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RESEARCH ARTICLE

THE FORMULATION BETWEEN PENETRATION DEPTH AND CRITICAL TEMPERATURE OF SUPERCONDUCTORS BY THERMAL PHYSICS AND ELECTROMAGNETIC THEORY.

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Abstract

Several phenomena associated with superconductivity are expressed in terms of concentration of superconducting electrons, penetration depth and temperature etc. The empirical relation for the density of superconducting electrons and the relation in terms of penetration depth are discussed in the present paper. These empirical relations are obtained on the basis of experimental data. These relations are derived mathematically on the basis of thermodynamically and electro dynamically properties with interaction between superconducting electrons and phonons.

Introduction:-

Superconductivity is the phenomenon in which the electrical resistivity of the material is zero around the transition temperature (T_c). It was discovered by in 1911 by H.K.Onnes[1].The superconducting state is an ordered state of the conduction electrons of the metal. The order is in the formation of loosely associated pairs of electrons. The electrons are ordered at temperature below the transition temperature and they are above the transition temperature [2-3]. The nature and the origin of the ordering electrons was described by Bardeen, Cooper and Schrieffer [4]. The theory of superconductivity requires a net attractive interaction between electrons in the neighbourhood of the fermi surface, which gives the basic concept of cooper pairs and interaction with lattice [5]. Basic theory of superconductivity relates to transitions with respect to critical temperature , critical magnetic field, superconducting, concentration of electrons and London penetration depth [6-10]. Currently the mechanism of high temperature superconductivity is also investigated which is ceramics compounds [11-12]. In this paper, we establish the relation between critical temperature and the density of superconducting electrons and also the relation between the London penetration depth and critical temperature, which is given in empirical analysis already.

Theory:-

Consider a fermi surface at which Cooper pairs are formed and electrons interacts with lattice, so energy density of phonons in superconductors is ‘u’ while the density of concentration of superconducting electrons is different at various levels in superconductors.
Now, pressure P exerts on superconducting electrons

$$P = \int_0^{\pi} dP = \int_0^{\pi} \frac{uCos^2\theta 2\pi Sin\theta}{4\pi} d\theta$$

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$$P = \frac{u}{2}\int_0^{\pi} Cos^2\theta Sin\theta d\theta$$

$$P = \frac{u}{3} \quad \ldots (1)$$

Thermodynamically, relation between total interaction energy (E) and pressure (P) is given as

$$\left(\frac{\partial E}{\partial V}\right)_T = T\left(\frac{\partial P}{\partial T}\right)_V - P \quad \ldots (2)$$

Since the total interaction energy of phonons in superconductor is given by
E= u V
Where, V is the volume of superconductor.

$$\frac{d(u,V)}{\partial V} = T\frac{\partial}{\partial T}\left(\frac{u}{3}\right) - \frac{u}{3}$$

$$u = \frac{T}{3}\frac{du}{dT} - \frac{u}{3}$$

$$\frac{T}{3}\frac{du}{dT} = \frac{4u}{3}$$

$$\frac{du}{u} = 4\frac{dT}{T} \quad \ldots (3)$$

Normal state concentration of electrons in superconductor is n_n. Then interaction energy density of phonons per unit concentration of superconducting electron is $\frac{u}{n_n}$ at critical temperature T_C.

Now Eq.(3) can be written as

$$\int_0^{u/n_n} \frac{du}{u} = 4\int_0^{T_C} \frac{dT}{T}$$

$$u = n_n T_C^4 \quad \ldots (4)$$

Therefore, the total concentration of electrons is n_0 in superconductor at absolute zero temperature. Now energy density of phonons per unit concentration of electron in superconductors is $\frac{u}{n_0}$ at temperature T, then

$$\int_0^{u/n_0} \frac{du}{u} = 4\int_0^{T} \frac{dT}{T}$$

$$\frac{u}{n_0} = T^4$$

$$u = n_0 T^4 \quad \ldots (5)$$

From equation (4) and (5) we have

$$n_n = n_0\left(\frac{T}{T_C}\right)^4 \quad \ldots (6)$$

Since total concentration of electrons in superconductors is given as
$n_0 = n_n + n_s$… (7)

where, n_s is the concentration of superconducting electrons in superconductors.

$$n_s = n_0 - n_n \qquad \ldots (8)$$

$$n_s = n_0 - n_0 \frac{T^4}{T_C^4}$$

$$n_S = n_0 \left(1 - \frac{T^4}{T_C^4}\right) \qquad \ldots (9)$$

This is the required expression for the variation of density of super electrons with temperature and this is equivalent with empirical relation.

Consider that an electric field occurs within a superconductor. The superconducting electrons will be freely accelerated without dissipation. Therefore, the average velocity of the electrons is v_s . The equation of motion of electrons in electric field (E) is given by

$$m \frac{d\boldsymbol{v}_s}{dt} = -e\boldsymbol{E} \qquad \ldots (10)$$

Since the electron density current carried by these electrons is

$$\boldsymbol{j} = -e\boldsymbol{v_s} n_s \qquad \ldots (11)$$

From Eq. (10) and (11) we obtained

$$\frac{d\boldsymbol{j}_s}{dt} = \frac{n_s e^2}{m}\boldsymbol{E} \qquad \ldots (12)$$

This is called first London equation.

From Faraday's law

$$curl\,\boldsymbol{E} = -\left(\frac{d\boldsymbol{B}}{dt}\right) \qquad \ldots (13)$$

Let us take curl of Eq. (12) and then substituting the value of curl E from equation (13) we obtained

$$\frac{d}{dt}\left(\frac{m}{n_s e^2} curl\,\boldsymbol{j}_s + \boldsymbol{B}\right) = 0 \qquad \ldots (14)$$

For superconductors we integrate Eq. (14) w.r.t. time and equate the constant of integration equal to zero, we have

$$curl\,\boldsymbol{j}_s = -\frac{n_s e^2}{m}\boldsymbol{B} \qquad \ldots (15)$$

Maxwell equation for static field is

$$curl\,\boldsymbol{B} = \mu_0 \boldsymbol{j}_s \qquad \ldots (16)$$

Taking the curl of Eq. (16)

$$curl\,curl\,\boldsymbol{B} = curl\,\mu_0 \boldsymbol{j}_s \qquad \ldots (17)$$

On using Eq. (15) and (17) we have

$$grad\,div\,\boldsymbol{B} - \nabla^2 \boldsymbol{B} = -\mu_0 \frac{n_s e^2}{m}\boldsymbol{B} \qquad \ldots (18)$$

Since $div\,\boldsymbol{B} = 0$, for superconductors

Therefore,

$$\nabla^2 \boldsymbol{B} = \mu_0 \frac{n_s e^2}{m}\boldsymbol{B} \qquad \ldots (19)$$

$$\lambda = \left(\frac{m}{\mu_0 n_S e^2}\right)^{1/2} \qquad \ldots (20)$$

Where, we define eq. (20) is called the London penetration depth. Therefore, the concentration of superconducting electrons varies with the penetration depth as

$$n_S \propto \frac{1}{\lambda_S^2} \qquad \ldots (21)$$

Therefore, the concentration of total electrons varies with the penetration depth as

$$n_0 \propto \frac{1}{\lambda_0^2} \qquad \ldots (22)$$

From Eq. (9), (21) and (22) we obtain

$$\frac{1}{\lambda_S^2} = \frac{1}{\lambda_0^2}\left(1 - \frac{T^4}{T_C^4}\right)$$

$$\lambda_S^2 = \frac{\lambda_0^2}{\left(1 - \frac{T^4}{T_C^4}\right)}$$

$$\lambda_S = \lambda_0\left(1 - \frac{T^4}{T_C^4}\right)^{-1/2} \qquad \ldots (23)$$

This is the London penetration depth in superconductors which is equivalent to empirical relation.

Results and Discussion:-

We compare the experimental results with the result of eq. (9) and eq. (23). These relations represent the dependence of critical temperature. The nature of this variation is inverted parabolic shape in concentration of superconducting electrons versus temperature and penetration depth versus temperature. Therefore both the physical quantities are function of temperature. These equations representthe phase boundary between the superconducting state and normal state. In general, for λ investigation of high temperature superconductor materials, three important approaches can be preferred to the total penetration depth calculation, phonon contribution, electron contribution and both electron-phonon contributions.

Conclusion:-

The eq. (9) is derived on the basis of thermal Physics and eq. (23) on the basis of thermal physics and electro dynamics. The concentration of superconducting electron depends on the temperature and its nature parabolic. The penetration depth depends on the temperature and becomes quite large as temperature approaches the transition temperature.

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