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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

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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.

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The discovery of high T_c ($\simeq 50$ 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 $La_{2-x}Ba_xCuO_4$. It is known (Mc Millan 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 (Tüttö 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

$$H = \sum_{\mathbf{k}} \varepsilon_l(\mathbf{k}) c_{\mathbf{k}}^+ c_{\mathbf{k}} + \sum_{\mathbf{k}} \varepsilon_h(\mathbf{k}) d_{\mathbf{k}}^+ d_{\mathbf{k}} + \sum_{\mathbf{q}} \omega_{\mathbf{q}} (\beta_{\mathbf{q}}^+ \beta_{\mathbf{q}} + \tfrac{1}{2}) + \sum_{\mathbf{q}} \Omega(\mathbf{q}) (\alpha_{\mathbf{q}}^+ \alpha_{\mathbf{q}} + \tfrac{1}{2}) + \sum_{\mathbf{q}} V_1 \rho_{\mathbf{q}} (\beta_{\mathbf{q}} + \beta_{-\mathbf{q}}^+) + \sum_{\mathbf{k}} V_2 \rho_{\mathbf{q}} (\alpha_{\mathbf{q}} + \alpha_{-\mathbf{q}}^+) \quad (1)$$

where

$$\rho_{\mathbf{q}} = \sum_{\mathbf{k}} (c^{+}_{\mathbf{k}+\mathbf{q}} c_{\mathbf{k}} + d^{+}_{\mathbf{k}+\mathbf{q}} d_{\mathbf{k}}), \tag{2}$$

$c^{+}_{\mathbf{k}}\ c_{\mathbf{k}}$ and $d^{+}_{\mathbf{k}}\ d_{\mathbf{k}}$ are the electron operators and ε_l and ε_h the energies for the light and heavy electrons, $\beta^{+}_{\mathbf{q}}$, $\beta_{\mathbf{q}}$ are the phonon operators and $\alpha^{+}_{\mathbf{q}}$ and $\alpha_{\mathbf{q}}$ are the plasmon operators. $\Omega(\mathbf{q})$ 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 λ_{ph} and λ_{pl}. Following Vujicic *et al* (1981) and after incorporating suitable modifications one can obtain an effective coupling constant λ given by

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

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

$$T \simeq 1{\cdot}14\ \omega_D \exp(-1/\lambda). \tag{4}$$

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

$\mu^* = 0{\cdot}1$;	$\omega_{\text{pl}} = 2000$ K;	$\omega_D = 300$ K
$\lambda_{\text{pl}} = 0{\cdot}3$;	$\lambda_{\text{ph}} = 0{\cdot}3$;	$T_c \simeq 68$ K
$\lambda_{\text{pl}} = 0{\cdot}3$;	$\lambda_{\text{ph}} = 0{\cdot}4$;	$T_c \simeq 86$ K
$\lambda_{\text{pl}} = 0{\cdot}4$;	$\lambda_{\text{ph}} = 0{\cdot}4$;	$T_c \simeq 137$ K

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

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.

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