Can the bosonic coupling constant be extracted from the ARPES scattering rate in cuprate superconductors?

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The recent ARPES results for the imaginary part of the self-energy $\Sigma''(\omega,T)$ obtained on a number of HTSC bismuthates \cite{1} are analyzed. By accepting the ”Fermi-Bose” division-procedure of $\Sigma''(\omega,T)$ into the Fermi-liquid and bosonic parts - which is proposed in \cite{1}, one obtains very small bosonic coupling constant $\lambda_{B,lm} < 0.2$. If this procedure would be correct then the standard Eliashberg theory makes any bosonic mechanism of pairing irrelevant! As a consequence we are confronted with a trilemma: (1) to abandon the “Fermi-Bose” division-procedure \cite{1}; (2) to abandon the Eliashberg theory; (3) to abandon the interpretation of ARPES data within the three-step model, where the ARPES intensity is proportional to the quasiparticle spectral function $A(k,\omega)$. However, since the bosonic coupling constant extracted from the ARPES nodal kink at 70 meV \cite{2}, which measures the real part of the self-energy $\Sigma'(\omega,T)$, is much larger than the one extracted from the ARPES line-width ($\lambda_{B,lm} \ll \lambda_{B,Re} > 1$) this means that the “Fermi-Bose” division procedure done in \cite{1} is ambiguous.

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Recently, very interesting results were reported on ARPES measurements in a number of HTSC compounds \cite{1}, such as the superstructure free $Bi_{2-x}Pb_xSr_2CaCu_2O_{8+\delta}$ ($\text{Bi}(\text{Pb}) - 2212$), $Bi_2Sr_2CaCu_2O_{8+\delta}$ ($\text{Bi} - 2212$) and $Bi_2Sr_2La_2CaCu_2O_{8+\delta}$ ($\text{Bi} - 2201$). By measuring the width ($\Delta k_{FW}(\omega)$) of momentum distribution curves (MDCs) in the nodal direction the authors of \cite{1} were able to extract the imaginary part $\Sigma''(\omega,T)$ of the quasiparticle self-energy $\Sigma(\omega,T) = \Sigma(\omega,T) + i\Sigma''(\omega,T)$ by using the relation $\Sigma''(\omega,T) \approx v_F\Delta k_{FW}(\omega)/2$ with $hv_F = 4\text{ eV} \lambda_1$ \cite{1}.

Let us discuss the results for $\Sigma''(\omega)$ in the nodal direction obtained in \cite{1} which are presented in Fig.1 (which is also Fig.1 in Ref. \cite{1}). In \cite{1} the experimental results are analyzed by assuming that the ”Fermi-Bose” division of $\Sigma''(\omega,T)$ holds, i.e. there is a Fermi-part due to the Landau-Fermi liquid $\Sigma''_F(\omega,T)$ and the Bose-part due to the scattering via the boson channel $\Sigma''_B(\omega,T)$ \cite{1}. We show below that experiments in Ref. \cite{1} give evidence for the significant contribution of the impurity scattering to $\Sigma(\omega,T)$, which we also take into account. In that case the self-energy is given by

$$\Sigma''(\omega,T) = \Sigma''_F(\omega,T) + \Sigma''_B(\omega,T) + \Sigma''_{imp}(\omega,T). \quad (1)$$

The Fermi part is given approximately by

$$\Sigma''_F(\omega,T) \approx A_\omega \omega^2 + A_T \pi^2 T^2, \quad (2)$$

where it is expected that like in the isotropic Landau-Fermi liquid one has

$$A_\omega \approx A_T. \quad (3)$$

In the inset of Fig.1a the authors in \cite{1} determine $\Sigma_F(\omega,T)$ by fitting the data in the highly overdoped sample ($OD69$ with $T_c = 69\text{ K}$) at $T = 130\text{ K}$ by Eq.(1). Unfortunately, the authors in \cite{1} do not report the value for $A_\omega$. Let us determine $A_\omega = [\Sigma''(\omega,T) - \Sigma''(\omega = 0,T)]/\omega^2$ from the data in Fig.1a, i.e. from the data for $OD69$ at $T = 130\text{ K}$. From the inset in Fig.1a one has $\Sigma''_{exp}(\omega = 0,130\text{K}) \approx 0.06\text{ eV}$ and $\Sigma''(\omega = 0,130\text{K}) \approx 0.25\text{ eV}$ which gives a reasonable value $A_\omega \approx 2/\epsilon_\omega$. $\omega$ is given in eV.

Since the authors of \cite{1} do not estimate the contribution of impurities $\Sigma''_{imp}(\omega,T)$ let us do it here. The latter contribution is appreciable since from the inset in Fig.1a one has that $\Sigma''_{imp}(\omega = 0,T)(= \Sigma''_{exp}(0,T) - \Sigma''(\omega = 0,T))$ is large fraction of $\Sigma''_F(0,T)$. The term $\Sigma''_{imp}(\omega = 0,T)$ can be extracted (in a semi-quantitative way) by considering the experimental results for $\Sigma''(\omega = 0,T)(\lessapprox \Sigma''_{imp}(0,0))$ at $T \ll T_c$. By taking the data from Figs.(1-3) in \cite{1} for $T \ll T_c$, we conclude that for a number of systems with $T_c = (60 - 90)\text{ K}$ one has

$$\Sigma''_{imp}(\omega = 0, T \ll T_c) \approx (0.02 - 0.03)eV. \quad (4)$$

Let us analyze the effect of impurities on $T_c$. Before doing this, we stress that in the systems which are studied in \cite{1} d-wave pairing is realized. If one assumes that the standard Eliashberg theory holds and that $\Sigma''_{imp}(0,0)$ is momentum independent, i.e. it contains the s-wave scattering channel only $\Sigma''_{imp}(0,0) \approx \Sigma''_{imp,s}(0,0)$, then this isotropic impurity scattering is strongly pair-breaking for d-wave pairing. Since in $T_c$ is smaller than the bare $T_{c,0}$ (for the clean system), then the interesting question is how big is $T_{c,0}$? The theory \cite{3} predicts the following formula for $T_c$ in the case when there is the s-wave impurity channel only

$$\ln \frac{T_c}{T_{c,0}} = \psi(\frac{1}{2}) - \psi(\frac{1}{2} + \rho^2_{pb}), \quad (5)$$
where the pair-breaking parameter $\rho^{\ast}_{pb} = |\Sigma''_{imp,s}| / 2\pi T_c$. By taking the values for $\Sigma''_{imp,s}$ from Eq.(3) one obtains $T^{OD}_{c} = (115-150) K$ with $T^{OP}_{c} = 69 K$ for the overdoped SC, and for the optimally doped $T^{OP}_{c} \approx (130-160) K$ with $T^{OP}_{c} = 90 K$. However, this analysis might be inappropriate for HTSC, which are strongly correlated materials and which show surprising robustness of d-wave pairing in the presence of non-magnetic impurities when the dependence $T_c(\rho_{imp})$ is studied. Here, $\rho_{imp}$ is the residual resistivity - see Ref.[3]. The theory of the impurity scattering in strongly correlated systems done in [4], and which is based on the theory of strong correlations [5], shows the existence of the forward scattering peak in the scattering amplitude. The latter gives rise to the pronounced d-wave impurity scattering channel $\Sigma''_{imp,d}$, thus lowering the impurity pair-breaking effects since in that case $\rho_{pb} = |\Sigma''_{imp,s} - \Sigma''_{imp,d}| / 2\pi T_c$. For a further analysis of the impurity effect on $T_c$ the experimental data for $T_c(\rho_{imp})$ are necessary.

The large values of $T_c$ (and $T_{\sigma}$) need also a large bosonic coupling constant $\lambda_B \approx 2$ in the Eliashberg theory. In that respect one can rise an important question - how large is the bosonic coupling constant $\lambda_B$ extracted from the ARPES line-width measurements in [7]? In absence of a reliable microscopic theory for HTSC oxides one can proceed by using a phenomenological approach to analyze the ARPES data. From Fig.1b (also Fig.1b in [1]) we see that the bosonic part of $\Sigma''_B(\omega)$ is linear in $\omega$ at low $T_c$ similarly as in the “marginal” Fermi liquid where $\Sigma''_B(\omega) \approx (\pi/2)\lambda_B T_c \omega$. From the values of $\Sigma''_B(\omega)$ at energies $\omega > 0.05 eV$ - where the self-energy is weakly affected by superconductivity, which we extract from the top curve in Fig.1b for the optimally doped SC with $T_c = 88 K$ and at $T = 40 K$, one obtains a conservative value $\lambda_B < 0.2$! Note, that the curve at $T = 90 K$ (slightly below $T_c$) in Fig.1b of Ref. [1] - below the top one, gives even smaller $\lambda_B$! Such a small (bosonic) coupling constant ($\lambda_B < 0.2$) gives very small $T_c(\approx 100 K)$ already for s-wave pairing, in the standard Eliashberg theory. This means that if the “Fermi-Bose” division in [1] would be appropriate than all bosonic mechanisms of pairing (EPI, SFI, etc) would be ineffective and irrelevant in cuprate superconductors!

As a consequence we are confronted with a trilemma: (1) to abandon the “Fermi-Bose” division-procedure from [1]; (2) to abandon the Eliashberg theory; (3) to abandon the interpretation of ARPES data within the three-step model, where the ARPES intensity is proportional to the quasiparticle spectral function $A(k,\omega) = -\Im G(k,\omega)/\pi$? It seems that the case (1) is most probable. The argument for this claim is based on the ARPES measurements of the real part of the self-energy $\Sigma''(\omega)$.

The latter [2], [3], [4] show kink in the nodal quasiparticle energy at the phonon energies $\omega \approx 70 - 70 meV$, which gives the coupling constant $\lambda_{B,Re} = |\partial \Sigma''/\partial \omega| > 1$. The latter coupling is most probably due to the pronounced electron-phonon interaction in HTSC [2]. The above analysis shows that $\lambda_{B,Imp} \ll \lambda_{B,Re}$ thus questioning the “Fermi-Bose” division procedure done in Ref.[1], which gives $\lambda_{B,Imp} < 0.2$. However, the cases (2)-(3) might interfere too.

In fact, if (i) the (bosonic-like) spin-fluctuation scattering would be the dominant one - as it is claimed in [1], and (ii) if the “Fermi-Bose” division of Ref. [1] holds, then the ARPES results in [1] tell us that (because $\lambda_{B,Imp} \ll 1$) the spin-fluctuation scattering mechanism is irrelevant for pairing in cuprate superconductors. We stress that, there are other reliable arguments against the spin-fluctuation pairing mechanism and which are in favor of the electron-phonon interaction Refs.[3], [4], [5].

Finally, we stress, that the small value of the bosonic coupling constant $\lambda_{B,Imp}$, which is extracted from $\Sigma''_{ARPES}$ for $\omega > 0.05 eV$, is common to all ARPES measurements [7]. For instance, in the very recent ARPES measurements of the scattering rate in optimally and highly overdoped Bi2212 and Bi2201 compounds [10] it was found that $\Sigma''_{ARPES}(k,\omega) = a_k + b_k \omega$ with $a_k$ strongly momentum dependent while $b_k \approx \text{const} = b$ is isotropic. By taking again $v_F \approx 4 eV \AA$ we obtain $b \approx 0.4$ and $\lambda_{B,Imp} \approx 0.3$. It is hardly to believe that such a small $\lambda_{B,Imp}$ can give $T_c \approx 100 K$ in the Eliashberg...
theory. Therefore, the analysis of the ARPES scattering rate solely by the marginal Fermi liquid phenomenology is inadequate and the electron-phonon interaction must be inevitable taken into account. More on that see in Refs. [9], [11].

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