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Excess conductivity analysis of the $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+y}$ system: an estimation of interlayer coupling strength

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Abstract. The excess conductivity of the $Bi_2Sr_2CaCu_2O_{8+y}$ system is measured as a function of carrier concentration. The analysis shows that the system is highly anisotropic and the interlayer coupling strength decreases very rapidly with the decrease of holes. In the low-hole-concentration region T_c depends strongly on the interlayer coupling as compared to that in the optimally and heavily-doped regions. From the value of the interlayer coupling, the out-of-plane coherence length and dimensional crossover temperature are estimated.

A common feature of all the high-T_c superconductors is the presence of a layer-like structure with one or more CuO_2 planes in the unit cell. Both the superconductivity and the anomalous behaviour of normal and superconducting state properties are due to the motion of holes in these quasi-two-dimensional (2D) CuO_2 planes [1]. The in-plane and out-of-plane coherence lengths, $\xi_{ab}(0)$ and $\xi_c(0)$, extracted from $H_{c2}(T)$ data are very short. Such small values of the coherence length are a direct consequence of the high transition temperature and low carrier density. The short coherence length, on the other hand, gives a coherence volume so small as to contain only a few Cooper pairs. As a result the thermodynamic fluctuations play an important role in these systems. Because of the very short coherence length, planar structure and high transition temperature, the fluctuation contribution in cuprates is quite large and can be detected quite easily even beyond the critical region [2]. The fluctuations of the superconducting order parameter are manifested in transport, magnetic and thermodynamic properties, like electrical conductivity, susceptibility and specific heat [1]. The study of the effect of fluctuation is important in understanding the intrinsic superconducting characteristics and their dimensionality.

The rounding of the resistivity cuve slightly above T_c can be analysed in terms of superconducting fluctuations. Aslamazov and Larkin (AL) [3] first derived an expression for the fluctuation-induced excess conductivity:

$$\Delta\sigma = A\epsilon^{\lambda} \tag{1}$$

where $A = (e^2/16\hbar d)$ and $\lambda = -1.0$ for 2D systems, $A = (e^2/32\hbar\xi(0))$ and $\lambda = -0.5$ for 3D systems, $\epsilon = (T - T_c^{mf})/T_c^{mf}$ is the reduced temperature and d is the characteristic thickness for a 2D system and T_c^{mf} is the mean field transition temperature.

The coherence length, $\xi_c(0)$, along the c-axis for the high-T_c superconductors is very short but not zero. Such systems may be considered as layered superconductors. For the

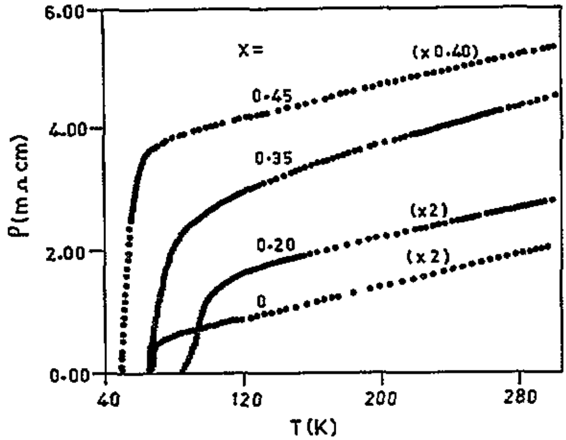

Figure 1. The temperature dependence of the resistivity of $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+y}$ for $x = 0$, 0.20, 0.35 and 0.45. The resistivities of the $x = 0$, 0.20, and 0.45 samples are multiplied by 2, 2 and 0.4, respectively.

layered superconductors with Josephson coupling between adjacent layers, Lawrence and Doniach (LD) [4] calculated the fluctuation-enhanced conductivity of the system as

$$\Delta\sigma = (e^2/16\hbar d)\epsilon^{-1}[1 + J\epsilon^{-1}]^{-1/2} \qquad (2)$$

where $J(= (2\xi_c(0)/d)^2)$ is the interlayer coupling constant. Equation (2) shows that for $T \gg T_c^{mf}$ where $J \ll \epsilon$, $\Delta\sigma$ varies as ϵ^{-1} (2D behaviour) while very close to T_c^{mf} where $J \gg \epsilon$, $\Delta\sigma$ varies as $\epsilon^{-1/2}$ (3D behaviour). Thus, the LD expression predicts a crossover from 2D to 3D fluctuations at $T_0 = T_c^{mf}\exp(J)$.

A large number of excess conductivity analyses have been reported for $YBa_2Cu_3O_{7-\delta}$ with varied conclusions. Both 2D [5], 3D [6] and also a crossover from 2D to 3D [7] in fluctuations have been reported in this system. However, both resistivity measurements and fluctuation analysis of Bi- and Tl-based systems support a quasi-two-dimensional interpretation [8, 9].

In all high-T_c systems anisotropy decreases with carrier concentration and its behaviour is very similar to that of the conventional isotropic Fermi liquid in the over-doped region [10]. However, there is no report on the determination of J as a function of carrier density. In this paper, we present the excess conductivity analysis of the $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+y}$ system using both AL and LD expressions. From the LD fittings we have calculated J and $\xi_c(0)$ for different values of x. Because of the large inelastic scattering rate [11] we have not considered the indirect Maki–Thompson term in our zero-field excess conductivity analysis.

The samples used in the present study have been prepared by the standard solid state reaction method [12]. To improve the sample quality we have annealed these samples for a much longer time. For samples with $x \geqslant 0$ we increased the annealing temperature by 5–10 K than that mentioned in our ealrier work [12]. X-ray analysis shows no impurity phases over the composition range of our study. Resistivity was measured by the four-probe method. The temperature dependence of the resistivity for $x = 0$, 0.2, 0.35 and 0.45 samples is shown in figure 1. The increase in transition width for our present samples with $x \geqslant 0.2$ has been observed to be small compared to that of our earlier samples [12]. A similar increase in transition width has also been observed in the case of single crystals [13].

The deviation of the measured resistivity ($\rho(T)$) from the normal state resistivity ($\rho_n(T)$), defined as $\Delta\rho(T)$, measures the excess conductivity

$$\Delta\sigma(T) = 1\rho(T) - 1/\rho_n(T) = \Delta\rho(T)/\rho(T)\rho_n(T).$$

Thus to compare this $\Delta\sigma$ with theoretical predictions one has to know $\rho_n(T)$ and T_c^{mf}. The strong linear temperature dependence of resistivity of our samples leads us to assume that the normal state resistivity may be of the form $\rho_n(T) = a + bT$. This assumption is justified because it is an experimental fact that almost all high-T_c systems show strong linear temperature dependence up to a very high temperature and also down to very low temperature for some Bi-based superconductors. We have determined a and b by a least-squares fitting method using the resistivity data above $2T_c$ ($\sim$ 200–305 K). A completely different approach to analysing $\Delta\sigma$ is also used by some authors [14]. In this method a and b are treated as free parameters in the expression for $\Delta\sigma$ and are determined from the best-fit results. However, $\rho_n(T)$ determined using these values of a and b deviates considerably from the measured resistivity even at high temperatures. The values of other parameters obtained from this kind of fit are also not physically reasonable. On the other hand, Winzer and Kumm and Hopfengartner *et al* [15] analysed $\Delta\sigma$ for high-quality single crystals and epitaxial films of $YBa_2Cu_3O_7$ using the value of $\rho_n(T)$ determined by a linear extrapolation method similar to ours. The values of all the parameters obtained by them are physically reasonable and comparable with those obtained by other measurements. Winzer and Kumm also analysed the magnetoconductivity of the same crystals and observed a good agreement between excess conductivity and magnetoconductivity results. Other than ρ_n, determination of T_c^{mf} is perhaps the most important problem in the analysis of $\Delta\sigma$. Several methods are generally followed to evaluate the T_c^{mf} namely (i) finding the position at which $d\rho/dT$ shows a maximum [9], (ii) from the extrapolation of a $(\Delta\sigma)^{1/\lambda}$ versus T plot [7] and (iii) treating T_c^{mf} as a free parameter in the fitting process [16]. In this work we have followed methods (i) and (iii) for the estimation of T_c^{mf} and found that the values of T_c^{mf} determined from these methods are close to each other. In figure 2 we have shown log–log plots of $\Delta\sigma$ and ϵ for the $x = 0.10$, 0.20 and 0.45 samples. To compare the nature of the temperature dependence of this excess conductivity with theoretical predictions we have fitted $\Delta\sigma$ over a wide temperature range using (1) from AL theory. During the least-squares fit, A, λ and T_c^{mf} are treated as free parameters. The best fit is obtained in a temperature range $-3.5 \leqslant \ln\epsilon \leqslant -0.5$, where the experimental points fit closely with AL theory (the solid line). The values of different parameters obtained from this fitting are listed in table 1. For $x \geqslant 0.20$ samples the value of λ is very close to -1, the characteristic value for 2D fluctuations. On the other hand, the values of λ for $x = 0$ and 0.10 samples are not as close to -1 as for $x \geqslant 0.20$ samples. It has also been observed that if we fix the value of λ very close to -1 for $x = 0$ and 0.1 samples then (1) deviates considerably from the experimental curves even in a small temperature range. This clearly indicates that for $x < 0.20$ the system cannot be described by the 2D or 3D AL theory. It is also interesting to note that the value of the parameter A obtained from the best-fit results is smaller by a factor C than the AL prediction with $d = 15.4$ Å (the average separation between two adjacent CuO_2 layers). This type of discrepancy between the theory and experiments has also been observed by Oh *et al* [7] in the excess conductivity of $YBa_2Cu_3O_{7-x}$ single crystals. They pointed out that one possible source of this scaling factor is the non-uniform current flow on a submacroscopic scale due to poor grain boundaries, microcracks, or uneven oxygen content which vary from sample to sample.

We have already mentioned that for layered superconductors, LD theory is more appropriate to describe the nature of these fluctuations. In figure 2 we have also shown the

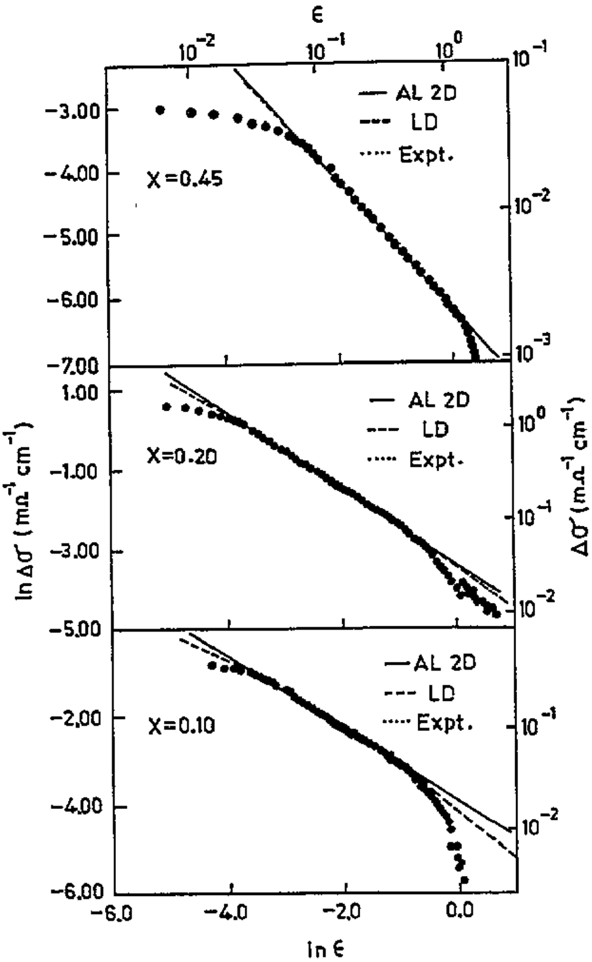

Figure 2. A plot of $\ln(\Delta\sigma)$ versus $\ln\epsilon$ for the $x = 0.10$, 0.20 and 0.45 samples.

Table 1. The parameters obtained from $\rho_n(T)$ and the AL fit.

x	a (10^{-3}mΩ cm)	b (mΩ cm K^{-1})	T_c^{mf} (K)	C	λ	χ^2
0	0.0703 ±0.0015	3.215 ±0.012	70.44	3.68	0.83	2.5×10^{-3}
0.10	0.3715 ±0.002	2.724 ±0.014	87.93	5.16	0.87	8.0×10^{-4}
0.20	0.522 ±0.002	2.995 ±0.011	92.45	3.17	0.98	4.1×10^{-3}
0.30	0.5869 ±0.003	3.687 ±0.015	88.96	3.25	0.99	9.5×10^{-3}
0.35	2.3178 ±0.0037	7.261 ±0.027	67.10	3.63	1.02	4.7×10^{-3}
0.45	8.9395 ±0.0063	14.816 ±0.051	55.00	39.76	1.02	5.0×10^{-6}

predictions of LD theory (2). Fitting is done over the same temperature range as in the case of AL theory, with three adjustable parameters, $A(= e^2/16\hbar d)$, $\xi_c(0)$ and T_c^{mf}. It is clear from the value of χ^2, the sum of squared deviations, that the LD fit is better than the AL fit (table 2). We also observed that the LD model fits the experimental points over a wider temperature range compared to the AL model. Different physical parameters obtained from the LD fittings are presented in table 2. The 2D to 3D crossover temperature (T_0) calculated using the value of J shows the T_0 approaches very rapidly to T_c^{mf} as J decreases. We have also calculated $\xi_c(0)$ for different samples using d = 15.4 Å. The value of $\xi_c(0)$ for the x = 0.10 sample is about 1.5 Åwhich is comparable to that reported from other measurements [1].

Table 2. The parameters obtained and estimated from the LD fit.

x	T_c^{mf} (K)	C	J (10^{-3})	$\xi_c(0)$ (Å)	$T_0 = T_c^{mf}\exp(J)$ (K)	χ^2
0	70.50	3.60	86.80 ±2.6	2.25	77.0	1.4 ± 10^{-3}
0.10	88.00	5.20	37.30 ± 1.4	1.48	91.34	6.0 ± 10^{-4}
0.20	92.49	3.24	6.26 ± 0.3	0.61	93.07	2.3 ± 10^{-3}
0.30	89.03	3.31	2.96 ± 0.11	0.41	88.29	5.3 ± 10^{-3}
0.35	67.00	3.59	0.76 ± 0.05	0.21	67.05	4.5 ± 10^{-3}
0.45	55.00	39.86	0.25 ± 0.03	0.12	55.01	4.8 ± 10^{-6}

The interlayer coupling strength J obtained from the best-fit results is plotted in figure 3 as a function of x. Figure 3 shows that the interlayer coupling strength decreases monotonically with x. For the $x = 0.45$ sample J is very small and the fluctuation is almost 2D in nature over a wide temperature range. The decrease of J with x suggests that the system becomes more and more anisotropic as the carrier density decreases. Evidence of this type of behaviour has also been reported from other measurements [10]. For example, in the $YBa_2Cu_3O_{7-\delta}$ system, the resistivity anisotropy (ρ_c/ρ_{ab}) is observed to increase with the decrease of O_2 content [10]. Several theoretical models have been proposed to explain the role of interlayer coupling in superconductivity [17, 18]. In order to investigate the effect of the interlayer coupling on the superconductivity we have plotted T_c as a function of J (figure 4). Figure 4 shows that T_c increases with J, reaches a maximum and then decreases slowly with further increase of J. The dependence of T_c on J is stronger in the under-doped region ($x \geqslant 0.35$) than that for the over-doped region ($x \leqslant 0.10$). From the pressure dependence of T_c in high-T_c systems Chu *et al* [19] observed that in the under-doped region dT_c/dp is large and positive whereas in the over-doped region it is small and negative. From this unusual dependence of T_c on pressure they concluded that the mechanisms of superconductivity in the under-doped and over-doped regions may be different. A very similar type of comment has been made by Uemura *et al* [20] on the basis of μSR studies. Their results suggest that the high-T_c cuprate, bismuthate, organic, Chevral-phase and heavy-fermion systems belong to a unique group of superconductors. In these systems T_c is proportional to n_s/m^* (carrier density/effective mass) in the under-doped region. The values of T_c of these exotic superconductors lie in the range $(10^{-2}–10^{-1})\epsilon_F/k_B$ (where ϵ_F is the Fermi energy) whereas this value is less than 10^{-3} ϵ_F/k_B in conventional BCS superconductors like Nb and Sn [20]. Uemura *et al* also observed that the values of T_c of these exotic superconductors lie close to the BE condensation in a thermodynamic sense. Theoretically, for such systems with very short coherence length, formation and condensation of local bosons have been predicted by many groups [17, 21, 22]. Das *et al* [18] studied the effect of interlayer coupling on T_c for fermion pairing and Bose condensation. They found that for fermion pairing the interlayer coupling (J) is small and T_c depends weakly on J whereas the Bose condensation temperature increases rapidly with J.

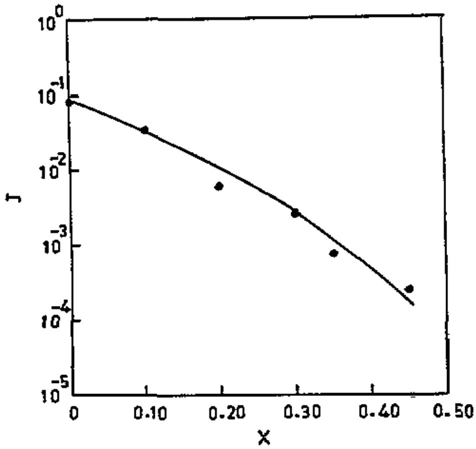

Figure 3. The variation of the interlayer coupling constant (J) with the Y content (x) in $Bi_2Sr_2Ca_{1-x}Y_xCu_2O_{8+y}$.

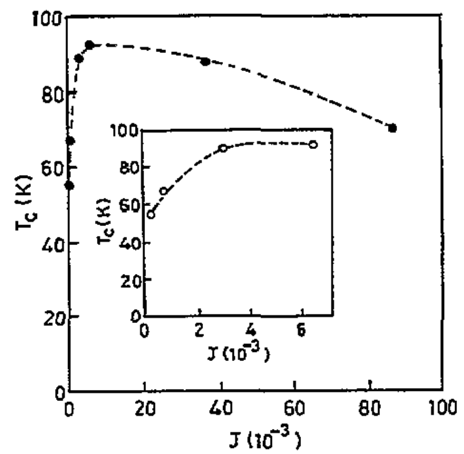

Figure 4. The dependence of T_c on J. Inset: expanded view around the low-J region.

In conclusion, the observed strong dependence of T_c on interlayer coupling in the underdoped region and the μSR studies of Uemura *et al* suggest that Bose condensation may play an important role in cuprate superconductors. Further studies in this direction are necessary to understand the true mechanism of superconductivity in high-T_c systems.

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