Observations on Cooper-limit-like behavior in strong coupling: Normal-superconducting bilayers at critical fields

H.-J. Tao,* T.-P. Chen, and E. L. Wolf†
Ames Laboratory, U.S. Department of Energy, Iowa State University, Ames, Iowa 50011
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Tunneling measurements of clean Mg/Nb and Al/Nb (normal-superconducting, *NS*) bilayers, with *N*-metal thicknesses ≤ 100 Å, reveal a superconducting order parameter at the *N* surface proportional in magnitude to that in *S*, even in fields closely approaching the critical values for bulk *S* (Nb). The parallel decay of *N* and *S* phonon features with field, as first observed here, implies an order parameter nearly constant over the *NS* structure even under strong local depairing conditions.

The central assumption of Cooper's treatment[1] of a small (dimension $d \ll \xi$) inhomogeneous weak-coupling superconductor is constancy of the pair amplitude $F(\vec{r})$, i.e., equal pairing correlations across the Fermi surfaces, throughout the whole structure. This feature is retained in the strong-coupling Eliashberg-like expression of Arnold[2] for the pair potential $\Delta_N(E)$ in a clean *NS* bilayer with $d_N \ll \xi$, $d_S \gg \xi$:

$$\Delta_N(E) = [Z_N(E)]^{-1} \times \int_0^\infty d\omega \, \mathrm{Re}\left(\frac{\Delta_S(\omega)}{[\omega^2 - \Delta_S^2(\omega)]^{1/2}}\right)[K_+(\omega,E)]_N \ , \tag{1}$$

where $Z_N(E)$ is the renormalization function in *N*. Here, K_+ is the local electron-phonon coupling[2] *in N*, while the pair density (brackets) in *N* is taken equal to that *in S*. In this Cooper-like limit, $\Delta_N(E)$ is dominated by the flood of pairs from *S* acting on the local coupling $[K_+(\omega,E)]_N$. On the assumption $d_N \ll d_S$, the effect of *N* on superconductivity in *S* is shown to be small.[2]

An intuitive test of such Cooper-limit-like behavior in an *NS* bilayer occurs in parallel magnetic fields increasing toward the critical fields H_{c2}, H_{c3}, respectively, for bulk and surface sheath superconductivity in *S*, assumed to be of type II. Cooper-like behavior implies $\Delta_N(E) \propto \Delta_S(E) \neq 0$ up to H_{c3}, while an alternative possibility is invasion of *N* by flux at a well-defined breakdown field $H_B \ll H_{c3}$, thus driving *N* normal before *S*.[3] The breakdown case has been extensively studied[4] in ranges of *N* thickness d_N typically larger than 500 Å and *NS* interfacial coupling typically weaker than achieved in the present work. In an intermediate range, $d_N \sim 500$ Å, smaller than required for the sharp breakdown effect, a previous tunneling study of *NS* (Ag/Pb) junctions by Chaikin *et al.*[5] indicated a substantially more rapid decay of *N* phonon features than *S* phonon features with increasing magnetic field. Donovan-Vojtovic *et al.*,[6] in a recent study of tunneling phonon structure in strongly gapless superconductors, have demonstrated in the *conventional C-I-S* geometry (*C* is the counterelectrode) that *S* phonon structure can be observed to parallel fields approaching H_{c3}, decaying proportionally to $(H_{c3} - H)$, and confirming that such observations provide a reliable monitor of the order parameter at the surface.

The present observations, in contrast, reveal for the first time a strictly parallel decay of the order parameter in *N* and *S* (Cooper-limit behavior) with increasing field, as inferred unequivocally from the corresponding phonon features in the tunneling density of states.

Questions related to the persistence of superconductive pair correlations, despite local depairing conditions, are currently of considerable fundamental and applied interest. Such questions occur in relation to superconductivity in coexistence with magnetism, as may occur, e.g., in $HoMo_6S_8$,[7] and with regard to optimal critical-field behavior of superconducting cables with discontinuous filaments.[8] Indeed, the present results indicate, contrary to the earlier literature,[3–5] that the inherent reduction of critical field of a repeating *NS* laminar structure, with *N* thicknesses d_N in the 100-Å range and $d_N \ll d_S$, can be negligible.

Electron tunneling into thin ($50 < d_N < 100$ Å) Al and Mg layers (*N*) backed by $\sim$50-μm Nb foils (*S*) in Ag-oxide—*N*/*S* junctions[9] provides an unambiguous probe of the *N* pair potential [and, from Eq. (1), the local pair density] within a few times $2\pi/k_F$ of the *N*-oxide interface.[10,11] The *N*-metal phonon features (arrows in Fig. 1) in the reduced conductance of such clean, thin-*N NS* junctions have been clearly identified and treated quantitatively[9,12] within the specular-theory expression,[2] valid for $E \gg \Delta_N, \Delta_S$:

$$N_T(E) \cong 1 + \tfrac{1}{2}\,\mathrm{Re}(\Delta_N^2/E^2) + \tfrac{1}{2}\,\mathrm{Re}\{[(\Delta_S - \Delta_N)^2/E^2]I(2E)\} + \mathrm{Re}\{[\Delta_N(\Delta_S - \Delta_N)/E^2]I(E)\} \ , \tag{2}$$

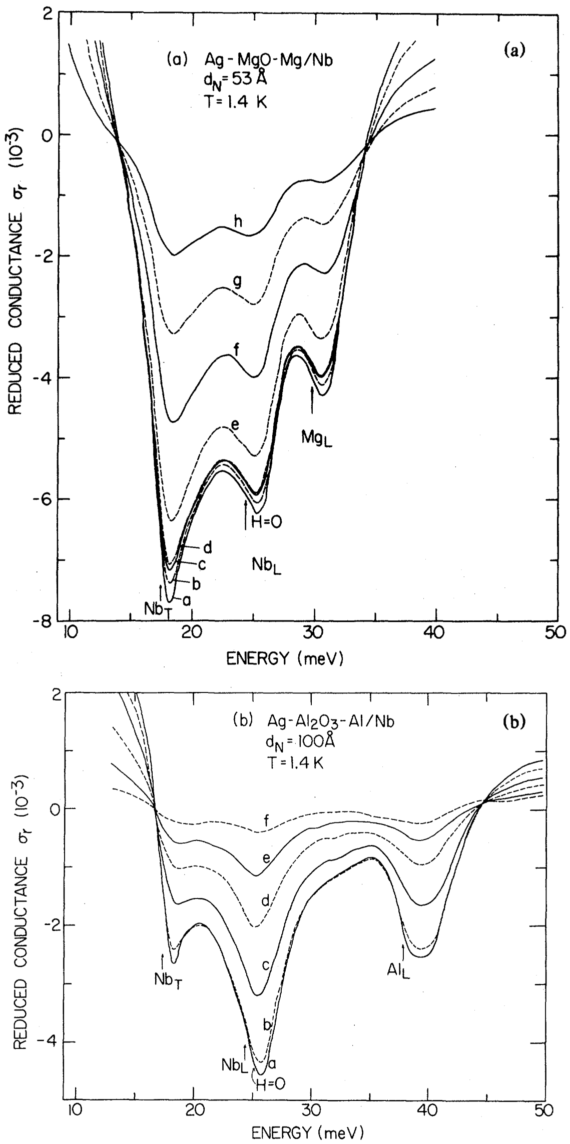

FIG. 1. (a) Reduced conductance $\sigma_r = \sigma_S / \sigma_N - 1$ of typical Ag-MgO-Mg/Nb foil tunnel junction, $d_N = 53$ Å, as measured at 1.4 K in increasing parallel magnetic fields. Arrows locate phonon peaks of Nb and Mg, which correspond to points of most negative slope in $\sigma_r(V)$. Similar results are obtained in perpendicular orientation. (b) σ_r spectra obtained similarly from Ag-Al_2O_3-Al/Nb foil junction, $d_N = 100$ Å. Analysis of such spectra at $H = 0$ is discussed in Refs. 9 and 12.

where I is a slowly varying function near unity in value, and Δ_N [calculated from Eq. (1)] and Δ_S are well known to exhibit characteristic rapid variations near peaks ($\hbar\omega_{ph}$) of the underlying NS, phonon spectra. As is evident from Fig. 1, the observed Mg and Al features (arrows) decay at 1.4 K with increasing magnetic fields at essentially the same rate as the Nb phonon features (16 and 24 mV, corresponding to points of most negative slope in conductance) and, in fact, persist to fields $H_{\parallel} \geq 0.5$ T, well above H_{c2} and, in the 50-Å Mg case [Fig. 2(a)] to 0.625 T, very close to the reported[13] $H_{c3} = 0.66$ T for pure bulk Nb at the same temperature. (The small reduction of H_{c3} below its bulk value for the thicker Al film, $d_{Al} = 100$ Å, is an expected[14] and previously studied[15] consequence of a thin N layer.) Spectra (not shown) for increasing $H_{\perp}$ are nearly indistinguishable, except for the increased initial rate of decay, shown in Fig. 2. The H variation of the three phonon features in parallel and perpendicular orientation is shown in Figs. 2(a) and 2(b) for Mg and Al, respectively. The Mg_L points in Fig. 2(a) fall slightly below the Nb points, possibly indicating a slightly lower critical field in the Mg layer. We tentatively interpret this small departure, not present in the Al case, from the basic parallel decay of N and S features to a greater degree of quasiparticle scattering in the Mg than in the Al overlayers, as can be inferred from analysis of the proximity spectra. The arrows in Fig. 2 locate the critical fields H_{c1}, H_{c2}, and H_{c3} as reported[13] for bulk

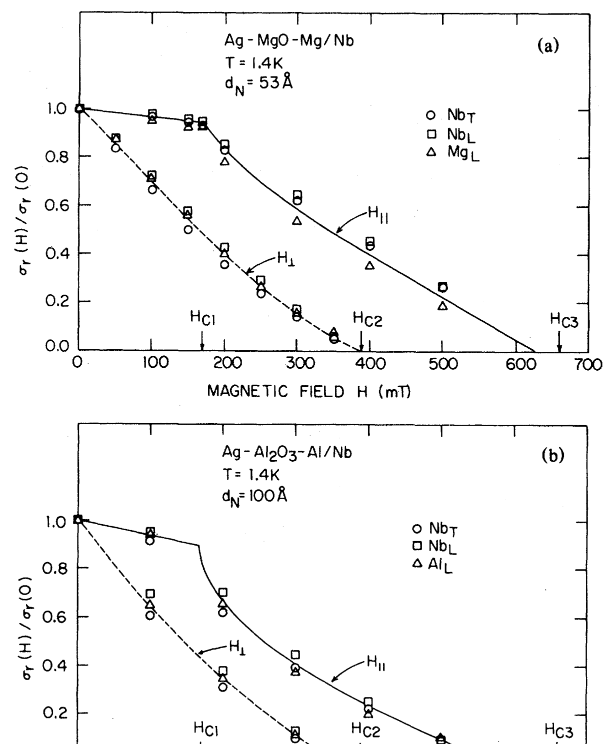

FIG. 2. (a) Dependence of normalized strengths of $\Delta_{Nb}[\sigma_r(18.5, 25.3)]$ and $\Delta_{Mg}[\sigma_r(30.5)]$, from Fig. 1(a), with $H_{\parallel}$ and $H_{\perp}$. Arrows locate values of H_{c1} (1.71 mT), H_{c2} (3.9 mT), and H_{c3} (6.6 mT) for bulk Nb, after Ref. 13. (b) Similar results from typical Al/Nb bilayer of Fig. 1(b).

Nb at 1.4 K. In parallel fields, the observed break to more rapid decay of phonon features (pair potentials) with increasing $H_{\parallel}$ is expected beyond H_{c1}, where flux first enters the (type II) Nb foil; all superconducting effects vanish at H_{c3}. In the $H_{\perp}$ case, flux enters the foil immediately at low $H_{\perp}$ and the normal state occurs at H_{c2}. Since the measured ratios H_{c3}/H_{c2} (1.67 and 1.63 from the Mg and Al spectra, respectively) are close to the theoretical ratio[14] 1.695, we assume that in parallel fields beyond H_{c2} (arrows) the well-known state of vortex-free surface sheath superconductivity[14,16] (Fig. 3) of depth $d \sim 2\xi \times(H_{c2}/H_{\parallel})^{1/2} >> d_N$ ($\xi \cong 450$ Å for Nb at 1.4 K) occurs at both surfaces of the Nb, including the region directly behind the tunnel junction to the N layer. Since the N layer thicknesses d_N are small compared with d, the magnetic field in the N layer is large, essentially equal to the applied field. This may be seen from the small values near $x=0$ of the internal field (the dashed curve in Fig. 3, after the calculation of Fink and Kessinger in Ref. 16) generated by sheet currents in the sheath, which partially cancel the applied field within the sheath. Hence, the persistence of spectral features, due to Mg and Al (arrows, Fig. 1) near H_{c3} (parallel field) and H_{c2} (perpendicular field) of bulk Nb, unequivocally indicate induced superconductivity in Mg and Al at fields on the order of 50 times the H_c of Al. These results therefore are a strong indication of persistence of pair correlations in N and of a Cooper-limit-like behavior.

The fact that the observed critical fields are slightly below the bulk values does not detract from the main argument which is that pair correlations in N, seen via Δ_N at the Mg and Al energies, persist proportionally to the pair correlations in S, observed via Δ_S in the Nb peaks at 16 and 24 meV.

We see no conflict between the present tunneling observations and the breakdown field behaviors previously reported[3-6,17] for structures having much larger values of d_N and possibly less transmissive NS interfaces. Further work delineating the boundary between the two types of behavior is underway.

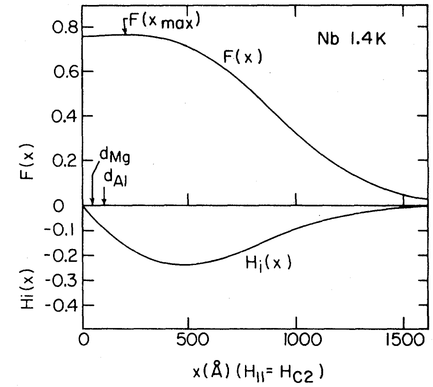

FIG. 3. Expected spatial behavior of pair density F (upper) and internal opposing magnetic field H_i (lower) (dashes) in the surface sheath in arbitrary units, after calculation by Fink and Kessinger (Ref. 16), for $\kappa=1$ and $H_{\parallel}=H_{c2}$. The distance scale is based on $\xi=450$ Å for Nb at $H_{\parallel}=H_{c2}$; the sheath width is expected to scale as $(H_{c2}/H_{\parallel})^{1/2}$. Since d_N values 53 Å, 100 Å for Mg/Nb and Al/Nb bilayers are much smaller than sheath thickness d, the external magnetic field is essentially unscreened in the N layer.

Behavior similar to that in Figs. 1 and 2 is also observed as the temperature is increased toward the T_c of Nb, in zero field. A complete report of this work is in preparation.

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*Permanent address: Institute of Physics, Academica Sinica, Beijing, The Peoples' Republic of China.
†Also at Department of Physics, Iowa State University, Ames, Iowa 50011.

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