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PROBABLE OBSERVATION IN TUNNELING OF TWO DISTINCT GAPS AND T_c's in $Bi_2Sr_2CaCu_2O_8$*

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Abstract

The tunneling conductance G(V,T) of (Pb film)-I-$Bi_2Sr_2CaCu_2O_8$ junctions on cleaved ab planes typically reveals two gap features. The inner gap Δ_i closes, in a BCS-like fashion, at a temperature T_{ci} below the crystal T_c (90K). We can explain the inner gap behaviour $\Delta_i(T)$, and anomalous observation of the Pb gap at V=0, on a model assuming three superconducting layers per cell, between which carriers hop and pair.

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Anisotropy of the resistivity ρ in the cuprate superconductors is well established; ρ_c in the c-direction in $Bi_2Sr_2CaCu_2O_8$ (2212) exceeds ρ_{ab} by 1-4 x 10^5 at 100K[1]. The unit cell (c=15.4 A) contains at center two CuO_2 layers sandwiched between Bi-O layers which are exposed by cleavage; the intervening Sr-O layers are non-metallic[2]. Superconducting anisotropy in 2212 is indicated by different coherence lengths $\xi_{ab}(0)$ = 20.4A, $\xi_c(0)$=0.37 A [3]. The small values of ξ imply the clean limit, so that electrons in separate bands may have distinct energy gaps Δ_i and critical temperatures T_{ci}; an example is $SrTiO_3$:Nb[4]. Superconducting fluctuation diamagnetism in 2212 [3] has been treated on a theory[5] of coupled layers, which allows for several order parameter bands, with possibly distinct gaps and T_c's. Anisotropy of Δ has been inferred from infrared measurements on $YBa_2Cu_3O_{7-x}$ (123) [6], from tunneling on 2212 [7,8] , and from angle resolved photoemission (ARPES) spectra[9,10] on 2212. Recent ARPES data[10] give distinct Δ's near 27 meV and 15meV at the BiO-vacuum interface, at Fermi surface locations associated with different parts of the unit cell[11].

Tunneling spectroscopy provides the classic measure of $N_s(E)$, the energy density of excitations of a superconductor. In normal metal-insulator-superconductor (N-I-S) junctions, the tunneling DOS, $N_T(V) = G_s/G_n$, with $G_{s,n} = dI/dV_{s,n}$, is the convolution of $N_s(E)$ with the derivative of the Fermi function, i.e., broadened by 1.76 kT. In the present work, electrons tunnel into the ab plane of 2212 from the Pb counterelectrode, conserving transverse wavevector k_t. Since k_F in Pb is large, all final states in the ab plane, as well as those in the c-direction (which have higher tunneling probability[12]) are reached. An example of tunneling spectroscopy of purely transverse states is given by Tsui[13]. Inner gap structures have been observed in $N_T(V)$ of $YBa_2Cu_3O_7$ crystals[14] and Bi-Sr-Ca-Cu-O films[15].

Recent calculations of $N_s(E)$ in layered superconductors will be described below[16,17]. Calculations of $N_T(V)$ for cuprates considering d-wave pairing, but neglecting interlayer effects, have also been reported[18].

Our experiments are based on single crystals of 2212 grown from Bi_2O_3 rich melt[19]. Cleaved ab planes, exposed to dry air, acquire a barrier when the 0.3μm Pb is deposited. dV/dI spectra, taken using methods described earlier[20], are numerically converted to $G_S(V)=dI/dV$. The inner gap features Δ_i appear in Fig. 1. (arrows) as shoulders, which remain sharp and close with increasing temperature, finally merging in Fig. 1(a) (Jn. 3) in the 85K curve. The generally sharper curves of Jn. 1 in Fig. 1(b) anomalously reveal the energy gap of Pb at $\pm$ 1.2meV. This feature is expected near V=0 when tunneling into a normal metal, and could arise if portions of a defective 2212 crystal surface were not superconducting. We cannot rule this out entirely. However, the Pb gap was also anomalously seen at V=0 tunneling into $YBa_2Cu_3O_7$ [14]. Thus, we argue (below) that this observation implies that some states may exist in the gap in 2212.

Fig. 2 shows that the T-dependence of the Δ_i is consistent with a BCS dependence (solid line). We observe T_{ci} values of 80, 73 and 58K, for the inner gaps of Jns. 3, 1, and 2, respectively, compared to the crystal T_c of 90K. In Jn. 2, not shown, the Pb gap was also visible. The corresponding $2\Delta_i(T)$ values (taken as the spacings between shoulders in G(V)) are 43, 29, and 42 meV, respectively, or $2\Delta_i/kT_{ci}$= 6.3, 4.6, and 8.5 for Jn's 3,1 and 2. The inner gaps have been seen in 8 out of 20 junctions studied. We will return to the possible origin of variations in the $2\Delta_i$ and T_{ci} values.

In discussion of these G(V), we first describe general features, followed by the inner gap. Note that G(V) in Fig. 1 (b) is somewhat V-shaped about V=0, rather than the square well expected in an s-wave BCS gap 2Δ= 52 meV measured at 4.2K[21]. G(V) is not conventional BCS, by virtue of G(0)=0.4 and reduction of the BCS peak near Δ to about 1.5 from the expected $G(\Delta)$ = 4.7. Rather, the G(V) is suggestive of a gap function with a node[17,18], leading to a characteristic V-shape about V=0.

Temperature dependent sharp structures are sometimes seen (e.g., in Fig. 1(b), near 0 and near 70 meV) possibly related to layering[11]. Two other general features are onset of level broadening near T_c [20] and the persistence of a G(V) minimum above T_c. The latter feature, which is possibly related to fluctuations, will be discussed elsewhere. In junctions, such as those reported earlier[20], with a larger energy broadening even at low temperatures, the inner gap feature is not observed.

The inner gap likely arises from interactions between three conducting layers within the 15.4 A unit cell. With this in mind, the variability observed in the inner gap Δ_i and T_{ci} features is perhaps not unexpected. Tunneling probes the first few coherence lengths of a superconductor, here only a few A. Thus, the extreme difficulty of these measurements is apparent, since atomic scale perfection of the first superconducting unit cell is crucial. Further, the barrier is grown by air exposure of the cleaved surface (BiO), and probably by oxidation of some of the subsequently deposited Pb film. Chemical reactions act on the first unit cell, 15.4 A along the c-direction, likely turning the first cell into insulating barrier. If this reaction proceeds at all into the outer BiO layer of the second cell, likely the superconductor being probed, one may expect details of the spectra to be affected. We believe the results are important, even though not identical in detail, because of the superior energy resolution and ability to survey a wide temperature range. We note systematics of G(V) depending upon time of air exposure, and junction age after Pb deposition, leading eventually to broadening in G(V). The data in Fig. 1b are relatively free of such effects.

In the theoretical discussion we will show how both the unusual temperature dependence of the inner gap feature Δ_i, the Pb gap at V=0, and G(0) > 0 can be understood on the basis of an interlayer pairing model for layered superconductors developed by Klemm and Liu.[16,17] The model was motivated by the observations of c-axis versus ab-plane gap anisotropy in $YBa_2Cu_3O_7$ and $Bi_2Sr_2CaCu_2O_8$.[6-8,14] It is shown that gap anisotropy can be explained naturally if the Cooper pairs are assumed to reside in different layers. The details depend on the number of layers per unit cell and the various pairing and hopping interactions. We here briefly review some general conclusions relevant to the present problem: 1) In a system with one layer per unit cell, the singlet gap function is simply $\Delta_s(k_z)=\Delta_{so}\cos(k_z c)$, where k_z is the wavevector along the c-axis and c the cell constant. $\Delta_s(k_z)$ has a node halfway between the center and the boundary of the Brillouin zone, which would lead to a V-shape in G(V), provided that the triplet state is suppressed[16,17]. 2) With two identical layers in the cell, $\Delta_s(k_z)$ for some values of parameters may occasionally have a node. The situation is more complex if the layers are not identical. The band calculation[2] for 2212 predicts two bands apiece associated with Cu-O and Bi-O planes; the four hybridize where they cross such that two Cu-O bands and one Bi-O band cross the Fermi level. Since ARPES[9,10] confirms the predicted Fermi surface, we interpret our tunneling data on a generalization of the Klemm-Liu model to the 2212 band structure[2]. We temporarily ignore the small region on the Fermi surface where the bands hybridize. Then the separation of the two-dimensional band energies of Bi-O and Cu-O layers implies, to the lowest approximation, that the electrons on these two sets of bands form two independent superconducting systems, with separate Δ and T_c values. A simple counting of bands reveals that the Bi-O electrons should be modeled as a one-layer system while the Cu-O electrons belong to a two-layer system. Thus, $\Delta_s(k_z)$ for the single Bi-O band has a node, and it gives rise to a V-shape at the center of $N_T(V)$. (If Δ_s of the 2-layer Cu-O system also has a node, it will reinforce the "V".) The existence of electron levels near zero energy allows the Pb gap to be seen in Jn. 1.

In general, the two systems have different critical temperatures, which are denoted by T_{cn} with n = 1,2. We now turn on the hybridization interaction. It will be shown in detail elsewhere that the interaction, which transfers electrons between Bi-O and Cu-O bands, linearly mixes the singlet order parameters of the two systems, which we denote by Δ_n, n = 1,2. As a result, the G-L free energy of the total system has the form

$$F_s - F_n = 1/2\ [N_1(0)|\Delta_1|^2 \ln(T/T_{c1}) + 1/2\ b\ N_1(0)|\Delta_1|^4 + N_2(0)|\Delta_2|^2 \ln(T/T_{c2}) + 1/2\ b\ N_2(0)|\Delta_2|^4 - 2\xi N_{12}(0) \mathrm{Re}(\Delta_1^* \Delta_2)],$$

where $N_n(0)$ is the density of states of the nth band, $N_{12}(0) = [N_1(0)N_2(0)]^{1/2}$, ξ is a dimensionless parameter which measures the hybridization, and $b = 7\zeta(3)/8(\pi T)^2$. Since it is easily shown that $F_s - F_n$ is minimized with the two order parameters in phase, we take them as real.

The T_c of the coupled system is found by diagonalizing the quadratic part of $F_s - F_n$. If $T_{c1} \cong T_{c2}$, we find

$$T_c = 1/2\ \{T_{c1} + T_{c2} \pm [(T_{c1} - T_{c2})^2 + 4\xi^2 T_{c1} T_{c2}]^{1/2}\}.$$

We identify the "+" solution with T_c and the "-" solution with T_{ci}. We do not know which band system has the higher T_c. If we assume $T_{c1} > T_{c2}$ and $\Delta_1 > \Delta_2$, it follows that $T_c > T_{c1}$ and $T_{ci} < T_{c2}$ for small ξ. In the range $T_{ci} < T \lesssim T_c$, the gaps of the two systems are given by

$$\Delta_1 \cong [(T_c - T)/bT_c]^{1/2},$$

and

$$\Delta_2 \cong \xi [N_1(0)/N_2(0)]^{1/2} T_{c2}\Delta_1/(T_{c1}-T_{c2}) \ll \Delta_1.$$

Both gaps emerge at the same temperature T_c. For $T<T_{ci}$, Δ_1 has nearly the same expression, but Δ_2 grows rapidly with decreasing T according to $\Delta_2 \cong [(T_{ci}-T)/bT_{ci}]^{1/2}$.

The T-dependence of the two gaps is shown qualitatively in Fig. 3(a). Therefore, Δ_2 can be identified as the inner gap Δ_i, with T_{ci} as its apparent T_c. The fact that Δ_2 remains small but non-vanishing above T_{ci}, and an unusual shape of $N_s(E)$ at E=0, may explain the small peak in G(V) at V=0 just above 80K in Fig. 1. The total $N_s(E)$ at 0 K, shown qualitatively in Fig. 3(b), displays two gaps and the V-shape due to the node. In comparison with finite T data, probably also subject to some lifetime or other broadening, we may expect the sharp features of Fig. 3b to be smoothed and G(0) filled in to resemble experiment. The preference of the tunneling transmission for final states in the c-direction, where the node is predicted by the model, in addition to broadening, will also enhance gaplessness in the $G_s(V)$, relative to $N_s(E)$ in Fig. 3b. Notice that if we assume $T_{c2} > T_{c1}$, Δ_i becomes Δ_1 and $T_c > T_{c2}$, $T_{ci} < T_{c1}$, and qualitative features are retained.

We believe that the degree of agreement of experiment and theory makes probable the existence of the inner gap feature along the lines presented. We have explained the extreme difficulty of the tunneling experiment on the layered material of small coherence length, relating to a lack of complete reproducibility. It is not clear at present whether our model can account for all of the below gap states in Fig. 1, and we cannot rule out some extrinsic effects.

The weight of below gap states in $N_s(E)$ (Fig. 3(b)) is reduced by one third compared to a single band d-wave superconductor[18]. Such weak gaplessness may be consistent with (relatively high temperature) specific heat and penetration depth data, generally associated with an s-wave gap[22]. A recent S-I-S tunneling study of 2212[8] concludes that N(V) is linear for $0<V<20$ mV, consistent with Fig. 3b. ARPES[9] indicates an averaged gap near 25 meV, in agreement with our fit of the overall G(V)[21]. At present ARPES is probably inadequate to resolve the weak V-shape in Fig. 3(b). Finally, it seems likely that the two gaps reported here correspond to the two gaps (27 meV and 15 meV) recently angularly resolved in ARPES[10]. One of these was reported as very sensitive to BiO surface perfection.

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FIGURE CAPTIONS

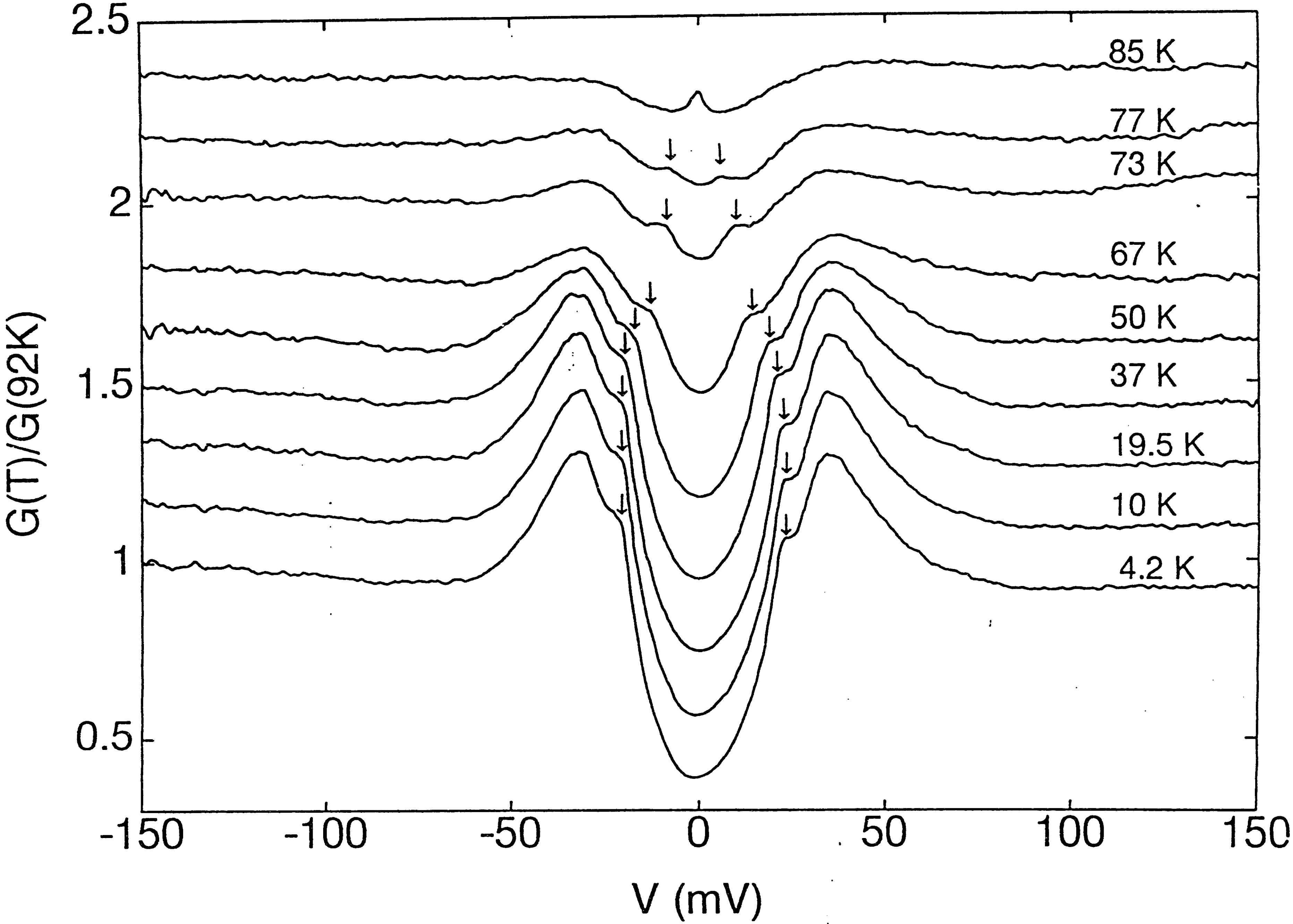
1. (a) Normalized conductance G(V,T)/G(V,92) of Jn. 3 at several temperatures, showing the inner gap features which close at T_{ci} of 80K. In order to show the Δ_i features more clearly, the curves have been normalized by a 92K curve, not shown.

(b) Conductance G(V,T) for Jn. 1, as converted from dV/dI, at various temperatures. The 4.2K curve reveals Pb gap structure near V=0, validating a tunneling mechanism, but anomalous in an S_1-I-S_2 junction.

2. Comparison of the temperature dependence of the normalized inner gap peak to peak spacing $2\Delta_i$ to the BCS gap temperature dependence. The fitted T_{ci} values are 80, 73 and 58K for Junctions 3, 1, and 2, respectively.

3. (a) Δ(T) obtained for layered superconductor model of 2212, describing distinct singlet gaps arising from interlayer pairing. The model describes two separate electron systems, two bands per unit cell arising from CuO and one band per cell from BiO, see text. Interaction of the two systems leads to the crossover shown near T_c, and is associated with merging of the inner gap feature in the 85K curve of Fig. 1 (a).

(b) Total density of states shows the distinct inner gap and the V-shape arising from node of one gap function. The node, shown occurring in one of the three bands, can explain the Pb gap feature at V=0, lead to G(0) > 0 in the presence of broadening, and the roughly triangular appearance of the spectra, as in Fig. 1b.



2.5
2
1.5
1
0.5
G(T)/G(92K)
-150
-100
-50
0
50
100
150
V (mV)
85 K
77 K
73 K
67 K
50 K
37 K
19.5 K
10 K
4.2 K

FIG 1 (A)

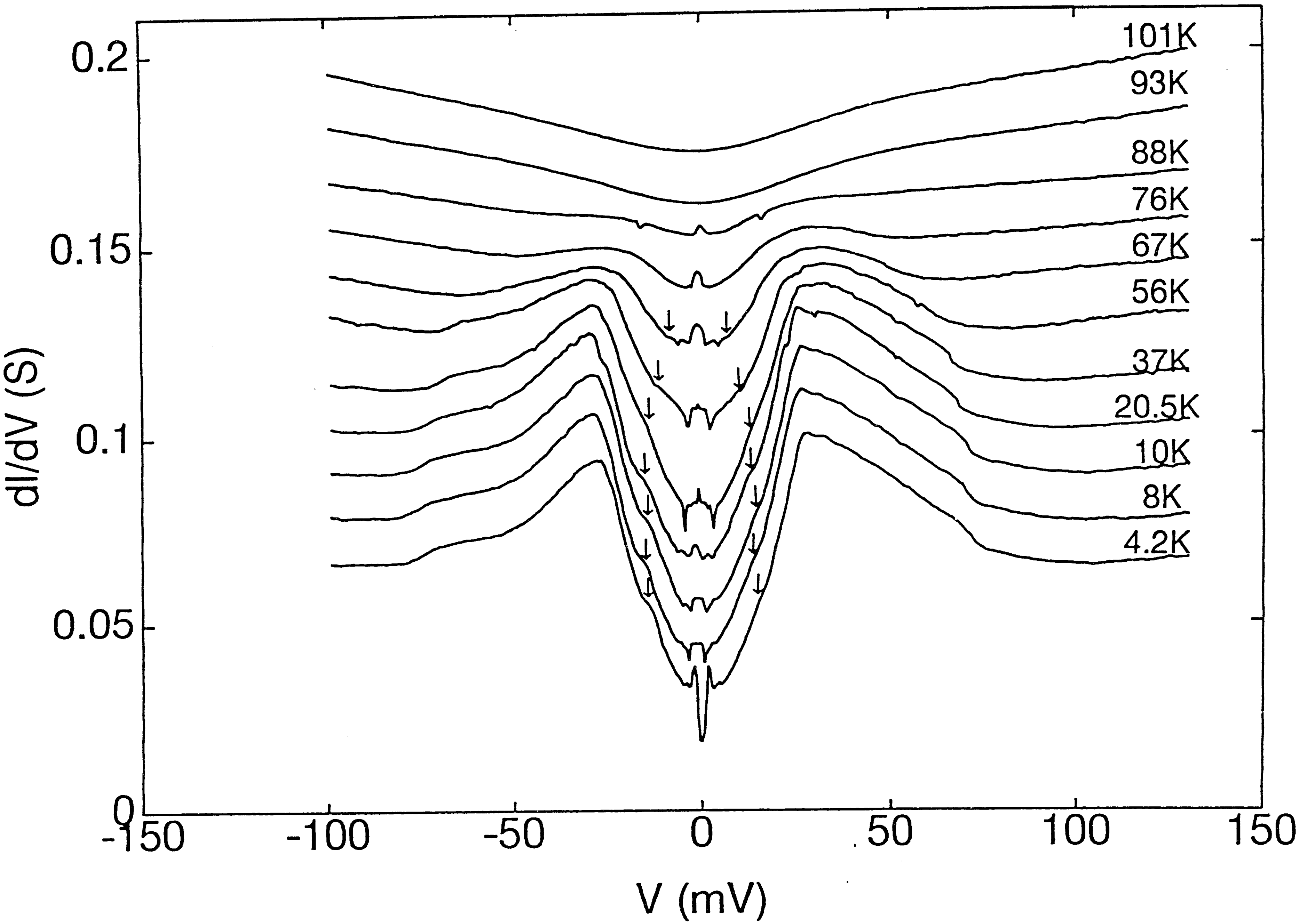
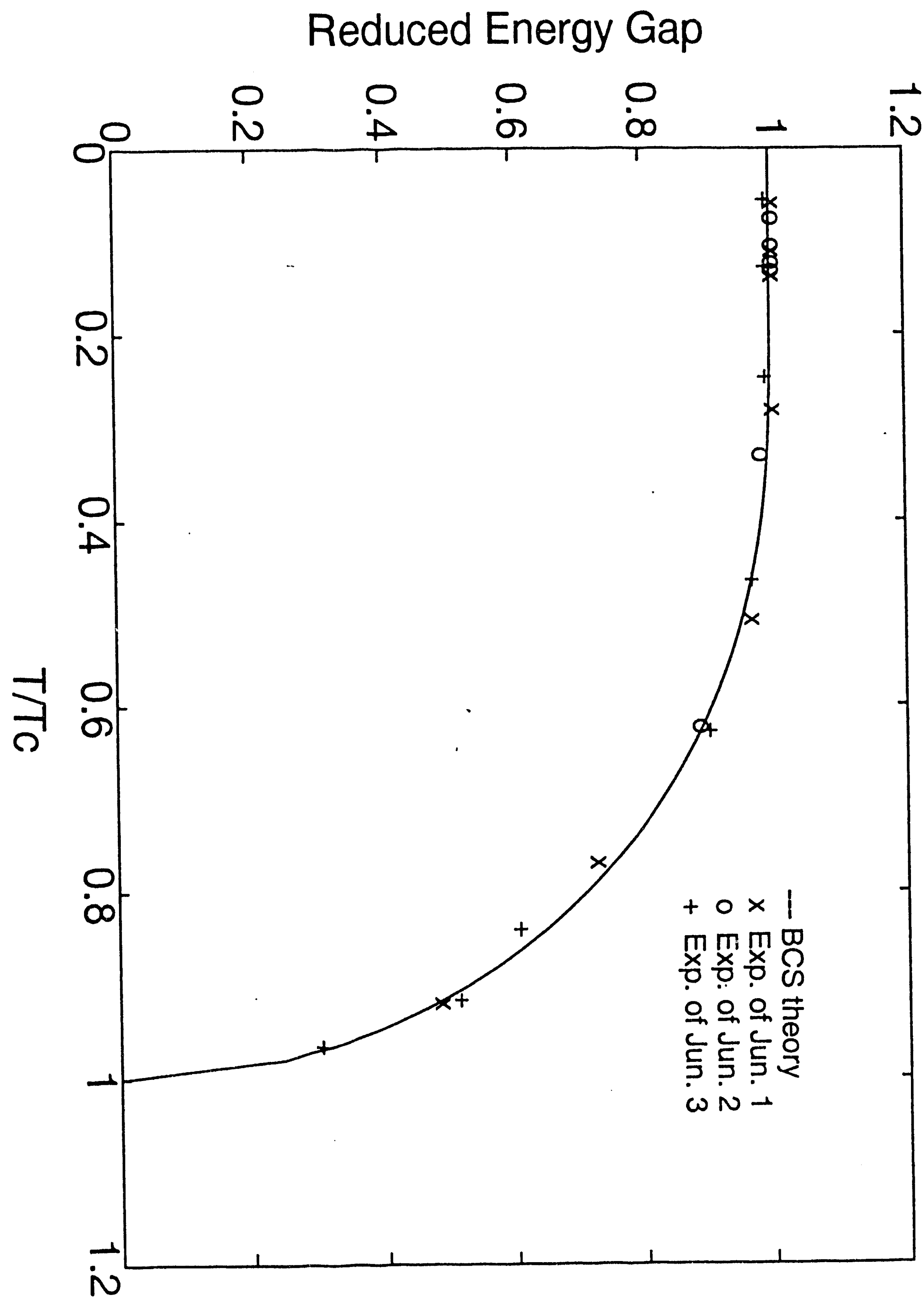

101K
93K
88K
76K
67K
56K
37K
20.5K
10K
8K
4.2K
0.2
0.15
0.1
0.05
0
-150
-100
-50
0
50
100
150
dI/dV (S)
V (mV)

FIG 1 (B)



Reduced Energy Gap
T/Tc
0
0.2
0.4
0.6
0.8
1
1.2
— BCS theory
x Exp. of Jun. 1
o Exp. of Jun. 2
+ Exp. of Jun. 3

FIGURE 2

ORNL-DWG 91M-8073

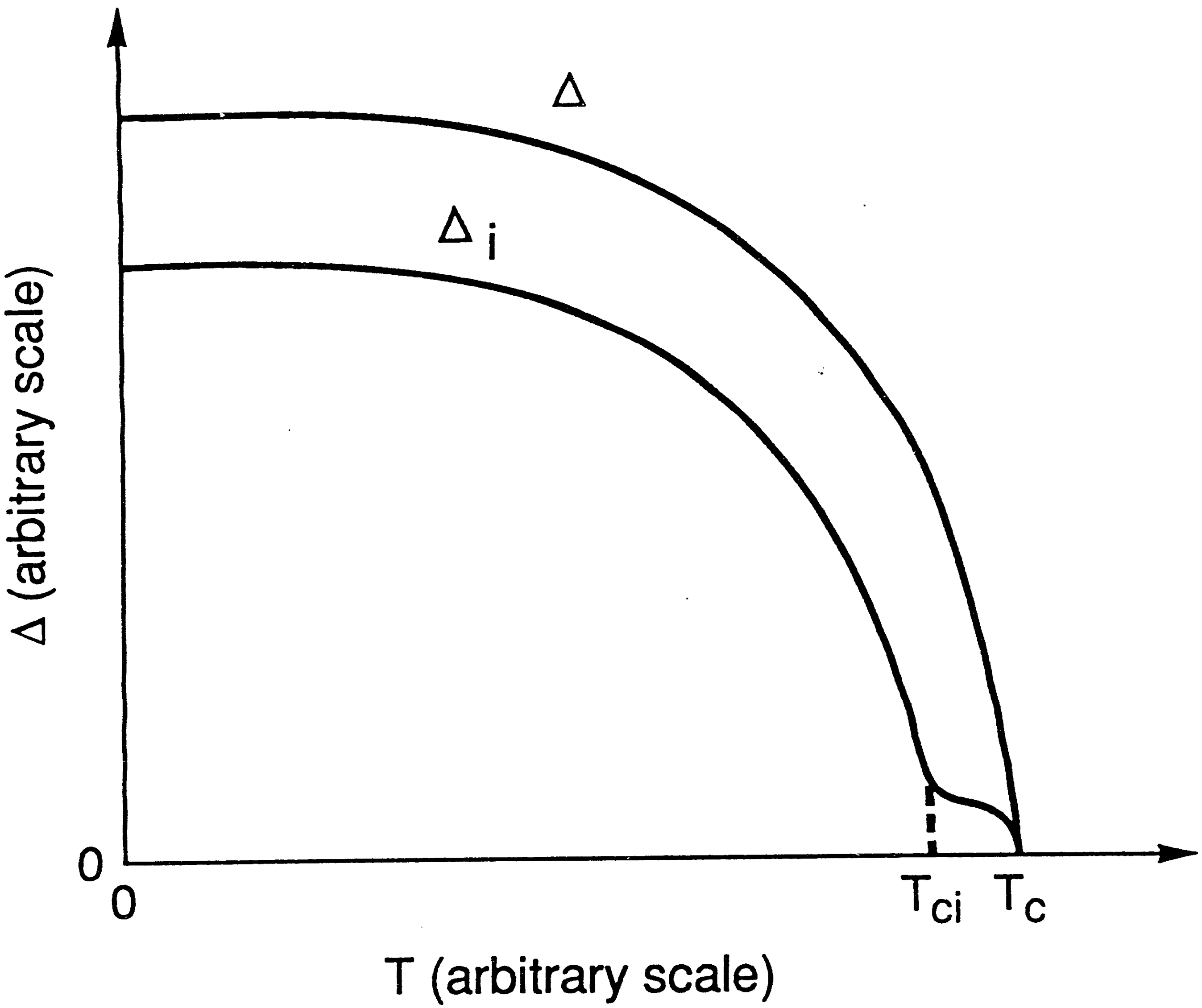


FIG 3 (A)

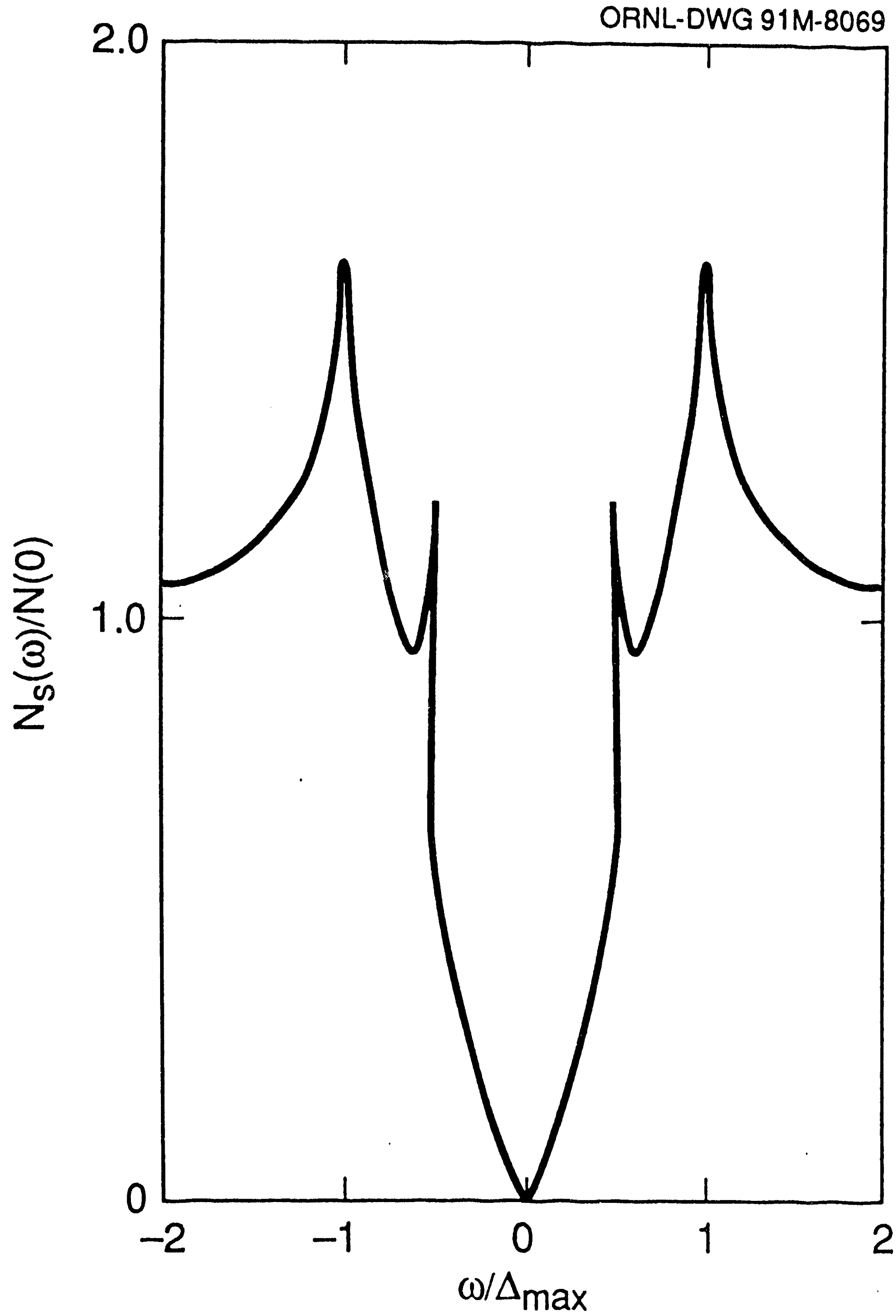


FIG 3 (B)

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