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N. Kumar

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Highly anisotropic layered systems: intraplanar metallicity and inter-planar non-metallicity

By N. Kumar

Raman Research Institute, Bangalore 560080, India

It is shown that strong intraplanar incoherent scattering can effectively cut off the interplanar coherent tunnelling between weakly coupled layers in highly anisotropic but clean materials such as the layered cuprates. The calculated c-axis resistivity $\rho_c(T)$ then follows the metal-like temperature dependence of the ab plane resistivity $\rho_{ab}(T)$ at high temperatures. At low enough temperatures, however, $\rho_c(T)$ exhibits a non-metal-like upturn while $\rho_{ab}(T)$ remains metallic. In the metallic regime, $\rho_c(T)$ is not limited by the maximum metallic resistivity of Mott. This correlation between $\rho_c(T)$ and $\rho_{ab}(T)$ is observed in the normal state of the high-T_c cuprates.

Keywords: intraplanar metallicity; layered systems; highly anisotropic materials

A question closely related to the problem of the metal–non-metal transition is whether or not a highly anisotropic system of weakly coupled layers (ab planes) can be metallic parallel to the planes, but non-metallic in the direction (c) perpendicular to the planes. Also, whether the two resistivities $\rho_{ab}(T)$ and $\rho_c(T)$ are correlated. Now, for the case of transport dominated by disorder, we expect $\rho_{ab}(T)$ and $\rho_c(T)$ to be both finite or both infinite at $T = 0$, according to whether the Fermi level is above or below the mobility edge. The latter is isotropic by its very nature. However, the characteristic length scale, for example, the coherence length above the mobility edge, can be anisotropic in general. Thus, for the weakly coupled metallic layers, coherence length is expected to be shorter along the planes than perpendicular to the planes. As a result, weak localization can make $\rho_c(T)$ non-metallic ($TCR \equiv \partial\rho_c(T)/\partial T < 0$), while $\rho_{ab}(T)$ remains metallic ($TCR > 0$) at finite T.

The good quality single crystals of the optimally doped layered cuprates are, however, different. These are clean with small zero-temperature resistive intercepts, and are characterized by high anisotropy $\rho_c/\rho_{ab} \sim 10^2$–$10^5$, $\rho_{ab}(T) < \rho_{\max}$(metal), $\rho_c(T) > \rho_{\max}$(metal), and most-importantly, by having T-linear $\rho_{ab}(T)$ and $\rho_c(T)$ (Iye *et al.* 1988; Friedmann *et al.* 1990; Ito *et al.* 1991*a*; Xiang *et al.* 1992). More generally, however, while $\rho_c(T)$ is T-linear at high temperatures, it shows a low temperature non-metallic upturn (Ito *et al.* 1991*b*; Jin *et al.* 1995). Moreover, $\rho_c(T)$ is known to be incoherent (Zha *et al.* 1996). Earlier, we had proposed that large incoherent intra-planar scattering rate ($1/\tau_{ab}$) can cut-off the coherent inter-planar tunnelling (matrix element t_c) leading to a direct correlation between $\rho_c(T)$ and $\rho_{ab}(T)$, namely $\rho_c(T) \propto \rho_{ab}(T)$ (Kumar & Jayannavar 1992). This *quantum-Zeno* effective mechanism now seems to have been generally accepted (Zha 1996). We have recently recalculated $\rho_c(T)$ using the microscopic Kubo–Matsubara conductivity formalism and have validated our earlier physical arguments for high temperatures. At low enough temperatures, however, our calculation gives $\rho_c(T) \propto 1/\rho_{ab}(T)$, which is consistent with the upturn of $\rho_c(T)$ as noted above.

The main point of our treatment is that in the high temperature limit, i.e. for $\hbar/2\tau_{ab} \equiv \Delta(T) \gg |t_c|$, we can neglect the vertex corrections (due to tunnelling) for the Green function self-energy for in-plane propagation, and take as our input the isolated-plane Green function with a self energy consistent with the observed T-linear $\rho_{ab}(T)$. This at once gives us $\rho_c(T) \propto \rho_{ab}(T)$. At low enough temperatures, $\hbar/2\tau_{ab} < |t_\perp|$, however, we must diagonalize the tunnelling Hamiltonian first and then use, as our input, a propagator parallel to the ab planes to be consistent with the T-linear $\rho_{ab}(T)$. This then automatically results in $\rho_c(T) \propto 1/\rho_{ab}(T)$ and hence gives the upturn. In these calculations we have assumed the tunnelling to conserve the electron momentum parallel to the plane. It is to be noted here that for this intrinsically incoherent mechanism, $\rho_c(T)$ is not limited by $\rho_{\max}$(metal).

The problem of c-axis resistivity still remains somewhat unsettled because of the possibility of extrinsic contamination of $\rho_c(T)$ by $\rho_{ab}(T)$ due to misalignment and defects, made plausible by the high anisotropy (Jin *et al.* 1995). Also, the possible connection of this upturn to the opening up of an energy gap as a precursor to T_c is not ruled out (Zha 1996; Balestrino *et al.* 1993). Moreover, as has been pointed out by Nakamura *et al.* (1996), the metallicity of $\rho_c(T)$ may only be 'apparent', arising from the c-axis thermal expansion effects. Besides, in many, mostly underdoped, samples, $\rho_c(T)$ seems semiconducting over the entire temperature range (Ong 1994; Kimura *et al.* 1996). Further work is in progress.

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