Electron-phonon induced superconductivity in high T_c superconductors

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Abstract. It is proposed that phonon induced mechanism is capable of explaining the observed range of T_c for the newly discovered high temperature superconductor within the Allen and Dynes strong coupling theory.

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Following the recent discovery of superconductivity in $\text{La}_{2-x}\text{R}_x\text{CuO}_4$ ($\text{R} = \text{Ba}, \text{Sr}^-$) at about 36 K or more (Bednorz and Muller 1986; Uchida *et al* 1987; Chu *et al* 1987; Cava *et al* 1987; Ganguly *et al* 1987) there has been an explosion of research activity in this field all over the world. Subsequently superconductivity at still higher temperature of 93 K in mixed phase Y-Ba-Cu-O compound system (Wu *et al* 1987) and at 155 K in $\text{Y}_1\text{Ba}_2\text{Cu}_3\text{F}_2\text{O}_y$ (Ovshinsky *et al* 1987) has been reported. There are reports of still high T_c 's with the onset of superconductivity almost at room temperature (Jayaram *et al* 1987).

In fact the question that is uppermost in the minds of both experimentalists and theorists is whether these oxide superconductors are BCS superconductors driven by phonon coupling of electron pairs. Several new mechanisms have already been proposed namely resonating valence bond model (Anderson 1987), charge transfer excitations (Varma *et al* 1987), structural distortion interaction (Vujicic *et al* 1981) and virtual exchange of electronic excitations (Jagdish and Sinha 1987) and coupling through excitons (Singh 1976, unpublished; Singh and Sinha 1987). There are doubts amongst theorists about the efficacy of the electron phonon mechanism of superconductivity in the high T_c oxide superconductors. This is based on the notion that there is an upper limit for T_c and temperatures above $T_c \sim 28$ K cannot be reached using phonon-assisted mechanism although this view is not shared by many others (Ginzburg 1972; Allen and Dynes 1975a, b).

The purpose of this note is to reassert that phonon-mediated electron-electron coupling is capable of explaining the observed range of transition temperatures at least in $\text{La}_{2-x}(\text{BaSr})_x\text{Cu-O}_4$ systems and for superconductors of Y-Ba-Cu-O series other mechanisms such as excitons (Allender *et al* 1973; Singh 1976) plasmons (Kresin 1987) polaron and bipolarons (Chakraverty 1979; Alexandrov and Ranninger 1974; Nasu 1987) and resonating valence bond model (Anderson 1987) would have to be invoked.

Following Allen and Dynes (1975a, b) the solution of the Eliashberg equation for

electron-phonon coupling constant larger than unity, the transition temperature is given by

$$T_c \sim 0.18 (\lambda \langle \omega^2 \rangle)^{1/2}$$

where λ is the electron-phonon coupling constant and ω is the vibrational excitation frequency of the atomic mass in the present case of oxygen atom/ion. It is clear from the above as demonstrated by Allen and Dynes that there is no upper limit for T_c as T_c scales as fast as $\lambda^{1/2}$ for large $\lambda > 1$. T_c can therefore be arbitrarily large. It is in fact interesting to note the remark of Allen and Dynes that T_c values are not limited by λ but by the metallurgy and chemistry of the compound as perhaps exemplified by the newly discovered oxide superconductors.

There is evidence of strong coupling of optical phonons of the oxygen atoms to the Cu 3d electrons (Weber 1987). Weber in his study of the electron-phonon interaction in $\text{La}_{2-x}(\text{BaSr})_x\text{CuO}_4$ superconductors based on energy band structure results of Mattheiss (1987) finds $\lambda \sim 2$. This suggests that these are strong coupled superconductors and we should exploit strong coupling theory of McMillan (1972) as modified by Allen and Dynes (1975).

Following Allen and Dynes the transition temperature can be expressed as

$$T_c \sim \langle \omega \rangle \exp[-1.04(1 + \lambda)/\lambda]$$

where $\langle \omega \rangle$ is the average phonon frequency which we shall take as the phonon frequency for the optical vibrations of the oxygen atoms which are very high frequency modes due to the light mass of the O atoms and these span comparatively large temperature scale (Debye temperatures). Here we have neglected screened Coulomb interaction μ as it is believed that $\lambda > \mu$ (Varma *et al* 1987) is the result of screening of the conduction electrons.

Using the above expression we get the following values of T_c .

λ	$\langle \omega \rangle$	T_c (K)
0.5	600	26.4
1.0	300	36
1.5	500	90
2.0	400	84

Thus it is obvious that the optical phonon assisted mechanism of superconductivity is capable of explaining the entire range of values of T_c . It should be noted here that Kwok *et al* (1987) on the basis of the results of the measurements of resistivity, magnetoresistance, transition temperature and upper critical field have concluded that phonon mechanism of superconductivity can explain high transition temperatures in these materials.

For $\lambda = 1$ and $\langle \omega \rangle = 300$ K the value of T_c is 36 K which is appropriate for $\text{La}(\text{Ba/Sr})\text{CuO}$ systems. Weber (1987) in his study of electron-phonon interaction in these new high T_c superconductors has found that the coupling of the specific O phonons to the conduction electrons is very strong ($\lambda \gtrsim 2$) and this leads to T_c values of the order of 30–40 K for these oxide superconductors. Leavens and Carbotte (1974)

and Cowan and Carbotte (1978) have also studied enhancement of T_c with electron-phonon interaction.

The absence of isotope effect (Batlogg *et al* 1987) in these oxide ceramic superconductors is intriguing and seems to cast doubts about the phonons being involved in the formation of the superconducting ground state. Although it is not entirely clear as to what exactly is the nature of the mechanism of superconductivity, the enhancement of T_c may be due to the combined effect of large electron-phonon parameter and involvement of high frequency optical phonons (Strongin *et al* 1987). It should however be pointed out that other mechanisms such as excitonic and bipolaronic may also be important.

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References

- Alexandrov A and Ranninger J 1981 *Phys. Rev.* **B24** 1164
 Allen P B and Dynes R C 1975a *Phys. Rev.* **B12** 905
 Allen P B and Dynes R C 1975b *J. Phys.* **C8** L158
 Allender D, Bray J and Bardeen J 1973 *Phys. Rev.* **B7** 1020
 Anderson P W 1987 *Science* **235** 196
 Batlogg B *et al* 1987 *Phys. Rev. Lett.* **58** 2333
 Bednorz J G and Muller K A 1986 *Z. Phys.* **B64** 189
 Cava R J, Van Dover R B, Batlogg B and Rietman E A 1987 *Phys. Rev. Lett.* **58** 408
 Chakraverty B K 1979 *J. Phys. (Paris)* **40** L99
 Chu C W, Hor P H, Meng R L, Gao L, Huang Z J and Wang Y Q 1987 *Phys. Rev. Lett.* **58** 405
 Cowan W B and Carbotte J P 1978 *Solid State Phys.* **C11** L265
 Ganguly P, Mohan Ram P A, Sreedhar K and Rao C N R 1987 *Pramana-J. Phys.* **28** 321
 Ginzburg V L and Kirzhnits D A 1972 *Phys. Rep.* **4** 343
 Jagdish R and Sinha K P 1987a *Pramana-J. Phys.* **28** L317
 Jagdish R and Sinha K P 1987b *Curr. Sci.* **56** 291
 Jayaram B, Agarwal S K, Gupta A and Narlikar A V 1987 *Curr. Sci.* **56** 572
 Kwok W K, Crabtree G W, Hinks D G, Capone D W, Jorgensen J D and Zhang K 1987 *Phys. Rev.* **B35** 5343
 Kresin V Z 1987 *Phys. Rev. B* (to be published)
 Leavens R C and Carbotte J P 1974 *J. Low Temp. Phys.* **14** 195
 Mattheiss L F 1987 *Phys. Rev.* **58** 1028
 McMillan W L 1968 *Phys. Rev.* **167** 331
 Nasu K 1987 *Phys. Rev.* **B35** 1978
 Ovshinsky S R, Young R J, Alfred D D, DeMaggio G and Van der Leeden G A 1987 *Phys. Rev. Lett.* **58** 2579
 Singh P and Sinha K P 1987 (to be published)
 Strongin M, Welch D and Davenport J W 1987 *Nature (London)* **335** 664
 Uchida S, Takagi H, Kitazawa K and Tanaka S 1987 *Jpn. J. Appl. Phys.* **26** L1
 Varma C M, Rink Schmitt and Abrahams E 1987 *Solid State Commun.* **62** 681
 Vujicic G M, Aksenov V, Plankida N M and Stamenkovic S 1981 *J. Phys. Solid State Phys.* **14** 2377
 Weber W 1987 *Phys. Rev. Lett.* **58** 1371
 Wu M K, Ashburn J R, Torng C J, Hor P H, Meng R L, Gao L, Huang Z J, Wang Y Q and Wu C W 1987 *Phys. Rev. Lett.* **58** 908