Investigation of Theoretical Considerations of High Temperature Oxide Superconductors

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Abstract: ***Since the discovery of high temperature oxide superconductors, a large number of theoretical researches have been carried out to explain salient features of superconductivity. Accordingly a plenty of theoretical work have been subjected to the high temperature oxide superconductors and several theories have been proposed by the researchers. In present study, a classification of the theories has been reviewed in terms of two main categories namely, BCS type and Bose condensation type and the same has been presented.***

Keywords: High temperature oxide superconductors, theoretical considerations, Bardeen - Cooper - Schrieffer (BCS) theory, and Bose condensation

1. Introduction

Kamerlingh Onnes has reported superconductivity in Mercury at 4.2 K in the year 1911 [1]. Since the discovery of superconductivity, numerous researchers have been conducted with focused effort of finding a room - temperature superconductor [1 - 58]. Bednorz and Müller have reported superconductivity in a new class of superconductors at a transition temperature around 35.1 K [2]. Recently, the superconductor with the transition temperature at around 133 K has been reported by Schilling et al [57]. There has been a report of other superconductors with higher recorded transition temperatures as high as 250 K under the application of very high pressure [58]. Several theoretical considerations have been reported in order to explain the occurrence of superconductivity in high temperature superconductors [1 - 58]. The origin of high - temperature superconductivity is still not well clear. Present study attempted to review the theoretical considerations [1 - 58] in order to explain the phenomenon of superconductivity in high temperature oxide superconductors.

2. Theoretical Considerations

Since the discovery of superconductivity, an abundance of theoretical models have been proposed to explain the superconductivity [1 - 58]. London theory [19], Pippard model [20], Ginsburg - Landau theory [21] and Arbikosov model [22] and Bardeen - Cooper - Schrieffer (BCS) theory [23] have been proposed in case of classical or conventional superconductors (low temperature). Out of these theories only the BCS theory, was found quite satisfactory for classical superconductors, but has failed completely to explain the observed properties e. g. Isotope effect [24], electronic specific heat at low temperature [25] and independent of transition temperature (T_C) on the number of charge carriers [26] in high temperature oxide superconductors. It is generally accepted that high temperature oxide superconductors are a class apart from conventional superconductors due to following salient features:

- The superconducting pairs occupy CuO_2 planes or sheets inlayers separated by insulating inter growth layers, which makes them extremely anisotropic.
- TheCuO_2 sheets are all anti - ferromagnetic and semiconducting where their formal valence is $(CuO_2)^{2-}$, oxidation or reduction of these sheets leads to superconductivity.
- The transition temperature (T_C) is at the limit or quite well in excess of what is accessible within the frame work of BCS - type theory.
- A coherence length (ζ=10Å) is at least an order of magnitude smaller than that found in conventional superconductors. These high temperature oxide superconductors represent extreme examples of type II superconductivity.

The crucial parameters of high temperature oxide superconductors [27] are: oxygen stoichiometry, O - axis Cu - O distance in a square pyramidal site, formal charge difference across on intergrowth interface, width of the conduction band and significant role of copper.

The high temperature oxide superconductors have been subjected to a plenty of theoretical research works [1 - 58]. Many theories have been proposed by the researchers. In present study, a classification of these theories into two main categories namely, BCS type and Bose condensation type has been provided and a brief review of the same is given below:

3. BCS Type Theories

The Bardeen - Cooper - Schrieffer (BCS) theory predicts the transition temperature (Tc) very low (<40K), so vital issue is to understand as to why the transition temperature (Tc) of high temperature oxide superconductors is so high. In weak coupling, the limit of transition temperature (Tc) may be expressed as:

$$KT_c = 1.14\, h\omega_0 \exp[-1/N(o)V] \ldots (1)$$

Where $h\omega_0$ being the out off energy comparable to the maximum energy of excitations which mediate the pairing within the Bardeen - Cooper - Schrieffer (BCS) frame work. There are three possibilities to increase the transition temperature (T_c) i. e., by increasing the density of states (N (o)) at Fermi surface, the effective electron - electron attraction (V) and the cut off frequency (ω_0). According to earlier theories proposed by Ginsburg and A1lender [28], an attractive interaction between carriers may be radiated by the exchange of virtual electron hole pairs the so called excitonic mechanism for superconductivity, In order to work this mechanism two distinct types of carriers are required; conducting carriers in a metallic region and polarizable electrons in adjacent region. It is possible that the polarizable, non - conducting electrons in the BaO planes or the carriers in CuO chains may mediate a pairing between the conducting carriers in CuO planes in the high temperature oxide superconductor like $YBa_2Cu_3O_{7-\delta}$ (YBaCuO) compound. On the other hand, according to theory of 'charge transfer excitation exchange' proposed by Varna et al. [29], the virtual electronic polarization occurs through the transfer between copper and oxygen sites within a CuO plane.

The excitation mechanism [30] is predicted to yield a considerably higher transition temperature (Tc) than the phonon mechanism because the cut off energy ($h\omega_o$) is expected to be comparable to the electronic excitation energies. In this excitonic system the interaction is mediated by the movement of electrons rather than by the much heavier ions of a phonon superconductor. The transition temperature (T_c) for an excitonic superconductor would thus be scaled up from that of conventional superconductors by a factor of $(M_{ion} / M_o)^{1/2}$, if al1 other parameters are kept constant. Similar arguments hold for theories proposing the exchange of Plasmon [29, 30] or virtual magnetic excitations, such as anti - ferromagnetic spin fluctuations [31]. Again, the higher energies of the relevant virtual excitations increase the energy range over which the electron interaction is attractive, leading to a higher fraction of paired carriers and thus a higher transition temperature (T_c). It can be pointed out from the above discussion that this category of theories assume that the pairs are formed at T_c and the pairing between carriers via certain virtual excitations is responsible for leading to superconductivity.

4. Bose Condensation Type Theories

These theories assume that pairs already exist above transition temperature (T_c). The unpaired carriers follow Fermi - Dirac (FD) statistics, but as soon as pairing takes place the statistics of the particles change to Bose - Einstein (BE) wherein the distribution function may be expressed as

$$f_{BE} = [exp(\alpha + \beta E) - 1]^{-1} \ldots (2)$$

where β =1/kT and α is given by the equation

$$e^{-\alpha} = \left[nh^3 \, (2nm^* kT)^{-3/2}\right] \ldots (3)$$

n is concentration of the integral spin particles of effective mass m*. Here more than one particle can occupy the same state contrary to Fermi–Dirac (FD) statistics. The maximum number of particles n' occupying states above ground state in Bose–Einstein (BE) statistics may be expressed as for $T < T_o$

$$n' = n\,(T / T_o)^{3/2} \ldots (4)$$

where n being the concentration of particles and T_o is the temperature when α in expression (2) is zero. Hence, the number of remaining particles n_0 is given by

$$n_o = n - n' = n\,[1 - (T/T_o)^{3/2}] \ldots (5)$$

As the temperature is lowered, beginning at $T = T_o$ the particles fall rapidly into ground state. This is some sort of condensation generally known as Bose condensation.

One of the leading theories for high temperature superconductors of this category is the Resonating Valence Bond (RVB) theory suggested by Anderson [32]. The basic idea behind this theory is that strong electron - electron correlations result in a separation of charge degree of freedom from the spin degree of freedom. The pairing mechanism is magnetic in origin in this theory. The starting point of RVB is a 2D Hubbard nodal. Coulomb repulsion U and an attractive inter site hopping energy T without oxygen doping, the ground state of the above model is expected to be a long range anti - ferromagnetic (AF) state, but Anderson argued that the frustration might favour a RVB state over an AP ground state.

Another theory named as Bi - polaron mechanism [33] has been proposed. In this mechanism the high temperature oxide superconductors are considered to be as doped semiconductors [34] where the conductivity is due to doping. This produces mixed valance - conditions for the metal ions, loading to the formation of smal1 - polarons. The nobility of these small polarons is ensured through the mixed valence charge transfer mechanism. They may be viewed as dilute gas of charged particles in a lattice moving in the random fluctuating potential due to impurities. Under peculiar conditions these small polarons may combine to form small bi - polarons. The bi - polarons act like a weakly interacting Bose gas capable of condensing into its ground state at relatively elevated temperatures and hence becoming superconducting. Besides the aforesaid discussed models/mechanisms for high temperature oxide superconductors, a plausible choice is yet to be establishing which can accomplish the status of a full - fledged theory.

5. Conclusion

It is concluded that in - spite of the fact that numerous models /mechanisms/ theories have been proposed to explain the phenomenon of superconductivity in high temperature oxide superconductors. However, a plausible choice is yet to be found which can attain the status of a full - fledged theory.

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