Tunneling and the electron-phonon-coupled superconductivity of Nb_3Sn

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A substantially improved description of published electron-tunneling spectra from Nb_3Sn is obtained by taking account of a probable surface proximity layer in the junctions studied. The results satisfactorily describe the superconducting properties of Nb_3Sn within the conventional framework of strong electron-phonon coupling theory, with $\lambda = 1.8 \pm 0.15$, $\mu^* = 0.16 \pm 0.03$.

I. INTRODUCTION

Considerable fundamental and technological interest exists in the properties of the high transition temperature $A15$ phase superconductors, of which class Nb_3Sn is probably the most thoroughly investigated. Yet the fundamental coupling constants λ and μ^* describing, respectively, the electron-phonon and Coulomb interactions in this material are as yet imprecisely determined, apparently leaving some possibility that coupling mechanisms other than the electron-phonon mechanism might occur in Nb_3Sn.

The most sensitive probe of the strong coupled superconducting state is the Giaever tunneling experiment as developed by McMillan and Rowell.[1] Pioneering tunneling measurements on Nb_3Sn were made by Shen,[2] who concluded that a description of superconducting Nb_3Sn could be made with $\lambda = 1.55$ to 1.69 (assuming $\mu^* = 0.11$ to 0.15, respectively), consistent with pairing induced solely by electron-phonon coupling. More recently, greatly improved thermally oxidized Nb_3Sn tunnel junctions have been made and preliminary results reported.[3] However, as had earlier been the case with oxidized Nb tunnel junctions,[4,5] the *conventional quantitative analysis* (of the phonon-induced structure in the tunneling I-V characteristic) *yields* λ *values too small to reasonably account for the* T_c *of the material.* The preliminary values $\lambda = 0.76$ and $\mu^* = -0.10$ obtained straightforwardly from conventional analysis of tunneling data from the Nb_3Sn-oxide-Pb junctions reported in Ref. 3, are indeed anomalous. Taken at face value, the negative value of the Coulomb repulsion parameter, μ^*, suggests the possibility of an unconventional mechanism for the superconductivity. On the other hand it may simply signal that the assumptions of the experimental or theoretical analysis are inappropriate at some stage. It is this latter possibility that is investigated in the present paper.

Specifically, in this paper we describe what we believe is an entirely realistic analysis of these recent Nb_3Sn tunneling data,[3] based on a proximity junction model[6–8] which seems appropriate for Nb_3Sn-Pb junctions of the type reported in Ref. 3. This analysis permits a greatly improved description of the data and leaves minimal doubt that a satisfactory description of the superconductivity of Nb_3Sn is possible within the conventional framework of strong electron-phonon coupling theory. We obtain parameter values for Nb_3Sn of $\lambda = 1.8 \pm 0.15$ and $\mu^* = 0.16 \pm 0.03$, describing electron-phonon and Coulomb effects, respectively. Hence, we conclude that the tunneling results of Ref. 3, in spite of some complications, do not require the occurrence of other than electron-phonon coupling in the superconductivity of Nb_3Sn.

The basic assumption of the present analysis is that a thin (10–50 Å) proximity layer of weakened superconducting properties exists on the Nb_3Sn electrode surface. This slightly alters the measured tunneling conductance in such a way as to give, with conventional data inversion, parameter values which do not correctly reflect the bulk electrode superconducting properties, and may thus appear as anomalous. The first application of such an analysis[9] was to thermally oxidized Nb tunnel junctions.[5] The connection

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between weakened superconductivity in oxidized surfaces of Nb and V and observation of proximity effect anomalies in tunneling characteristics had earlier been emphasized by Shen.[10] The origin of the proximity layer on the present Nb_3Sn junctions is not known with certainty and is likely to be different than in the case of thermally oxidized Nb, hence the origin of the proximity layer in niobium will not be further discussed here. Of primary relevance to the present discussion, however, is that application of the proximity analysis to the Nb cases[9,11] has given a working understanding of the consequences (independent of its origin) of a thin and diffusely scattering surface proximity layer on the inversion of tunneling data. [It should be said that the first two authors of Ref. 11 still assert, on the basis of various types of surface treatment (Refs. 4 and 18) that the λ and μ^* parameters of Nb are genuinely anomalous.] Further, the proximity theory has been successfully applied to *intentionally formed* proximity junctions on Nb-,[7] $Nb_{0.75}Zr_{0.25}$-, and V-based[12,13] electrodes. Thin layers of Al were deposited in measured amounts ($d_N \approx 25$–50 Å) and subsequently oxidized, leading to well understood Al_2O_x barriers; the analysis in these cases benefits from the fact that the proximity layer composition and thickness are more certainly known than in the cases of Nb,[4,5] and Nb_3Sn.[3]

Although the thermal oxide of Nb_3Sn appears to be suitable for tunnel barrier formation,[14,15] the inherently high sensitivity of T_c in Nb_3Sn to degradation by nonstoichiometry and/or disorder, as is likely to occur in the first few atomic layers below any real surface, suggests that the proximity junction model may be relevant for Nb_3Sn junctions as well. An even more compelling reason may be the accumulating evidence[3,16] that the procedures used in the fabrication of the Nb_3Sn junctions reported in Ref. 3 may have led to an excess of Sn on the surface that was subsequently oxidized to form the tunneling barrier. A Sn-rich layer of depth up to ~ 100 Å is consistent with Auger and electron microprobe studies[16] of the Nb_3Sn and also with Fiske modes measured in similar Nb_3Sn-oxide-Pb Josephson tunnel junctions from which a dielectric constant close to that of SnO_2 can be deduced.[17]

The procedures for applying the proximity junction model and the effects of a surface proximity layer on the conventional tunneling data inversion to provide $\alpha^2F(\omega)$, λ, and μ^* have been described previously.[7–9] In the model the pair potential in the weakened surface layer of thickness $d_N < \xi$ is assumed to take a spatially constant value Δ_N much smaller than the bulk superconductor value Δ_S, to which the pair potential discontinuously rises at the *NS* interface. The consequent interference effects which occur in the surface proximity layer have been analyzed and the corresponding tunneling density of states at the oxide interface evaluated.[6] Scattering events in the proximity layer are characterized by an effective mean free path l. In the limit that d_N is small and l sufficiently large, the contributions of $\Delta_N(E)$ substantially cancel out of the density of states expression. Hence, a useful approximate application of the model is to assume $\Delta_N(E) = 0$.[8,9] In this case the tunneling density of states is given approximately, for $E >> \Delta_s$, as

$$\sigma(E) \equiv \left[\frac{dI}{dV}\right]_S \Big/ \left[\frac{dI}{dV}\right]_N \cong 1 + \tfrac{1}{2} e^{-2d/l}\,\mathrm{Re}\left[\left(\frac{\Delta_s}{E}\right)^2 \exp\left(\frac{i4dE}{\hbar V_F^*}\right)\right],$$

where the *two* undetermined parameters are d/V_F^* and d/l.

Turning to the data reported in Ref. 3 (specifically those shown in Figs. 1–4 of that paper) we note (see Fig. 1) that these behave[9] in conventional reduction in a fashion similar to the oxidized-Nb data,[5,18] giving a characteristic *positive offset* of the calculated value of $\sigma/\sigma_{BCS} - 1$, with $\sigma = (dI/dV)_S/(dI/dV)_N$, relative to the experimental quantity, along with unexpectedly small values of λ and μ^*. Note also that there is evidence in some of the I-V data[3] of a "knee"[10] at a bias just above the sum of the (counterelectrode and Nb_3Sn) energy gaps $\Delta_C + \Delta_S$, which is characteristic of a proximity layer. In this circumstance the identification of $\Delta_C + \Delta_S$ as the center of the current rise is believed to underestimate the sum gap $\Delta_C + \Delta_S$.[19,20]

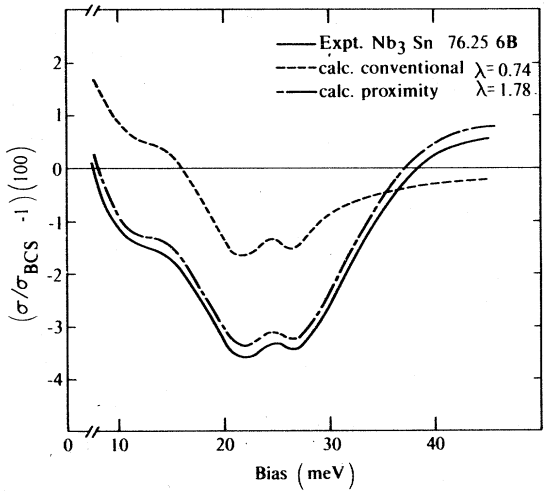

FIG. 1. Experimental and calculated reduced conductances from Nb_3Sn junction 76.25 6B of Ref. 3, here reanalyzed, taking $\Delta = 3.3$ meV, and adopting a proximity model for the junction (see text). Slight scatter in experimental data points below 8 meV, here omitted, leads to some noise in the 8-meV peak in $\alpha^2F(\omega)$, Fig. 2, which negligibly affects quoted parameters.

Figure 1 shows the experimental reduced conductance $\sigma/\sigma_{BCS}-1$ for Pb-Nb_3Sn junction number 76.25 6B as a solid line. The dashed and dash-dot lines, respectively, show the calculated quantity after conventional and proximity model inversions, taking $\Delta_{Nb_3Sn}=3.3$ meV. The conventional inversion (dashed) corresponds closely to that obtained in Figs. 3 and 4 of Ref. 3, here giving $\lambda=0.74$ and $\mu^*=-0.11$. The large positive offset is characteristic of a proximity junction with diffuse scattering, reduced conventionally.[9] The proximity inversion (dash-dot line) manifestly yields a superior, but not perfect, description of the data. The gap parameter in both cases in Fig. 1 corresponds closely to the *experimental* gap value, 3.25 ± 0.1 meV, which, as we have noted, may be a slight underestimate in a proximity case. In the proximity inversion we have chosen $d_N/V_F^*=47\times10^{-16}$ sec and $d/l=0.13$, and have made the approximation $\Delta_N=0$.[7-9] The corresponding $\alpha^2F(\omega)$ function is shown in Fig. 2, and corresponds to $\lambda=1.78$ and $\mu^*=0.167$.

Returning to Fig. 1, we emphasize that a necessary condition for an accurate and self-consistent determination of parameters from an inversion of tunneling data is that the calculated and experimental reduced conductance agree. Because of the nature of the inversion procedure, there exists a range of values for d/l and d/V_F^* which yield a good fit of the conductance data up to the maximum energy where $\alpha^2F(\omega)$ is determined. However, proper determination of the parameters requires agreement with the conductance data over the full energy range, i.e., to energies *beyond* this cutoff in $\alpha^2F(\omega)$. We find upon examining the data within the field of d_N/V_F^* and d_N/l values that a well-defined minimum in rms deviation (over the *full* energy range) of calculated versus measured reduced conductance exists near $d_N/V_F^*=47\times10^{-16}$ sec, $d/l=0.13$ and agreement to 2×10^{-3} has been achieved. It is important to note that only those values of d_N/V_F^* and d/l determined in this fashion yield an $\alpha^2F(\omega)$ spectrum with a high-energy tail which goes to zero at the same energy as $F(\omega)$. The calculated T_c is 16 K, in reasonable agreement with the observed value of 17.5 K. Allowing for our approximate treatment of Δ_N the overall accuracy of λ and μ^* is estimated at ±0.15 and ±0.03, respectively.

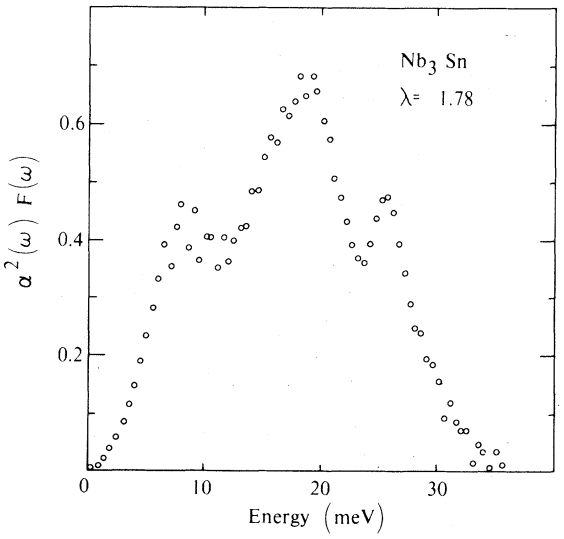

FIG. 2. The effective phonon spectrum $\alpha^2F(\omega)$ for Nb_3Sn, obtained by reanalysis of tunneling data of Ref. 3.

II. DISCUSSION

The nature of the proximity layer is not known with certainty, but presumably is either a layer of Sn or a layer of Sn-rich and possibly disordered Nb_3Sn. In the former case a Fermi velocity $V_F=2\times10^8$ cm/sec is likely, corresponding to $d_N\simeq65$ Å, which is not unacceptable in light of the other information available about junctions of this type.[3,16] If the layer is really Nb_3Sn, whose V_F is smaller,[21] the d_N value would be proportionately reduced, which is also quite acceptable. At the same time, we cannot entirely rule out the possibility that the oxide contributes in some way to the proximity layer, as appears to be the case for Nb.

In comparison of the $\alpha^2F(\omega)$ function of Fig. 2 with that obtained by conventional analysis (Fig. 4, curve B, of Ref. 3), three changes are noteworthy. The scale of the function is increased, leading to values of $\lambda\equiv2\int_0^\infty\alpha^2(\omega)F(\omega)d(\ln\omega)$ increased from 0.8 to 1.8. *This occurs with a change of shape such that the high-energy region is enhanced relative to the low-energy region.* The high-energy cutoff is now 34 ± 1 meV, to be compared with 28 meV obtained in Ref. 3. The present cutoff is in good agreement with that of the related neutron scattering function $G(\omega)$.[22] While agreement on the cutoff of the three related functions $\alpha^2F(\omega)$, $F(\omega)$, and $G(\omega)$ is necessary, a detailed agreement in shape is *not* necessary. In particular, as explained in Ref. 22, $G(\omega)$ is expected to be distorted with respect to $F(\omega)$ because the relevant neutron scattering cross sections of Nb and Sn differ substantially.

The moments of the present, improved, $\alpha^2F(\omega)$ are of some interest in connection with theoretical calculations of the thermodynamic properties of superconducting Nb_3Sn.[23,24] These are $\omega_{log}=\exp\langle\ln\omega\rangle=10.8$ meV, $\langle\omega^2\rangle=226$ meV^2, and $\langle\omega\rangle=13.1$ meV. Our results are also relevant to recent attempts[25,26] to explain the superconductivity of Nb_3Sn, and in particular the tunneling data,[3] by going beyond the electron-phonon mechanism. While our results may not directly disprove such possibilities, it is clear that the present improved analysis of the tunneling data leads to parameters adequately describing the properties of Nb_3Sn within the conventional assumption of electron-phonon coupling.

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