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Evidence for multi-component superconducting order parameter from microwave measurements of $YBa_2Cu_3O_{7-\delta}$ single crystals *

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The microwave complex conductivity in the superconducting state ($\sigma_s = \sigma_1 - i\sigma_2$) of high quality $YBa_2Cu_3O_{7-\delta}$ single crystals measured at $10GHz$ using a high-Q Nb cavity reveal two new features - (i) A new peak in σ_1 at $\sim 80K$ and (ii) enhanced pair conductivity σ_2 below $\sim 65K$. The results indicate two pairing temperature scales and point to a multi-component superconducting order parameter in $YBCO$.

Electrodynamic measurements of the complex conductivity ($\sigma_s = \sigma_1 - i\sigma_2$) yield important information regarding the quasiparticle density of states and the nature of the superconducting condensate [1,2]. Microwave experiments have played an important role in understanding fundamental issues in both low (LTS) and high temperature superconductivity (HTS).

In HTS, improvement of materials quality over the years has gradually led to many experimental results which reflect the intrinsic properties untainted by defects. The recent growth of $YBa_2Cu_3O_{7-\delta}$ single crystals in $BaZrO_3(BZO)$ crucibles has ushered in a new generation of high quality samples [3]. This growth method avoids the critical problem of crucible corrosion and leads to single crystals with extremely clean surfaces and purity exceeding 99.995%.

We have carried out precision measurements of the surface impedance ($Z_s = R_s + iX_s$) of these new high quality $YBa_2Cu_3O_{7-\delta}$ single crystals grown in BZO crucibles. The experiments were done in a superconducting Nb cavity resonator operating at $10GHz$ [4]. Three single crystals from different batches grown in BZO crucible and one crystal of comparable dimensions grown in YSZ crucible were measured to study the systematics in the different samples. The crystals grown in BZO had $T_c = 93.4K$ and the one grown in YSZ had $T_c = 92.4K$.

In Figs.1 and 2, the typical temperature dependence of $\sigma_2(T)$ and $\sigma_1(T)$ are plotted for $YBCO/BZO$ and $YBCO/YSZ$ samples. Two striking features emerge clearly from a comparison of the data:

(i) $\sigma_2(T)$ shows two distinct regions of variation for $T < 65K$ and $65K < T < T_c$ respectively in the $YBCO/BZO$ samples. Since the estimated $\lambda(0)$ is lower in these crystals, this feature implies enhanced pair conductivity indicating an onset of additional pairing below $65K$.

(ii) The normal conductivity $\sigma_1(T)$ shows a new peak at around $80K (\sim 0.9T_c)$ in $YBCO/BZO$ crystals which is absent in $YBCO/YSZ$.

Very near T_c, a third sharp peak is present in $\sigma_1(T)$ of all four samples and its sharpness attests to the quality of the crystals. The sharpness of the superconducting transition is evident in the R_s data which indicated a transition width of $0.2K$ at $10GHz$ [5], and is confirmed by the sharpness of the σ_1 peak. A comparison of the inelastic scattering rates extracted from the normal state conductivity of all the samples shows that the second peak at $80K$ is prominent in samples with lower inelastic scattering in the normal state.

The data indicate that in addition to the pairing at $93K$, additional pairing develops below around $65K$. This strongly suggests the presence of multiple pairing interactions in $YBa_2Cu_3O_{6.95}$. A peak in σ_1 around $30K$ is seen in all YBCO crystals and to account for its location, an argument based on a precipitous drop in quasiparticle scat-

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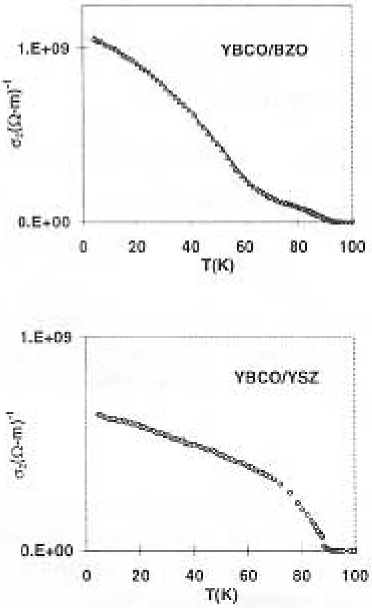

Figure 1. Pair conductivity $\sigma_2(T)$ for the YBCO/BZO sample and YBCO/YSZ sample. Note the enhanced pairing turning on below $65K$ for YBCO/BZO shown in the top panel.

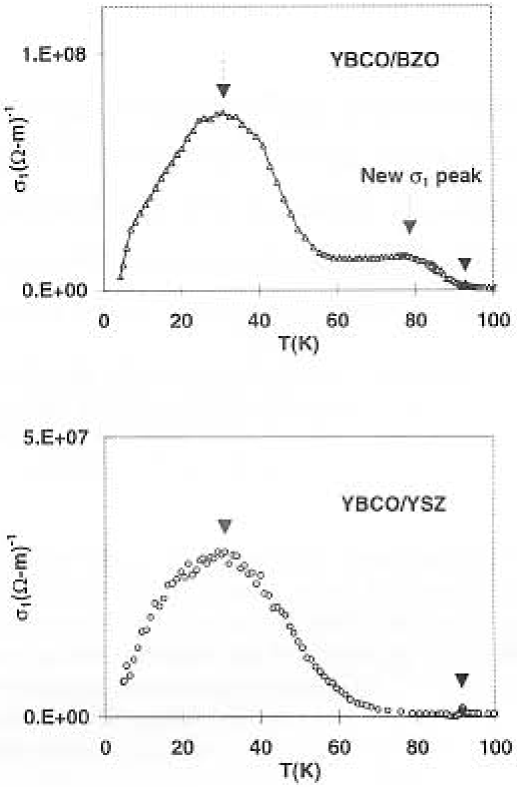

Figure 2. Normal conductivity $\sigma_1(T)$. The arrows denote the location of the conductivity peaks. The new peak observed is marked in the YBCO/BZO data.

tering rate below T_c has been proposed [6]. In light of our present results, it now becomes clear that the $30K$ conductivity peak in all samples is really associated with pairing at $65K$ and not with pairing at $93K$, since we are now able to observe and associate the new $80K$ conductivity peak with pairing at $93K$. This two component picture provides a satisfying explanation of the $30K$ peak without invoking a rapid temperature dependence of the scattering rate of a single component.

It is rather difficult to reconcile the data with a single order parameter of any symmetry. One needs two, possibly coupled, superconducting components to account for this data. Simple models which incorporate decoupled superconducting components with separate pairing temperature scales around $65K$ and $93K$ and in which the conductivities of the two components are treated additively describe the observed data for σ_2 and σ_1 [5]. In order to reproduce the low T behavior which is linear, at least one of the components has to have nodes in the gap. We have found good agreement with the σ_2 data for a model using one s-wave and one d-wave component .

However the two components are likely to be coupled. A Ginzburg-Landau calculation can be carried out (*eg.* [7]) using order parameters Ψ_A

and Ψ_B with pairing temperatures T_{cA} and T_{cB} ($> T_{cA}$). For weak coupling between the components, the calculation yields a single superconducting transition near T_{cB}. As the temperature of the superconductor is lowered, the superconducting state would have symmetry corresponding to Ψ_B just below T_{cB}, with mixed symmetry $A+B$ appearing below T_{cA} which could be dominated by the symmetry of Ψ_A. This will be reflected in measurements of the penetration depth as well as many other properties, which will show a crossover at T_{cA} well below T_{cB}, similar to the σ_2 data in Fig. 1.

Earlier a two-component order parameter was suggested in $Bi:2212$ on the basis of photoemission data [8]. However penetration depth data on $Bi:2212$ crystals [2] do not resemble the present data on $YBCO/BZO$ and instead look similar to the $YBCO/YSZ$ results. It should be pointed out here that materials quality played a crucial role in the case of $Bi:2212$ too. Although prior measurements indicated a T^2 dependence of the low temperature penetration depth [9,10], data on purer crystals grown using the Traveling Solvent Floating Zone method (TSFZ) yielded a linear-T dependence similar to the case of $YBCO$ [2,11].

The present results are consistent with several other experimental observations in $YBCO$ and also other cuprates. Earlier measurements on $YBCO$ thin films yielded penetration depth data which are similar to the present results and were there interpreted in terms of a 2-gap model [12]. We note that STM tunneling measurements on similar $BaZrO_3$ grown $YBCO$ crystals show multiple structure at around 5 mV and $20-25$ mV [13], close to the pairing energy scales in the present work. If indeed this correspondence is relevant, then our results would suggest that these features should have different temperature dependences which should be explored.

The possibility of multiple pairing energy scales in YBCO is not surprising in view of the crystal structure. The Fermi surface of $YBCO$ is believed to consist of multiple sheets associated with two plane bands and a chain band. This raises the possibility of superconductivity with multiple pairing energies. Recent thermal conductivity studies on $YBCO$ have also revealed enhanced pairing below $55K$ which has been interpreted as evidence for chain superconductivity [14].

We now remark on the sharp peak in σ_1 very near T_c which is present in all samples [15] and has been commonly attributed to inhomogeneties [16,17] or fluctuations [18,19]. The multicomponent scenario raises a new possibility for this sharp peak near T_c as being due to a third superconducting component (C). Such a sharp peak can be obtained from Mattis-Bardeen calculations assuming an s-wave order parameter when a very large gap value $\Delta_C(0)/kT_c \sim 10-15$ is used. This speculation receives support from the fact that structure at very high energies of $100mV$ is also observed in STM tunneling characteristics [13] which may match with the high energy scale of the sharp peak near T_c.

While phase sensitive experiments [20,21] suggest a dominant d-wave superconducting state, an $s+d$ state is likely in $YBCO$ because of its orthorhombic crystal structure. This would be consistent with c-axis tunneling experiments [22]. However all of these experiments appear to be carried out at low temperatures near $4.2K$. Our present results would suggest that the underlying symmetry could change with temperature. Hence careful experiments should be performed above and below $60K$ in high quality $YBCO$ samples.

Several theories [23–26,7,27,28] have addressed the issue of mixed order parameter symmetry or multi-component superconductivity in cuprates and scenarios based on many of these ideas would be consistent with our striking microwave results.

In summary, these data represent direct observation of the presence of *multiple* components in the superconducting state of $YBa_2Cu_3O_{6.95}$ [5].

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