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Study of coherence length of Hg-1201 cuprate within the Fermi liquid approach

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Abstract

We study the thermodynamical parameter describing the superconducting state and their anisotropy of high- T_c mercury based Hg-1201 system. The role of two dimensional conducting CuO_2 planes and their numbers in a unit cell are significant and important features of Hg- based cuprates. We have deduced the ab- plane and c-value of the coherence length within the Fermi liquid approach. The result isanalysed and discussed with the available experimental data.

Introduction :

The discovery of Hg- based cupratehomologous series $HgBa_2Ca_{n-1}Cu_nO_{2n+2+\delta}$ $\{Hg-12\ (n-1)n\}$, where n represents the number of CuO2 planes per unit cell, has again stimulated intense interest in the nature of pairing mechanism and the physical properties of layered cuprates.Putilin et al.have reported superconductivity in $HgBa_2CuO_{4+\delta}$ (Hg-1201) $T_c = 94$ K with mono CuO_2 layer per unit cell, the first member of homologous series [1].
The mercury based cuprates have remarkable high transition temperature and relative defined crystal structures. The fundamental parameters in the superconductivity, the coherence length provides information regarding the effective mass ($m*$) and the charge carrier densityas well possible anisotropy.
Thompson et al.using a non-oriented sample determined the coherence length $\xi_{ab} = 21$Å of $HgBa_2CuO_{4+\delta}$ superconductors[2]. The superconducting coherence length of $HgBa_2CuO_{4+\delta}$ have been estimated as 27 Å using Werthamer- Helfand and Hohenberg formula by Chang et al. [3].
The availability of a wide range ofexperimental data and our earlier theoretical investigations on some cuprates have provided the motivation of this work.
The Model :
The structure of Hg- based cuprate can be modelled as an infinite array of twodimensional conducting CuO_2 planes and metal oxide layers along the c- axis of the unitcell. The structure is based on the complex layer sequence. The stacking of layers for Hg-1201 is like[$(H$ $)(BaO)c$ $(CuO2)$o $(BaO)c$ $](HgO\delta\ )o$............... .Thesquare brackets include the contents of one unit cell and the subscript c and o indicatewhether the cation is at the centre or at the origin of each layer. The apical Cu-O distancesalong the c- axis are significantly greater than the Cu-O distances in the plane perpendicularto c direction. The oxygen atoms located on the CuO_2 layer are coplanar, or almostcoplanar, with the Cu atoms [4].To a first approximation these layers are well separated and treated as non-interacting.Thescreened Coulomb potential for a series of identical CuO_2 planes separated by the distance d(=c for Hg-1201). The free holes as charge carriers are constrained to move within CuO_2layer and the hole gas lies in this plane. Also the coupling of holes as charge carriers in theperpendicular direction is considered as weak.
The layered electron gas consists of a super lattice with spacing of each layer (d) containing$n$ carriersembedded in a uniform neutralizing background. The interaction Hamiltonian forsuch infinitely thin layers is[5]

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$$H = \sum_k \epsilon_k c_k^+ c_k + \frac{1}{2}\sum_q V(q) \sum_{kk'} c_k^+ c_{k'}^+ c_{k'+q} c_{k-q} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

With an interaction potential of the form

$$V(q) = \frac{2\pi e^2}{q} \frac{\sinh(qd)}{\cosh(qd) - \cos(q_z d)} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(2)$$

Considering open Fermi surface, the energy of free particle is given as

$$\epsilon_k = \frac{\hbar^2 k^2}{2m_{ab}} + \frac{\hbar^2}{m_c d^2}[1 - \cos(k_z d)] - \mu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(3)$$

Here k and kzare the wave vector along and perpendicular to the conducting CuO2 plane.The m_{ab} and m_c are the effective mass of holes as carriers in the k and k_z directionsrespectively. The distance between two consecutive CuO2planes is denotedby d and the chemical potential is represented by μ.
With the use of Eq. (3) the electronic group velocity$v(k) = \left({}^{1}/_{\hbar}\right)[\partial\mathcal{E}(\mathrm{k})/\,\partial \mathrm{k}]$ yield Fermivelocities along and perpendicular to the CuO_2 plane as $v_F^{ab} = {}^{\hbar k}/_{m_{ab}}$ and $v_F^c = [{}^{\hbar}/_{m_c d}]\sin(k_z d)$.

This enables one to write$m_{ab} = {}^{\hbar k}/_{v_F^{ab}}andm_c = [{}^{\hbar}/_{v_F^c d}]\sin(k_z d)$.
Here we restrict ourselves to a case $|k_z,\ max| = \pi/c$ where c is lattice parameter in the $k_z$direction and d is related with the lattice parameter c asdiscussed earlier. With the above approximation m_c reduces to${}^{\hbar}/_{v_F^c d}$.
The estimation of superconducting parameter essentially depends on the value of carrierdensity of the volume surrounded by Fermi surface. For the sack of 2-D conducting planeswhich are well separated, the condition of optimized pairing allows that the 2-D chargecarrier density will follow$n_c d^2 = 1$. In general the behaviour of the system critically depends only on the planar electrondensity and the spacing between the planes.
In layered systems with 2-D identical planes the effective mass of the carriers along theplane is related to the electronic specific heat coefficient (γ) through

$$m_{ab} = \frac{3\pi\hbar^2\gamma d}{k_B^2} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4)$$

With K_B as the Boltzmann constant.
By considering the Hg-based system as 2-D superconductors with 2-D Cooper pairs in theCuO_2 layer, the coherence length is anisotropic as the conduction of charge carriers takesplace in the both k and k_z directions. For direction parallel to ab- plane, the coherence length of a superconductor at T= 0 K is given as

$$\xi_{ab}(0) = \frac{\hbar v_F^{ab}}{1.76\,\pi k_B T_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..(5)$$

For the other direction perpendicular to the plane, the coupling is very weak and we expect ξ_c to be the separation distance between the consecutive CuO_2 planes. We estimated the thermodynamical properties describing the superconducting state of Hg- based cuprates within the frame work of Fermi liquid description. The result obtained are presented in the following section.

Result and Discussion:

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While estimating the superconducting state parameters for Hg- based cuprates, we used the realistic physical parameters based on experimental information as follows. We use γ value from the specific heat measurements as 3 mJ/mol/K^2 for Hg-1201[6]. Using Eq. (4) the effective mass along the conducting CuO_2 plane is estimated as $m_{ab} = 3m_e$ for Hg-1201 system. The charge carrier density is obtained from the lattice parameter c for the condition of optimised pairing. From the above description the deduced in plane coherence length is obtained to be 14.63 A which is consistent with the experimental data [2].Turning to ξ_c we keep in mind that the coupling of the carriers to form a Cooper pair is weak in the perpendicular direction and approximate the out of plane coherence length ξ_c as c for Hg-1201 system.It is concluded that the coherence length and their anisotropy on these superconductors are consistent with the publisheddata when the physical parameters are deduced from the Fermi Liquid approachdescription.

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