Deduce ab-plane and c-plane value of the magneticpenetration depth of Hg-1223 System

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Abstract:
The ab-plane and c-plane value of the magnetic penetration depth of mercury based cuprate Hg- 1223is deducedwithin the Fermi liquid approach. The two dimensional conducting CuO_2 planes and their numbers in a unit cell are significant and important features of Hg- based cuprates. The estimation of superconducting parameter essentially depends on the value of carrier density of the volume surrounded by Fermi surface.The anisotropy of the layered structured is well reflected in the shape of open Fermi surface. The result isanalyzed and discussed with the available experimental data.

Introduction :
The discovery of Hg- based cupratehomologous series $HgBa_2Ca_{n-1}Cu_n O_{2n+2+\delta}$ $\{Hg-12\ (n-1)n\}$, where n denotes the number of CuO_2 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.[1] have first reported superconductivity in $HgBa_2CuO_{4+\delta}$ (Hg-1201) T_c = 94 K with mono CuO_2 layer per unit cell. Later on, superconductivity up to 133 K and zero resistance at 95 K were observed in multi-phased samples of Hg-Ba-Ca-Cu-O
With 15% of the sample volume containing Hg-1212 and Hg-1223 an observed superstructure [2].The optimal T_c is found initially increase with n and reach a maximum of 136 K for n=3 in Hg-1223 $\{\delta = 0.4\}$ [3].
The mercury based cuprateshave remarkable high transition temperature and relative defined crystal structure. The fundamental parameters in the superconductivity, the magnetic penetration depth provides information regarding the effective mass (m^*) and the charge carrier density(n_v) as well possible anisotropy. Couach et al. have investigated the ac response of mixed phase randomly oriented materials and determined the ab component of penetration depth in Hg-1223 as $1100\mathring{A}$[4].
Panagopoulos et al. have reported the temperature dependence of magnetic penetration depth with $\lambda_{ab} = 2100\mathring{A}$ and $\lambda_c = 61000\,\mathring{A}$ of magnetically aligned powders of crystalline $HgBa_2Ca_2Cu_3O_8$ [5].

The ab-plane and c-plane value of the magnetic penetration depth of mercury based cuprate Hg- 1223is deducedwithin the Fermi liquid approach.The magnetic penetration depth and their anisotropy on this are consistent with the published data when the physical parameters are deduced from the Fermi liquid approach. The availability of a wide range of

experimental data and our earlier theoretical investigations on some cuprateshave provided the motivation of this work.

The Model :

The crystal structure of Hg- based cuprate can be modeled as an infinite array of two dimensional conducting CuO_2 planes and metal oxide layers along the c- axis of the unit cell. The structure is based on the complex layer sequence. The stacking of layers for Hg-1223 is like $[(HgO_\delta)_o(BaO)_c(CuO_2)_c(Ca)_c(CuO_2)_o(Ca)_c(CuO_2)_o(BaO)_c](HgO_\delta)_o$..... .The square brackets include the contents of one unit cell and the subscript c and o indicate whether the cation is at the centre or at the origin of each layer. The apical Cu-O distances along the c- axis are significantly greater than the Cu-O distances in the plane perpendicular to c direction. The oxygen atoms located on the CuO_2 layer are coplanar, or almost coplanar, with the Cu atoms[6].

To a first approximation these layers are well separated and treated as non-interacting.The screened Coulomb potential for a series of identical CuO_2 planes separated by the distance *d* (= *c/3*for Hg-1223). The free holes as charge carriers are constrained to move within CuO_2 layer and the hole gas lies in this plane. Also the coupling of holes as charge carriers in the perpendicular 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 for such infinitely thin layers is [7]

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

With an interaction potential of the following form

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

The energy of free particle by considering open Fermi surface is given as

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

Where k and $k_z$are the wave vector along and perpendicular to the conducting CuO_2 plane. The m_{ab} and m_c are the effective mass of holes as carriers in the k and k_z directions respectively. The inter-planar separation between two consecutive CuO_2planes is denoted by d and the chemical potential is represented by μ. Josephson tunneling weakly couples the 2-D layers(planes).

With the use of Eq. (3) the electronic group velocity $v(k) = \left(\frac{1}{\hbar}\right)[\partial\mathcal{E}(k)/\partial k]$ yield Fermi velocities 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 $m_{ab} = \hbar k/v_F^{ab}$and $m_c = [\hbar/v_F^c d]\sin(k_z d)$. 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 as mentioned earlier.By considering the above approximation m_c reduces to $\hbar/v_F^c d$.

The estimation of superconducting parameter essentially depends on the value of carrier density of the volume surrounded by Fermi surface. For the sack of 2-D conducting planes which are well separated, the condition of optimized pairing allows that the 2-D charge carrier density will follow $n_c d^2 = 1$. For optimized doping the three lengths viz. d (separational distance between sheets), k_F^{-1} (inverse Fermi wavevector), and w (transeverse confinement width) should roughly equal, while the dimensionless Wigner-Seitz radius should have a value $r_s = r_s^0$, somewhat less than $r_s \approx 37$ at which Wigner crystal forms for a single layer 2-D electron gas[8].

In general the behaviour of the system critically depends only on the planar electron density and the spacing between the planes. Thus the condition for optimized pairing would follow $n_c d^2 = \beta$, where β is of the order of unity and weakly dependent on w/d [9].In addition,$n_c = n_v d$with d is the average spacing for a stack of two dimensional conducting planes.

In layered systems with 2-D identical planes the effective mass of the carriers along the plane is related to the electronic specific heat coefficient (γ) through

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

With K_B as the Boltzman constant.

By considering the Hg-based system as 2-D superconductors with 2-D Cooper pairs in the CuO_2 layer, the penetration depth is anisotropic as the conduction of charge carriers takes place in the both k and k_z directions. For direction parallel to ab- plane, the penetration depth$\lambda_{ab}$and $\lambda_c$is evaluated from London relationship as

$$\lambda_{ab}(0) = \left[\frac{m_{ab}c^2}{4\pi n_v e^2}\right]^{1/2} \quad (5)$$

and

$$\lambda_c(0) = \left[\frac{m_c c^2}{4\pi n_v e^2}\right]^{1/2} \quad (6)$$

Result and Discussion:

While estimating the anisotropic superconducting state parameters for Hg- 1223 system, we have used the realistic physical parameters based on experimental data as follows. The

effective mass of holes as charge carriers along the plane is well estimated from the specific heat measurements. We use γ value from the specific heat measurement as 12mJ/mol/K^2[10].

Using eq. (4) the effective mass of holes as charge carriers along the conducting CuO_2 plane incorporating the inter-layer distance is estimated as $m_{ab}=7m_e$. The charge carrier density of superconducting carriers in the CuO_2 plane is obtained from the lattice parameter c for the condition of optimised pairing.

With the above values for the input parameters, the in plane penetration depth λ_{ab} and c-plane value of λ_c for Hg-1223 system are found to be 1682 Å and 2588 Å, which are consistent with the experimental data[5].It is concluded that the magnetic penetration depth and their anisotropy on these superconductors are consistent with the published data when the physical parameters are deduced from the Fermi Liquid approach description.

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