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ELECTRICAL TRANSPORT IN $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-y}$

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Abstract. The variations of the resistivity with temperature and composition of $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-y}$ reported by Awana et al. (J. Phys.: Condens. Matter **4**(1992) 4971) can be described quantitatively by an equation based on small Fermi energies ($\sim 10^{-4}\text{eV}$) and small gap energies ($\sim 10^{-2}\text{eV}$).

Measurements of the resistivity vs. temperature and composition, $\rho(T;x)$, like those reported by Awana et al. [1] and by Tanaka [2] for $\text{La}_{2-x}\text{Sr}_x\text{CuO}_{4-y}$ and of $\rho(T;\delta)$ by several others [3-6] for $\text{YBa}_2\text{Cu}_3\text{O}_{7-\delta}$ yield information that can be used to elucidate the mechanism of conductivity in the normal state of the superconducting oxides. However, only qualitative discussions are presented generally concerning the shapes of the $\rho(T;x)$'s and the metal-nonmetal and metal-insulator transitions identified with them [7]. If our understanding of the normal state is to be accomplished, there is needed a quantitative interpretation of these variations of conductivities with temperature and composition so that the parameters of the conductivity can be identified. The present report is a quantitative attempt to interpret the measurements reported by Awana et al.

The pattern of the $\rho(T,\text{comprn.})$'s is as follows (See Figure 1 in Awana et al): For the most resistive compositions, $\rho(T)$ displays an apparently exponential decay with increasing temperature similar to the variation observed with semiconductors. As the composition is changed so that the resistivity decreases, $\rho(T)$ displays non-monotonic variations with a maximum or a minimum or both; the maximum followed by a rapid decrease as the temperature is decreased is generally associated entirely with the onset of the superconducting state. Finally, as the optimum concentration is attained, $\rho(T)$ is nearly linear to the onset of the superconducting state. Several attempts have been made to use this linearity to understand the conductivity [8].

Because all the measurements of the resistivity are made at or below 300 K, which corresponds to $kT = 2.6 \times 10^{-2} \text{ eV}$, the energies associated with the conductive mechanism should be of this order or less. Thus, it is slowly being recognized [9-12] that small gap energies and small Fermi

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energies must be associated with the unusual properties of these materials. For these small values of the Fermi energies, the Fermi-Dirac distribution, $f(\varepsilon;T)$, is not relatively sharp and the usually used derivative, $-\partial f/\partial \varepsilon$, is not sharply peaked [13] An analysis of the situation that exists when the Fermi and gap energies are small has been accomplished [13] and is used herein.

The essential feature in this analysis is that the density of carriers,

$$N(T) = \int_0^{\infty} g(\varepsilon) f(\varepsilon;T) d\varepsilon, \quad (1)$$

in which $g(\varepsilon)$ is the density of states and $f(\varepsilon;T)$ is the Fermi-Dirac distribution function can be treated as follows: Since there is a gap between the conduction and valence bands,

$$N(T) = \int_0^{E_f} g(\varepsilon) f(\varepsilon;T) d\varepsilon + \int_{E_g}^{\infty} g(\varepsilon) f(\varepsilon;T) d\varepsilon. \quad (2)$$

If one defines an average value of $g(\varepsilon)$ evaluated at the energies E_f , the Fermi energy, and E_g , the top of the gap-energy, one can write:

$$N(T;E_f,E_g) = \langle g(E_f;T) \rangle \int_0^{E_f} f(\varepsilon;T) d\varepsilon + \langle g(E_g;T) \rangle \int_{E_g}^{\infty} f(\varepsilon;T) d\varepsilon. \quad (3)$$

Thus the integrand in equation (1) is separated into two factors so that one can possibly determine the extent to which the two factors in the integrand contribute the conductivity. If one expands $g(\varepsilon)$ in Taylor series about E_f and E_g and if one expresses a mean relaxation time for scattering as being proportional to T^{-s} , then the zeroth order approximation for the conductivity is

$$\sigma = C T^{(1-s)} \ln \{ \exp[(\beta E_f) + 1]/2 \} [\exp(-\beta(E_g - E_f)) + 1] \} \quad (4)$$

in which C is a normalization constant that contains the averaged values defined above.

The results of the least squares' analyses of points obtained from

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some of the curves published in Figure 1 by Awana et al are shown in Figures 1 and 2; the determined values of the parameters are listed in Table I. For all of the selected curves, the agreements between the points and the least squares' calculated values are within the errors with which the values can be obtained from the curves, except the one point in the case of $x=0.06$ in Figure 1 and for the points connected by the dotted lines in Figure 2. An examination of the figures and the chi squared/degree of freedom shows that equation (4) describes quantitatively the measurements reported by Awana et al except for those at the lowest temperatures and for all temperatures in the case of $x=0.08$. For the values of the composition equal to 0.06 in Figure 1, the least squares' curve has a minimum whereas the measured curve is monotonic; for the composition equal to 0.08 the chi square/degree of freedom is large. Where disagreement does occur, it is not possible to ascertain the extent to which experimental error is the cause. Certainly one observes that the data by Awana et al. and by Tanaka do not agree where values for x are the same. The shapes of the curves are sensitivity to the composition and uniformity of the composition, so that precise determinations are difficult to make. In Figure 2 the disagreement represents the onset of the superconducting state.

The curves displayed in Figure 1 show the changes described by equation (4) and by the experimental data when the conductivity vs. temperature varies from that for a semiconductor with $x=0.02$ to that for a metal like material with $x=0.15$. Between these two extremes, the curves and the data are non-monotonic with minima and maxima. In Figure 2 are shown the conductivities vs. temperature for compositions ranging from $x=0.10$ to $x=0.19$ as the optimum superconducting composition is approached and exceeded. The dotted parts of the curves represent the places at which the experimental data deviate from the least squares' curves and hence represent the onset of the superconducting states with respect to the least squares' curves. For those cases in which there are minima, these defined onsets occur at temperatures lower than those at the minima. Thus in the resistivity curves that display maxima with rapid decreases as the temperatures are decreased, these features are predicted by equation (4) and do not necessarily represent the precise onsets of the superconducting states.

The analysis given above indicates that there occurs a continuous variation of the structures of the curves with composition. There occurs no abrupt transitions. There does occur a continuous change as the maxima and minima approach each other when the composition is increased, and as they merge the temperature at the extrema becomes imaginary and the monotonic curve with $d\sigma/dT < 0$ occurs. Presumably

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this corresponds to what deJongh [7] identified as a non-metal-metal transition wherein $d\rho/dT$ changes from a value less than zero to one greater than zero; he attributed this to Anderson localization. The minimum in equation (4) is associated with the competition between the two factors in the argument of the logarithm, the semiconductor-like part with derivative that is negative and the metal-like part with a derivative that is positive. The maximum in equation (4), which is generally associated with a metal-insulator transition, is attributable to the competition between the increase in the density of carriers and the increase in scattering as the temperature is increased.

Since a variation like that for $x=0.17$ is one of the total set that describes quantitatively the systematic change with composition and since it is nearly linear, $\sigma(T)$ for this case must have the two factors in equation (4), so that the near linearity is a fortuitous combination of these two factors. Such is illustrated in Figure 3.

Acknowledgement

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Table

Table I

VALUES OF LEAST SQUARES' PARAMETERS FOR EQUATION (4).

x	Fermi Energy $E_f \times 10^4$ (eV)	Top of Gap Energy $E_g \times 10^2$ (eV)	s*	Chi ² /deg free $\times 10^5$
0.10	2.67 ± 0.25	1.05 ± 0.03	1.97 ± 0.04	36
0.12	2.74 ± 0.17	1.15 ± 0.04	2.13 ± 0.04	13
0.13	3.12 ± 3.31	0.505 ± 0.166	1.58 ± 0.06	4.3
0.14	8.46 ± 1.08	0.632 ± 0.103	1.71 ± 0.05	3.3
0.15	8.54 ± 0.67	1.15 ± 0.06	2.01 ± 0.06	6.8
0.17	8.89 ± 3.37	4.87 ± 1.83	1.54 ± 0.06	4.3
0.19	6.54 ± 3.44	0.529 ± 0.205	1.72 ± 0.08	8.7

* scattering exponent

Figure Captions

Figure 1. Normalized conductivity vs. temperature at various values of x in $\text{La}_{2-x}\text{Sr}_x\text{CuO}_4$. (a) x=0.02; (b) x=0.06; (c) x=0.10; (d) x=0.15. Data from Awana et al.[1].

Figure 2. Normalized conductivity vs. temperature at various values of x in $\text{La}_{2-x}\text{Sr}_x\text{O}_4$. (a) x=0.10; (b) x=0.12; (c) x=0.13; (d) x=0.15; (e) x=0.19. Dotted lines represent the superconducting state. Data from Awana et al [1].

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Figure 3. Normalized conductivity vs. temperature for $\text{La}_{1.83}\text{Sr}_{0.17}\text{CuO}_4$. In this case the resistivity vs. temperature is very nearly linear. (a) contribution of factor containing E_f in equation (4); (b) contribution of factor containing $E_g - E_f$ in equation (4). Data from Awana et al.[1].

NORMALIZED CONDUCTIVITY

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