STRONG ELECTRON-PHONON COUPLING AND ORIGIN
OF HIGH Tc SUPERCONDUCTIVITY

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ABSTRACT

The superconducting state in the high Tc oxides can be fully understood by strong electron coupling to low frequency phonon modes. The major features of this state and the parameters are described.

The discovery of high Tc superconductivity has resulted in the remarkable development of various mechanisms of pairing. In this paper we are going to discuss our present view. Some aspects of our the approach were discussed in 2-4.

The problem of the origin of the superconducting state in the cuprates has to be addressed by some critical experiments. With regard to such experiments, let us ask ourselves about the determination of the phonon origin of conventional superconductivity. Indeed, what makes us convinced that pairing in conventional superconductors is mediated by phonons? The isotope effect is not conclusive, particularly for various compounds (see discussion in 2). The answer is based on a unique experimental technique, namely, on tunneling spectroscopy (see e.g., reviews in 5). This analysis based on spectroscopy is a two-step process: 1. The inversion of the Eliashberg equation and comparison of the shape of the Eliashberg function with the phonon density of states from neutron scattering data; the positions of the peaks is particularly important and 2. Determination of Tc, which should be equal to the measured value. This method allows one to determine the key contribution of the phonons to the pairing. In the absence of tunneling spectroscopy the problem of the pairing mechanism in conventional materials would be controversial even at the present time.
The absence of tunneling spectroscopy data is the main source of controversy over the origin of superconductivity in organics and heavy fermions.

We think that strong electron-phonon coupling plays a key role as the mechanism of superconductivity in the cuprates. The high $T_c$ oxides are characterized by a rich phonon spectrum (see e.g. 6). An important feature of the spectrum is the presence of low frequency optical phonon modes ($\omega_{opt}=15-20$ mev in LaSrCuO, and $\omega_{opt} = 30-35$ meV in YBCO). These modes have a large density of states $F(\omega)$ and this leads to an increase in the coupling constant $\lambda$. We think that coupling to these modes is a key ingredient of high $T_c$. A detailed description of the coupling can be obtained by tunneling spectroscopy. As was noted above, this spectroscopy appears to be a powerful tool for studying conventional superconductors. However, a number of factors such as the short coherence length in the cuprates makes the use of this technique very complicated. Nevertheless, because of recent progress in thin films preparation and the further development of the tunneling technique (e.g. the break junction method) we expect a breakthrough in the near future.

It is important to stress that phonons, in principle, can provide a high value of $T_c$. It is interesting, that a limiting value of $T_c (=40K)$ was obtained twice in the past, but each time this conclusion was erroneous (see discussion in 4, Ch.6). There is nothing which can prevent the phonon-mediated superconductivity from having $T_c > 10^2$ K. Probably, at some point the growth of the strength of the coupling will be limited by the instability of the lattice, but this question has not been studied in detail.

The problem of the strength of the coupling is very important. Indeed, if the pairing is caused by electronic or magnetic excitations which are characterized by a large energy scale ($\Delta E > 0.1$ eV), then the observed value of $T_c$ can be caused by weak coupling ($\lambda \ll 1$). For example, for the La-Sr-Cu-O compound ($T_c=40K$), the value of $\lambda$ should not exceed 0.25. However, if the pairing is provided by low frequency phonons, then we are dealing with the strong coupling case. That is why the problem of the determination of the strength of the coupling is of great interest.

In the absence of tunneling spectroscopy data, one can use an alternative method of determining the strength of the coupling to optical
phonons. This method is based on heat capacity data and has been employed in\textsuperscript{7}. The determination of $\lambda$ is based on the fact that the low temperature value of the Sommerfeld constant in the layered oxide contains the renormalized value of the effective mass $m^* = m_b (1+\lambda)$, where $m_b$ is the band value, whereas at high temperatures $m^* \approx m_b$. A detailed and careful analysis carried out in\textsuperscript{7} has resulted in the value of $\lambda \approx 2.5-3$, and this means strong coupling. For such a large value of $\lambda$ it is not acceptable to use the BCS expression for $T_c$ which is valid only for $\lambda \ll 1$ nor can one use the McMillan-Dynes equation (valid for $\lambda < 1.5$). One can employ the equation\textsuperscript{8}:

$$T_c = \frac{0.25 \tilde{\omega}}{[e^{2\lambda_{\text{eff}}-1}]^{1/2}}$$

(1)

$$\lambda_{\text{eff}} = (\lambda - u^*) [1+2\mu^* + \lambda\mu^*\tau(\lambda)]^{-1}$$

$\tau(\lambda)$ is defined in\textsuperscript{8}.

Eq.(1) is valid for any $\lambda$. Note also that contrary to the usual 3D system, the layered conductors such as the cuprates are characterized by the presence of acoustic plasmons modes and by their antiscreening dynamic effects. This leads to weakening of the Coulomb repulsion, so that $\mu^*$ is in the range 0. to -0.1\textsuperscript{2}. Substituting the value $\lambda=3$ (see above) and $\mu^*=-0.1$ we obtain $T_c = 90$ K.

Note that our analysis is based on the Eliashberg equation; this equation is valid if the characteristic phonon energy $\Omega$ which is important for the pairing, is smaller than the Fermi energy $E_f$. Another mechanism, which also related to the strong polarization of the lattice, namely, the bipolaronic picture, is based on the opposite criteria (electronic energy below $\Omega$)\textsuperscript{9}. In the case $\Omega < E_f$ the value of the coupling constant can be large without the appearance of the lattice instability. Our analysis of the normal properties\textsuperscript{2,10} has resulted in the values $E_f=0.1$ eV for LaSrCuO and $E_f=0.3$eV for YBCO. Therefore $E_f > \Omega$, and the use of the Eliashberg equation is justified.

An increase in the value of the ratio $2\Delta/T_c$ also indicates the presence of strong coupling. It is interesting to note that the measured value of this ratio in the oxides is much large than the BCS value of 3.52.
We think that the superconducting state of the LaSrCuO compound is characterized by the following values of the major parameters: $\lambda = 2.2 - 2.5$, $\mu = -0.1$, $\Omega = 12 - 15$ meV; For YBCO $\lambda = 2.5 - 3$, $\mu = -0.1$, $\Omega = 30 - 35$ mev. Therefore, high $T_c$ in the oxides is due to strong coupling to low frequency optical phonon modes. We expect that future tunneling measurements will support our conclusion.

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References.

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