

Resonant Pair Tunneling and Singular effects of c-axis disorder in cuprate and organic superconductors

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Abstract

In the interlayer pair tunneling (ILPT) theory of superconductivity the large scale T_c has its origin in the k-space locality of the inter layer pair tunneling matrix elements. We reinterpret the same physics as a process of resonant pair tunneling and illustrate it through cooper pair analysis. This interpretation is used to give a mechanism which leads to a singular suppression of T_c as function of c-axis(off plane/axis) disorder. In this mechanism the non resonant tunneling processes arising from the c-axis disorder in general contributes a pair binding energy which is reduced by a factor $\frac{T_J}{\epsilon_F}$, where T_J is the interlayer pair tunneling matrix element and ϵ_F is the fermi energy. This leads to a simple theorem which states that the scale of T_c is controlled by the space average value of the bare one electron interlayer hopping matrix element. After briefly discussing that the ET and TMTSF molecule based organic superconductors are strongly correlated narrow band systems, the dramatic reduction of T_c by anion disorder in organic superconductors is explained by our mechanism. Off plane disorder effects in some of the cuprates are also discussed.

I. INTRODUCTION

One of the important component of the RVB theory for the cuprates is the inter layer pair tunneling (ILPT) mechanism for superconductivity proposed by Wheatley, Hsu and Anderson [1] (WHA). This mechanism owes its existence to the anomalous normal state of the CuO_2 layers which i) suppresses the coherent one electron tunneling at low energies between two adjacent CuO_2 planes and ii) does not suppress the second order process of coherent pair tunneling. The blocking of coherent one electron tunneling has been called [2] ‘confinement’. Anderson suggested [3] sometimes back a BCS like formalism that incorporates the physics of interlayer pair tunneling. He also traced the origin of the large scale of T_c to a k-space local character of the pair tunneling matrix elements. Following this the WHA theory got a recent revival and important applications [4] have been made to the cuprate superconductors. ILPT processes as a source of pairing has been invoked in the past for quasi 1-d organic conductors [5].

From experimental point of view, the anomalous c-axis transport $\rho_c(T)$ and $\sigma_c(w)$ for cuprates exhibit striking features suggesting confinement [6]. Families of quasi 1-d and 2-d organic conductors, where strong correlation and narrow band character is manifest, has also been suggested [?] to exhibit confinement by an analysis of the commensurability effects in the angle dependent magneto resistance in $(TMTSF)_2X$ family.

The aim of the present paper is two fold: i) to give a reinterpretation of the origin of large scale of T_c as a consequence of “pair tunneling resonance” arising from the k-space locality of pair tunneling process and ii) To provide a simple mechanism of how c-axis (off plane or off axis) disorder can remove the pair tunneling resonance and lead to a strongly reduced scale of T_c ; and discuss existing experimental results in cuprate and organic conductors from the point of view of our new mechanism. At the end we discuss our result in the light of Anderson’s theorem [8] on dirty superconductors. We find that the simple cooper pair analysis, to which we restrict ourselves in this paper, already brings out the consequences of resonant pair tunneling and also shows how the off plane disorder can

affect T_c in a singular way. We state our result in the form of a theorem. We also feel that our explanation of the anomalous suppression of T_c by off plane disorder gives support to a substantial contribution from the ILPT mechanism of for superconductivity in organic superconductors [5].

II. RESONANT PAIR TUNNELING AND THE LARGE SCALE OF T_C

As mentioned in the introduction, the spin-charge decoupled anomalous normal state prevents coherent one electron tunneling at the lowest energies. This blocking has been explained as an orthogonality catastrophe [2] arising in the two non fermi liquids planes after the event of one electron transfer between the them. What is remarkable is the suggestion that this orthogonality catastrophe is absent when two electrons with zero centre of mass momentum in a spin singlet state is transferred from layer to layer in a second order quantum mechanical process. The presence of coherent interlayer pair tunneling and absence of coherent interlayer one electron tunneling is the origin of the novel WHA mechanism. Anderson [3] incorporates the key features of the above physics in a BCS type reduced Hamiltonian.

$$\begin{aligned}
 H = & \sum (\epsilon_k - \mu) (c_{k\sigma}^\dagger c_{k\sigma} + d_{k\sigma}^\dagger d_{k\sigma}) + \sum T_J(k) (c_{k\uparrow}^\dagger c_{-k\downarrow}^\dagger d_{-k\downarrow} d_{k\uparrow} + h.c.) \\
 & + \sum V_{kk'} (c_{k\uparrow}^\dagger c_{-k\downarrow}^\dagger c_{-k'\downarrow} c_{k'\uparrow} + d_{k\uparrow}^\dagger d_{-k\downarrow}^\dagger d_{-k'\downarrow} d_{k'\uparrow})
 \end{aligned} \tag{1}$$

Here c's and d's are the electron operators of the two layers and $k = (k_x, k_y)$ is the in plane momentum of the electron. $T_J(k) \approx \frac{t_\perp^2(k)}{t}$, is the interlayer pair tunneling matrix element. Here $t_\perp(k)$ is the inter layer one electron bare hoping matrix element and t is the in-plane hoping matrix element. And $V_{kk'}$ is the residual in plane pair scattering matrix element which summarizes formally the effect of phonon mediated and residual correlation induced attraction processes. For convenience we will concentrate on two coupled layers throughout this paper. The two layer case captures most of the important aspects of an n-layer system.

The entire physics of spin-charge decoupling, confinement and pair tunneling is approximately modeled through the presence of pair tunneling and absence of one electron tunneling

terms between planes in an otherwise fermi liquid like BCS Hamiltonian. Anderson [3] argues that this fermi liquid approximation is a reasonable one below T_c in view of the fact that the electron propagator changes its branch point singularity into BCS quasi particle poles. Recovery of a pole structure of the propagator is argued to be a self consistent justification for starting with a fermi liquid like picture to study the superconducting state.

Another important aspect of the above Hamiltonian is the individual electron momentum conserving nature of the pair tunneling terms, which Anderson calls as k-space locality. This k-space locality, however, does not simply follow from the non fermi liquid or spin - charge decoupled character of the normal state of CuO_2 planes. Recently I have argued [9] that it arises if one assumes a tomographic Luttinger liquid normal state.

Anderson argued that it is the k-space locality that leads to a scale of T_c which is linear in the pair tunneling matrix element. Anderson, on solving the resulting gap equation in the limit of interlayer pair tunneling matrix element T_J large compared to $V_{kk'}$, finds

$$k_B T_c \approx \frac{T_J}{4} \quad \text{for } T_J > V_{kk'} \quad (2)$$

In the other limit he finds the usual BCS expression

$$k_B T_c \approx \hbar \omega_D e^{-\frac{1}{\rho_0 V_0}} \quad (3)$$

where ω_D is the Debye frequency, ρ_0 is the density of states at the fermi energy and V_0 is the fermi surface averaged matrix element $V_{kk'}$ of equation 1.

The above result of Anderson for the case $T_J > V_0$ lends itself to an interpretation of a binding energy arising from splitting of two degenerate pair states (one from each layer), which are resonantly coupled by the pair tunneling matrix element T_J . Our interpretation of T_c enhancement or the corresponding pair condensation energy or the gap, as arising out of a resonant phenomenon brings out the singular effects of off plane disorder in a natural way as we will see in the following sections. What we are going to do is a cooper pair analysis for various cases. It turns out that this simple minded analysis brings out the basic physics that we are after.

Mention should be made of phase fluctuations associated with the ultralocal interlayer pair tunneling processes of equation 1. This process, as explained recently [9], has a local U(1) invariance in k-space and by itself is not capable of generating a finite T_c . It needs the help of additional k-space non local terms such as the third term of equation 1. What is important is that even with a little help from these non local terms, the local term can become important and even provide a large scale for $k_B T_c \approx \frac{T_J}{t}$. In other words, Anderson's mean field analysis of the Hamiltonian of equation 1 is meaningful only in the presence of the third term which is non local in k-space. Our Cooper pair analysis should be also understood in the above light. The ultra locality in k-space is only an idealization. In general the k-space locality will be smeared by finite temperature effects or the locality can change from a delta function type to a power law one [9]

When the two adjacent planes of a bilayer are identical, the k-space locality of pair tunneling also implies a resonant tunneling of a pair of electrons between two states $(k, -k)$ and $(k, -k)$ of the two planes. To understand the resonant tunneling, let us consider the Cooper pair problem with the Hamiltonian given by equation (1). We consider two electrons in an otherwise frozen fermi sea of the two layers. The Schrodinger equation for the Cooper pair problem is

$$2(\epsilon_k - \mu)\phi_k - T_J\eta_k + \sum_{k'} V_{kk'}\phi_{k'} = E\phi_k \quad (4)$$

$$2(\epsilon_k - \mu)\eta_k - T_J\phi_k + \sum_{k'} V_{kk'}\eta_{k'} = E\eta_k \quad (5)$$

where ϕ_k and η_k are the pair amplitudes in layers 1 and 2 respectively. We will assume a simple BCS kind of model potential for $V_{kk'}$: a value $-V_0$ for k, k' lying in an energy shell of $\hbar\omega_D$ around the fermi surface and zero otherwise.

The above Schrodinger equation is easily solved for $T_J > V_0$ to get an expression for Cooper pair binding energy:

$$E_B \approx T_J + \hbar\omega_d e^{-\frac{1}{\rho_0 V_0}} \quad (6)$$

where ρ_0 is the density of states at the fermi level. The first term is the binding arising from pair tunnel splitting and the second term arises from the usual BCS type in plane pair scattering processes. This interpretation is also obvious if we look at Anderson's analysis of the gap equation and T_c for the above limit. It is interesting to note that our explanation of resonant pair tunneling also brings out the 'kinetic' or interlayer delocalization origin of the pair binding energy of the Cooper pairs.

III. NON RESONANT PAIR TUNNELING AND REDUCTION IN THE COOPER PAIR BINDING ENERGY

The resonant cooper pair tunneling together with the presence of other non-local terms can lead to a superconducting state with a large T_c . In this paper we will concentrate on how this resonant character of pair tunneling can be offset by off axis or off plane disorder. Application to cuprates and organic conductors will be discussed in the next section.

We model the c-axis or off plane randomness by a position dependent one electron interplane hoping matrix element $t_{\perp ij}$. For simplicity we assume $t_{\perp ij} \approx \delta_{ij} t_{\perp i}$, a short ranged form. Here i and j are the site indices of the two planes respectively. It is important to introduce randomness at the level of bare one electron inter layer hoping and see how the pair tunneling terms that are generated by the physics of the non-fermi liquid state of the planes get modified. The bare one electron tunneling term is

$$\begin{aligned} H_{12} &= \sum t_{\perp i} (c_{i\sigma}^\dagger d_{i\sigma} + h.c.) \\ &= \sum t_{\perp} (k, k') (c_{k\sigma}^\dagger d_{k'\sigma} + h.c.) \end{aligned} \quad (7)$$

The c-axis disorder does not conserve the in plane momentum in the one electron interlayer hoping process. This term, when small compared to the in plane t, which is the case with the anisotropic conductors under study, does not directly affect the anomalous normal state of the plane and the nature of the quasi particles. As we will mention in the last section, this assumption is not really valid if we have a weakly coupled fermi liquid at

zero temperature. In view of this, while constructing the pair tunneling Hamiltonian we need not go to scattering eigen state representation, i.e. the eigen states of the one electron hamiltonian of the two layers including the random one electron inter layer hoping terms. At the level of approximating the in plane physics by a fermi liquid physics a la' Anderson, the relevant one electron eigen states continue to be plane waves. This is an important difference, when we contrast it with the situation of Anderson's theorem [8] for disordered superconductors.

Using a procedure recently suggested by the author [9], we get an expression for the pair tunneling term

$$\sum \frac{t_{\perp}^2(k, k')}{t} c_{k\uparrow}^{\dagger} c_{-k\downarrow}^{\dagger} d_{k'\downarrow} d_{k'\uparrow} + h.c. \quad (8)$$

The pair tunneling term, while it conserves the in plane center of mass momentum does not conserve the individual electron's in plane momentum. Thus the pair tunneling term loses the local U(1) invariance in k-space. While this is good for stabilizing the phase fluctuations, it is not so good in the sense of losing resonant pair tunneling processes at the expense of introducing non-resonant tunneling processes as we will see below.

A general matrix element $t_{\perp}(k, k')$ of equation 8 represents a pair tunneling between two states $(k, -k')$ and $(k', -k')$ of layers 1 and 2. Since in general $\epsilon_k \neq \epsilon_{k'}$, it causes non resonant pair tunneling processes. The reduction in cooper pair binding can be easily estimated by concentrating on the pair subspace $(k, -k)$ and $(k', -k')$ of layers 1 and 2. This is a good approximation in the limit $T_J(k, k') \gg V_{kk'}$. The corresponding 2×2 matrix to be diagonalized is:

$$\begin{pmatrix} 2(\epsilon_k - \mu) & T_J(k, k') \\ T_J(k, k') & 2(\epsilon_{k'} - \mu) \end{pmatrix}$$

The lowest eigen value of this matrix gives us the new energy eigen value of a pair of electron taking into account the tunneling. The shift in the lowest eigen value, which is a measure of inter plane pair delocalization energy or pair binding energy E_B is given by

$$E_B = \sqrt{(\epsilon_k - \epsilon_{k'})^2 + T_J^2(k, k')} - |\epsilon_k - \epsilon_{k'}| \quad (9)$$

This pair binding energy is the largest in the resonant case, $\epsilon_k = \epsilon_{k'}$:

$$E_B = T_J(k, k) \quad (10)$$

When it is maximally nonresonant, $\epsilon_k - \epsilon_{k'} \gg T_J(k, k')$ the pair binding is given by

$$E_B \approx \frac{T_J^2(k, k')}{|\epsilon_k - \epsilon_{k'}|} \quad (11)$$

We will discuss two simple cases of randomness and calculate reduction in average cooper pair binding energy: a) the interlayer hoping parameter $t_{\perp i}$ becomes an uncorrelated random variable with a mean $\langle t_{\perp i} \rangle$ and spread δt_{\perp} and b) $t_{\perp i} = \pm t_{\perp 0}$ with probability p and $(1-p)$. And the average $\langle .. \rangle$ symbol stands for a spatial average over the plane. For case a,

$$\begin{aligned} H_{12} &= \sum t_{\perp i} (c_{i\sigma}^\dagger d_{i\sigma} + h.c.) \\ &= \sum \langle t_{\perp i} \rangle (c_{i\sigma}^\dagger d_{i\sigma} + h.c.) + \sum \delta t_{\perp i} (c_{i\sigma}^\dagger d_{i\sigma} + h.c.) \end{aligned} \quad (12)$$

where $\delta t_{\perp i}$ is an uncorrelated random variable with mean 0 and spread δt_{\perp} . In momentum representation

$$\begin{aligned} H_{12} &= \langle t_{\perp i} \rangle \sum (c_{k\sigma}^\dagger d_{k\sigma} + h.c.) + \sum \delta t_{\perp}(k, k') (c_{k\sigma}^\dagger d_{k'\sigma} + h.c.) \\ &= \sum (\langle t_{\perp i} \rangle \delta_{kk'} + \delta t_{\text{perp}}(k, k')) (c_{k\sigma}^\dagger d_{k'\sigma} + h.c.) \end{aligned} \quad (13)$$

The first term, the average term, conserves the in plane momentum in the hoping process. The second term, the fluctuation term, does not conserve the in plane momentum. The one electron tunneling term leads to a pair tunneling matrix element of the form

$$T_J(k, k') \approx \delta_{k,k'} \frac{\langle t_{\perp i} \rangle^2}{t} + \frac{(\delta t_{\perp}(k, k'))^2}{t} \quad (14)$$

Since we have a spatially uncorrelated random variable, a typical value of $|k - k'| \approx \frac{\pi}{a}$. For this type of momentum transfer, the typical value of $\epsilon_k - \epsilon_{k'} \approx \epsilon_F$, of the order of the fermi energy or band width. Thus for a typical value of k and k' the pair delocalization energy is

$$E_B \approx \frac{T_J^2(k, k')}{|\epsilon_K - \epsilon_{k'}|} \approx \frac{T_J^2(k, k')}{\epsilon_F} = \left(\frac{T_J(k, k')}{\epsilon_F} \right) T_J(k, k') \quad (15)$$

The pair binding energy is thus reduced from a resonant value of the order of T_J to a fraction $\frac{T_J}{\epsilon_F}$ of T_J . For the case of the cuprate superconductors for a bi-layer of 123 material, $T_J \sim 40$ meV and assuming a fermi energy of 2 eV we get $\frac{T_J}{\epsilon_F} \sim \frac{1}{50}$. Thus a typical pair binding energy due to the process of pair tunneling is reduced by a factor of 50.

The first term of equation (14) leads to resonant tunnelling, whereas the second term is non resonant. By the fact that the mean $t_{\perp i}$ gets reduced as we introduce randomness and also the fact that the second term is non resonant, the cooper pair binding energy and the corresponding T_c decreases. Since the typical momentum transfer due to the c axis randomness is large $\approx \frac{\pi}{a}$, the non resonant term practically leads to no pair tunneling binding energy. Hence in the first approximation the pair tunneling binding energy is controlled by the diagonal value $T_J(k, k) \approx \frac{\langle t_{\perp i} \rangle^2}{t}$, the resonant part of the pair tunneling processes.

For the second type of disorder, arguing in a similar fashion, T_c is given by

$$k_B T_c \approx \frac{\langle t_{\perp i} \rangle^2}{4t} = \frac{(p - \frac{1}{2})(t_{\perp 0})^2}{4t} \quad (16)$$

We summarize the discussion of this chapter in the form of a theorem: ‘The transition temperature in the interlayer pair tunneling mechanism of superconductivity is governed primarily by the spatial average of the interlayer one electron bare hoping matrix element’. We are of course inspired by Anderson’s theorem on dirty superconductor to call our semi quantitative conclusion a theorem!

IV. APPLICATION TO CUPRATES AND ORGANIC SUPERCONDUCTORS

It has been well established that the layer cuprate superconductors are strongly correlated electron systems. There are also families of organic superconductors [10] which are strongly correlated electronic systems. Two major groups are the TMTSF and the ET molecule (Bechgaard salt) based organic conductors. The first group are quasi one dimensional and the second one are quasi 2 dimensional. These are also essentially narrow one

band systems in which electron-electron interaction is important and the scale of electron repulsion energy is large compared to the one electron band width. Systematic experimental studies involving NMR, photoemission and transport studies on the TMTSF based organic conductor in its normal state has brought out the Luttinger liquid character of the conducting chains. The existence of spin density wave states, spin Peierl's phase also brings out the importance of electron correlation in these one band tight binding systems. One of the remarkable manifestations of strong correlation, is the recent suggestion that there is 'confinement': Strong and collaborators have suggested that the anomalous angular dependence of the magneto resistance in $(TMTSF)_2X$ could be explained as a commensurability effect arising from confinement.

One of the puzzling and ubiquitous features of the organic superconductors [10] is the universal sensitivity of T_c to off plane or off axis disorder. It is so dramatic that in one of the ET based systems that in one case the T_c is reduced from 8 K to nearly 0 K by the disordering of the anion group, which is non centro symmetric. What is remarkable is that the disorder is a physical effect rather than a chemical effect in the sense of not changing the charge transfer to the planes and not changing the nature of the chemical bonds. The normal state properties of the chains and planes are perhaps not strongly affected.

One of the systematically studied compounds is the solid solution $\beta(ET)_2(I_3)_{1-x}(IBr_2)_x$. The anions I_3 or IBr_2 are located at crystallographic inversion centers. Thus a non centro symmetric anion like IBr_2 can be orientationally ordered or disordered, even though positionally it is ordered. For the case of $x = 0$, the above compound has a $T_c \approx 8K$. And for the case of $x = 1$, it has a $T_c \approx 2K$. The anions I_3 and IBr_2 continue to be powerful acceptors and are in valence state of 1. It is found [14] that as x is varied continuously, T_c falls rather fast and is essentially zero in the range $0.2 < x < 0.7$. In this region the anions IBr_2 are orientationally disordered.

Similarly the quasi one dimensional conductor $(TMTSF)_2ClO_4$ exhibits singular suppression of T_c with the anion disorder: in this case also the non centro symmetric ClO_4 ion is situated at a crystallographic inversion center leading to a possibility of the orientational

disorder of the anions.

Even more remarkable is the salt $(ET)_2I_3$ itself, which can occur in three closely related crystallographic forms: β, β_c, β^* , and their enomalous T_c differences. The ethylene side groups of the ET molecule is capable of being in two conformations called the eclipsed and staggered conformations. In the above three crystallographic forms the essential difference is in the conformation of the ethylene side group. If these two conformations occur in a random fashion, the anion molecules are also correspondingly disordered, leading to a large suppression of T_c .

Some explanations [11] invoking Anderson type of localization induced in the chains by the off axis randomness exists. However, in view of the reduction of Anderson localization phenomenon for weak disorder in a strongly correlated system such as the organic conductors, one needs a more satisfactory explanation. Brazovskii and Yakavenko were one of the first to study the sensitivity of T_c to the type of anion order in organic conductors. Even though they talk about conservation of coherence of cooper pairs between the conducting chains, our mechanism that we will discuss here seems to be natural and simple.

We argue that the off plane chain randomness suppression the resonant pair tunneling process is the major source of reduction of T_c . The non centro symmetric character of the anion group plays an important role, as we demonstrate below.

The effective electronic Hamiltonian for these systems is a spatially anisotropic Hubbard model:

$$H = - \sum t_{ij} c_{i\sigma}^\dagger c_{j\sigma} + \text{h.c.} + U \sum n_{i\uparrow} n_{i\downarrow} \quad (17)$$

The details of anisotropy is contained in the one electron hopping matrix elements t_{ij} . For the *TMTSF* family of conductors [7] the hoping matrix element along the chain is $\approx 0.25eV$. The hoping matrix element in the two directions normal to the chain is low by about $\frac{1}{20}$ and $\frac{1}{30}$. The on site U is at least twice as large as the band width along the chain. For the ET salts the electronic parameters are very similar except that it is quasi 2-dimensional. There are also strong electron phonon interactions (both intra molecular and inter molecular), whose

real role in stabilizing a relatively high T_c is not very clear. It is likely, like in the cuprates the effect strong electron correlation masks the importance of electron phonon interaction. Electron lattice coupling stabilized their own phases such as Spin Peierls' with the help of electron correlations for some value of the parameters.

For us the important thing to understand is the nature of the bare one electron hopping matrix elements between two adjacent molecules in the two planes or two chains. In tight binding systems like the cuprates or the organic conductors, it is natural to think, while discussing about one electron hopping matrix element between adjacent layers, in terms of symmetry adapted molecular or Wannier orbitals. The tunneling is from one Wannier orbital of a layer to a nearby Wannier orbital of the adjacent layer. In view of the large separation between the adjacent planes or chains, the direct hopping matrix elements between the adjacent Wannier orbitals are negligibly small. Some LUMO bridging orbitals of the anion groups play important role in establishing an appreciable bare one electron tunneling matrix element.

Let us take the case of TMTSF system . The relevant Wannier orbitals of the two adjacent planes are the HOMO of the TMTSF molecules $\phi_{i\alpha}$, ($\alpha = 1, 2$). It is a $p\pi$ bonded molecular orbital. Direct tunneling matrix element between them in adjacent planes is negligibly small: $\langle \phi_{i1} | H | \phi_{i2} \rangle \approx 0$. However, there is a finite overlap of the above orbital with the LUMO of the ClO_4 group. The LUMO orbitals could be degenerate in general. Let us denote the bridging orbitals by $\phi_{bi\mu}$, where μ is the degeneracy index and the subscript b stands for the bridging orbital. The effective one electron tunneling matrix element through the bridging orbital in a second order process is given by

$$t_{\perp i} \approx \sum_{\mu} \frac{\langle \phi_{i1} | H | \phi_{bi\mu} \rangle \langle \phi_{bi\mu} | H | \phi_{i2} \rangle}{E_i - E_b} \quad (18)$$

where E_i and E_b are the energy of the Wannier orbital of the planes and the bridging orbital respectively. And H is the one electron Hamiltonian.

The LUMO's have in general nodes and change sign as we move within the anion group. Thus, when the anion molecules are disordered the matrix elements $\langle \phi_{i1} | H | \phi_{bi\mu} \rangle$ can

change in sign and magnitude depending on the orientation of the anion molecule. That is, $\langle \phi_{i1} | H | \phi_{bi\mu} \rangle$ can change in sign and induce sign disorder in the bare one electron hopping matrix element $t_{\perp i}$ (equation 18).

This is the way the disordered cation group can introduce disorder in the sign of $t_{\perp i}$, This in turn suppresses the resonant pair tunneling by the reduction in the spatial average value $\langle t_{\perp i} \rangle$. Using our earlier argument we have a simple prediction. For a completely disordered cation,

$$\langle t_{\perp i} \rangle = 0 \Rightarrow T_c \approx 0 \quad (19)$$

In general if a fraction p of the anions are disordered,

$$k_B T_c \approx \frac{(p - \frac{1}{2})^2 \langle t_{\perp i} \rangle^2}{4t} \quad (20)$$

We are able to make a reasonable fit of this with the experimental results [14] on the solid solution $\beta(ET)_2(I_3)_{1-x}(IBr_2)_x$ discussed earlier. It will be important to find this quadratic decrease of T_c with the degree of orientational disorder of the non-centro symmetric anyons in organic superconductors in related systems.

we will now turn briefly to the case of cuprates, where the nature of coupling between the planes is more complicated and has different solid state chemistry. It has been experimentally seen [?] that the oxygen vacancies in the CuO_2 have little effect at low concentrations, while those that form between the planes systematically lower T_c . What is important is that it is not a mere charge transfer change that reduces T_c .

It has been noticed [?] that the structural coherence of the CuO_2 planes, even though do not change the normal state properties does affect the T_c rather strongly. It is generally believed that both in the 214 and 123 compounds any tendency to have orthorhombic short range order suppresses superconductivity. A good example could be the 214 compound for the magic value of $x = 0.12$. At this value T_c almost vanishes. Various explanations have been put forward to understand this. What is striking is that there is no true long range orthorhombic order. We believe that the reduction in the pair resonant pair tunneling matrix

element caused by the structural incoherence at atomic scales (owing to the well developed short range orthorhombic distortions) in the CuO_2 planes is responsible for the reduction in T_c . The lack of structural coherence in the plane and its environment severely suppression the resonant tunneling of pairs between neighboring layers could be an important source of T_c reduction as we go to the overdoped region, i.e. $x > .24$. The conventional explanation for the reduction in T_c this region is overdoping and the associated recovery of fermi liquid character.

Recently a family of CuO_2 layered superconductors also having bridging CO_3 groups have been synthesised. Unusual sensitivity of the superconducting T_c to the disordering of the non centro symmetric carbonate group has been observed often. This could again be explained by our mechanism of reduction of T_c by c-axis disorder.

V. RELATION TO ANDERSON'S THEOREM ON DIRTY SUPERCONDUCTORS

It is important to point out that Anderson's theorem [8] on dirty superconductor was proposed in the context phonon mediated superconductivity. We point out below that there are important modifications to this theorem in the context of anisotropic superconductors in the presence of strong correlations. Soon after the appearance of BCS theory, Anderson explained the unexpected insensitivity of the superconducting T_c on time reversal symmetry respecting disorder like positional disorder or alloying or non magnetic impurities. Anderson's first point with respect to setting up an effective BCS Hamiltonian was to emphasize the formal use of the exact eigen states in the presence of the random potential. Electron phonon scattering among these exact eigen states is used to construct the phonon mediated two body interactions. He emphasized the pairing among time reversed eigen states as the basic and relevant two body terms that will lead to a coherent superconducting state.

Our case is different and we can not use Anderson's theorem directly. In view of the phenomenon of confinement and in view of the fact the system is anisotropic, to a first approximation the off plane disorder does not affect the anomalous normal state. This

means while employing a fermi liquid like BCS Hamiltonian for the physics of interlayer pair tunneling a la' Anderson, one needs to use only plane wave states. The exact eigen states of the one electron problem of the coupled planes (including the random $t_{\perp i}$) is something that is not relevant for the problem in the presence of strong correlation in the plane. In this sense the presence of strong correlation defies Anderson's dirty superconductor theorem.

Recently Fay and Appel [15] have argued that it is the non retarded character of superconductivity in cuprates that is responsible for the violation of Anderson's theorem. What we have argued in our paper is a more fundamental reason which relies on the resonant tunneling character of the interlayer pair tunneling mechanism, and not on its non retarded character.

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