On the role of acoustic plasmons in high $T_c$ superconductors

V M NANDAKUMARAN
Department of Physics, Cochin University of Science and Technology, Cochin 682 022, India

MS received 1 June 1987

Abstract. The role of acoustic plasmons in the recently discovered high $T_c$ superconductors is discussed. It is shown that the exchange of acoustic plasmons together with the usual phonon exchange between electrons can give rise to a $T_c \sim 100$ K.

Keywords. High temperature superconductivity; lanthanum barium copper oxide; acoustic plasmon.

PACS Nos 74·10; 74·20; 74·70

The discovery of high $T_c$ ($\sim 50$ K) superconductivity in doped lanthanum copper oxide systems has activated intense research all over the world (Bednorz and Muller 1986; Cava et al 1987; Chu et al 1987; Uchida et al 1987; Ganguly et al 1987). These materials typically have the composition La$_{2-x}$Ba$_x$CuO$_4$. It is known (McMillan 1968) that the electron-electron interaction mediated by acoustic phonons cannot give a transition temperature greater than 28 K. Therefore, one has to look for alternative mechanisms to account for the observation of superconductivity at such high temperatures. In the past, various mechanisms involving excitations such as excitons have been suggested for increasing the transition temperature (Allender et al 1973; Ginzburg and Kirzhnits 1982). In a recent paper Jagadish and Sinha (1987) proposed an electronic mechanism for explaining the observed high $T_c$ in the doped lanthanum copper oxide systems. In this communication, we discuss the role of acoustic plasmons in giving rise to the high $T_c$. This mechanism could in fact supplement the others in enhancing the transition temperatures.

Acoustic plasmons can be excited in systems consisting of two species of electrons having different effective masses (Töttö and Ruvalds 1979; Kahn and Ruvalds 1979; Ruvalds 1981). In solids containing lanthanum or any of the rare earth elements the electrons in the s and f bands have quite different effective masses. Denoting the respective effective masses by $m_s$ and $m_f$ we have $m_f > m_s$. Therefore in compounds containing rare earth atoms acoustic plasmons can be excited. The Hamiltonian for such a system can be written as

$$H = \sum_k \epsilon_f(k)c_k^+c_k + \sum_k \epsilon_n(k)d_k^+d_k$$
$$+ \sum_q \omega_q(\beta_q^+\beta_q + \frac{1}{2}) + \sum_q \Omega(q)(\alpha_q^+\alpha_q + \frac{1}{2})$$
$$+ \sum_q V_1\rho_q(\beta_q + \beta_{-q}^+) + \sum_k V_2\rho_q(\alpha_q + \alpha_{-q}^+)$$

(1)
where

\[
\rho_q = \sum_k (c_{k+q}^+ c_k + d_{k+q}^+ d_k),
\]

\[
(2)
\]

\(c_k^+\), \(c_k\) and \(d_k^+\), \(d_k\) are the electron operators and \(\epsilon_l\) and \(\epsilon_h\) the energies for the light and heavy electrons, \(\beta_q^+\), \(\beta_q\) are the phonon operators and \(\alpha_q^+\) and \(\alpha_q\) are the plasmon operators. \(\Omega(q)\) is the acoustic plasmon energy. \(V_1\) and \(V_2\) are respectively the electron-phonon and the electron-plasmon interaction constants.

It is known (Ruvalds 1981) that under certain conditions the exchange of acoustic plasmons can lead to an attractive interaction between the electrons. In what follows, we assume that these conditions are met. We also assume that the usual phonon-induced electron-electron interaction is also present in the system.

The effective interaction between the electrons can be characterised by two coupling constants \(\lambda_{ph}\) and \(\lambda_{pl}\). Following Vujicic et al. (1981) and after incorporating suitable modifications one can obtain an effective coupling constant \(\lambda\) given by

\[
\lambda = \lambda_{ph} + \frac{\lambda_{pl} - \mu^*}{1 - (\lambda_{pl} - \mu^*) \ln (\omega_{pl}/\omega_D)} \tag{3}
\]

In (3), \(\mu^*\) gives the effect of Coulomb interactions, \(\omega_{pl}\) and \(\omega_{ph}\) are the average plasmon and phonon energies. The transition temperature is given by (Vujicic et al. 1981)

\[
T = 1.14 \omega_D \exp (-1/\lambda). \tag{4}
\]

The average acoustic plasmon energy is quite large ~ 2000 K and \(\omega_D \sim 300\) K. \(\lambda_{pl}\) and \(\lambda_{ph}\) are roughly of the same order of magnitude (Tütto and Ruvalds 1979). Below we give some typical values of the parameters and the corresponding transition temperatures.

\[
\mu^* = 0.1; \quad \omega_{pl} = 2000 \text{ K}; \quad \omega_D = 300 \text{ K}
\]
\[
\lambda_{pl} = 0.3; \quad \lambda_{ph} = 0.3; \quad T_c = 68 \text{ K}
\]
\[
\lambda_{pl} = 0.3; \quad \lambda_{ph} = 0.4; \quad T_c = 86 \text{ K}
\]
\[
\lambda_{pl} = 0.4; \quad \lambda_{ph} = 0.4; \quad T_c = 137 \text{ K}
\]

Thus the interaction mediated by acoustic plasmons along with the usual phonon mechanism could give \(T_c \sim 100\) K.

\textit{Note added:} After sending the manuscript we have come to know that similar ideas have been independently suggested by V Kresin (Kresin 1987, to be published) and also by J Ruvalds (Ruvalds 1987, to be published). We thank one of the referees for bringing this fact to our notice.

\textbf{References}

Bednorz J G and Müller K A 1986 \textit{Z. Phys. B} 64 189
Acoustic plasmons in high $T_c$ superconductors

McMillan W L 1968 Phys. Rev. 167 331