Aust. J. Phys., 1989, **42**, 541–4

A Dielectric Approach to High Temperature Superconductivity*

J. Mahanty and M. P. Das

Department of Theoretical Physics, Research School of Physical Sciences,
Australian National University, Canberra, A.C.T. 2601, Australia.

Abstract

In this paper we investigate the dielectric response of an electron–ion system to the presence of a pair of charges. From the nature of the dielectric function, it is shown that a strong attractive pair formation is possible depending on the dispersion of the ion branches. The latter brings a reduction to the sound velocity which is used as a criterion for the superconductivity. By solving the BCS equation with the above dielectric function, we obtain a reasonable value of T_C.

The theory of superconductivity is usually considered in two steps: (a) a mechanism for the formation of pairs of charges and (b) condensation of such pairs analogous to Bose condensation in the superfluids. During the past two years there has been intense activity in the field of high temperature superconductivity and a number of mechanisms (with or without phonons) have been proposed. Yet, there is no consensus on which microscopic mechanism is operative in making the pairs.

Experiments on flux quantisation, the AC Josephson effect, measurement of the unit flux of a vortex lattice and Andreev reflection have unambiguously established that the charge carrier of the superconducting current in the high T_C oxide materials has the charge $2e$, as on a Cooper pair. Therefore, an explanation of high T_C superconductivity must lie in a pairing mechanism that leads to strongly bound Cooper pairs.

While some believe that the phonon mechanism of the sort considered in the original BCS theory is not likely to give a T_C value in excess of 25 K, this has not been rigorously established. There are many other models which rely on the BCS picture but replace the phonon by another boson, such as a plasmon, exciton or magnon, as the mediator causing the attraction between a pair of charges. It is well known that in the strong coupling regime, the BCS equation is inadequate. It does not take into account the retardation effects due to the electron–phonon interaction. Therefore, it is necessary to solve the Eliashberg equation instead of the BCS equation. It is to be noted that the latter approach is not easy to implement since one requires a knowledge

* Paper presented at the DITAC Conference on Superconductivity held in Canberra, 13–14 February 1989.

0004-9506/89/050541$03.00

of the self-consistent phonon spectrum and the electronic structure (Pickett 1989). In the extreme strong-coupling limit (Allen and Dynes 1975; Kresin 1987) it has been shown that the critical temperature T_c is $\sim\sqrt{\lambda}$, where λ is the coupling strength. In this limit one has to be careful about satisfying Migdal's theorem, which demands the stability of the lattice. If one is not in the strong-coupling limit, a solution of the BCS equation should provide a reasonable qualitative answer.

The normal state electrical and magnetic properties of the high T_c phase clearly show that the oxide superconductors are Pauli paramagnetic metals. Contrary to the claim made in a class of theories based on magnetism, there is little evidence of spin correlations in the high T_c composition. On the other hand, there seem to be several experimental results which favour phonons as a possible mediator for the attractive interaction of the pairs:

(1) The shift of T_c on the oxygen isotopic substitution is observed in all oxide superconductors (Allen 1988; Hoen *et al.* 1989; Katayama-Yoshida *et al.* 1988). Though the value of the shift is lower than expected quantitatively in the conventional BCS theory, the shift implies some role for phonons.

(2) Temperature dependence of the velocity of sound shows an anomaly around T_c (Chernozatonskii *et al.* 1988) which is indicative of a phonon branch going soft.

(3) Tunneling and neutron data are compatible (Bulaevski *et al.* 1988) which implies that the electron–electron interaction is phonon-mediated. Besides, there is asymmetry in the dI/dV versus V plot in the tunneling spectra (de Lozanne 1989) that relates to the retarded interaction, possible in the case of the electron–phonon interaction.

In view of these observations we consider phonons to be relevant in high T_c superconductors and feel that the theory requires modification by taking into account the complexity of the structure and the excitations of the systems. The attractive interaction that leads to the formation of Cooper pairs should, by necessity, arise out of the screening property of the medium in which the charges pair up. Primarily, it is this aspect which we report in this paper (see also Mahanty and Das 1988, 1989).

We consider a pair of charges in a medium treated as a multi-component plasma consisting of electrons and several kinds of ions. The bare Coulomb interaction between the charges is screened by the medium dielectric function $\epsilon(\boldsymbol{q},\omega)$. From the zeros of the dielectric function the ion acoustic branch can be obtained. The dispersion slope of this branch gives the velocity of sound and the latter depends on the average mass of the ion species. It is to be noted that the isotopic shift depends on this average mass. We calculate the static dielectric function which is obtained in the Thomas–Fermi form by

$$\epsilon^{-1}(\boldsymbol{q},0)=1/(1+q_0^2/q^2)\,, \tag{1}$$

where

$$q_0^2=\sum_{\nu}(\omega_\nu^2/\beta_\nu^2)\,, \tag{2}$$

and where ω_ν and β_ν are the frequency and dispersion parameters of the νth plasma branch. If some of the ion plasma branches have small negative dispersion because of the non-Coulombic nature of interionic potentials, there is a possibility of q_0^2 becoming negative. The sound velocity is obtained as

$$v_s^2 = \sum_\nu{}' \beta_\nu^2 + v_0^2, \qquad \text{where} \quad v_0^2 = \sum_\nu{}' \omega_\nu^2/\kappa_{TF}^2 . \tag{3}$$

Here κ_{TF} is the Thomas–Fermi screening length. The prime over the summation sign excludes the electron branch. For the system to be stable, sound must pass through the system. For some negatively dispersed ionic branches, if the first term of (3) is negative but less than the second term so that v_s^2 is positive, the stability of the system is maintained. The reduction of sound velocity ($v_s < v_0$) was earlier considered by Kulik (1965) as a criterion for superconductivity. Negative values of q_0^2 make the screened Coulomb potential negative in certain regions in $\boldsymbol{q}$ space (Mahanty and Das 1988) and hence there is attraction between the pair of charges.

We consider a two component electron and ion plasma and then calculate the dielectric function and the screened potential. Although for strong coupling it would be better to use the more general Eliashberg equation, here we study the simpler BCS equation in order to obtain some idea of the possible effects of the type of dielectric function we are discussing. Now we use the screened potential in the BCS gap equation and solve it in the isotropic case. Denoting $x = v_s^2/v_0^2$ as a parameter accounting for the reduction of sound velocity, we find that the solution of the gap equation exists in the range $x_0 < x < 1$, where $x_0 = 2k_F^2/(2k_F^2+\kappa_{TF}^2)$. Here k_F is the Fermi momentum. The scale of energy in our case is the highest energy of the ion acoustic mode (i.e. the Debye energy). It is possible to have the gap energy of the order of the Debye energy in the range of x values.

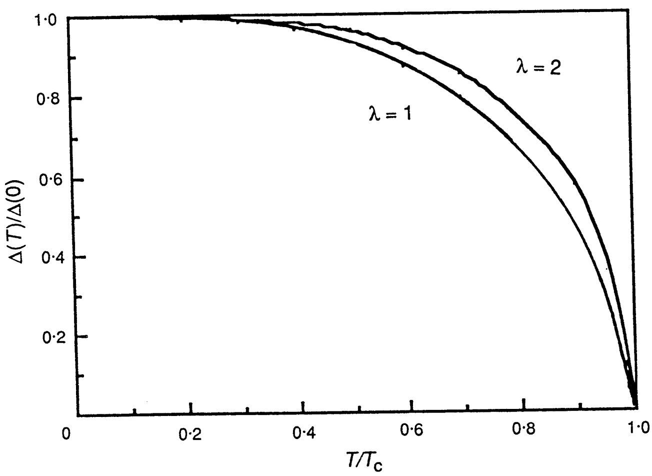

Fig. 1. Ratio $\Delta(T)/\Delta(0)$ as a function of T/T_c for the two different couplings $\lambda = 1$ and $\lambda = 2$.

Since $k_B T/\hbar\omega_D$ is not very small as in the weak-coupling BCS model, we solve the temperature-dependent gap equation numerically. At $T = T_c$, we have $\Delta \to 0$. In Fig. 1 we show $\Delta(T)/\Delta(0)$ as a function of T/T_c for two coupling strengths λ, defined as $\lambda = [N(0)V]^{-1}$, where $N(0)$ is the density of states at the Fermi level,

$$V = (2\pi e^2\,|I|)/k_F^2, \tag{4}$$

$$I = \int_0^{2k_F} dq\, q/(q^2 - \kappa_0^2), \tag{5}$$

and where $\kappa_0^2 \equiv |q_0^2|$. Note that our definition of λ is the inverse of λ in the conventional theory. Larger values of λ correspond to weaker coupling. Experimentally observed gaps in far IR and tunneling are qualitatively similar, as shown in Fig. 1.

In summary, we have studied a possible mechanism in the high T_c oxides through a dielectric screening approach. In the presence of negative dispersion of the ion plasma branches satisfying certain conditions like stability of the system, the screened potential is oscillatory in real space. In this situation we have shown that it is possible to have strongly bound Cooper pairs which lead to high T_c superconductivity. One consequence of negative dispersion is in a lowering of the sound velocity, as seen in experiments on $YBa_2Cu_3O_{7-y}$ systems (Jericho *et al.* 1988). As an improvement of the model described above, we have considered the ions on a lattice and the electrons forming a continuous distribution. We are presently investigating the dielectric response of such electron–ion systems to the presence of a pair of charges.

We wish to note here that a number of papers have appeared recently in which electronic polarisation has been considered in a different manner as a possible mechanism for high T_c superconductivity (Ashcroft 1987; Hirsch 1989; Mattis 1988; Tachiki and Takahashi 1989). These results in some respect are complementary to the picture we have presented here.

References

Allen, P. B. (1988). *Nature* **335**, 396.

Allen, P. B., and Dynes, R. C. (1975). *Phys. Rev.* B **12**, 905.

Ashcroft, N. W. (1987). *In* 'Novel Superconductivity' (Eds S. E. Wolf and V. Z. Kresin), p. 301 (Plenum: New York).

Bulaevski, L. N., Dolgov, O. V., Ptitsyn, M. O., and Vedeneev, S. I. (1988). Proc. First Asia–Pacific Conf. on Condensed Matter Physics (Eds B. E. Baaquie *et al.*), p. 18 (World Scientific: Singapore).

Chernozatonskii, L. A., Golovashkin, A. I., Ivanenko, O. M., Mitsen, K. V., Pal'tsev, L. L., Pustovolt, V. I., Tokarev, E. F., Khatomov, F. Sh., and Shorin, V. N. (1988). *Sov. Phys. Solid State* **30**, 510.

de Lozanne, A. (1989). *Mod. Phys. Lett.* B **3**, 107.

Hirsch, J. (1989). *Phys. Lett.* A **134**, 451.

Hoen, S., Creager, W. N., Bourne, L. C., Crommie, M. F., Barbee, T. W. III, Cohen, M. L., and Zettl, A. (1989). *Phys. Rev.* B **39**, 2269.

Jericho, M. H., Simpson, A. M., Tarascon, J. M., Green, L. H., McKinnon, R., and Hall, G. (1988). *Sol. State Commun.* **65**, 987.

Katayama-Yoshida, H., *et al.* (1988). *Physica* C **156**, 481.

Kresin, V. Z. (1987). *Phys. Lett.* A **122**, 434.

Kulik, I. O. (1965). *Sov. Phys. JETP* **20**, 1450.

Mahanty, J., and Das, M. P. (1988). *Int. J. Mod. Phys.* B **2**, 873.

Mahanty, J., and Das, M. P. (1989). *J. Phys.* (in press).

Mattis, D. C. (1988). Theory of high temperature superconductivity: Overlap of Wannier functions and the role of dielectric screening. Univ. of Utah preprint.

Pickett, W. E. (1989). *Rev. Mod. Phys.* **61**, 433.

Tachiki, M., and Takahashi, S. (1989). *Phys. Rev.* B **38**, 218.

Manuscript received 10 April, accepted 1 August 1989