C-axis resistivity and high-\(T_c\) superconductivity

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Abstract

Recently we had proposed a mechanism for the normal-state C-axis resistivity of the high-\(T_c\) layered cuprates that involved blocking of the single-particle tunneling between the weakly coupled planes by strong intra-planar electron-electron scattering. This gave a C-axis resistivity that tracks the ab-plane T-linear resistivity, as observed in the high-temperature limit. In this work this mechanism is examined further for its implication for the ground-state energy and superconductivity of the layered cuprates. It is now argued that, unlike the single-particle tunneling, the tunneling of a boson-like pair between the planes prepared in the BCS-type coherent trial state remains unblocked inasmuch as the latter is by construction an eigenstate of the pair annihilation operator. The resulting pair-delocalization along the C-axis offers energetically a comparative advantage to the paired-up trial state, and, thus stabilizes superconductivity. In this scheme the strongly correlated nature of the layered system enters only through the blocking effect, namely that a given electron is effectively repeatedly monitored (intra-planarily scattered) by the other electrons acting as an environment, on a time-scale shorter than the inter-planar tunneling time. Possible relationship to other inter-layer pairing mechanisms proposed by several workers in the field is also briefly discussed.

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The two electronic-structural features, now become central to a proper understanding of the normal-state resistivity as well as the high-temperature superconductivity of the highly anisotropic marginal metals, namely the layered cuprates, are the strong electron-electron correlation and their effectively low (two) dimensionality.\(^1,2\) We have, thus, the oxygen-hole doped CuO\(_2\) planes representing the strongly correlated electronic system, while the weak inter-planar tunneling through the thick spacer layers of the reservoir oxides, e.g., SrO, Bi\(_2\)O\(_3\), etc., gives the near two-dimensionality. In our recent work,\(^2,3\) it was shown that these two features, namely
the strong intra-planar electron-electron scattering and the weak interplanar tunneling, can give rise to a C-axis resistivity that tracks the T-linear metal-like ab-plane resistivity in the high-temperature limit, with an insulator-like upturn at low enough temperatures. Also, the metal-like C-axis resistivity ($\rho_c(T)$) can have a magnitude not bounded by Mott’s maximum metallic resistivity. These results are in qualitative agreement with the measured $\rho_c(T)$ on high quality single-crystal samples that reflect, presumably, their intrinsic transport behaviour.\textsuperscript{5} Furthermore, the C-axis transport is found to be necessarily incoherent as indeed supported by observations.\textsuperscript{2,6} This mechanism for incoherent C-axis transport was also proposed independently by Leggett,\textsuperscript{6} and has now been followed up by a number of workers in the field.\textsuperscript{7} The physics underlying our proposed mechanism is that of the blocking of the weak interplanar tunneling by the relatively strong intraplanar inelastic scattering. This is, of course, a particular case of the celebrated Quantum Zeno effect – namely, the suppression of transition between two weakly coupled Hilbert subspaces due to strong intra-subspace coupling to environment.\textsuperscript{8} Thus, in the present case the two neighbouring CuO$_2$ planes (e.g., of the bilayer), coupled weakly through a small inter-planar tunneling matrix-element, constitute the two electronic subspaces, and the strong intra-planar scattering of a given electron by the other electrons represents the intra-subspace environmental coupling. We will now examine this blocking effect further for its implication for the ground-state energy of and for the superconductive electron-pairing in these layered strongly correlated systems. Our main finding is that the strong-intra-planar electron-electron scattering does indeed, at zero temperature, block the single-electron inter-layer tunneling but not the tunneling of (the time-reversed) electron pairs. The resulting inter-planar pair-delocalization energetically favours the pairing globally and hence stabilizes superconductivity. The
calculation is done for a simple bilayer model. The present work is much in the spirit of, and complements the work of, Chakravarty, Subdo, Anderson and Strong\textsuperscript{9} and that of Kumar,\textsuperscript{10} all based on the idea of confinement by orthogonality catastrophe.\textsuperscript{11} We also discuss in this context how the present mechanism differs essentially from the several other pairing mechanisms that involve inter-layer tunneling.

Let us first consider the possible blocking of the single-electron inter-planar tunneling due to intra-planar scattering at zero-temperature. Now, in the high-temperature limit the in-plane inelastic scattering can be viewed as a stochastic field acting on a given electron attempting to tunnel out-of-plane. This general picture is well known and well supported, experimentally as well theoretically, in the context of decoherence.\textsuperscript{11,12} The problem becomes rather subtle at low (zero) temperature, and is best probed in the present context by calculating the change $\Delta E_o$ of the ground-state energy $E_o$ of a weakly coupled bilayer as function of the strength ($\lambda$) of the inplane electron-electron scattering, maintaining, of course, the system in the normal state, i.e., without breaking spontaneously any global symmetry, such as the one responsible for superconductivity. Blocking effect is expected to reduce the change $\Delta E_o$ as $\lambda$ is increased. This is readily concluded by using the Hellmann-Feynman charging technique involving in the present case an integration with respect to the intra-planar tunneling matrix element ($-t_\perp$) as the variable coupling parameter.

The Hamiltonian for a bilayer of the weakly coupled planes, labelled A and B, can be written as

$$H = H_A + H_B + H_{AB}(\text{single particle}) ,$$

where the intra-planar Hamiltonians $H_A$ and $H_B$ describe the two interacting elec-
tron subsystems of the isolated planes A and B, and

\[ H_{AB}(\text{single particle}) = -\eta t_\perp \Sigma_{k\sigma} (a_{k\sigma}^\dagger b_{k\sigma} + b_{k\sigma}^\dagger a_{k\sigma}) , \]  

(2)

with \( t_\perp = t_\perp^* > 0 \), the tunneling Hamiltonian with the creation/annihilation fermionic operators \( a_{k\sigma}^\dagger (b_{k\sigma}^\dagger) / a_{k\sigma} (b_{k\sigma}) \) referring to the planes A(B). Here tunneling is taken to conserve the in-plane wavevector \( \mathbf{k} \) and the spin projection \( \sigma \). The tunneling matrix element \(-t_\perp\) is taken to be small in a sense to be made precise later. The dimensionless parameter \( \eta \) is to be set equal to 1 at the end. The exact ground-state energy \( E_o(\eta) \) of the bilayer varies with \( \eta \) parametrically according to the Hellmann-Feynman theorem as

\[ \frac{\partial E_o(\eta)}{\partial \eta} = \langle \eta | H_{AB} | \eta \rangle \]  

(3)

giving

\[ \Delta E_o \equiv E_o(1) - E_o(0) = -2t_\perp \int_0^1 d\eta \Sigma_{k} \langle \eta | a_{k\sigma}^\dagger b_{k\sigma} | \eta \rangle , \]  

(4)

where \( |\eta\rangle \) denotes the exact bilayer-ground state for a given value of the parameter \( \eta \). Here we have dropped the spin projection label \( \sigma \), and the wavevector summation includes summation over \( \sigma \).

Expressing the equal-time correlation \( \langle \eta | a_{k\sigma}^\dagger b_{k\sigma} | \eta \rangle \) in terms of the imaginary part of the retarded Green function \( G_{AB}^R(\mathbf{k}, w)(\equiv G_{\perp}^R(\mathbf{k}, w)) \), we get

\[ \Delta E_o = \frac{2t_\perp}{\pi} \Sigma_{k} \int_o^\infty d\omega \int_0^1 d\eta \text{Im} G_{\perp}^R(\mathbf{k}, w) \]  

(5)

Now, the exact retarded Green function \( G_{\perp}^R \) for the correlated metallic planes A and B coupled by the weak tunneling \(-\eta t_\perp \) is clearly not known. We can, however, adopt the following viewpoint. In the absence of the inter-planar tunneling, the correlated electron planes A and B can be well modelled by the semi-phenomenological Marginal Fermi-Liquid (MFL)\textsuperscript{13} which is known to be consistent
with the T-linear ab-plane resistivity. The corresponding retarded in-plane (∥) Green functions $G_{∥AA}(k, w) = G_{∥BB}(k, w) = G_{∥}(k, w)$ is then given by

$$G_{∥}(k, w) = \frac{1}{w - \epsilon_k - \Sigma^R(k, w)}$$

(6)

with

$$\text{Re}\Sigma^R(k, w) = \lambda w \ln(w/w_c)$$

$$\text{Im}\Sigma^R(k, w) = -\lambda \frac{\pi}{2} w$$

with $w_c > w > 0$. Henceforth we will drop the superscript $R$.

Now, for sufficiently small $t_{\perp}$, one can assume the electron-electron scattering to take place on a time scale $\ll$ the tunneling time $h/t_{\perp}$, and, therefore, ignore the vertex corrections to the inter-planar tunneling. We can then at once write down from the Dyson equation for the retarded inter-planar (⊥) Green function $G_{⊥}$:

$$G_{⊥}(k, w) = \frac{\eta t_{\perp} (G_{∥}(k, w))^2}{1 - \eta^2 t_{\perp}^2 (G_{∥}(k, w))^2}$$

(7)

Now, substituting from Eqs. (6) and (7) into Eq. (5), and performing the $k$-integration with a constant 2D-density of states $n_0$, we get

$$\delta e = \int_o^\infty dw [I(W, t_{\perp}, w) - I(-W, t_{\perp}, w) + I(W, -t_{\perp}, w) - I(-W, -t_{\perp}, w)],$$

(8)

where dimensionless energy change

$$\delta e = \frac{\Delta E_o}{4n_o t_{\perp}^2},$$

(9)
with
\[ I(W, t_\perp, w) = -t_\perp \arctan \left[ \frac{W + t_\perp - w + \lambda \text{ln}(\frac{w}{w_c})}{\frac{\pi}{2} \lambda w} \right] - \left( W - w + \lambda \text{ln}(\frac{w}{w_c}) \right) \]
\[ \arctan \left[ \frac{t_\perp w \lambda \frac{\pi}{2}}{\left\{ (W + t_\perp - w + \lambda \text{ln}(\frac{w}{w_c})) \times (W - w + \lambda \text{ln}(\frac{w}{w_c})) + \left( \lambda w \frac{\pi}{2} \right)^2 \right\}} \right] \]
\[ + \frac{\pi}{4} \lambda w \text{ln} \left[ \frac{(W + t_\perp - w + \lambda \text{ln}(\frac{w}{w_c}))^2 + \left( \lambda w \frac{\pi}{2} \right)^2}{(W - w + \lambda \text{ln}(\frac{w}{w_c}))^2 + \left( \lambda w \frac{\pi}{2} \right)^2} \right] \]

(10)

where \( W \) is the two dimensional bandwidth.

In Fig.1, we have plotted the energy gain (reduction \(-\delta e\) in the ground-state energy), due to delocalization by inter-planar single-particle tunneling \((-t_\perp)\), against the intra-planar electron interaction strength \( \lambda \). It is readily seen that the energy gain is a sharply decreasing function of the intra-plane interaction strength \( \lambda \). This clearly demonstrates the effective blocking of the single-particle inter-planar tunneling by intraplanar scattering – the Quantum Zeno effect – as anticipated on physical grounds.

Thusly encouraged, we now address the rather subtle question as to how this blocking of the single-particle tunneling becomes ineffective against the tunneling of (time-reversed) bosonic pairs. In order to clearly appreciate this point, let us consider the two electronic-subsystems forming the bilayer to be prepared in a BCS-like trial many-body state \( \psi \) (in the absence of tunneling). Thus we have for the decoupled bilayer,

\[ |\psi\rangle = \prod_{k,q} \left( u_k + v_k a_{k\uparrow}^\dagger a_{-k\downarrow} \right) \left( u_q + v_q b_{q\uparrow}^\dagger b_{-q\downarrow} \right) |0\rangle \]
\[ \propto e^{\delta (\alpha^\dagger + \beta^\dagger)} |0\rangle \equiv |A\rangle |B\rangle, \]

(11)

where \( \alpha^\dagger(\alpha), \beta^\dagger(\beta) \) are the pair creation (annihilation) operators for the two planes.
A and B of the bilayer. Here

\[
\begin{align*}
\phi_{\alpha}^\dagger &= \sum_k \left( \frac{v_k}{u_k} \right) a_{k\uparrow}^\dagger a_{-k\downarrow}^\dagger, \\
\phi_{\beta}^\dagger &= \sum_k \left( \frac{v_k}{u_k} \right) b_{k\uparrow}^\dagger b_{-k\downarrow}^\dagger,
\end{align*}
\]

where we can take as usual the operators \(\alpha\)'s and \(\beta\)'s to be bosonic to a good approximation. Thus, the unnormalized trial function \(|\psi>\) is a coherent state, i.e., a phased superposition of states with different number of pairs, with \(|\phi|^2\) representing eventually the mean bosonic pair-occupation number for each of the planes A and B.

However, these trial coherent states \(|A>\) and \(|B>\) are certainly not the ground states for the isolated 2D-electronic subsystems A and B, with (repulsive) electron-electron interaction in general. The crucial observation, however, is that the coherent states \(|A>\) and \(|B>\) are, respectively, eigenstates of the pair annihilation operators \(\alpha\) and \(\beta\). If, therefore, we now introduce a pair-tunneling \((-t'_\perp)\) term in the Hamiltonian, \(H_{AB}(\text{pair}) = -t'_\perp (\alpha^\dagger \beta + \beta^\dagger \alpha)\) (with \(t'_\perp \neq t_\perp\) in general), we at once verify that

\[
<\psi|H_{AB}(\text{pair})|\psi> = -2t'_\perp |\phi|^2.
\]

This implies adiabatic transfer of the bosonic pairs between the two planes A and B of the now coupled bilayer prepared in the coherent state \(|\psi>\). This inter-planar pair delocalization in turn stabilizes the trial state \(|\psi>\) energetically. Thus, given that the single-particle tunneling \((-t_\perp)\) is blocked effectively while the pair-tunneling \((-t'_\perp)\) is not as suggested by the above, we can expect \(t'_\perp \gg t_\perp\) and the coherent state \(|\psi>\) to be stabilized relative to the normal state. This is the central point of the pairing mechanism proposed in this work.

Once this is accepted, the energetic stabilization of such a BCS-like paired up
state due to the dominance of the pair tunneling over the single-particle tunneling can be readily treated within a mean-field approximation. For this, consider the reduced Hamiltonian that should suffice for describing the low-energy phenomena:

\[ H_{\text{red}}(\text{bilayer}) = H_A + H_B + H_{AB}(\text{single particle}) + H_{AB}(\text{pair}) \]

with

\[
H_A = \sum_{k\sigma} \epsilon_k a_k^{\dagger} a_k^{\dagger} + U_{\text{eff}} \sum_{k\sigma} \sum_{k'\sigma} a_{k\sigma}^{\dagger} a_{-k'\sigma} a_{-k\sigma}^{\dagger} a_{k'\sigma}^{\dagger}
\]

\[
H_B = \sum_{k\sigma} \epsilon_k b_k^{\dagger} b_k^{\dagger} + U_{\text{eff}} \sum_{k\sigma} \sum_{k'\sigma} b_{k\sigma}^{\dagger} b_{-k'\sigma} b_{-k\sigma}^{\dagger} b_{k'\sigma}^{\dagger}
\]

\[
H_{AB}(\text{single}) = -t_\perp \sum_k (b_{k\sigma}^{\dagger} a_{k\sigma}^{\dagger} + h.c.)
\]

\[
H_{AB}(\text{pair}) = -t'_\perp \sum_{k\sigma} (b_{k\sigma}^{\dagger} b_{-k\sigma}^{\dagger} a_{-k'\sigma}^{\dagger} a_{k'\sigma}^{\dagger} + h.c.),
\]

where \( t'_\perp \gg t_\perp > 0 \), and \( U_{\text{eff}} \) can even be moderately repulsive \((U_{\text{eff}} > 0)\) as considered by Zecchina,\(^{14}\) except for the retention of the single-particle tunneling here. The latter enables us to treat the effect of the degree of blocking of single-particle tunneling explicitly. Note that the reduced Hamiltonian maintains the condition of pairing involving electrons in time-reversed states.

Consider first the case of \( U_{\text{eff}} \) negative (attractive). Introducing the anomalous averages in the spirit of the mean-field approximation (MFA), we get

\[
H_{MFA} = \sum_{k\sigma} \epsilon_{k\sigma} a_{k\sigma}^{\dagger} a_{k\sigma}^{\dagger} + \sum_{k\sigma} \epsilon_{k\sigma} b_{k\sigma}^{\dagger} b_{k\sigma}^{\dagger}
\]

\[
+ \Delta V \sum_k \left( a_{-k\perp}^{\dagger} a_{k\perp}^{\dagger} + a_{k\perp}^{\dagger} a_{-k\perp}^{\dagger} \right)
\]

\[
+ \Delta V \sum_k \left( b_{-k\perp}^{\dagger} b_{k\perp}^{\dagger} + b_{k\perp}^{\dagger} b_{-k\perp}^{\dagger} \right)
\]

\[
- t_\perp \sum_k \left( b_{k\sigma}^{\dagger} a_{-k\sigma}^{\dagger} + a_{k\sigma}^{\dagger} b_{k\sigma}^{\dagger} \right),
\]

where the s-wave gap parameter

\[
\Delta = \sum_{k'} \langle a_{-k'\perp} a_{k'\perp}^{\dagger} \rangle = \sum_{k'} \langle b_{-k'\perp} b_{k'\perp}^{\dagger} \rangle
\]
and

\[ V = \left( \frac{U_{\text{eff}} - t_\perp'}{2} \right). \]

After straightforward diagonalization, the self-consistent gap equation for \( \Delta \) turns out to be

\[
\Delta = - \frac{1}{2} \Sigma_k \left[ \Delta V \frac{1 - 2 f(\epsilon_k - t_\perp)}{2\sqrt{\Delta^2 V^2 + (\epsilon_k - t_\perp)^2}} \right.
- \frac{1}{2} \Sigma_k \left[ \Delta V \frac{1 - 2 f(\epsilon_k + t_\perp)}{2\sqrt{\Delta^2 V^2 + (\epsilon_k + t_\perp)^2}} \right]
\]

(17)

where as usual \( f \) is the fermi function, \( f(\epsilon) = \frac{1}{(e^{\epsilon/k_BT} + 1)} \). The corresponding equation for the critical temperature \( T_c \) is then (for \( U_{\text{eff}} - t_\perp' < 0 \))

\[
1 = - \left( \frac{U_{\text{eff}} - t_\perp'}{2} \right) \left\{ \frac{1}{2(\epsilon_k - t_\perp)} \tanh \left( \frac{\epsilon_k - t_\perp}{k_BT_c} \right) + \frac{1}{2(\epsilon_k + t_\perp)} \tanh \left( \frac{\epsilon_k + t_\perp}{k_BT_c} \right) \right\}
\]

(18)

This reduces to the usual expression in the limit \( t_\perp \rightarrow 0 \) (i.e., total blocking of the single electron tunneling). It is also readily seen from the sub-linear \( x \)-dependence of \( \tanh x \) that incomplete suppression of the single-particle blocking \( (t_\perp \neq 0) \) leads to a reduction in \( T_c \). Thus we recover our claim that the blocking of the single-particle tunneling relative to the pair-tunneling stabilizes the paired-up superconducting state.

Some remarks are in order at this point. For an attractive \( U_{\text{eff}} \), the present pair-tunneling mechanism may well be viewed as an amplification of the (s-wave) superconductive pairing pre-existing in the isolated planes. (This, of course, remains true also for the case when the isolated planes support d-wave pairing, arising from the spin-fluctuation mechanism, say.) We would, however, like to emphasize here that our present mechanism provides for a global stabilization of the condensed state.
even when the pairing potential for the individual pairs \( U_{\text{eff}} \) is repulsive, but, of course, sufficiently small and the isolated planes are not superconducting on their own. Thus, for a short-ranged repulsive potential our inter-layer mechanism based on the Zeno-effect can stabilize a coherent condensate, albeit of d-wave pairs. (The case of a strongly negative \( U_{\text{eff}} \) supporting a repulsive bound state lying above the top of the band is quite different. It can give high lying d-wave pairs that may get stabilized coherently through interlayer pair tunneling mechanism.) Indeed, the present mechanism involves global stabilization, and cannot be reduced to a pairing potential arising, say, from virtual exchange of some excitations.

It will be apt now to view the present mechanism in relation to others involving pairing by inter-layer coupling as reported in the literature. First, let us note that the important role of interlayer coupling is strongly suggested by the experimental fact that the bilayers (or the intimate layers in general) are a necessary minimum for the occurrence of superconductivity in these layered cuprates.\(^{15}\) There is also a definite evidence for the Josephson coupling between these layers.\(^{16}\) Furthermore, it has become increasingly clear that a simple one-band two-dimensional Hubbard model does not support high-\( T_c \) superconductor. All this has prompted several workers to propose and treat models involving interlayer coupling, or indeed, plain-chain or chain-chain coupling.\(^{2}\) These could be introduced phenomenologically through the macroscopic Josephson coupling of the order parameters,\(^{17}\) or microscopically through the introduction of interplanar pair tunneling,\(^{14}\) or through interplanar pair-pair interactions.\(^{18}\) The essential contrasting feature of our present work is our demonstration of the blocking of the single-particle tunneling (our equation 8), and our argument for the unblocking of the pair tunneling (our equation 14). Our work is closest in spirit that of Chakravarty and Anderson\(^{9}\) which it complements. It is,
however, different from the earlier inter-layer pair mechanism of Wheatley, Hsu and Anderson\textsuperscript{19} which involves spin charge separation and exchange of spinons mediating the interlayer tunneling of a pair of the otherwise confined physical electrons of opposite spins. It is, however, quite likely that the non-Fermi liquid feature involved in this exotic model is in the ultimate analysis a yet another and novel route to realizing the Quantum Zeno effect in the extreme total confinement by the orthogonality catastrophe.

In conclusion, we have extended the mechanism proposed by us earlier for the C-axis resistivity, involving the blocking of the interplanar single-particle tunneling by the intra-planar scattering, to low temperatures to possibly explain the High-$T_c$ superconductivity of the layered cuprates. We have given an argument based on coherence and supported by simple analysis that, in-contrast to the single-particle tunneling, the tunneling of the bosonic pairs remains unblocked and thus stabilizes the superconducting state. In this scheme, the strongly correlated nature of the two-dimensional layers enters only through this single-particle blocking effect. The present mechanism admits d-wave pairing without recourse to pairing mechanisms such as that of the spin-fluctuation theory.\textsuperscript{20}
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Figure Caption

**Fig. 1** Dimensionless energy gain due to interplanar single particle tunneling as a function of intraplanar interaction parameter $\lambda$. The decreasing energy gain with increasing $\lambda$ demonstrates the blocking effect. The plot is for the choice of parameters $(t_{\parallel}/t_{\perp})=20.0$ and $(\omega_{c}/t_{\perp})=100$. 