Impurity Substitution in Bismuth and Thallium Cuprates: Suppression of $T_c$ and Estimation of Pseudogap

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Abstract

Suppression of $T_c$ in bilayer bismuth and thallium cuprates, by substitution of Co impurities at Cu sites, are taken for examination. $T_c$ suppression data on differently doped Bi2212 and Tl2212 are analysed within the unitary pair-breaking formalism due to Abrikosov and Gorkov, by fitting data points to a phenomenological relation valid for weak coupling $d$-wave superconductors. Values of the pseudogap magnitude at each doping are thereby estimated within a “fermi-level density of states suppression” picture. Pseudogap magnitude from our estimation is observed to have a correspondence with a related characteristic temperature $T^*$ obtained by thermoelectric power measurements. Effects of pseudogap, on the density of states, is studied by calculating the susceptibility which shows a broad peak at high temperature. This peak feature in susceptibility is indicative of an unusual metallic state which could further be explored by systematic other measurements.

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I. Introduction

In high-\(T_c\) layered superconductors (HTLS), studying the suppression of \(T_c\) by impurity substitution at the Cu-site of the CuO\(_2\) plane is of considerable importance, because it can provide useful information regarding the symmetry of the superconducting order parameter, and could also throw light on the recent striking issue of the observation of a normal state pseudogap in underdoped materials. In fact, in the recent years, there have been growing interest in the studies of suppression of \(T_c\) in HTLS by intentional substitution of both magnetic (Co, Ni) as well as non-magnetic (Zn) impurities at copper (Cu) sites. These impurities essentially cause pair breaking \([1, 2]\) leading to the reduction of \(T_c\) while leaving the carrier concentration in the CuO\(_2\) plane unaltered \([3, 4]\). It has been shown previously \([5]\) that depending on the symmetry of the superconducting order parameter, the pair breaking rate or the variation of the experimentally measured \(T_c\) would be different. This is due to the fact that a pairing state of reduced symmetry is unstable to impurity scattering to a very high degree, i.e., depression of \(T_c\) is significantly stronger for a superconductor with \(d\)-wave symmetry than for a superconductor with pure \(s\)-wave symmetry.

The issue of the symmetry of the superconducting order parameter (OP) in HTLS has attracted considerable attention in the recent past and has been discussed widely in the high-\(T_c\) literature, a large fraction of which reported evidence of a \(d_{x^2-y^2}\) OP symmetry \([6, 7]\), and a consensus seems emerging in this direction. But, the striking results relating the pseudogap, as reported in NMR \([8, 9, 10]\), optical conductivity \([11, 12]\), heat capacity \([13]\), transport data \([14]\) and ARPES studies \([15]\), are yet to be understood within an unified framework. In other words, there have been no consensus so far regarding the origin of the pseudogap and the issue regarding the role played by the pseudogap to affect the physical characteristics of HTLS. In this paper, we will primarily be concerned about the extraction of the pseudogap and its effects on the in-plane (CuO\(_2\) plane) physical characteristics. Our basic task is three-fold. First, we analyse the \(T_c\)-suppression data (by impurity substitution) in Bi2212 \([4]\) and Tl2212 \([16]\) within the Abrikosov-Gorkov
formalism \cite{3,17,18} and investigate the suppression of the in-plane density of states (DOS) for variously doped samples. Secondly, we extract the pseudogap magnitude at different dopings within a “fermi-level density of states suppression” picture \cite{19}. And finally we study the effects of the pseudogap on a measurable physical characteristic of HTLS i.e. susceptibility. Note that, $T_c$ suppression data, which are obtained by substitution of only magnetic impurities (Co) at the Cu-sites, are considered here. An estimation of the pseudogap as well as the understanding of its effects on the in-plane physical characteristics is of importance for the purpose of a consistent theoretical modelling \cite{20} of HTLS as well as for further enlightening of the important issues in the subject.

The paper is organised as follows. In section-II, we describe the procedural steps involving the extraction of the pseudogap from the analysis of $T_c$-suppression data. Results are presented in section-III together with discussions of them. Section-IV comprises of a brief summary of the work done and some relevant comments.

II. Data Analysis: Estimation of the Pseudogap

The variation of $T_c$ as a function of increasing Co impurity concentration has been reported elsewhere by B. Bandyopadhyay et al. \cite{4}. Here, we have fitted the $T_c$-variation data to the Abrikosov-Gorkov (AG) equation \cite{17} valid for the weak coupling $d$-wave superconductors. Within the AG formalism pair breaking rate is inversely proportional to the DOS at fermi level denoted by $N(E_F)$. Experimental data are fitted to the AG relation using $N(E_F)$ as a fitting parameter and its values are thereby found out corresponding to each doping. This DOS at the fermi level $N(E_F)$ shows a progressive depletion towards underdoping which could imply the opening up of a gap of growing magnitude. Assuming that the depletion in $N(E_F)$ is caused by a pseudogap $E_g$ \cite{15}, we calculate a DOS within the “DOS-suppression picture” using a phenomenological form of the quasiparticle energy proposed previously \cite{11,13}. Values of the magnitude of $E_g$ are then obtained by fitting the calculated DOS at the fermi level (within the DOS-suppression picture) to the $N(E_F)$ values found out by data analysis. The $E_g$
values thus obtained are used to calculate the susceptibility at different doping and experimental susceptibility measurement data [21] are compared. We also do a similar analysis, as above, of the $T_c$ suppression data on Tl2212 and report the results here.

From the analysis of $T_c$ reduction data within the AG framework, it is found that both Bi2212 and Tl2212 cuprates bear qualitatively similar characteristic features regarding the pseudogap and other related properties investigated here. It is evident in the data analysis that the rate of suppression of $T_c$ becomes faster towards underdoping as reported earlier by other groups [2, 9]. We find that the magnitude of $E_g$, as obtained within the DOS suppression picture, grows as an inverse power of the carrier concentration towards underdoped side and is qualitatively similar to a related temperature scale $T^*$ estimated by thermoelectric power measurements [4].

For Bi2212 cuprates the sample composition is given by $\text{Bi}_2\text{Sr}_2\text{Ca}_{1-x}\text{Y}_x\text{(Cu}_{1-y}\text{M}_y)_{2}\text{O}_8$, where M represents cobalt (Co) impurity and $y$ gives the concentration of impurity in percentage. Here $x$ is the amount of yttrium (Y) substituted in place of calcium (Ca) which controls the carrier concentration. Details of sample preparation and measurements of $T_c$ versus $y$ (for Bi2212) are presented earlier [4] and here we consider an analysis of the $T_c$ suppression data.

For Tl-cuprate the sample composition is $\text{Tl}_2\text{Ba}_2\text{Ca}_{1-x}\text{Y}_x\text{(Cu}_{1-y}\text{M}_y)_{2}\text{O}_8$ where M and $y$ again represent Co impurity and its concentration respectively. Values of $T_c$ for both Bi2212 [4] and Tl2212 [16] at different impurity levels are estimated by studying the temperature variation of the resistivity. It should be mentioned that the carrier concentration for the samples used here are changed by substitution of yttrium (Y) at Ca sites [21, 22]. This procedure of changing carrier concentration does not affect the CuO$_2$ plane responsible for superconductivity. Whereas a change of the carrier concentration by oxygenation procedure might directly affect the CuO$_2$ plane by leaving traces of inherent impurities during sample preparation. These impurities are not accounted for while studying the $T_c$ suppression by impurity substitution and hence, the samples (of
varied carrier concentration) prepared by Y-substitution procedure are better suited for the purpose. Thus, \( T_c \) suppression data used here \[4, 16\] for analysis are expected to be more reliable.

III. Results and Discussions

In Fig.1 we present \( T_c \) versus \( y \) data (symbols) for various values of \( x \) (corresponding to different doping levels) where Fig.1(a) includes data for Bi2212 and Fig.1(b) gives that for Tl2212 samples. Clearly, for overdoped situation (small \( x \)) the reduction of \( T_c \) with Co-impurity concentration \( (y) \) is slower than that for the underdoped situation (large \( x \)). The \( T_c \) reduction data are fitted to the AG equation \[17, 18\] given as

\[
- \ln \left( \frac{T_c}{T_{c0}} \right) = \psi \left[ \frac{1}{2} + \frac{\Gamma}{2\pi k_B T_c} \right] - \psi \left[ \frac{1}{2} \right],
\]

where \( T_{c0} \) is the value of \( T_c \) at \( y = 0 \), i.e., without any impurity scattering centre in the sample. Here \( \psi[z] \) represents the digamma function for argument \( z \) and \( \Gamma = n_i/(\pi N(E_F)) \) is the pair breaking scattering rate for unitary scattering. The quantity \( N(E_F) \) is the DOS at fermi level (in units of \( /eV/A^3 \)) and \( n_i = \alpha y/abc \) is the density of impurity scatterers per unit volume where \( \alpha \) is the number of CuO\(_2\) planes per formula unit and \( a, b, c \) are lattice constants. A justification for using the AG equation for the short coherence length cuprate superconductors can be found in references \[3\] and \[13\]. In Fig.1(a) and Fig.1(b) solid and dashed lines are fitted curves using Eq.(1). Matching of the fitted lines with the experimental data are quite good, as seen in Fig.1. Notice, that the experimental data points (\( T_c \) versus \( y \)) exist only up to a limited value of the impurity concentration \( y = 7 - 8\% \). This is because samples of a pure single phase are not available \[4\] beyond this value of impurity concentration, \( y > 8\% \).

In the curve fitting process, \( N(E_F) \) is taken as a fitting parameter and its values are found out by a least square fitting of \( T_c \) versus \( y \) data. Fitted \( N(E_F) \) values corresponding to different doping levels (different \( x \)) are listed in table-I. It may be noted here that the typical r.m.s. deviation in the least square fitting of data is of the order of 1 \( K \) which reaffirms the visual excellence of data fitting curves presented in Fig.1.
The ratio $|dT_c/dy|$ is calculated for the fitted curves ($T_c$ versus $y$) of Fig.1. It is seen that with the increase of $y$, the slope $|dT_c/dy|$ increases monotonically for small $y$ and then registers a steep rise before falling sharply to zero at some value of $y$ denoted as the critical value of the impurity concentration $y_c$. Values of $y_c$ are different for different doping levels of the samples. For overdoping $y_c$ is considerably large and decreases progressively but rapidly towards underdoping. Noting the values of $y_c$ for each curve, one could calculate the corresponding critical values of the pair breaking scattering rate as $\Gamma_c = \alpha y_c/(\pi N(E_F)a b c)$ which are listed in table-I. The AG relation used here (in Eq.(1)) is valid for the weak coupling $d$-wave superconductors for which the critical scattering rate (at which $T_c$ reduces to zero) is evaluated \[18\] to be $\Gamma_c = 0.88 k_B T_{co}$. Values of $\Gamma_c$, calculated by this empirical relationship, are also presented in table-I which are within 1\% of the values obtained by data analysis. This correspondence might be taken as a crosscheck for the data fitting procedure and could also signify the validity of the AG relation used for the purpose.

Next we calculate the DOS using the normal state quasiparticle dispersion given as \[10, 13\]

$$E_k = \left[\epsilon_k^2 + E_g(k)^2\right]^{1/2}, \quad (2)$$

where $\epsilon_k$ represents the tight binding band energy for which we consider a realistic band structure obtained by a six parameter tight-binding fit $[t_o,t_1,t_2,t_3,t_4,t_5] = [0.131,-0.149,0.041,-0.013,-0.014,0.013] \text{eV}$ to the ARPES data on Bi2212 \[23\]. Here $E_g(k) = (E_g/2) |\eta_k|$ with $E_g$ being the pseudogap magnitude and $\eta_k = \cos k_x a - \cos k_y a$ ($a$ is the in-plane lattice constant of a square lattice) is the $d_{x^2-y^2}$ symmetry factor associated with the pseudogap \[13\]. Appearance of $E_g$ in the quasiparticle dispersion effectively causes suppression of the DOS at the fermi level. In our analysis, we estimate $E_g$ at a fixed doping level by fitting its value such that the DOS at Fermi energy calculated by using relation (2) (within the “DOS-suppression picture”) matches $N(E_F)$ found out previously from the data analysis (see table-I). A plot of scaled $E_g$ (open squares) and $T_{co}$ (solid triangles) as a function of carrier concentration ($p$), for Bi2212 samples, is given
in Fig.2. Here, $E_g$ at different $p$ are scaled to its value at optimal doping $p = 0.16$, that is $\bar{E}_g = E_g(p)/E_g(p = 0.16)$. $T_{co}$ values obtained in experimental measurements are also scaled similarly $\bar{T}_{co} = T_{co}(p)/T_{co}(p = 0.16)$. Solid line in the main figure, representing the locus of $\bar{T}_{co}$ data, is a guide to the eye and the dashed line is a power law fit to the $\bar{E}_g$ data. Notice that the pseudogap magnitude $E_g$ shows a sharp rise towards underdoping which is seen to vary as a power of inverse doping $(1/p)$. For the case of Tl2212 samples, the data points (not included in the figure) show similar characteristic features [24] as in the case of Bi2212. It would be of relevance to point out that in a recent experiment, Demsar et al. [25] studied the gap-structure in YBCO single crystals employing real-time measurements of the quasiparticle relaxation dynamics. They found a $T$-independent pseudogap to remain dominant for the underdoped samples and even persists in the overdoped state with its magnitude being inversely proportional to doping.

In the inset of Fig.2, we include the variation of $T^*$ versus $p$ (solid squares) as estimated from TEP measurement on Bi2212 where $T^*$ is the temperature at which thermoelectric power shows a peak and is much higher than the corresponding superconducting transition temperature $T_c$. The quantity $T^*$ can be thought of as an energy scale related to the pseudogap $E_g$, although in some places it has been termed as the temperature where the pseudogap opens up [26]. Solid line in the inset is a fit to the data and depicts that $T^*$ grows towards underdoping as a power of $1/p$, although the power is different from that involving $\bar{E}_g$ versus $p$ in the main figure. This similarity observed within $T^*$ and $\bar{E}_g$ emboldens the idea that $T^*$ is an energy scale related to $E_g$. It is important to note that $E_g$ values towards overdoping do not fall to zero, but shows monotonic decrease or remain nearly flat implying existence of $E_g$ even in the overdoped cuprates. This feature is visible in both the main figure as well as in the experimental $T^*$ data presented in the inset. Similar results of the existence of pseudogap in the overdoped region has been reported in a recent experiment on YBCO samples [25] and for the case of Bi$_2$Sr$_2$(Ca,Y)Cu$_2$O$_{8}$ as observed in several other experiments [27, 28]. This is also consistent with earlier experimental observations in Hg-cuprates [28].
With the assumption, that quasiparticles are well defined in the vicinity of the fermi surface, susceptibility can be written involving DOS as

$$\chi = 2 \mu_B^2 \int_{-\infty}^{\infty} \left[ -\frac{\partial f(E)}{\partial E} \right] N(E) \, dE$$

where $N(E)$ is the DOS at energy $E$ and $f(E) = (e^{\beta E} + 1)^{-1}$ is the fermi distribution function. Susceptibility $\chi$ becomes temperature dependent through the fermi function $f(E)$. Using the quasiparticle dispersion as in Eq.(2), we calculate $\chi$ for different carrier concentrations (different $E_g$). A plot of $\chi/\mu_B^2$ as a function of $T$ is given in Fig.3. The quantity $\chi/\mu_B^2$ has the dimension of DOS denoted by $N(E)$ in Eq.(3). In each curve in the plot, towards low temperature $\chi$ falls off rapidly and tends to zero in the limit $T \to 0$. With increasing temperature, $\chi$ increases slowly, peaks at a temperature ($T_\chi$) and then decreases slowly towards its high-$T$ saturation. Occurrence of the broad peak in $\chi$ at high $T$ (above the corresponding experimentally measured $T_{co}$) is due to the presence of $E_g$ in the quasiparticle energy and is not observable in case of a normal metal. As one goes towards reduced doping level, $E_g$ increases, the value of $T_\chi$ gets shifted towards higher temperatures and the peak becomes more and more broader. In the inset of Fig.3, we include the experimental data [21] of $\chi$ versus $T$ for Bi2212 which shows the feature that $\chi$ has a broad peak above $T_c$ and the peak position shifts towards higher $T$ with underdoping. This consistency of the earlier experimental data with that calculated using the quasiparticle dispersion in Eq.(2) lends some support to the physical picture that the existence of $E_g$ affects the in-plane (CuO$_2$-plane) charge transport by suppressing the quasiparticle DOS at the fermi level. It may be noted here that, within a similar DOS suppression picture, NMR data [3, 10] as well as the normal state heat capacity and magnetic susceptibility data [30] on different HTLS materials were analysed earlier in terms of a $d$-wave pseudogap.

IV. Summary and Comments

To summarize, we have considered experimental $T_c$-suppression data by impurity substitution in Bi2212 and Tl2212 cuprates, analysed them within Abrikosov-Gorkov
formalism of \textit{pair breaking by impurity scattering} and estimated the pseudogap magnitude within the DOS suppression picture. Our analysis shows that the pseudogap energy varies as a power of inverse doping and the variation bears close resemblance to that of $T^*$ found by thermoelectric power measurement on Bi2212. Presence of $E_g$ affects the susceptibility $\chi$ by inflicting the occurrence of a broad peak above the corresponding experimental $T_{co}$ indicating an unusual metallic state. A systematic study of $\chi$ and other properties connected to the pseudogap, for differently doped samples of various layered cuprates could be useful to further explore the relevance of the DOS suppression (by pseudogap) viewpoint in layered cuprates.

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References

[1] K. Ishida, Y. Kitaoka, N. Ogata, T. Kamino, K. Asayama, J. R. Cooper and N. Athanassopoulou, J. Phys. Soc. Japan 62, 2803 (1993); S. S. Ata-Allah, Physica C 221, 39 (1994); P. Mendels, H. Alloul, G. Collin, N. Blanchard, J. F. Marucco, J. Bobroff, Physica C 235–240, 1595 (1994); D. Goldschmidt, Y. Direktovitch, A. Knizhnik and Y. Eckstein, Phys. Rev. B 54, 13348 (1996).

[2] J. L. Tallon, Phys. Rev. B 58, 5956 (1998).

[3] A. Maeda, T. Yabe, S. Takebayashi, M. Hase and K. Uchinokura, Phys. Rev. B 41 530 (1990).

[4] B. Bandyopadhyay, P. Mandal and B. Ghosh, Phys. Rev. B 60 3680 (1999).

[5] R. Fehrenbacher and M. R. Norman, Phys. Rev. B 50, 3495 (1994); C. Bernhard, J. L. Tallon, C. Bucci, R. De Renzi, G. Guidi, G. V. M. Williams and Ch. Niedermayer, Phys. Rev. Lett. 77, 2304 (1996).

[6] W. N. Hardy, D. A. Bonn, D. C. Morgan, R. Liang and K. Zhang, Phys. Rev. Lett. 70, 3999 (1993); D. A. Brawner and H. R. Ott, Phys. Rev. B 50, 6530 (1994); J. R. Kirtley, C. C. Tsuei, J. Z. Sun, C. C. Chi, L. S. Yu-Jahnes, A. Gupta, M. Rupp and M. B. Ketchen, Nature (London) 373, 225 (1995).

[7] Z. X. Shen, D. S. Dessau, B. O. Wells, D. M. King, W. E. Spicer, A. J. Arko, D. Marshall, L. W. Lombardo, A. Kapitulnik, P. Dickinson, S. Doniach, J. Dilarlo, A. G. Loeser and C. H. Park, Phys. Rev. Lett. 70, 1553 (1993); H. Ding, M. R. Norman, J. C. Campuzano, M. Randeria, A. F. Bellman, T. Yokoya, T. Takahashi, T. Mochiku and K. Kadowaki, Phys. Rev. B 54, 9678 (1996).

[8] M. Takigawa, A. P. Reyes, P. C. Hammel, J. D. Thompson, R. H. Heffner, Z. Fisk and K. C. Ott, Phys. Rev. B 43, 247 (1991).

[9] G. V. M. Williams, J. L. Tallon, R. Michalak and R. Dupree, Phys. Rev. B 54, 6909 (1996).
[10] G. V. M. Williams, J. L. Tallon, E. M. Haines, R. Michalak and R. Dupree, Phys. Rev. Lett. 78, 721 (1997).

[11] C. C. Homes, T. Timusk, R. Liang, D. A. Bonn and W. N. Hardy, Phys. Rev. Lett. 71, 1645 (1993).

[12] A. V. Puchkov, P. Fournier, D. N. Basov, T. Timusk, A. Kapitulnik and N. N. Kolesnikov, Phys. Rev. Lett. 77, 3212 (1996).

[13] J. W. Loram, K. A. Mirza, J. R. Cooper and W. Y. Liang, J. Supercond. 7, 243 (1994).

[14] B. Batlogg, H. Y. Hwang, H. Takagi, R. J. Cava, H. L. Kao and J. Kwo, Physica C 235-240, 130 (1994).

[15] H. Ding, T. Yokoya, J. C. Campuzano, T. Takahashi, M. Randeria, M. R. Norman, T. Mochiku, K. Kadowaki and J. Giapintzakis, Nature 382, 51 (1996); A. G. Loeser, Z. -X. Shen, D. S. Dessau, D. S. Marshall, C. H. Park, P. Fournier, A. Kapitulnik, Science 273, 325 (1996).

[16] B. Bandyopadhyay et al., (to be communicated)

[17] A. A. Abrikosov and L. P. Gorkov, Zh. Eksp. Teor. Fiz. 39, 1781 (1960) [Sov. Phys. JETP 12, 1243 (1961)].

[18] P. J. Hirschfeld, P. Wölfle, D. Einzel, Phys. Rev. B 37, 83 (1988); Y. Sun and K. Maki, Phys. Rev. B 51, 6059 (1995).

[19] B. Chattopadhyay et al., High-T_c update 13, 4 (1999).

[20] P. W. Anderson et al., The Theory of Superconductivity in the High-T_c Cuprate Superconductors (Princeton Univ. Press, Princeton, 1997); S. Chakravarty, A. Sudbo, P. W. Anderson and S. Strong, Science 261, 337 (1993); B. Chattopadhyay and A. N. Das, Phys. Lett. A 246, 201 (1998); A. N. Das and B. Chattopadhyay, Physica C 308, 226 (1998).
[21] P. Mandal, A. Poddar, B. Ghosh and P. Choudhury, Phys. Rev. B 43, 13102 (1991); P. Mandal, Ph.D. thesis, Calcutta University (1991).

[22] D. Mandrus, L. Forro, C. Kendziora and L. Mihaly, Phys. Rev. B 44, 2418 (1991).

[23] M. R. Norman, M. Randeria, H. Ding and J. C. Campuzano, Phys. Rev. B 52, 615 (1995); R. Fehrenbacher and M. R. Norman, Phys. Rev. Lett. 74, 3884 (1995).

[24] For the case of bilayer Tl-cuprates, only two sets of $T_c$ suppression data are available, none of which corresponds to optimal doping. Thus, values of $E_g$ obtained within DOS-suppression picture could not be scaled suitably and hence not presented in Fig.3. The unscaled data show a rising trend towards underdoping.

[25] J. Demsar, B. Podobnik, V. V. Kabanov, Th. Wolf and D. Mihailovic, Phys. Rev. Lett. 82, 4918 (1999).

[26] V. J. Emery and S. A. Kivelson, Nature (London) 374, 434 (1995); M. R. Norman, H. Ding and D. G. Hinks, Nature 392, 157 (1998).

[27] G. Deutscher, Nature (London) 397, 410 (1999); R. Nemetschek, M. Opel, C. Hoffmann, P. F. Müller, R. Hackl, H. Berger, L. Forró, A. Erb and E. Walker, Phys. Rev. Lett. 78, 4837 (1997).

[28] Ch. Renner, B. Revaz, J.-Y. Genoud, K. Kadowaki and Ø. Fischer, Phys. Rev. Lett. 80, 149 (1998); Ch. Renner, B. Revaz, K. Kadowki, I. M-Aprile and Ø. Discher, 80, 3606 (1998).

[29] Y. Itoh, T. Machi, S. Adachi, A. Fukuoka, K. Tanabe and H. Yasuoka, J. Phys. Soc. Japan 67, 312 (1998); B. Bandyopadhyay, J. B. Mandal and B. Ghosh, Physica C 298, 95 (1998).

[30] J. W. Loram, K. A. Mirza, J. M. Wade, J. R. Cooper, N. Athanassopoulou and W. Y. Liang, Advances in Superconductivity VII (Springer-Verlag, Tokyo, 1995), pp. 75-80.
| Material | $x$ | $p$ | $N(E_F)$ \text{(}/eV/Å$^3$/) | $\Gamma_c$ values (in meV) | From curve fitting | From the relation $\Gamma_c=0.88 \ k_B T_{co}$ |
|----------|-----|-----|----------------------------|--------------------------|-------------------|----------------------------------|
| Bi2212   | 0.0 | 0.225 | 0.0805 | 5.90 | 5.86 |
|          | 0.2 | 0.160 | 0.0435 | 6.77 | 6.73 |
|          | 0.3 | 0.135 | 0.0250 | 7.09 | 6.98 |
|          | 0.4 | 0.110 | 0.0191 | 6.09 | 6.03 |
| Tl2212   | 0.2 | 0.102 | 0.0547 | 5.94 | 5.89 |
|          | 0.25 | 0.085 | 0.0466 | 4.19 | 4.15 |
Figure captions:

Fig.1. Superconducting transition temperature $T_c$ is plotted as a function of substituted Co impurity concentration for different values of yttrium content $x$ as shown in the figure. Figure (a) corresponds to Bi2212 and (b) corresponds to Tl2212 samples. In both the panels, the symbols represent experimentally measured $T_c$ values and lines (solid and dashes) represent fitted curves using the AG equation (1) as written in the text.

Fig.2. Phase diagram of bilayer bismuth cuprate. Solid triangles are scaled $T_{co}$ values corresponding to different carrier concentration ($p$) as measured experimentally. Solid line is a parabolic fit to these experimental data and serves as a guide to the eye. Open squares are scaled values of the pseudogap magnitude ($E_g$) as estimated within the DOS suppression picture. Dashed line is a power law fit to $E_g$ data. [Inset: Solid squares represent values of $T^*$, as estimated by thermoelectric power measurement, as a function of $p$. Solid line is a power law fit to the data.]

Fig.3. Susceptibility for Bi-cuprate, as calculated using Eq.(3) of the text, is plotted as a function of temperature for three different values of $x$ mentioned in the figure. The temperature $T_P$ for each curve, at which susceptibility has a broad peak, is marked by an arrow and the corresponding value is written. [Inset: Susceptibility data for Bi2212 as a function of temperature corresponding to three different values of yttrium (Y) concentration as noted in the figure. These data are taken from Ref.[21].]
