DETERMINATION OF RETARDATION EFFECTS IN THE HIGH Tc CUPRATES FROM SHARVIN CONTACT MEASUREMENTS

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Abstract

It is well known that retardation effects are essential to allow the attractive part of the electron-electron interaction (for instance, phonon mediated) to overcome the Coulomb repulsion. In new superconductors such as the cuprates for which the interaction is a priori unknown, it is therefore essential to determine the retarded .and non retarded parts of the interaction. We show how this can be achieved by an analysis of Sharvin contact measurements between a noble metal tip and a cuprate. It turns out that both the retarded and non retarded parts are large, the former being however larger than the later.

1 Introduction

In the known theory of superconductivity, retardation effects play an essential role. The phonon mediated electron-electron interaction can overcome the Coulomb repulsion because of the large difference between the (low) phonon frequencies and the (high) electronic frequency: this large difference allows the interacting electrons to *avoid each other in time.* In usual superconducting metals (such as, say, Al) the phonon and electronic frequencies differ by 2 to 3 orders of magnitude. The effective Coulomb repulsion is then a fraction of its bare value (1) and represents indeed only a small correction to the attractive term.

In terms of Landau's Fermi liquid description, the retarded part of the electron-electron interaction is given by the frequency derivative of the self energy $\sum$ taken at k=k_F, $\epsilon = \epsilon_F$. Although in principle $\sum = \sum(k,\omega)$, it is well known that in

the case where the phonon mediated term dominates over correlation effects the wave vector dependence is nègligible compared to the frequency dependence (2). In simple metals this is indeed the case, i.e. corrections to the effective mass due to correlation effects are small. They have been evaluated for instance by Rice(3). In fact, as shown by Ashkroft and Wilkins (4), the total Coulomb correction to the effective mass is small because the contributions of $\partial \sum / \partial \omega$ and $\partial \sum / \partial k$ are of opposite signs and nearly cancel each other. This is in contrast with the phonon mediated interaction, precisely because of the strong retardation effects mentionned above: $\partial \sum_{ph} / \partial \omega$ is large because of the small characteristic frequencies of the phonons compared to those of the electrons, but $\partial \sum_{ph} / \partial k$ is small because the wave vectors characteristic of the phonons are of the same order as that of the electrons. In the end, in simple metals, $\partial \sum_{ph} / \partial \omega$ dominates the interaction corrections to the effective mass: $\left(\frac{m^*}{m}\right) \equiv \left[1 + \partial \sum_{ph} / \partial \omega\right]$.

Since m^*/m is in principle accessible through experiments conducted in the normal state (for instance by comparing low temperature heat capacity experiments to band mass predictions), it is in principle possible to check the validity of the BCS expression for Tc:

$$T_c = \omega_D \exp\left(-\frac{1}{\lambda}\right) \tag{1}$$

where ω_D is the Debye frequency, or more complex versions of it for the strong coupling case $\lambda > 1$.(5).

It is a priori doubtful that this simple description, where $\lambda = \partial \sum_{ph} / \partial \omega$, is applicable to the cuprates. The vicinity of an insulating, antiferromagnetic state, implies strong electron-electron interactions. $\partial \sum_{el} / \partial \omega$ and $\partial \sum_{el} / \partial k$ may both be large, and not cancel each other out as is practically the case in simple metals. In the absence of a first principle calculation of the self energy, it is then necessary to determine separately *experimentally* its wave vector and frequency derivatives. Should the wave vector dependence turn out to be indeed significant, it would need to be taken into account in a generalised strong coupling Eliashberg theory. An example of such a theory is that of Monthoux and Pines (6) where it is assumed that the main electron interaction takes place through spin fluctuations, rather than through phonons . The wave vector dependence of the interaction is then essential.

In this spirit we review here some recent Point Contact (PC) experiments which show that in the cuprates the retarded and non retarded parts of the interaction are both large and of the same order. It would thus appear that the BCS theory in its simple form does not apply to them. The respective parts of the phonon mediated and direct electron-electron interaction are discussed.

2 Experimental

In their classical work, Blonder, Tinkham and Klapwijk (7) (BTK) have explained the variety of shapes that the I(V) characteristics of superconducting /normal PCs can assume. They have shown that the shape depends primarily on the value of an interface mismatch parameter Z:

$$Z^2 = Z_b^2 + \frac{(1-r)^2}{4r} \tag{2}$$

where Z_b is due to a dielectric barrier and r = (v_{FN}/v_{FS}), v_{FS} and v_{FN} being respectively the superconductor and the normal metal Fermi velocity.

When Z<<1 (high transparency barrier), a quasi-particle incident from the normal side, and having an energy (counted from the Fermi level) smaller than the superconducting gap, cannot penetrate into the S side: instead, it is reflected as a quasi-particle of opposite charge and momentum while a Cooper pair flows into the S side. This is the so called Andreev reflection, which in the considered limit Z<<1 is the only kind of reflection taking place at the S/N interface. The conductance of the PC is then twice as large below the gap than it is above it (or in the normal state).

When Z>>1, reflections at the interface are principally normal reflections and conductance through the PC takes place by tunneling rather than through the Andreev process. The characteristic of the PC is then basically a Giaever characteristic, with a strongly reduced conductance below the gap.

For intermediate values of Z, the zero bias conductance, normalized to the normal state conductance, assumes values between 0 and 2; it crosses 1 for Z $\approx$ 0.5. And the conductance shows a peak at a voltage equal to the gap.

Thus, the .shape of the I(V) characteristic is highly sensitive to the value of Z. This is precisely what allows one to determine the value of Z for a given PC (together with that of the gap) by fitting its characteristic to the BTK theory. For Au/Nb contacts, BTK report Z values as low as 0.2 to 0.3 [?], corresponding to Andreev like characteristics (enhanced conductance below the gap). This is consistent with a weak dielectric barrier and a good match of the Fermi velocities (r not very different from 1).

Because of the known small velocities in the Cuprates, roughly one order of magnitude smaller than in Au, one would expect a different behavior for Au/Cuprate PCs. Then, from Eq.2, Z$\geq$ 2 (the lower bound assumes Z_b = 0) and the characteristics should be Giaever like (with a reduced conductance below the gap). Yet, Hass et al. report observing Au/YBCO (8) and Au/LSCO (9) PCs (with the Au tip oriented along the CuO planes) having Andreev like characteristics (enhanced conductance below the gap) that they fit with Z$\approx$0.3. They conclude from Eq.2 that 0.5 $\leq$r$\leq$ 2 , i.e.that the in plane Fermi velocity in these cuprates must be at least equal to half that in Au or $v_{FS} \succeq 7.10^7$cm/sec.

As noted by the authors, this velocity is significantly higher than the calculated average in plane band velocities in LSCO and YBCO (about 2 to 3.10^7cm/sec (!0)), and it is much larger than quasi-particle velocities obtained from the BCS expression for the coherence length:

$$\xi = \frac{\hbar v_F}{\pi \Delta} \tag{3}$$

Using experimental values for ξ obtained from H_{c2} measurements and Δ values obtained from the PC measurements (about 7meV for LSCO and 20meV for YBCO), one gets $v_F \approx 1.10^7$cm/sec.

It is thus clear that one is in each case dealing in fact with a different kind of velocity. We shall call $\overline{v_F}$ the velocity obtained from PC measurements, v_{FO} the velocity given by band calculations, and v_F the quasi particle velocity entering for instance in the expression for ξ. According to the observation of Hass et al.(8,9) one has for the cuprates:

$$\overline{v_F} > v_{F0} > v_F \tag{4}$$

The last part of this inequality can easily be explained by mass renormalization effects due for instance to the electron-phonon interaction. But why is $\overline{v_F}$ different from (and larger than) the quasi - particle velocity? And how can it even be larger than the band velocity while mass renormalization effects usually produce a mass enhancement (whether their origin lies in the electron-phonon or electron-electron interaction)? . We give below a brief summary of the results of Deutscher and Nozieres (11) (DN) regarding this problem.

3 Theory

The Hamiltonian of an electron gas in a periodic potential, possibly coupled to other degrees of freedom, can be wrtitten as:

$$H = \sum_i \frac{p_i^2}{2m} + V(x) + H_{int} \tag{5}$$

where V(x) is the one body lattice periodic potential and H_{int} contains all interaction terms (including through the electron-phonon coupling).

The one particle Green's function can be wrtitten as:

$$G(k,\omega) = \frac{1}{\epsilon_k - \omega - \sum(k,\omega)} \tag{6}$$

where ϵ_k is the Bloch state bare energy and $\sum$ is the total interaction self energy.

Expanding the self energy near $k = k_F, \omega = \mu$, it is easily seen that:

$$v_F = \left(v_{F0} - \frac{\partial \sum}{\partial k}\right).z \tag{7}$$

where:

$$z = \frac{1}{1 + \frac{\partial \sum}{\partial \omega}} \tag{8}$$

is the mass renormalization factor, often written as $(1+\lambda)^{-1}$.

In simple metals, with weak electron-electron interactions, $(\partial \sum / \partial k)$ can be neglected (compared to v_{F0}) and $v_F = v_{F0}.z$, $z = (1+\lambda_{ep})^{-1}$, where λ_{ep} is the MacMillan parameter for the electron - phonon interaction.. But in general, $v_F = \overline{v_F}.z$, where:

$$\overline{v_F} = \left(v_{FO} - \frac{\partial \sum}{\partial k}\right) \tag{9}$$

In the superconducting state, the Fermi liquid is characterized by an anomalous self-energy Δ_0 and a real gap $\Delta = z.\Delta_0$,the coherence length being given by :

$$\xi = \left(\frac{\hbar v_F}{\pi \Delta}\right) = \left(\frac{\hbar.\overline{v_F}}{\pi \Delta_0}\right) \tag{10}$$

While BTK (7) did not take into account interaction effects in their discussion of the boundary conditions at the S/N interface, DN(11) have considered the case where interaction effects are important on the S side (finite $\partial \sum / \partial k$ and $\partial \sum / \partial \omega$) and negligible on the N side. If the non local part of the interaction is not too large (moderate $\partial \sum / \partial k$) it is still possible to consider the interface as basically sharp. Then it is shown that the relevant Fermi velocity on the S side entering in the boundary condition and the expression for the mismatch parameter Z is $\overline{v_{FS}}$, and not v_F. The local, retarded part of the interaction does not enter in the boundary condition.

This result is particularly applicable to the case of heavy Fermions for which $\partial \sum / \partial \omega$ is very large. It readily explains the observation of Andreev reflections (small z value) in Au/UPt_3 and other PCs with Heavy Fermions (12): since $\partial \sum / \partial \omega$ does not enter in the reflection coefficient, there is no large mismatch between the relevant Fermi velocities of the normal metal and the Heavy Fermion.

We discuss in the next section the significance of the results obtained on the High Tc cuprates.

4 Discussion

As described in the experimental section, analysis of the PC characteristics in terms of the BTK(7) theory lends a value for the mismatch parameter Z. Assum-

ing that the mismatch is due entirely to that of the Fermi velocities, one obtains a lower bound for a Fermi velocity in the S side of the contact, using the Fermi velocity in the N side as a reference. In a Au/cuprate contact one can assume that interaction effects are negligible in N. The relevant velocity in the S side is then $\overline{v_{FS}} = v_F.z^{-1}$. Since v_F can be obtained from the BCS expression for ξ, we have here, as pointed by DN(11), a method for determining experimentally the mass renormalization factor z. It turns out that for both YBCO and LSCO, $z^{-1} \geq 5$. In other words, $\partial \sum / \partial \omega \geq 4$. Retardation effects in the cuprates are thus quite strong, and in that sense they are conventional superconductors. Yet, the possibility exists that retardation in the cuprates is not only due to the electron-phonon interaction, but also to correlation effects. In fact, a value $\lambda_{ep} \geq 4$ may appear as suspiciouly large.

A clue to the possibility that the large retardation effect is not only due to the electron phonon interaction may be found in the previously noted fact that the experimentally determined $\overline{v_{FS}}$ is larger than the calculated "band " velocity v_{FO}, by a factor of 2 to 3.

According to the definition of $\overline{v_F}$, this implies a large correction term $\partial \sum / \partial k$ to the band velocity. The possibility of a large velocity has been discussed by Eliashberg in the vicinity of a Mott transition (13) and by Weger and Burlachkov (14) in a layered srtucture. In any case, a large correction can only be due to electron correlation effects, not to the electron-phonon interaction. In that case we also expect a significant contribution of correlation effects to $\partial \sum / \partial \omega$. As already pointed out, both terms are of the same order in simple metals (4) and there is no reason to believe that it should be otherwise in the Cuprates. In principle, it might even be that the mass renormalisation is entirely due to correlation effects, and we would have a non conventional (non phononic) superconductor. A significant mass enhancement through spin fluctuations has been calculated by Monthoux and Pines (6). The value that they give, $\lambda = 1.8$, is however smaller than the one we deduce from the measurements of Hass et al.(8,9).

Of course a word of caution is necessary concerning the conclusions that can be drawn when we compare $\overline{v_F}$ to the band velocity. While the value of $\partial \sum / \partial \omega$ is obtained by comparing quantities that are all determined experimentally, the value of $\partial \sum / \partial k$ is obtained by comparing an experimental quantity ($\overline{v_F}$) to a calculated one (v_{FO}). The exact significance and accuracy of the later is still not completely clear in view of the lack of consensus regarding the electronic structure of the Cuprates.

Band calculations on the cuprates(10) are performed in the Local Density Approximation (LDA), and therefore do include correlation effects in the approximation of a slowly varying electronic density. What they do not include are fluctuation effects (and also the mass enhancement due to the electron-phonon interaction). Now, we have two independent indications that fluctuation effects are important in the Cuprates. The first, indirect one, is that $v_{FO} \cong 2v_F$, from

which it would follow that $\partial \sum_{ph} / \partial \omega \approx 1$ (2). Such a moderate value of the electron-phonon interaction is in any case insufficient to explain the high Tc. The LDA calculation must thus underestimate v_{FO}: a likely explanation is that it does not include a $\partial \sum / \partial k$ correction due to fluctuations. The second indication is that $\overline{v_F} \geq 2v_{FO}$. Since v_{FO} already contains correlation effects *except for fluctuations* the later must be important, and possibly play a role in determining the high Tc of the Cuprates.

On the other hand, there are independent indications (15) that the electron-phonon interaction in the cuprates is sizeable. Yet, our measured mass enhancement factor is larger than one would expect from the electron-phonon interaction only. As already pointed out above, it is also larger than the predicted mass enhancement due to spin fluctuations.

Thus, a tentative conclusion is that the electron-phonon interaction (local and retarded) and an interaction taking place through fluctuations (non local, magnetic or other, we of course cannot say) both play a role in the velocity renormalization factor and presumably in the superconductivity of the cuprates.

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