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Effect of Electric Field on Energy Gap and Transition Temperature of a YBCO Superconductor.

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Abstract: Since superconductivity in cuprates occurs along the Cu-O planes, the Cooper pairs and positive ions can interact with each other leading to the creation of an electric field. The effect of this field leads to the increase in the value of energy gap (Δ) that turns out to be 62.5meV. This value is three times the experimental value of 20meV. The value of T_c lies between $181K$ and $290K$ for $\rho = \frac{2\Delta}{K_B T_c}$ that may lie between 5 and 8. For a typical experimental value of ρ = 6, the value of T_c turns out to be $240K$.
Key words: Electric Field, Energy gap, Transition Temperature.

1. Introduction.

There have been experimental studies to understand and measure the role of external electric field in creating a superconducting state [1-8]. An important outcome of these measurements is that the transition temperature T_c increases when an electric field is applied compared to when doping is done for an oxide insulator. This means that an electric field can enhance the transition temperature, T_c, of an oxide superconductor.

It has been shown experimentally that the origin of superconductivity in insulators by the application of the external electric field is due to the accumulation of charge carriers that are responsible for the high superconducting currents. There is a high- density carrier accumulation such that high-density electrons and holes, both of the order of $10^{20} cm^{-3}$, intrinsically co-exist [9]. Thus, it is plausible that the origin of high temperature superconductivity is due to field accumulated carrier doping [10,11]. Hall effect measurements suggest that T_c value is significantly enhanced, and the relationship between T_c and the accumulated carrier density increases monotonically [12,13].

In fact, one of the key methods for obtaining higher superconducting critical temperatures (T_c) is to dope carriers into an insulator parent material with strong electron correlation. When an external electric field is applied, it is known as electrostatic carrier doping. Prediction of the new high critical temperature (T_c) superconductor is one of the significant unsolved problems in condensed matter physics. However, theories and calculation methods have recently been advancing [14]. By now it is well known that the superconductivity of copper-based-oxides (cuprates) [15] emerges when the long-range anti-ferromagnetic order in their parent phases is suppressed by doping with a high density of carriers; and the value of T_c is related to the different electron correlation interactions in different types of superconductors. Finally, [16] one can say that the application of the external electric field can lead to electrostatically accumulated charge carriers in an oxide (or insulator), and this can also lead to the enhancement of the transition temperature T_c of a superconductor. In the next section, a plausible theory is developed to study the properties of such a system. However, the effect of electric field created by interactions between the charge carriers in the superconductor alone is considered; no external electric field is considered. It is assumed that the fields or self-fields created in the material due to the movement of charges can lead to changes in the carrier density that can result in the enhancement of T_c. It is well known that a very small fraction of electrons constitute Cooper pairs; the rest of the electrons are free. The internal fields created by the movement of Cooper pairs can drag in more of these free electrons, resulting in the enhancement of the carrier density and finally the increase in T_c.

Since superconducting charge carriers in CuO_2 plane flow along the CuO_2 planes, the superconducting Cooper pairs may interact with each other as they flow along the CuO_2 planes. The Cooper pairs and positive ions interact with each other and this leads to creation of an electric field, E, that acts on the Cooper pairs. The effect of this field was investigated to understand its contribution to the energy gap (Δ) and the transition temperature (T_c) of a YBCO superconductor. The BCS theory predicts that the energy gap is related to the critical temperature by the relation $\frac{2\Delta(T)}{K_B T_c}$ = 3.52, for any superconductor[17,18]. This turns out to be true and where deviations occur they can be understood in terms of modifications of BCS theory. For high temperature superconductors, a higher value of the energy-gap-T_c ratio is observed as compared to the weakly coupled BCS superconductors. Anisotropy in the energy gap value along *c*-axis and in the *ab*-plane is also noticed. For YBCO, the energy gap to T_c ratio has been found to be 3.5 for tunneling perpendicular to the Cu-O plane and value of~*6* has been found for tunneling in copper oxide planes[19].

A similar higher value of the same ratio is observed for tunneling in Cu-O plane in BSCCO [20-22], Tl-Ba-Ca-Cu-O[23,24] and Hg-Ba-Ca-Cu-O[25].For high T_c superconductors [26], the energy gap to T_c ratio is given by $\frac{2\Delta(T)}{K_B T_c}$ = 5→ 8.

2. The Theoretical Calculations.

Recently it has been argued [28] that the Meissner effect in superconductors necessitates the existence of an electrostatic field of in their interiors originating in the expulsion of negative charge from the interior to the surface when a metal becomes superconducting. The charge distribution becomes macroscopically inhomogeneous and an electric field exists everywhere in the interior of the superconductor. In a superconducting state, there exist Cooper pairs with charge 2e, electric dipoles and some free electrons which are not paired. In this calculation, it is assumed that the Cooper pairs oscillate along CuO plane, and the dipoles mediate between the two electrons in a superconductor to create an electric field.

Due to oscillating Cooper pairs along the CuO plane, the Cooper pairs interact with each other and also with positive ions. This leads to creation of an electric field E which in turn acts on the Cooper pairs. For the i -*th* Cooper pair, the Hamiltonian is written as,

$$H_i = \frac{{p_i}^2}{2m_i} + \frac{1}{2} k{x_i}^2 + E\,(2e)\,x_i \tag{1}$$

where $k = m\omega^2$ is the force constant, *x* is the displacement distance over which the electric field acts. For an assembly of *N* interacting Cooper pairs, the total Hamiltonian H can be written as

$$H = \sum_{i=1}^{N} \left[\frac{{p_i}^2}{2m_i} + \frac{1}{2}\, k{x_i}^2 + E(2e)\, x_i\right] \tag{2}$$

The third term refers to energy added to the system when an electric field is constant over distance *x*. The electric field created by dipoles that mediate between the two electrons in a superconductor is of the form γx^4 where $\gamma = \frac{m\omega^2}{4\pi L^2}$.*L* is the range of the electric field of the dipole such that

$$H = \frac{P^2}{2\text{m}} + \frac{1}{2} m\omega^2 x^2 + \frac{2em\omega^2}{4\pi^2 L^2} x^4 \tag{3}$$

Using $x = \left(\frac{\hbar}{2m\omega}\right)^{½} (b + b^{\dagger})$ and $p = -i\left(\frac{m\hbar\omega}{2}\right)^{½} (b - b^{\dagger})$. Then,

$$H = \frac{1}{2}\hbar\omega(bb^{\dagger} + bb^{\dagger}) + \frac{2em\omega^2}{L^2 4\pi^2}\left[\frac{\hbar^2}{4m^2\omega^2}(b + b^{\dagger})^4\right] \tag{4}$$

Applying second quantization formalism, the expectation value of energy E_n is calculated by$\langle n|H|n\rangle$ such that

$$E_n = \frac{\hbar\omega}{2}\{(n+1) + n\} + \frac{\hbar^2 e}{8m\pi^2 L^2}(6n^2 + 6n) = \frac{\hbar\omega}{2}(2n+1) + \frac{\hbar^2 e}{8m\pi^2 L^2}(6n^2 + 6n) \tag{5}$$

Eq. (5) gives energy excitation spectrum where n=0, 1, 2,…

For *n = 0*, we get the ground state energy E_0,

$$E_o = \frac{\hbar\omega}{2} \tag{6}$$

For *n = 1*, we get the next state E_1 above E_0,

$$E_1 = \frac{3\hbar\omega}{2} + \frac{3e\hbar^2}{2m\pi^2 L^2} \tag{7}$$

Using Eqs. (6) and (7) we calculate the energy gap Δ where $\Delta = E_1 - E_O$

$$\Delta = E_1 - E_O = \frac{3\hbar\omega}{2} + \frac{3e\hbar^2}{2m\pi^2 L^2} - \frac{\hbar\omega}{2} = \hbar\omega + \frac{3e\hbar^2}{2m\pi^2 L^2} \tag{8}$$

Eq. (8) reduces to (9) such that,

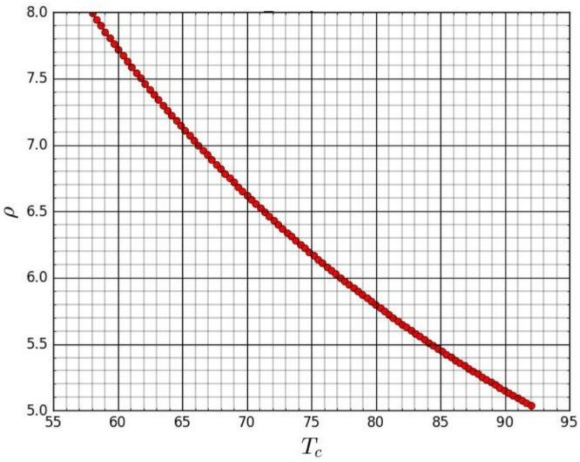
$$\Delta = E_1 - E_O = \frac{2m\pi^2\hbar\omega L^2 + 3e\hbar^2}{2m\pi^2 L^2} \tag{9}$$

Equation (9) is used in calculating the energy gap

3. Results and Discussions.

To determine the value of the energy gap for a YBCO system[27] $\hbar\omega$ = 0.08eV and L = *1.0* x$10^{-6}m$, using equation (9) the value of Δ turned out to be 62.5meV, which was three times experimental value[19] of

20meV. The effect of electric field on the value of Δ appears via the value of L which is the range of the electric field. If the range L of the electric field is infinitely large, then L → ∞, and equation (9) gives $\Delta = \hbar\omega$ = 0.08eV which is very large compared to Δ = 0.002 eV. It gives a value of T_c = 440K which is very large and thus infinite range electric field is physically uninteresting. For $\rho = \frac{2\Delta(T)}{K_B T_c}$ when $\rho = 5 - 8$, the value of T_c lies between 289.86K and 181.16K, respectively. For a typical experimental value of ρ = 6, then T_c = 240K.



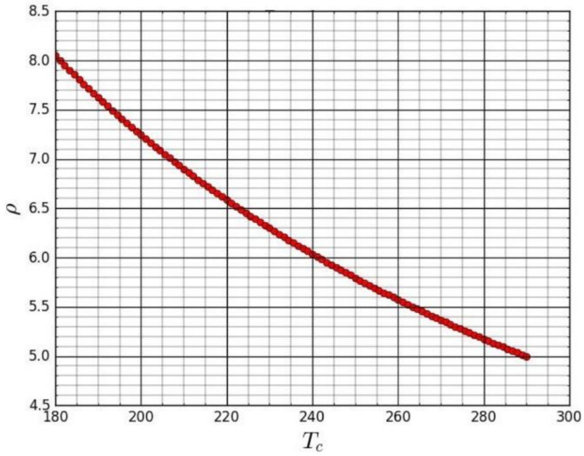


Fig. 1. Plot of Variation of ρ With T_c for Δ = 20meV **Fig. 2**. Plot of Variation of ρ With T_c for Δ = 62.5meV

Fig. 1 and 2 above show that there is a non-linear increase in the values of T_c with decrease in the values of ρ when Δ = 20meV and Δ = 62.5meV is for a YBCO system due to an electric field created by oscillating Cooper pairs along CuO_2 planes. Fig 1 and 2 further show that the values of T_c lie between 58K and 92K for Δ = 20meV and 181.16K to 289.86K for Δ = 62.5meV. It is noted that increase in energy gap due to the created electric field or internally developed electric field leads to increase in the values of T_c. Earlier electric field induced superconducting transition and the effect on T_c have been experimentally studied [29,30] and induce the superconducting state and also enhance T_c.

4. Conclusion

It is believed that conductivity in HTSCs takes place along the CuO_2 planes and due to this the oscillating Cooper pairs may interact with each other. If the Cooper pairs and positive ions also interact with each other, they may lead to creation of an electric field which may in turn act on the Cooper pairs. The created electric field E, acts as the perturbation in the Hamiltonian describing the interaction. The expectation value of energy is calculated using, ($E_n = \langle n|H|n\rangle$) and the energy gap Δ= 62.5meV for a YBCO system. The value of the energy gap lies in the experimental range of 20meV to 100meV. The variation of superconducting parameter ρ $(2\Delta/k_B T_c)$ with transition temperature T_c is similar in nature to graphs obtained for different values of different materials which confirms correctness of the calculations (Figures 1 and 2). The calculations give the highest value of $T_c \cong$ 289K in the range of 181K – 289K, for ρ values of 5 – 8. The highest value of $T_c \cong$ 289K is close to the room temperature $T \cong$ 300K.

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