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Consequences of d-Wave Superconductivity for High Frequency Applications of Cuprate Superconductors

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***Abstract*—A number of recent experiments suggest that the superconducting ground state wave function in $YBa_2Cu_3O_{7-\delta}$ (YBCO) has d-wave symmetry. However little attention has been given to the consequences of d-wave pairing symmetry on applications of the cuprates. An intrinsic finite residual loss, approximately one order of magnitude below the lowest losses measured in YBCO thin films at 10 GHz, is one important consequence. In addition, an unusual sensitivity to disorder, an intrinsic non-linear power dependence, and unique mid-gap states associated with specific film textures and possibly twin boundaries, are also expected. We present our own attempts to identify these unique properties of d-wave superconductors, and discuss how these results may dictate the ultimate limitations of the cuprates in high frequency applications.**

I. INTRODUCTION

Since the discovery of cuprate superconductors in 1986, there have been many experiments and theories searching for the mechanism of high temperature superconductivity. As we know, essentially all of the equilibrium properties of most conventional superconductors (defined as those without CuO planes) can be explained by the BCS model which consider electrons forming Cooper pairs through a phonon mediated attractive interaction. Conventional Cooper pairs are spin singlets with s-state orbital angular momentum (s-wave pairing). It has been demonstrated that high T_c superconducting carriers also consist of paired electrons [1][2] and that the ground state is a spin-singlet state[3]. Hence low-T_c and high-T_c materials share at least two fundamental properties in the superconducting state.

In the search for the orbital symmetry of cuprate superconductors, there are a series of experiments consistent with a strong $d_{x^2-y^2}$ symmetry component to the order parameter. Angular resolved photoemission spectroscopy of $Bi_2Sr_2CaCu_2O_{8+\delta}$ (Bi2212) crystals, which can provide direct gap information, is consistent with a $d_{x^2-y^2}$ gap, or a highly anisotropic s-wave gap[4]. More recently, experiments seeking phase information about the gap have been developed. The results of flux quantization measurements in tricrystal superconducting rings of YBCO by Tsuei, *et al.*, [5] shows spontaneous magnetization with half a magnetic flux quantum in the 3-junction ring, but not in the 2-junction rings, consistent with d-wave pairing symmetry. Also SQUID interference and corner junction experiments indicate a π phase shift over a 90° rotation on the Fermi surface, but do not rule out a small s-wave gap [6]. Studies of other properties, such as the magnetic penetration depth of YBCO, which shows linear behavior in temperature at low temperatures, are consistent with nodes in the energy gap [7-10].

However there are many other experiments which are not consistent with pure d-wave symmetry, such as Sun *et al.*, obser-ving Josephson pair tunneling currents in Pb/ Insulator/ YBCO c-axis oriented tunnel junctions [11], and surface impedance experiments on $Nd_{1.85}Ce_{0.15}CuO_{4-y}$ (NCCO) which appear to be consistent with an s-wave interpretation [12]. Note that most of these experiments can be understood in terms of a linear combination of gaps, Δ_S and $\Delta_{dx^2-y^2}$, with a relative weighting that varies with material [13]. A composite gap of this nature is consistent with the symmetry of the orthorhombic crystal structure of most hole-doped high-T_c cuprates.

In this paper, we shall present our measurements of the magnetic penetration depth and surface resistance of high quality YBCO single crystals, and focus on the consequences of d-wave superconductivity for the applications of cuprate superconductors at high frequencies.

II. EXPERIMENT

YBCO single crystals are made by the standard flux method in zirconia crucibles with T_c in the range of 92-94 K by AC, DC and SQUID measurements. The size of the sample is about 1mm x 1mm x 20μm. All the microwave measurements were done in a bulk Nb cavity at 9.6 GHz [8]-[9]. The surface resistance and the penetration depth data are obtained via the simultaneous measurement of the quality factor Q and the resonant frequency f_0, as $R_s = \Gamma_S(1/Q-1/Q_{cav})$, $\delta X_s = 2\pi f \mu_0 \delta\lambda$ and $\delta\lambda = -\zeta_S \delta f$. Here Q_{cav} is the quality factor of the cavity without a sample with a typical value 2.3×10^7 at 4.2 K and 9.6 GHz, while Γ_S and ζ_S are the geometric factors which depend on the resonant mode, the size of the cavity, and the sample size and shape. With the high Q and stable signals in the frequency domain, we have a resolution $\Delta R_s \approx 10 - 50\ \mu\Omega$ and $\Delta\lambda \approx 1 - 4$ Å, depending upon the size of the sample.

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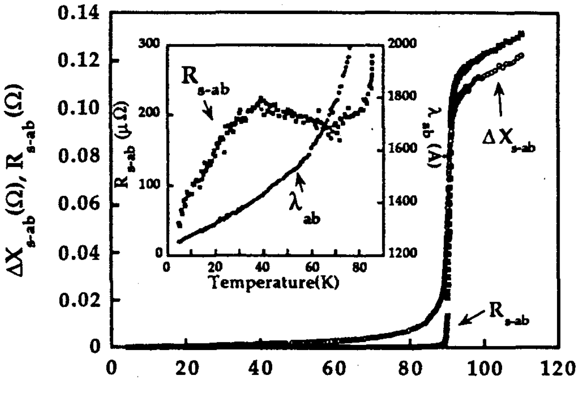

Fig. 1. Temperature dependence of the surface impedance of a YBCO crystal measured at 9.6 GHz. Inset shows the detailed low temperature dependence of $R_{s,ab}(T)$ and $\lambda_{ab}(T)$.

III. RESULTS AND DISCUSSION

Figure 1 shows the temperature dependence of the surface impedance of YBCO single crystals in the superconducting and normal state at 9.6 GHz. The sharp transition at T_c, which shows that the loss drops by 3 orders of magnitude in a few degrees below T_c, demonstrates the high quality of the sample. The difference between $R_{s\text{-}ab}$ and $\Delta X_{s\text{-}ab}$ in the normal state arises from $\omega\mu_0\lambda_{ab}(T=4.2\text{ K})$, allowing us to determine $\lambda_{ab}(4.2\text{ K})$. The lowest value of $R_{s\text{-}ab} \sim 165\ \mu\Omega$ at the minimum dip around 70 K(210 $\mu\Omega$ at 77K) is among the lowest reported surface resistance measured at 10 GHz near 77 K in YBCO. Note that the "plateau" area in $R_{s\text{-}ab}(T)$ around 70 K, with much less temperature dependence, may have its advantage in terms of applications. The surface resistance at 4.2 K is about 50 $\mu\Omega$. The peak near 30 K in R_S, which corresponds to the large peak in the conductivity $\sigma_1(T)$[9][14], may be explained by the competition of the rapid increase of quasiparticle lifetime below T_c and the decrease of the quasiparticle density[14]. The linear behavior of the penetration depth, and the slope of 5 Å/K, are consistent with the d-wave model (see below), and presumably arise from the linear in energy increase in the density of states due to nodes in the $d_{x^2-y^2}$ gap [7][9].

IV. WHAT IF THE CUPRATES ARE d-WAVE SUPERCONDUCTORS?

In this section, we would like to speculate about the implications of d-wave superconductivity on the applications of the cuprates to high frequency technology. We rely mainly on the theoretical arguments of P. Lee[15] and P. Hirschfeld, *et al.*[16], and explore the properties of both "pure" and "disordered" d-wave superconductors.

A. *"Pure" d-wave superconductors*

First, since the d-wave pairing state involves lines of nodes in the energy gap on the Fermi surface [9], a perfect cuprate will have a non-zero density of low-lying excited states down to arbitrarily low energies. This means that the surface resistance of such a material will not be thermally activated at low temperatures. P. Lee has estimated the minimum conductivity associated with a "pure" d-wave superconductor, and finds (in 3 dimensions) $\sigma_{min} \sim (e^2/h)\ [\xi_0/(a\ s)]$, where ξ_0/a is the ratio of the in-plane coherence length to the lattice parameter, and s is the inter-layer spacing [15]. Note that this minimum conductivity estimate is independent of disorder, hence it should hold for both single crystals and thin films. In the low temperature limit in the superconducting state, where $\sigma_2 >> \sigma_1$, the limiting surface resistance will be $R_{smin} \sim (\mu_0\omega)^2\ \lambda^3\ \sigma_{min}/2$. For YBCO ($\lambda \sim 1500$ Å, $\xi_0/a \sim 4$, $s \sim 7$ Å) at 10 GHz the estimate gives $R_{smin} \sim 1\ \mu\Omega$, roughly an order of magnitude lower than the lowest R_s ever recorded in YBCO thin films in the microwave range. This would imply that the surface resistance of YBCO can still be further improved by making more ordered samples, at least if this "pure" d-wave picture is appropriate for YBCO films, crystals, and ceramics. This estimate also indicates that pure cuprates with shorter ξ_0 will have lower residual surface resistances. Hence the lowest $R_{s,min}$ should be found in the material with the highest T_c, although the improvement may not be so great upon going from a material with $T_c = 90$ K to one with $T_c = 150$ K.

The penetration depth in a "pure" d-wave superconductor should increase linearly with temperature at low temperatures, $\lambda(T) = \lambda_L + c_1\ T$, ($T << T_c$) where λ_L is the London penetration depth, and $c_1 \sim \ln 2\ \lambda_L/(\Delta_0/k_B) \sim 2$ to 4 Å/K for YBCO (Δ_0 is the maximum value of the $d_{x^2-y^2}$ gap) [16][17]. This value is surprisingly close to the observations of Hardy, *et al.* and Mao, *et al.*, in twinned YBCO crystals [7][9][10], but is clearly not appropriate for the data on YBCO thin films and powders, or for NCCO. Superconductors with such a strongly temperature dependent penetration depth would clearly not be desirable for precision delay lines or low phase noise oscillators, particularly in the absence of an ultrastable cryocooler. As we shall see below, disordered d-wave superconductors should have less temperature dependence in their penetration depth, especially at low temperature.

B. *Disordered d-wave superconductors*

In reality, most cuprate superconductors used in applications are in thin-film form and are often highly defective. The fact that thin-film T_c's are often several degrees below those of single crystals is a sign that the films are either not optimally doped, or have sufficient disorder to decrease T_c by a "pair-breaking" effect. Both sources of a suppressed T_c involve some kind of disorder in the conducting layers of these materials. The effects of disorder on the properties of a d-wave superconductor are not entirely understood and are currently the subject of intense theoretical and experimental investigation. However, a few general remarks can be made about disorder.

In conventional s-wave superconductors, there are two types of defects which must be considered. Non-magnetic defects which produce elastic scattering have very little effect on superconductivity (Anderson's theorem). Magnetic impurities, on the other hand, break time-reversal symmetry, thus interfering with the Cooper pairing process. This results in a substantial decrease in T_c, as well as a modification of the BCS density of states. The singularity in the density of states at the gap energy is smeared out, and states begin to fill into the gap as magnetic impurities are introduced. At a critical concentration of magnetic impurities, an s-wave superconductor becomes "gapless," meaning that there are single particle excitations available even at zero energy. By the time this concentration is reached, the T_c of the material is just a small fraction of its original value.

In a d-wave superconductor things are somewhat different. Because of the symmetry of the d-wave state, non-magnetic impurities now become pair-breakers as well [18]. The effect of disorder on the electrodynamic properties depends on the strength of the interaction of an individual scattering event, c, which is the cotangent of the scattering angle in the collision. The limit $c \to \infty$ corresponds to weak scattering (Born approximation), and $c \to 0$ is strong scattering (unitary limit). It is found theoretically that any amount of disorder causes "gapless" behavior (as defined above) in any two- and three-dimensional d-wave superconductor [16]. The magnetic penetration depth would then vary as $\lambda(T) \sim \lambda_0 + c_2 T^2$, $(T << T_c)$ where $c_2 \sim \pi k_B{}^2 \lambda_L/(3.8\ \Gamma^{1/2} \Delta_0{}^{3/2})$, Γ is a scattering energy scale proportional to the density of strong scatterers, n_i, and λ_0 is related to the London penetration depth [16].

In the presence of disorder, theory predicts a cross-over temperature T^* between a low temperature "gapless" regime, and a high temperature "pure" regime. Estimates of $T^* \sim 0.83\ (\Gamma\Delta_0/k_B{}^2)^{1/2}$ show that it increases roughly as the square root of the number of strong scatterers, $n_i{}^{1/2}$, as does $(\lambda_0 - \lambda_L)/\lambda_L$ [16]. The penetration depth should therefore follow a general temperature dependence of the form $\lambda(T) \sim \lambda_0 + aT^2/(T^*+T)$. From this, one can estimate that $c_2 \sim c_1/T^*$, so for a typical YBCO film with $T_c = 90$ K and $T^* \sim T_c/4$, $c_2 \sim 0.2$ Å/K^2, surprisingly close to the values measured in YBCO films [19], and that obtained from the low temperature $(T << T_c)$ expansion of an empirical fit to experimental data on YBCO films: $\lambda(T) = 1500\text{Å}/(1-(T/T_c)^2)^{1/2}$ [14][20][21].

The losses in the "pure regime" $(T^* < T << T_c)$ in a d-wave superconductor may give us some insight into the losses at 77 K in the cuprates. At temperatures greater than T^*, but with a very low density of strong scatterers such that the measurement frequency $f >> \Gamma\Delta_0/(h\ k_B T)$, one expects $\sigma_1 \sim n_i$ [22], and therefore $R_{s,pure} \sim \sigma_1 \sim n_i$, so that the losses will increase with impurity density, as one expects for s-wave superconductors. This case probably pertains only to the purest of single crystals, and may require several more years of materials refinement to achieve. However, for much more defective materials (remember $\Gamma \sim n_i$) such that $f << \Gamma\Delta_0/(h\ k_B T)$, one expects $\sigma_1 \sim 1/n_i$ [22], and $R_{s,pure} \sim 1/n_i$, quite different from the clean limit. In this limit, the losses will actually decrease with additional non-magnetic disorder! This may have already been observed in surface resistance measurements on YBCO crystals doped with Zn.[23] However, the reduction in T_c due to the presence of strong scatterers is roughly $\Delta T_c/T_{c0} \sim \Gamma/\Delta_0$ and scales with n_i. Since it is more practical to make device materials with a large density of defects (especially in thin film form), a compromise must be found between the defects added to reduce the pure limit loss, and the need to keep the transition temperature substantially greater than the operating temperature of the device.

Finally, P. Lee has proposed that disorder in d-wave superconductors may lead to localization of low-lying quasiparticle states near the nodes of the energy gap [15]. This proposal may account for our observations of activated behavior in the surface impedance of NCCO [8][12], and YBCO thin films overdoped with oxygen [24]. In addition, it may also allow for the creation of s-wave-like cuprate materials which can mimic the low-loss properties of traditional isotropic s-wave superconductors.

V. OTHER EFFECTS OF d-WAVE SUPERCONDUCTIVITY

Due to the presence of nodes in the energy gap, a d-wave superconductor should exhibit a non-linear Meissner effect. This means that the superconductor will not generate a magnetization which is strictly proportional to the applied field, because supercurrent flowing in the direction of a node will gain kinetic energy sufficient to produce depairing, hence reducing the superfluid response. Because the gap increases for directions just away from the node, the amount of depairing will depend on the strength of the applied field. Yip and Sauls have estimated that for low temperatures and small applied fields H, the effective penetration depth will behave as $\lambda_{Eff}(H) = \lambda(H=0)/[1 - (2/3)\ H/H_0]$, where H_0 is on the order of the thermodynamic critical field [25].

This non-linear effect could limit the intrinsic linearity of cuprate devices operating in the Meissner state, although it is predicted to be rather small [25]. We can estimate the 1 dB compression point for the kinetic inductance of a thin film $(t < \lambda)$ device as follows. At low temperatures and fields, the kinetic inductance will increase as $L_{Kin}(H) = L_{Kin}(0)/[1 - (2/3)\ H/H_0]^2$. A 1 dB increase of kinetic inductance would therefore occur for a field strength of order $H/H_0 \approx 0.17$. For YBCO (with $B_0 \approx 1$ Tesla) this corresponds to a surface field on the order of 1500 Oe. Such field strengths are probably beyond the bulk H_{c1}, but are possible for fields parallel to the surface of a thin film, and can be achieved in stripline resonators [26]. However, most devices will become nonlinear at lower field levels due to the entry of magnetic flux at weak links. Hence this form of nonlinearity will not be an issue until other materials problems are resolved. So far, the non-linear Meissner effect has not been seen in either of two experiments on single crystals of YBCO [27][28].

Finally, d-wave superconductors may have unique mid-gap states associated with a free surface having a normal in the direction of a node in the energy gap, and also possibly at twin boundaries [29]. These states could contribute to residual microwave losses, and may explain the reduction in residual losses of untwinned YBCO crystals compared to their twinned counterparts [30].

VI. CONCLUSIONS

There is growing evidence for a strong $d_{x^2-y^2}$ component to the ground state wavefunction of the cuprate superconductors. d-wave superconductivity implies a finite microwave residual loss in the cuprates, although defects can be used to engineer the magnitude and temperature dependence of the surface impedance. Other consequences of d-wave superconductor include intrinsic non-linearity of the surface reactance in the Meissner-state, and the possibility of unique mid-gap states contributing to the microwave losses.

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