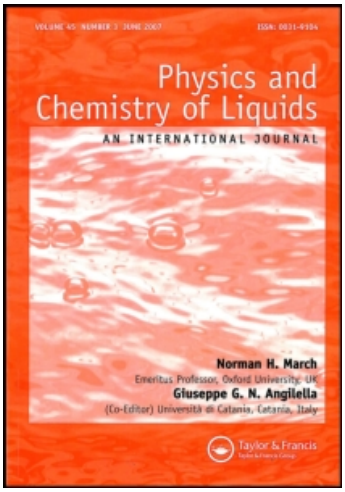

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Electron/hole liquids in high T_c superconductors and easy paths for supercarriers through the vibrational lattice

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In a recent study in this Journal, of manifestly BCS body-centred-cubic transition metals, we presented a picture of *easy paths* for the supercarriers (Cooper pairs) based on electron-lattice properties. Turning to high T_c cuprates, it has been advocated for a long time that phonons play only a minor role. That point of view is challenged here by appealing first to fairly recent experiments on the oxygen isotope effects in the CuO_2 planes of high T_c materials and secondly to measurements on the enhancement of T_c by epitaxial strain. Again, we advocate *easy paths* for supercarriers to travel through the vibrating lattice in a high T_c family as consistent with these quite different experiments. However, these arguments apply to $T_c/T_c^{\max}$ for such a family such that $T_c^{\max}$, which is the maximum T_c within a family, depends importantly on anti-ferromagnetic spin fluctuations. But, we expect the variation of $T_c/T_c^{\max}$ within such a family to correlate with *easy paths* for supercarriers to travel through the vibrating lattice.

Keywords: electron/hole liquids; high T_c cuprates; oxygen isotope effects

1. Introduction

In some earlier work, one of us [1] had been concerned with generalising the important Uemura plots [2–4] for the transition temperature T_c of the high T_c cuprates. While Uemura *et al*. clearly recognised the importance of the appearance in the denominator of any realiztic formula for T_c of the effective mass m^*, Angilella *et al*. [1] proposed, via a kinetic energy (KE) of localisation proportional to $\hbar^2/(m^*\xi^2)$, that the characteristic length ξ appearing in this localisation formula for KE should be the coherence length for these superconductors. Such an approach leads to $T_c \sim \hbar^2/(m^*\xi^2)$. This was brought into contact with experiment not only for the cuprates, but also for heavy fermion superconductors and for some doped fullerides.

More recently, we focussed on the more conventional BCS materials in the form of the bcc transition metals [5]. There, we put forward the concept of *easy paths* through the bcc vibrating lattice for Cooper pairs, or *supercarriers* to move without scattering. It is the purpose of the present study to examine whether this concept of *easy paths* for the *supercarriers* through the vibrating lattice continues to have validity in the cuprate high T_c superconductors (HTS).

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The motivation for re-opening this issue has come from a number of recent contributions. One is, in fact, a *toy model* of high T_c copper oxides proposed very recently by Jarlborg [6]. In this work, the generic band structure of high T_c cuprates was simulated by the nearly-free-electron model in two dimensions, with parameters obtained from *ab initio* linear muffin-tin-orbital calculations. This study stressed that the interaction between phonons and spin waves results in potential modulations. This subsumes into the toy model the relevance of phonons in the cuprates by isotope effects on T_c and pseudo-gaps [7,8], while the role of magnetic fluctuations has been detected by neutron scattering experiments [9]. However, Jarlborg [6], in conclusion, points out that the results obtained 'are not sufficiently complete for an evaluation of T_c through a BCS-like formula'.

This is the point then at which we shall attempt to relate the above considerations, when combined with the earlier studies of Schneider and Keller [10], to the ideas put forward by us on the bcc transition metal superconductors [5] of *easy paths* through the vibrating lattice for Cooper pairs, the known *supercarriers* in the BCS materials.

2. Zeroth-order proposal to separate T_c within a family of cuprates into a product of two terms: one dependent on the vibrating lattice and a second reflecting spin fluctuations

Following, for example, Khasanov *et al.* [7], we shall write T_c in dimensionless form as

$$t_c = \frac{T_c}{T_c^m}, \tag{1}$$

where T_c^m is the maximum transition temperature of a given family of cuprate HTS. The experimental isotope effect may be expressed through the equation

$$t_c \propto m^{-\alpha}, \text{ with } \alpha = -\frac{d\ln T_c}{d\ln m}, \tag{2}$$

where m is the isotopic mass and α the isotope effect exponent. In the simplest limit of weak-coupling BCS theory, $T_c \propto m^{-1/2}$ and $\alpha_{BCS} \approx 0.5$, the latter being in accord with experiment for a number of conventional metal superconductors. However, it should be noted here that there are important exceptions to this *Frohlich-like rule*: e.g. for Zr and Ru, $\alpha_{BCS} \sim 0$.

In their studies of muon spin rotation of the cuprate HTS, Khasanov *et al.* [7] plotted the oxygen isotope effect exponent, say α_O, *versus* the reduced temperature $t_c = T_c/T_c^{\max}$ for four different families of superconductors. They showed that the data is unified and well described by the formula

$$\alpha_O = \frac{1}{4}\frac{(1-t_c)^{1/2}}{t_c}. \tag{3}$$

This is in accordance with the earlier result of Schneider and Keller [10]. Interestingly, Schneider and Keller also showed that for the cuprate HTS, both the pressure co-efficient and the isotope effect co-efficient of the critical temperature had the same dependence on t_c.

Locquet *et al.* [11] have shown that the critical temperature T_c of a particular copper oxide can be increased by the use of epitaxial strain. The factor by which it is increased is greater than that was previously found in high pressure studies. We suggest that this

finding is consistent with the opening up of *easy paths* for the supercarriers, resulting in an increase in T_c as the distance between consecutive CuO_2 planes is increased.

For the underdoped cuprates, the superconducting transition temperature, T_c, depends on three physical properties of the family of materials under consideration: namely; (i) the effective mass of the carriers, as recognised by the early work of Uemura *et al.* [2]; (ii) the coherence length, ξ [1]; and (iii) the oxygen (O)-isotope effect parameter α_O [7]. Returning to Equation (1) above (see also [7]) and in the parlance of the Jarlborg model, we shall assume, in the zeroth-order approximation, that T_c^m is the place where the spin fluctuations play an essential role and that t_c is essentially to do with *easy paths* of the supercarriers through the vibrating lattice, prompted by the experimental findings of Locquet *et al.* [11] already referred to.

Then, combining the Jarlborg toy model with the experimental study of Khasanov *et al.* [7] and following the theoretical proposals of Schneider and Keller [10] and Angilella *et al.* [1], in this zeroth-order approximation, we propose that the dependence on α_O factorises out of T_c via a dimensionless function given explicitly below

$$T_c = T_c(m^*, \xi, \alpha_O) = \frac{(\sqrt{5}-1)}{16\alpha_O^2} f\left(\frac{h^2}{m^*\xi^2}\right) \tag{4}$$

and where the function $f(\frac{h^2}{m^*\xi^2})$ is intimately connected to the spin fluctuation temperature T_{sf} discussed by Monthoux and Lonzarich [12] and also by Abanov and Chubukov [13]. We reiterate that the basis for this proposal (Equation (4)) rests on both the experimental studies of Khasanov *et al.* [7], as shown especially in their Figure 4, and in the theoretical study of Angilella *et al.* [1], following work on the spin fluctuation temperature [12,13].

Angilella *et al.* [1] have proposed a small x expansion of the function $f(x)$ entering Equation (4) but it would take us too far from the major theme of the present article to go into further details. However, Equation (4) contracts the variable form $T_c(m^*, \xi, \alpha_O)$ into $T_c = T_c(m^*\xi^2, \alpha_O)$ where the α_O dependence is given explicitly in Equation (3), following from the form given in [10].

3. Conclusion

The main conclusion of the present study is that, for the families of under-doped cuprates, the superconducting transition temperature, T_c, which depends on three physical properties of the family, may be written as a product of a term depending on the spin-fluctuation temperature and one containing the oxygen isotope co-efficient. While the former is less tractable, the latter dependence is rather clearly defined through both experimental [7] and theoretical studies [10]. It is further proposed that as the t_c dependence on the isotope effect co-efficient and the pressure co-efficient is of similar form, the first term in Equation (4) may be restated as describing the pressure dependence of t_c which in turn indicates the presence of *easy paths* for the supercarriers in these materials.

With regard to the relative importance of spins *versus* phonons as one goes from underdoping through the 'T_c dome' to overdoping, this can be understood via a beautiful picture in the early article by Fisk and Pines [14]. In their Figure 1, they depict two sources of superconductivity. On the left is the interaction potential generated by a (test) charge moving through the material. On the right, they display an interaction potential having quite similar form, but due to the spin–spin interaction. The left-hand side can be thought

of as BCS, appropriate to materials discussed in [5] via 'easy paths' for Cooper pairs. In contrast, the right-handside is the other extreme picture: where all attention is focussed on the spin–spin interaction. The present work puts these two types together, and makes the proposal therefore that T_c takes the form shown in Equation (4) above for the cuprate HTS. Of course, it is important for the future to test Equation (4), and if it proves necessary, to add to the present proposal a (hopefully small) term which is not represented as a separable form but has both α_0, ξ and m^*. Finally, though no decisive answer is presently known to the referee's question posed above, we anticipate from the 'toy model' of Jarlborg [6] that the strength of the coupling between spins and phonons may weaken somewhat in the overdoped regime.

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