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A model of evaluating the pseudogap temperature for high-temperature superconductors

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Abstract. We have presented a model of evaluating the pseudogap temperature for high-temperature superconductors using paraconductivity approach. The theoretical analysis is based on the crossing point technique of the conductivity expressions. The pseudogap temperature T^* is found to depend on dimension and is calculated for 2D and 3D superconducting samples. Numerical calculation is given in favour of the YBCO and doped $SmFeAsO_{1-x}$ samples.

Keywords. Superconducting fluctuation; pseudogap temperature; dimensionality.

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1. Introduction

The observation of pseudogap in normal-state properties of high-temperature superconducting (HTS) oxide materials has raised many questions about the origin and its relation with superconductivity. Emery and Kevilson [1] first used the term pseudogap temperature for underdoped high-T_c materials. The temperature at which the gap is opening is called the pseudogap temperature and is denoted by T^*. T^* lies significantly above the superconducting transition temperature T_c. Above T^*, the resistivity is linear with temperature and below T^*, the resistivity acquires a downward curvature in which the superconducting Cooper pair fluctuations arise. On the other hand, near the normal superconducting transition (both phases appear together, in some temperature interval above T_c), the high-temperature superconductors (HTSCs) show a peculiar behaviour (round shape, deviates from linearity) in resistivity which is due to strong superconducting fluctuations observed experimentally. Many experiments, viz., scanning tunnelling microscopy (STM) and angle-resolved photoemission spectroscopy (ARPES), suggest that the pseudogap state is as usual an energy gap but the exact nature of this state and its relation to superconductivity is still a subject of great controversy [2]. Some researchers believe

that the appearance of a pseudogap is not due to superconducting pairing and is in no way related to superconductivity. Other researchers believe that the pseudogap is precisely due to superconducting fluctuations, which lead to the formation of paired fermions for $T \leq T^*$, and thus it is a precursor state for superconductivity, especially, for HTSCs. Recent theory and experiments [3,4] suggest that fluctuation and pseudogap state are at least related to each other with their parameters and both vary with hole concentrations. Below T^*, the density of quasiparticle states at the Fermi level starts to decrease. At the same time it can be shown that in HTSCs, cross-over occurs at $T = T^*$. Assume that above T^* (i.e., $T > T^*$), the resistivity is linear (shows metallic behaviour) and below T^* (i.e., $T < T^*$), the resistivity is nonlinear (shows downward curvature) and becomes zero at $T = T_c(\rho \to 0)$. Then, the resistivity and conductivity cross each other at a particular temperature $T = T^*$, which is the theoretical basis for the determination of pseudogap temperature.

2. Theoretical model

After having the information about the pseudogap state in doped oxide materials, the researchers were curious to find out the energy scale or temperature (so-called pseudogap temperature T^*) at which the gap opens. In transport measurements, the pseudogap temperature is usually determined from the departure of ρ from its linear high-T variation (i.e., the departure of ρ from its high- to low-temperature variation). Recent transport experiments [2,5–8] in high-T_c superconducting oxides have shown that the paraconductivity data follow pure Aslamazov–Larkin (A–L) (see ref. [9] and references therein for details) behaviour and this behaviour can be extended up to T^* provided a (linear) normal state resistivity is assumed. As soon as the temperature reaches T^*, the paraconductivity rapidly drops. We proceed with the well-known mathematical expressions for paraconductivity valid in two and three dimensions, respectively, which are written as

$$\Delta\sigma^{2D}(T) = \left(\frac{e^2}{16\hbar d}\right)\varepsilon^{-1}, \tag{1}$$

$$\Delta\sigma^{3D}(T) = \left(\frac{e^2}{32\hbar\xi_c(0)}\right)\varepsilon^{-1/2}. \tag{2}$$

Here, d is the distance between the CuO_2 layers, $\xi_c(0)$ is the zero temperature coherence length along c-axis, $\varepsilon = \left(T/T_c^{MF} - 1\right)$ is the reduced temperature and T_c^{MF} is the mean-field transition temperature. We introduce T_c^{MF} instead of T_c (which is the real transition temperature and is always less than T_c^{MF}) as T_c^{MF} exhibits [2] similar doping dependence behaviour as T^*, the pseudugap temperature.

The high-T_c oxide materials show linear (metallic) behaviour in normal resistivity, written as

$$\left.\begin{aligned}\rho(T) &= aT + b,\\ \sigma(T) &= \rho^{-1}(T) = (aT+b)^{-1}\end{aligned}\right\}, \tag{3}$$

where a and b are constants.

In a recent study, Islam [9] introduced a model of dimensional cross-over temperature using the crossing point technique of the temperature-dependent excess conductivity in reduced form. The same technique is used to determine the pseudogap temperature for high-temperature superconductors. The theoretical idea is that the two conductivities, i.e., eqs (1) and (3) or eqs (2) and (3) cross each other depending on the related parameters. Assume that the cross-over occurs between two conductivities and cross each other at a particular temperature, $T = T^*$. To get T^*, compare eqs (1) and (3); we have

$$\left(\frac{e^2}{16\hbar d}\right)\left(\frac{T^*}{T_c^{MF}}-1\right)^{-1} = \left(aT^*+b\right)^{-1},$$

$$aT^*+b = \left(\frac{16\hbar d}{e^2}\right)\left(\frac{T^*}{T_c^{MF}}-1\right) = A\left(\frac{T^*}{T_c^{MF}}-1\right)\left[\because A = \frac{16\hbar d}{e^2}\right],$$

$$T^*\left(\frac{A}{T_c^{MF}}-a\right) = b+A,$$

$$T^* = \frac{b+A}{\left(A/T_c^{MF}\right)-a}. \tag{4}$$

In a similar way, using eqs (2) and (3), we have

$$\left(\frac{e^2}{32\hbar\xi_c(0)}\right)\left(\frac{T^*}{T_c^{MF}}-1\right)^{-1/2} = \left(aT^*+b\right)^{-1},$$

$$\left(\frac{32\hbar\xi_c(0)}{e^2}\right)\left(\frac{T^*}{T_c^{MF}}-1\right)^{1/2} = \left(aT^*+b\right),$$

$$B\left(\frac{T^*}{T_c^{MF}}-1\right)^{1/2} = \left(aT^*+b\right)\left[\because B = \left(\frac{32\hbar\xi_c(0)}{e^2}\right)\right],$$

$$a^2T^{*2} + T^*\left(2ab - \frac{B^2}{T_c^{MF}}\right) + (B^2+b^2) = 0, \tag{5}$$

from which we can write

$$T^* = \frac{-\left(2ab-\left(B^2/T_c^{MF}\right)\right) \pm \sqrt{\left(2ab-\left(B^2/T_c^{MF}\right)\right)^2 - 4a^2(B^2+b^2)}}{2a^2}. \tag{6}$$

From eq. (6), we see that the theoretical value of T^* may vary due to ($\pm$) sign. For convenience, we have taken minus sign for the calculation of T^*.

3. Numerical result

To estimate T^*, we can take an example shown in figure 1. For numerical analysis, we took $b = 0.0605\,\mu\Omega$ m and $a = 0.4903\mu\Omega$ m k^{-1} (the linear part of the experimental resistivity data to fit well) for the sample YBCO reported in ref. [3] for which $\xi_c(0) = 1.65$Å, $d = 11.7$ Å, $T_c^{MF} = 88.46$ K, $T_c(\rho = 0) = 87.4$ K were used. Numerically, we

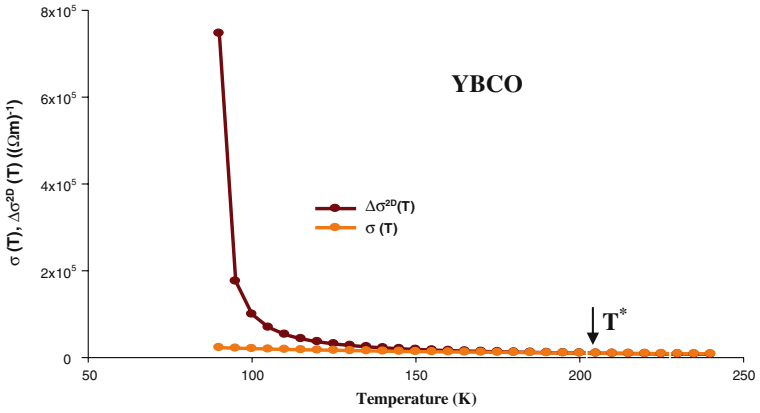

Figure 1. $\sigma(T)$, $\Delta\sigma^{2D}(T)$ vs. temperature.

have estimated $T^* = 203$ K (indicated by arrow) using the procedure mentioned in ref. [9]. This value is exactly the same as the value in ref. [3] determined experimentally.

For estimating T^*, we took another example shown in figure 2. The linear part of the resistivity data fitted well with $b = 8.42\,\mu\Omega$ m and $a = 0.102\,\mu\Omega$ m k^{-1}, for the sample-doped $SmFeAsO_{1-x}$ for which $\xi_c(0) = 1.4$ Å, $T_c^{MF} = 57$ K, $T_c(\rho = 0) = 55$ K were used [10]. The numerical result shows that $T^* = 163$ K, which is slightly smaller than the experimental value [10].

Now we proceed in a reverse way, i.e., we use the pararesistivity vs. temperature curve to determine T^* used by others [3,10,11]. The numerical result (shown in figure 3) indicates that $T^* = 163$ K, which is the same value determined by the previous method supporting our findings.

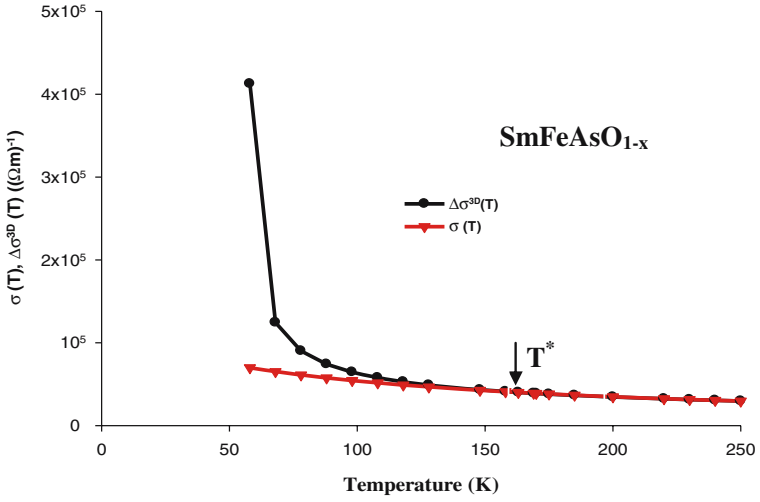

Figure 2. $\sigma(T)$, $\Delta\sigma^{3D}(T)$ vs. temperature.

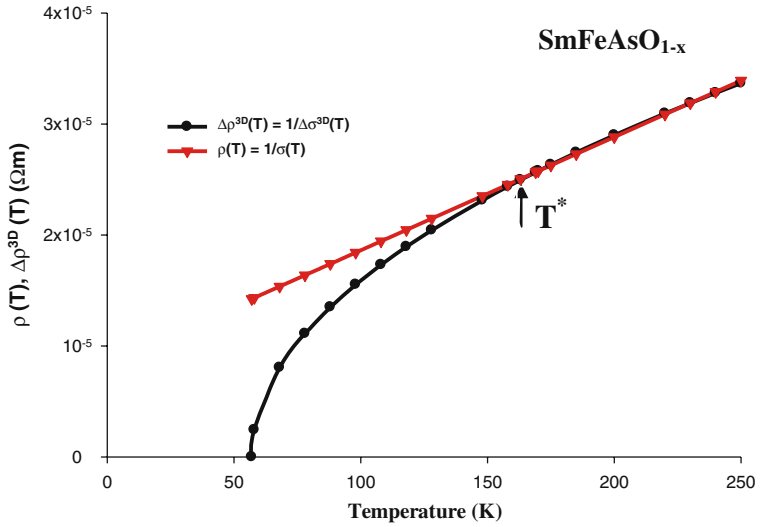

Figure 3. $\rho(T)$, $\Delta\rho^{3D}(T)$ vs. temperature curve of the sample $SmFeAsO_{1-x}$. The straight line indicates the normal state resistivity and round curve indicates the pararesistivity. The arrow indicates the crossing point at which $T = T^*$.

4. Discussion and conclusion

In this paper, we have included a theoretical idea to determine the pseudogap temperature of high-temperature superconductors. We obtained the pseudogap temperature in two- and three-dimensional superconducting samples using the paraconductivity approach. To calculate the pseudogap temperature T^* above T_c^{MF}, we have used the crossing point technique for the paraconductivity expressions. It should be mentioned here that T^* is very high compared to T_c or T_c^{MF}, especially for underdoped cuprates [8]. For heavily underdoped materials, it is found [11] that T^* is approximately 300 K and above. At this temperature, the effect of paraconductivity does not exist. This does not mean that the process of evaluating T^* is meaningless. However, the theoretical expression found here for T^* is well understood and clear for 2D and 3D. For calculating T^*, we have used the published values of the related parameters for specific superconducting samples. Numerical results are in good agreement with other published values of T^*. We repeated the calculation in a reverse way (a common, well-known method [10,11] of calculating T^*) for the sample $SmFeAsO_{1-x}$ to support our findings. Finally, we have concluded that the crossing point technique is appropriate for determining T^* and that this technique depends on the dimension of the superconducting samples.

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