Indian Journal of Pure & Applied Physics
Vol. 42, October 2004, pp 758-763

Correlation amplitude for quasi-particles in high T_c superconductors

K M Khanna[1], M S Karap Kirui[2], T W Sakwa[3], P K Torongey[1], K Y Ayodo[3] & S Rotich[1]

[1]Department of Physics, Moi University, P.O. Box 3900, Eldoret, Kenya

[2]Department of Physics, Egerton University, P.O. Box 001, Egerton, Kenya

[3]Department of Physical Science, Western University College, P.O. Box 190, Kakamega, Kenya

Received 13 February 2004; accepted 12 April 2004

The correlation amplitude for the quasi-particles in high T_c superconductors has been deduced. From this amplitude, the maximum critical transition temperature has been calculated. The assumption, which has been made is that, the superconductivity is due to condensation of electron pairs, which may be in a parallel spin-state, an antiparallel spin-state, or a mixture of the two states. It has been established that the maximum transition temperature in the optical phonon frequency is T_c = 262.6 K irrespective of the state of the electron pair.

[**Keywords:** High T_c superconductor, Transition temperature, Correlation amplitude, Optical phonon frequency]

IPC Code: H03F 15/00

1 Introduction

The discovery of high T_c superconductivity in copper oxide[1] has stimulated a lot of thinking into the possible mechanism responsible for superconductivity. This is because by now, it is clear that the weak-coupling BCS theory is not adequate to describe vast experimental data in this field. There is growing evidence that superconductivity in copper oxides is characterized by d-wave symmetry (S=0, L=2) (Ref. 2) or p-wave symmetry (S=L=1), while BCS pairs are spin singlets with s-wave pairing (S=L=0).

We have attempted, therefore, to develop a theoretical framework to study the properties of high T_c superconductors based on a well-known picture '*Electron pairing in exotic superconductors*'[3]. In this picture, an electron moving through the crystal lattice polarizes the positively charged ionic background and in turn attracts another electron moving through at a later time. The two electrons form an exotic bound pair, which can have a parallel spin-state, an antiparallel spin-state, or a mixture of both parallel and antiparallel spin-states. We have assumed that, because of spin-charge separation, the polarization electron does not affect the pairing of the bound pair.

Although there is no clear evidence of triplet pairing in superconductors, Annet[4] made a theoretical classification of the possible Ginsburg-Landau (GL) free energy function of unconventional superconductors with p-wave or d-wave pairing. Moreover, spin-triplet pairing (S=L=1) has also been considered in liquid ^{3}He (Ref. 5).

2 Theory

We define the correlation amplitude of the quasi-particles by the equation:

$$\langle G|G\rangle = \langle G_0|\gamma_{l\sigma}\gamma^+_{l\sigma}|G_0\rangle \qquad \ldots(1)$$

where $\gamma_{l\sigma}\left(\gamma^+_{l\sigma}\right)$ are the annihilation (creation) operators for quasi-particles.

Bogoliubov[6] pointed out that there is a canonical transformation of the Fermion operators $c^+_{l\sigma}$, $c_{-l-\sigma}$ into new operators $\gamma^+_{l\sigma}, \gamma_{-l-\sigma}$ defined by

$$c_{l\sigma} = \sum_{\sigma'}\left(u_{l\sigma\sigma'}\gamma_{l\sigma'} + v_{l\sigma\sigma'}\gamma^+_{-l\sigma'}\right) \qquad \ldots(2)$$

The interaction scatters a pair in states $(l',\sigma),(-l',\sigma')$ into $(l,\sigma),(-l,\sigma')$. In matrix form this transformation is of the form

$$\begin{bmatrix}\gamma_{l\sigma}\\ \gamma_{l-\sigma}\\ \gamma^{+}_{-l\sigma}\\ \gamma^{+}_{-l-\sigma}\end{bmatrix}=\begin{bmatrix}u^{*}_{l\sigma\sigma} & u^{*}_{l-\sigma\sigma} & v_{-l\sigma\sigma} & v_{-l-\sigma\sigma}\\ u^{*}_{l\sigma-\sigma} & u^{*}_{l-\sigma-\sigma} & v_{-l\sigma-\sigma} & v_{-l-\sigma-\sigma}\\ v^{*}_{l\sigma\sigma} & v^{*}_{l-\sigma\sigma} & u_{-l\sigma\sigma} & u_{-l-\sigma\sigma}\\ v^{*}_{l\sigma-\sigma} & v^{*}_{l-\sigma-\sigma} & u_{-l\sigma-\sigma} & u_{-l-\sigma-\sigma}\end{bmatrix}\begin{bmatrix}c_{l\sigma}\\ c_{l-\sigma}\\ c^{+}_{-l\sigma}\\ c^{+}_{-l-\sigma}\end{bmatrix} \quad \ldots(3)$$

Using the concise four-dimension notation of Balian and Werthamer[7], the transformation can be written as

$$c^{l}=U^{l}\gamma^{l} \quad \ldots(4)$$

while the orthonormality condition

$U^{l}U^{l+}=1$, where U^{l+} is the Hermitian conjugate. …(5)

It is important to note that the quasi-particle operators satisfy Fermi-Dirac statistics,

$$\{\gamma^{+}_{l\sigma},\ \gamma_{k\sigma}\}=\delta_{lk}$$
$$\{\gamma^{+}_{l\sigma},\ \gamma_{-k-\sigma}\}=\{\gamma_{l\sigma},\ \gamma_{k\sigma}\}=\{\gamma_{l\sigma},\ \gamma_{-k-\sigma}\}=0 \quad \ldots(6)$$

2.1 Superconducting state defined by |kσ, -k-σ⟩ (Singlet State)

The superconducting state is assumed to be formed through the association of electrons in pairs with opposite spins and vectors.

According to this model, the singlet state is described by

$$\left|G_S\right\rangle=c^{+}_{l\sigma}\prod_{k\neq l}\left(u_{k\sigma\sigma}+v_{k\sigma-\sigma}c^{+}_{k\sigma}c^{+}_{-k-\sigma}\right)\left|0\right\rangle \quad \ldots(7)$$

From Eq. (3), the canonical transformation for this pairing is given by

$$\begin{bmatrix}\gamma_{l\sigma}\\ \gamma^{+}_{-l-\sigma}\end{bmatrix}=U^{+}_{S}\begin{bmatrix}c_{l\sigma}\\ c^{+}_{-l-\sigma}\end{bmatrix} \quad \ldots(8)$$

where

$$U^{+}_{S}=\begin{bmatrix}u^{*}_{k\sigma\sigma} & v_{-k-\sigma\sigma}\\ v^{*}_{k\sigma-\sigma} & u_{-k-\sigma-\sigma}\end{bmatrix},$$

$$U_{S}=\begin{bmatrix}u_{k\sigma\sigma} & v_{k\sigma-\sigma}\\ v^{*}_{-k-\sigma\sigma} & u^{*}_{-k-\sigma-\sigma}\end{bmatrix} \quad \ldots(9)$$

with the conditions that

$$u^{*}_{k\sigma\sigma}u_{k\sigma\sigma}+v_{-k-\sigma\sigma}v^{*}_{-k-\sigma\sigma}=1$$
$$v^{*}_{k\sigma-\sigma}u_{k\sigma\sigma}+u_{-k-\sigma-\sigma}v^{*}_{-k-\sigma\sigma}=0 \quad \ldots(10)$$

and

$$u_{k\sigma\sigma}=u_{-k-\sigma-\sigma},\ v_{k\sigma-\sigma}=-v_{-k-\sigma\sigma}$$

We define the normalized ground state for this pairing by

$$\left|G_o\right\rangle=\prod_{k}\left(u_{k\sigma\sigma}+v_{k\sigma-\sigma}c^{+}_{k\sigma}c^{+}_{-k-\sigma}\right)\left|0\right\rangle$$

such that

$$c^{+}_{l\sigma}\left|G_0\right\rangle=c^{+}_{l\sigma}\prod_{k}\left(u_{k\sigma\sigma}+v_{k\sigma-\sigma}c^{+}_{k\sigma}c^{+}_{-k-\sigma}\right)\left|0\right\rangle$$

$$=c^{+}_{l\sigma}\left(u_{l\sigma\sigma}+v_{l\sigma-\sigma}c^{+}_{l\sigma}c^{+}_{-l-\sigma}\right)\prod_{k\neq l}\left(u_{k\sigma\sigma}+v_{k\sigma-\sigma}c^{+}_{k\sigma}c^{+}_{-k-\sigma}\right)\left|0\right\rangle$$

$$=u_{l\sigma\sigma}c^{+}_{l\sigma}\prod_{k\neq l}\left(u_{k\sigma\sigma}+v_{k\sigma-\sigma}c^{+}_{k\sigma}c^{+}_{-k-\sigma}\right)\left|0\right\rangle \quad \ldots(11)$$

and using Eq. (7) we get

$$\left|G_0\right\rangle=u_{l\sigma\sigma}\left|G_S\right\rangle.$$

Similarly,

$$c_{-l-\sigma}\left|G_0\right\rangle=-v_{l\sigma-\sigma}c^{+}_{l\sigma}\prod_{k\neq l}\left(u_{k\sigma\sigma}+v_{k\sigma-\sigma}c^{+}_{k\sigma}c^{+}_{-k-\sigma}\right)\left|0\right\rangle$$
$$=-v_{l\sigma-\sigma}\left|G_S\right\rangle \quad \ldots(12)$$

Therefore, from Eqs (8), (10), (11) and (12) we obtain,

$$\gamma^{+}_{l\sigma}\left|G_0\right\rangle=\left[u_{l\sigma\sigma}c^{+}_{l\sigma}+v_{-l-\sigma\sigma}c_{-l-\sigma\sigma}\right]\left|G_S\right\rangle$$
$$=\left[u_{l\sigma\sigma}u_{l\sigma\sigma}-v_{-l-\sigma\sigma}v_{l\sigma-\sigma}\right]\left|G_S\right\rangle \quad \ldots(13)$$
$$=\left|G_S\right\rangle$$

Thus, $\left|G_S\right\rangle$ is the excited state for the excitation that is created by the quasi-particles operator.

The correlation amplitude, therefore, is defined by

$$\langle G_S | G_S \rangle = \langle G_0 | \gamma_{l\sigma} \gamma^{+}_{l\sigma} | G_0 \rangle \\ = 1 - \langle G_0 | \gamma^{+}_{l\sigma} \gamma_{l\sigma} | G_0 \rangle \qquad \ldots(14)$$

2.2 Superconducting state with triplet pairing defined by |kσ, -kσ⟩

The superconducting state is formed through the association of electrons in pairs with opposite wave vectors and parallel spins (triplet pairing).

For this pairing, the state is described by

$$|G_t\rangle = c^{+}_{l\sigma} \prod_{k \neq l} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} \right) |0\rangle \qquad \ldots(15)$$

and the normalized state is given by

$$|G_0\rangle = \prod_{k} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} \right) |0\rangle \qquad \ldots(16)$$

From Eq. (3) the canonical transformation becomes

$$\begin{bmatrix} \gamma_{l\sigma} \\ \gamma^{+}_{-l\sigma} \end{bmatrix} = U^{+}_{t} \begin{bmatrix} c_{l\sigma} \\ c^{+}_{-l\sigma} \end{bmatrix} \qquad \ldots(17)$$

where,

$$U^{+}_{t} = \begin{bmatrix} u^{*}_{l\sigma\sigma} & v_{l\sigma\sigma} \\ v^{*}_{l\sigma\sigma} & u_{l\sigma\sigma} \end{bmatrix}, \text{ and } U_{t} = \begin{bmatrix} u_{l\sigma\sigma} & v_{l\sigma\sigma} \\ v^{*}_{-l\sigma\sigma} & u^{*}_{-l\sigma\sigma} \end{bmatrix} \ldots(18)$$

Thus the normalization condition becomes

$$u^{2}_{k\sigma\sigma} + v^{2}_{-k\sigma\sigma} = 1 \\ u^{*}_{k\sigma\sigma} v_{k\sigma\sigma} + v_{-k\sigma\sigma} u^{*}_{-k\sigma\sigma} = 0 \\ \text{and} \\ v_{-k\sigma\sigma} = -v_{k\sigma\sigma}, \; \mathrm{u}_{k\sigma\sigma} = u_{-k\sigma\sigma} \qquad \ldots(19)$$

Now,

$$c^{+}_{l\sigma} |G_0\rangle = c^{+}_{l\sigma} \prod_{k} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} \right) |0\rangle$$

$$= c^{+}_{l\sigma} \left(u_{l\sigma\sigma} + v_{l\sigma\sigma} c^{+}_{l\sigma} c^{+}_{-l\sigma} \right) \prod_{k \neq l} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} \right) |0\rangle$$

$$= u_{l\sigma\sigma} c^{+}_{l\sigma} \prod_{k \neq l} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} \right) |0\rangle$$

$$= u_{l\sigma\sigma} |G_t\rangle . \qquad \ldots(20)$$

Similarly,

$$c_{-l\sigma} |G_0\rangle = -v_{l\sigma\sigma} |G_t\rangle \qquad \ldots(21)$$

Therefore from Eqs (17), (19), (20) and (21) we have,

$$\gamma^{+}_{k\sigma} |G_0\rangle = \left[u_{k\sigma\sigma} c^{+}_{k\sigma} + v_{-k\sigma\sigma} c_{-k\sigma} \right] |G_t\rangle \\ = \left[u^{2}_{l\sigma\sigma} - v_{-k\sigma\sigma} v_{k\sigma\sigma} \right] |G_t\rangle \\ = |G_t\rangle \qquad \ldots(22)$$

Just as it was in the antiparallel spin-pairing, $|G_t\rangle$ is the excited state for the excitation that is created by the quasi-particles operator.

Similarly, the correlation amplitude is defined by

$$\langle G_t | G_t \rangle = \langle G_0 | \gamma_{k\sigma} \gamma^{+}_{k\sigma} | G_0 \rangle \\ = 1 - \langle G_0 | \gamma^{+}_{k\sigma} \gamma_{k\sigma} | G_0 \rangle \qquad \ldots(23)$$

2.3 Superconducting state defined by a mixture of |kσ, -k-σ⟩ and |kσ, -kσ⟩

The superconducting state is formed through the association of electrons in pairs with opposite wave vectors and spins and electrons in pairs with opposite wave vectors and parallel spins (mixture of singlet and triplet pairing).

We assume that for this pairing, the state is described by

$$|G_m\rangle = c^{+}_{l\sigma} \prod_{k \neq l} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} + v_{k\sigma-\sigma} c^{+}_{k\sigma} c^{+}_{-k-\sigma} \right) |0\rangle \ldots(24)$$

while, the normalized state is given by

$$|G_0\rangle = \prod_{k} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} + v_{k\sigma-\sigma} c^{+}_{k\sigma} c^{+}_{-k-\sigma} \right) |0\rangle \quad \ldots(25)$$

From Eq. (3), the canonical transformation is given by

$$\begin{bmatrix} \gamma_{l\sigma} \\ \gamma^{+}_{-l\sigma} \\ \gamma^{+}_{-l-\sigma} \end{bmatrix} = U^{+}_{m} \begin{bmatrix} c_{l\sigma} \\ c^{+}_{-l\sigma} \\ c^{+}_{-l-\sigma} \end{bmatrix} \quad \ldots(26)$$

where,

$$U^{+}_{m} = \begin{bmatrix} u^{*}_{l\sigma\sigma} & v_{-l\sigma\sigma} & v_{-l-\sigma\sigma} \\ v^{*}_{l\sigma\sigma} & u_{-l\sigma\sigma} & u_{-l-\sigma\sigma} \\ v^{*}_{l\sigma-\sigma} & u_{-l\sigma-\sigma} & u_{-l-\sigma-\sigma} \end{bmatrix}, \text{ and}$$

$$U_{m} = \begin{bmatrix} u_{l\sigma\sigma} & v_{l\sigma\sigma} & v_{l\sigma-\sigma} \\ v^{*}_{-l\sigma\sigma} & u^{*}_{-l\sigma\sigma} & u^{*}_{-l\sigma-\sigma} \\ v^{*}_{-l-\sigma\sigma} & u^{*}_{-l-\sigma\sigma} & u^{*}_{-l-\sigma-\sigma} \end{bmatrix} \quad \ldots(27)$$

with the following normalization conditions,

$$\begin{aligned} &u^{2}_{l\sigma\sigma} + v^{2}_{-l\sigma\sigma} = 1 \\ &u^{*}_{l\sigma\sigma} v_{l\sigma\sigma} + v_{-l\sigma\sigma} u^{*}_{-l\sigma\sigma} + v_{-l-\sigma\sigma} u^{*}_{-l-\sigma-\sigma} = 0 \\ &u^{*}_{l\sigma\sigma} v_{l\sigma-\sigma} + v_{-l\sigma\sigma} u^{*}_{-l\sigma-\sigma} + v_{-l-\sigma\sigma} u^{*}_{-l-\sigma-\sigma} = 0 \end{aligned} \quad \ldots(28)$$

and

$$\left\{ \begin{aligned} &v_{-l\sigma\sigma} = -v_{l\sigma\sigma}, v_{-l-\sigma\sigma} = -v_{l\sigma-\sigma}, v_{l\sigma\sigma} \neq v_{l\sigma-\sigma} \\ &\mathrm{u}_{-l\sigma\sigma} = u_{-l-\sigma-\sigma} = \mathrm{u}_{l\sigma\sigma}, v_{l\sigma-\sigma} u_{-l-\sigma\sigma} = v_{l\sigma\sigma} u_{-l\sigma-\sigma} = 0 \end{aligned} \right\}$$

Now,

$$c^{+}_{l\sigma} \left| G_0 \right\rangle = c^{+}_{l\sigma} \prod_{k} \left(u_{k\sigma\sigma} + v_{k\sigma\sigma} c^{+}_{k\sigma} c^{+}_{-k\sigma} + v_{k\sigma-\sigma} c^{+}_{k\sigma} c^{+}_{-k-\sigma} \right) \left| 0 \right\rangle$$

$$= u_{l\sigma\sigma} \left| G_m \right\rangle . \quad \ldots(29)$$

Similarly,

$c_{-l\sigma} \left| G_0 \right\rangle = -v_{l\sigma\sigma} \left| G_m \right\rangle$ and

$c_{-l-\sigma} \left| G_0 \right\rangle = -v_{l\sigma-\sigma} \left| G_m \right\rangle$

Therefore,

$$\begin{aligned} \gamma^{+}_{l\sigma} \left| G_0 \right\rangle &= \left[u_{l\sigma\sigma} c^{+}_{l\sigma} + v_{-l\sigma\sigma} c_{-l\sigma} + v^{*}_{-l-\sigma\sigma} c_{-l-\sigma} \right] \left| G_m \right\rangle \\ &= \left[u_{l\sigma\sigma} u_{l\sigma\sigma} + v^{*}_{-l\sigma\sigma} v_{l\sigma\sigma} + v^{*}_{-l-\sigma\sigma} v_{l\sigma-\sigma} \right] \left| G_m \right\rangle \\ &= \left[u^{2}_{l\sigma\sigma} + v^{2}_{l\sigma\sigma} + v^{2}_{l\sigma-\sigma} \right] \left| G_m \right\rangle \\ &= \left| G_m \right\rangle \end{aligned} \quad \ldots(30)$$

Thus, the correlation amplitude becomes

$$\begin{aligned} \left\langle G_m \middle| G_m \right\rangle &= \left\langle G_0 \middle| \gamma_{l\sigma} \gamma^{+}_{l\sigma} \middle| G_0 \right\rangle \\ &= 1 - \left\langle G_0 \middle| \gamma^{+}_{l\sigma} \gamma_{l\sigma} \middle| G_0 \right\rangle \end{aligned} \quad \ldots(31)$$

It can be seen from Eqs (14), (23) and (31) that the correlation amplitude is of the same form for the three types of pairing.

3 Results

Since the transition to superconducting state is a thermodynamic change of state, the quantity $\left\langle G_0 \middle| \gamma^{+}_{l\sigma} \gamma_{l\sigma} \middle| G_0 \right\rangle$ can be generalized by thermal average over canonical distribution.

Thus, from the definition of thermal average

$$\left\langle G_0 \middle| \gamma^{+}_{l\sigma} \gamma_{l\sigma} \middle| G_0 \right\rangle = \left\langle \gamma^{+}_{l\sigma} \gamma_{l\sigma} \right\rangle$$

$$= \frac{Tr\left(e^{-\frac{H}{kT}} \gamma^{+}_{l\sigma} \gamma_{l\sigma} \right)}{Tr\left(e^{-\frac{H}{kT}} \right)} \quad \ldots(32)$$

where, Tr stands for the trace operation and $H = (\varepsilon_1 - \mu) \gamma^{+}_{l\sigma} \gamma_{l\sigma}$ is the Bogoliubov Hamiltonian.

If $E = \dfrac{\varepsilon_1 - \mu}{kT}, n = \gamma^{+}_{l\sigma} \gamma_{l\sigma}$, then

$$\left\langle \gamma^{+}_{l\sigma} \gamma_{l\sigma} \right\rangle = \frac{Tr\left(e^{-n\varepsilon} n \right)}{Tr\left(e^{-n\varepsilon} \right)} = -\frac{\partial}{\partial \varepsilon} \ln\left\{ Tr\left(e^{-n\varepsilon} \right) \right\}$$

$$\begin{aligned} &= -\frac{\partial}{\partial \varepsilon} \ln\left\{ \sum_{n=0,1} e^{-n\varepsilon} \right\} \\ &= -\frac{\partial}{\partial \varepsilon} \ln\left\{ 1 + e^{-\varepsilon} \right\} \\ &= \frac{1}{1 + e^{-\varepsilon}} \end{aligned} \quad \ldots(33)$$

which is the population of the quasi-particles according to Fermi-Dirac distribution function. Thus from Eq (13), the correlation amplitude becomes,

$$\langle G_m | G_m \rangle = 1 - \frac{1}{1 + e^{-\left(\frac{\varepsilon_1 - \mu}{kT}\right)}}$$

$$= \frac{e^{-\left(\frac{\varepsilon_1 - \mu}{kT}\right)}}{1 + e^{-\left(\frac{\varepsilon_1 - \mu}{kT}\right)}} \qquad \ldots(34)$$

which represents the density of holes[8]. This indicates that superconductivity arises through hopping of holes from one crystal site to another site of the same symmetry in the conduction plane.

Equation (34) is normalized to unity if $e^{-\left(\frac{\varepsilon_1 - \mu}{kT}\right)} >> 1$ and this condition allows us to calculate the transition temperature. We assume that the electron-electron attraction responsible for superconductivity comes into play in a narrow range $|\varepsilon_1 - \mu| \leq \eta\omega_0$, where $\eta\omega_0$ is the phonon energy.

Fig. 1 is a graph of the normalization condition for the correlation amplitude $\langle G_m | G_m \rangle$,

where, $\frac{\varepsilon_1 - \mu}{kT} = E$.

From the graph, the correlation amplitude is normalized when $-\frac{\varepsilon_1 - \mu}{kT} \geq 4.42$.

For numerical calculation, we have considered phonon energies[9] $\eta\omega = 1.602 \times 10^{-20} J$ for the high frequency vibration (breathing mode) and $\eta\omega = 8.01 \times 10^{-21} J$ for the low frequency vibrations (buckling mode).

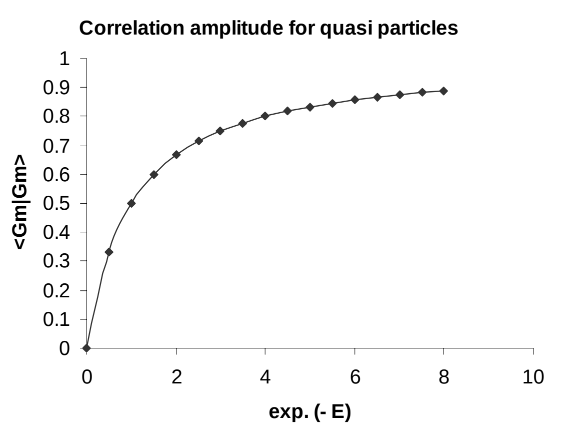

Fig. 1 — Normalization condition for correlation amplitude

(a) Breathing mode

$$\frac{\varepsilon_1 - \mu}{kT} \geq 4.42 \Rightarrow \frac{\eta\omega}{kT_C} \geq 4.42$$
$$\Rightarrow T_C \leq \frac{\eta\omega}{4.42\,\mathrm{k}} = 262.6\,\mathrm{K} \qquad \ldots(35)$$

(b) Buckling mode

$$\frac{\varepsilon_1 - \mu}{kT} \geq 4.42 \Rightarrow \frac{\eta\omega}{kT_C} \geq 4.42$$
$$\Rightarrow T_C \leq \frac{\eta\omega}{4.42\,\mathrm{k}} = 131.3\,\mathrm{K} \qquad \ldots(36)$$

Thus, the low frequency vibrations give a maximum transition temperature of 131.3K, while the high frequency vibrations give a maximum transition temperature of 262.6K. Now the maximum value of T_c = 125K was found in the compound $Tl_2Ba_2Ca_2Cu_3O_{10}$ which has been verified in many laboratories, but a higher T_c = 132K was discovered in Hg-Ba-Ca-Cu-O (Ref. 10).

This confirms that the low frequency vibrations mostly contribute to the electron-phonon coupling[11].

4 Discussion

We have calculated the correlation amplitude for the quasi-particles. We analyzed the effect of: (i) Parallel spin pairing; (ii) antiparallel spin pairing and (iii) mixture of parallel and antiparallel spin pairing.

We found out that the correlation amplitudes for the three cases are of the same form. Thus, the correlation amplitude does not depend on the type of pairing, which means that the attractive interaction of the superconducting pairs does not depend on the symmetry of the pairs. We still need to establish whether the pairs will be of *s*, *p* or *d*-wave symmetry. It has also been found that the normalization condition for the correlation amplitude is of the form $1 - f_0(\varepsilon_1 - \mu)$, where $f_0(\varepsilon_1 - \mu)$ is the Fermi-Dirac distribution function. This confirms the fact that the conduction process is confined to the motion of holes rather than electrons, which is consistent with the experimental results from the measurement of the Hall[12] coefficient, $R_H > 0$.

From this study, we have not been able to determine the transition temperatures for various layered copper-oxide compounds, but we have been able to find the maximum transition temperatures for both the breathing mode (T_c = 262.6K) and the buckling mode (T_c = 131.3K).

Further work needs to be done to establish the relationship between the oxygen content in a superconductor, the normalization condition and the transition temperature.

.

References

1 Bednorz J G & Muller K A, *Z phys B*, 64 (1986) 189.

2 Blatter G, *Physica C*, 282 (1997) 21.

3 Cox D L & Maple M B, *Phys Today*, 48 (1995) 32.

4 Annet J F, *Adv Phys*, 39 (1990) 83.

5 Leggett J, *Rev Mod Phys*, 47 (1975) 331.

6 Tilley D R & Tilley J, *Superfluidity and superconductivity*, [IOP Publishers Ltd], (1990) 393.

7 Balian R & Werthamer N R, *Phys Rev Lett*, 131 (1963) 1553.

8 Enz P C, *Lecture notes in physics*-V.11. World Scientific-Singapore, (1992) 125.

9 Piekarz P *et al*., *Phys Rev B*, 59 (1999) 14697.

10 Schilling A *et al*., *Nature*, 363 (1993) 56.

11 Shimada D *et al*., *Physica C*, 298 (1998) 195.

12 Uchide S *et al*., *Physica C*, 162 (1989) 1677