions and permits us to fit the well defined ''kink'' around T_c in the zero-bias conductance $G(V=0,T)$ behavior of Y-Ba-Cu-O–based junctions,[20,21] as well as to explain the appearance of the gaplike structures in the dI/dV characteristics of intrinsic Bi-Sr-Ca-Cu-O junctions at temperatures above T_c.[10]

By using the Lawrence-Doniach quasi-two-dimensional (2D) model for the electron spectrum, one can generalize the expression for the fluctuations' contribution to the differential conductance of a tunnel junction (see Refs. 18 and 22) with one HTS electrode being in the vicinity of T_c:

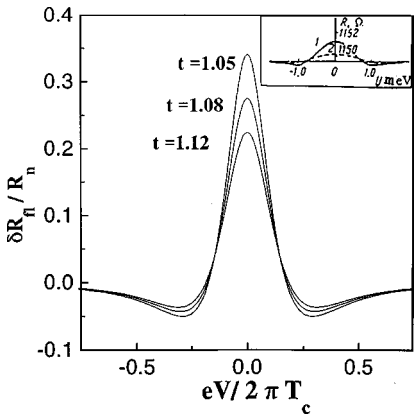

FIG. 1. Theoretical sketch of the fluctuation induced resistance zero-bias singularity for different reduced temperatures. Inset: differential resistance vs voltage measured in an Al-I-Sn junction (Ref. 19), at temperatures just above T_c(Sn).

$$\frac{\delta G_{fl}(V,\varepsilon)}{G_n} = \frac{1}{2T}\int_{-\infty}^{\infty} \frac{dE}{\cosh^2[(E+eV)/2T]}\,\delta N_{fl}(E,\varepsilon) = Gi_{(2)}\ln\left(\frac{2}{\sqrt{\varepsilon}+\sqrt{\varepsilon+r}}\right)\ \mathrm{Re}\,\psi''\left(\frac{1}{2}-\frac{ieV}{2\pi T}\right), \quad (1)$$

where $\psi(x)$ is the digamma function, $r=4\xi_\perp^2(0)/s^2$ is the Lawrence-Doniach anisotropy parameter ($\xi_\perp$ is the c-axis coherence length, s is the interlayer distance) which controls the dimensional crossover from the 2D to 3D regime. By means of $Gi_{(2)}$, the 2D Ginzburg-Levanyuk parameter,[22] characterizing the strength of fluctuations, is introduced [in the most interesting for our consideration, clean case $Gi_{(2)} = T_c/14\zeta(3)E_F$].

One can notice that the sharp decrease ($\sim 1/\varepsilon$) of the density of the electron states generated by IEI in the immediate vicinity of the Fermi level ($\delta E_c \sim T_c\sqrt{\epsilon}$) surprisingly results in the much more moderate growth of the tunnel conductance at zero voltage [$\sim \ln(1/\varepsilon)$] and in the appearance of some type of the pseudogap structure in the energy scale $\mathrm{eV}=\pi T \gg T-T_c$, as reported in Fig. 1 for different values of the reduced temperature. This striking contradiction to the habitual idea of the proportionality between the tunnel conductance and so-called tunneling density of states is the straightforward result of the calculation in (1) of the real convolution of the renormalized density-of-states function $\delta N_{fl}(E)$ with the Fermi-function derivative as the kernel (which cannot be supposed in this case as δ-functionlike kernel) side by side with the sum rule $\int_0^\infty \delta N_{fl}(E)dE=0$. The sense of the last identity can be easily understood: The account of IEI cannot create new electron states; it can redistribute the existing only. This condition leads to the exact cancellation of the main order contribution to the tunnel current (singular in $1/\varepsilon$), originating from the domain $E < T_c\sqrt{\varepsilon}$, and to the necessity of more delicate treatment of the tunnel current general expression, which was really done in order to carry out the logarithmic singularity of expression (1).

In the inset of Fig. 1, the measurements of the differential resistance of an Al-I-Sn tunnel junction at temperatures slightly above the critical temperature of an Sn electrode are presented.[19] It is worth mentioning that the experimentally measured position of the minima at $\mathrm{eV}\approx 3T_c$(Sn) is very close to the theoretical prediction $\mathrm{eV}=\pi T_c$(Sn).

If pseudogap phenomena in HTS's are related to a modification of the normal-state DOS, tunnel spectroscopy still remains one of the most powerful tools to investigate this puzzling aspect of these materials. However, the tunneling study of HTS's is a difficult task because of many reasons. For instance, the extremely short coherence length requires monolayer-level perfection at the surfaces which are subject to long oxygen annealings so that they, in general, do not satisfy this strict requirement. Another problem is the bias dependence of the normal background conductance $G_n(V)$ in a wide range of voltages (up to hundreds of mV),[23] which is necessary to scan for the study of the I-V characteristics of HTS junctions.

In spite of these difficulties, pseudogap structures in HTS tunneling characteristics have been observed in different Bi-Sr-Ca-Cu-O–based junctions,[7–10] while to our knowledge, no data have been reported for the Y-Ba-Cu-O compounds. This fact seems to confirm the more relevant role that fluctuations play in 2D systems. On the other hand, from an experimental point of view, it can be due to the fact that Bi-Sr-Ca-Cu-O junctions are relatively easier to obtain due to the better stability of the oxygen at the surface of this material. Nevertheless, we dispose of very accurate data obtained on high quality Y-Ba-Cu-O/Pb junctions in which elastic tunneling processes occur without any interaction in the barrier.[24] The appearance of the typical kink in the $G(0)$ vs T dependence in these as well as in other group experiments[25–28] induced us to apply expression (1) to calculate quantitatively the fluctuation contribution to the Y-Ba-Cu-O DOS and to demonstrate that a satisfactory fitting can be obtained in a quite wide temperature range around T_c.

In Figs. 2(a) and (b) the experimental data (dots) refer to two different Y-Ba-Cu-O/Pb planar junctions, as reported in Refs. 20 and 21. The theoretical fittings (full lines) for the normalized fluctuation part of the tunneling conductance at zero bias, $\delta G_{fl}(0,\varepsilon)/G_n(0,T=140\ \mathrm{K})$ by means of expression (1) at $V=0$, are also reported. The junction's critical temperature and the magnitude of the Ginzburg-Levanyuk parameter have been taken as fitting parameters.

To this respect, it is worth noticing that the tunneling spectroscopy probes regions of the superconducting electrodes to a depth of $(2-3)\xi$, in contrast with the resistive measurements which sense the bulk percolating length. The two critical temperatures can be quite different. In our case the resistive critical temperatures measured on both the Y-Ba-Cu-O crystals were $T_c(\rho=0)=91.6$ K, while the ''junction's T_c'' $=88.4$ K and 89 K were obtained from the fitting procedure. This fact indicates that a slightly oxygen deficient Y-Ba-Cu-O layer (on a scale of ξ) is probed by the tunneling measurements in both junctions.[29] However, the samples are still in the proper (metallic) region of the phase diagram. The magnitude of the fluctuation correction $|\psi''(\frac{1}{2})|Gi_{(2)} \simeq T_c/E_F$ is equal to 0.025 for junction (a) and 0.016 for junction (b), leading to the value of $E_F \simeq 0.3$ eV which is in the lower range of the existing estimates (0.2–1.0 eV).

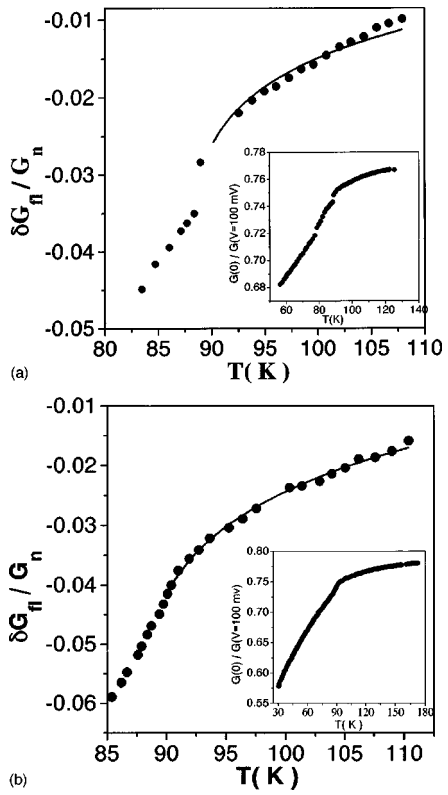

FIG. 2. Theoretical fittings (solid lines) of the measured zero-bias conductance behavior vs temperature (dots) for two different Y-Ba-Cu-O/Pb junctions, as reported in Refs. 20 and 21, respectively. Insets: Experiments on a larger temperature scale.

The value of Lawrence-Doniach parameter $r=0.08$ was taken from the crossover between 2D and 3D regimes in the in-plane conductivity measurements analysis.[30] It is worth mentioning that another independent definition of r from the analysis of the nonlinear fluctuation magnetization[31] leads to a very similar value $r=0.11$. However, our fittings turn out to be not too sensitive to the value of r . We observe that the temperature range in which the expression (1) satisfactorily reproduces the behavior of the zero-bias conductance extends up to 110 K for junction (a) with $T_c=88.4$ K, and up to 105 K for junction (b) with $T_c=89$ K.

Now, we would like to discuss in more detail the recent experimental evidence of pseudogap structures in the conductance curves of intrinsic Bi-Sr-Ca-Cu-O junctions.[10] As it was already mentioned, the IEI renormalization of the DOS at the Fermi level leads to the appearance of similar structures with the characteristic maximum position determined by the temperature T instead of the superconducting gap value: $eV_m=\pi T$. For the HTS compounds this means a scale of 20–40 meV, considerably larger than in the case of conventional superconductors.

In Fig. 3 the experimental data (dots) refer to thin stacks of $Bi_2Sr\,Ca\,Cu_2O_8$ intrinsic Josephson junctions. In the experiments,[10] the pseudogap opening in dI/dV characteristics was found for temperatures up to 180 K. The curve (a) in the figure (full line) is the theoretical fitting for the 90 K data. In view of the strong anisotropy of the Bi-Sr-Ca-Cu-O spectrum, $r=0$ has been assumed, while $|\psi''(\frac{1}{2})|Gi_{(2)}=0.0085$ and $T_c=87$ K have been extracted from the expression (1). One can observe that the structure amplitude is

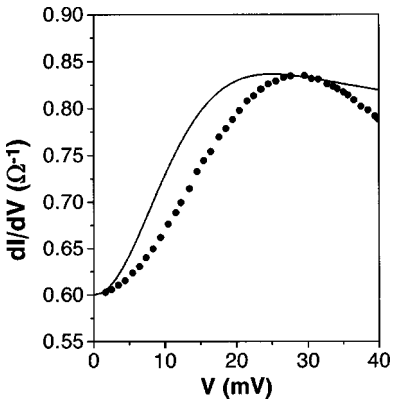

FIG. 3. Theoretical fittings (solid lines) of the $G(V,T)$ structures (dots) measured in intrinsic Bi-Sr-Ca-Cu-O tunnel junctions (Ref. 10) at $T=90$ K.

well reproduced with an error of less than 5% on the maximum position. We point out that the evaluation of the maxima positions at 90 K, $eV_m=\pi T=25$ meV, is consistent with the experimental results on Bi-Sr-Ca-Cu-O/Pb planar junctions[7] as well as with STM data,[10] but is quite lower than the value of pseudogap position observed on the experiments of Refs. 8 and 9.

In this respect, two important comments are necessary that concern the limits of applicability of the proposed approach. The first one is related to the magnitude of the effect. It is clear that expression (1), being a perturbative result, has to be small, so the criterium of the theory applicability to the HTS phase diagram is $Gi\ln(1/\varepsilon)\ll 1$. From the values for the junction T_c's found through the fitting procedure, one can believe in the increase of Gi with the decrease of the oxygen concentration from the value of the optimal doping, so concluding that the role of the IEI increases in the underdoped part of the phase diagram whose properties have to be discussed in the frameworks of some different theory, not based on the Fermi liquid.

It is also important to discuss the temperature range of the pseudogap-type phenomena observability following the proposed approach. The expression (1) is obtained in the mean field region $\ln(T/T_c)\ll 1$, neglecting the contribution of the short wavelength fluctuations and reproduces a maximum in conductance at the value of $eV_m=\pi T_c(1+\varepsilon)$. Nevertheless, the characteristic slow (logarithmic) dependence on ε of the fluctuation correction for 2D systems permits us to believe that the result (1) can be qualitatively extended on a wider temperature range. The study of the high-temperature asymptotic behavior $[\ln(T/T_c)\gg 1]$ for the e-e interaction in the Cooper channel[32] demonstrates the appearance of the extremely slow $\ln\ln(T/T_c)$ dependence which matches $\ln 1/\varepsilon$ in the intermediate region, and shows the importance of the interaction effects up to high temperatures. In such way one can consider the reported $T^*\sim 200$–300 K in the strongly underdoped part of the phase diagram as the temperature where the noticeable concentration of short-living ($\tau\sim\hbar/k_BT$) fluctuation Cooper pairs first manifests itself.[22]

To conclude, the idea to relate the tunneling pseudogap-type phenomena observed around T_c with the IEI renormalization effects allows us to fit the experimental data with a minimum of microscopic parameters (E_F,r) consistently with the independent measurements. It is worth stressing that

the developed approach allows us to explain in a unique way the set of pseudogap-type phenomena, like the increase of *c*-axis resistance, the sign-changing *c*-axis magnetoresistance, and the opening of the pseudogap in *c*-axis optical conductivity, and NMR spectra.[22] At the same time it is necessary to underline its restricted and schematic character, which permits us more to attract the readers' attention to the importance of the IEI renormalization effects in the metallic part of the phase diagram than to attend to the construction of the complete theory of the phenomena discussed. HTS compounds possess complex and still enigmatic properties, such as their linear in temperature normal resistance, the character of the establishment of long-range phase coherence when passing T_c, and the mechanism of its relaxation at these temperatures. Even the use of the traditional Fermi-liquid microscopic form of the IEI for these materials is hard to justify and it can be treated as some phenomenological approximation only.

We have seen that moving along the phase diagram of HTS's from the metal region to poor metals, the small parameter of the perturbation theory grows, causing the effects discussed to be more pronounced. Nevertheless, analyzing the rapid growth of the normal-state anomalies with the decrease of the oxygen content below the optimal doping concentration, one can notice that it strongly overcomes our theoretical prediction. We can attribute this discrepancy to the simplicity of the Fermi-surface model, supposed above to be isotropic in the ab-plane. The ARPES study of HTS's shows the presence of the strong anisotropy of the Fermi surface of such type and even the existence of two characteristic energy scales $E_F \approx 0.3$ eV and $\Delta \approx 0.01$ eV (extended saddle point of the spectrum). So one can suppose that as the oxygen concentration decreases below the optimal one, for some reasons the massive part of the Fermi surface is ''obliterated,'' and the crossover in properties related with the special role of ''slow'' electrons of extended saddle points takes place. Formally in this case the large value $E_F \approx 0.3$ eV in the denominator of the Ginzburg-Levanyuk parameter has to be substituted by small $\Delta \approx 0.01$ eV rapidly making the perturbation approach inapplicable.

The existence of the nonequilibrium Cooper pairs in the normal-metal phase of HTS's (the state with $\langle \Psi^2 \rangle \neq 0, \langle \Psi \rangle = 0, \langle \phi \rangle = 0$) resembles the state of preformed Cooper pairs in the underdoped phase[33,34] ($\langle \Psi^2 \rangle \neq 0, \langle \Psi \rangle \neq 0, \langle \phi \rangle = 0$). Both of them are determined by the presence of interelectron interaction, and it would be interesting to study the plausible ''condensation'' of the fluctuation pairs in the preformed ones at the region where $Gi_2 \approx 1$. Such crossover qualitatively was discussed by Randeria,[35] but its systematic study requires the formulation of the appropriate model.

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