Brief Reports

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Proximity-effect bilayers with magnetic impurities: The Abrikosov-Gor'kov limit

M. J. DeWeert
Condensed Matter Radiation Sciences Division (Code 4680), Naval Research Laboratory, Washington, D.C. 20875-5000
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A Bardeen-Cooper-Schrieffer superconductor with a surface layer contaminated by magnetic impurities is considered, in the case in which Abrikosov-Gor'kov theory holds for the contaminated layer. This structure is modeled as a proximity-effect bilayer. It is shown that the tunneling density of states can show significant gap depression even though the transition temperature is unaffected, complicating the interpretation of experiments sensitive to the presence of pair breaking.

INTRODUCTION

Layered structures composed of superconductors and materials with magnetic properties have long been of interest. One practical issue is how superconductivity is influenced by the diffusion of magnetic material into the surface of the superconductor. The influence of bulklike pure superconductor beyond the diffusion layer should prevent the full pair-breaking effect of the magnetic atoms. I modeled this system as a proximity-effect bilayer. The diffusion region will be assumed to have a small thickness d, and the transition to pure superconductor will be assumed to occur abruptly, over one atom layer. This model then resembles a proximity-effect system considered in a previous paper,[1] which dealt with resonant pair breaking associated with the Kondo effect. However, this paper considers dirtier surfaces, in which Kondo effects are *absent.*

The Kondo effect is a property of dilute alloys, and the configuration averages needed to calculate the Green's function are dominated by repeated scattering from an isolated impurity.[2] The local moment of an impurity organizes the electrons about it so as to form an $(S-\frac{1}{2})$ bound state. Effectively, one spin of electron is attracted and the other repelled by the moment. The range over which the electronic densities relax back to their unperturbed values is very long in superconductors, on the order of a coherence length. When randomly oriented local moments are much closer together than this length, they interfere with each others binding of conduction electrons, and cannot be considered isolated.[3] In this limit, it is more appropriate to average over spin directions before calculating configuration averages, as in Abrikosov-Gor'kov (AG) theory.[4] This eliminates first-order scattering terms from the self-energy. These terms are responsible for the subgap bands seen in superconducting Kondo alloys, so that these bands are eliminated, but the remaining terms lead to gap depression and gapless superconductivity.

PROXIMITY-EFFECT MODEL

The derivation of the Green's function for the layer containing the impurities, hereafter denoted as the N layer, follows the same steps outlined in Ref. 1. The Abrikosov-Gor'kov impurity self-energy is given by

$$\Sigma^{\text{imp}}=\begin{pmatrix} \left(\frac{i\hbar}{2\tau_1}+\frac{i\hbar}{2\tau_2}\right)N_n(E) & \left(\frac{i\hbar}{2\tau_1}-\frac{i\hbar}{2\tau_2}\right)f_n(E) \\ \left(\frac{i\hbar}{2\tau_1}-\frac{i\hbar}{2\tau_2}\right)f_n(E) & \left(\frac{i\hbar}{2\tau_1}+\frac{i\hbar}{2\tau_2}\right)N_n(E) \end{pmatrix}, \tag{1}$$

where f_n is the local pair density of states and N_n is the local normalized density of states. As in Ref. 1, these are the proximity effect[5] f_n and N_n. The scattering lifetimes τ_1 and τ_2 refer to ordinary scattering and spin-flip scattering, respectively, and correspond to the mean free paths l_1 and l_2. We assume that d/l_1 is large (>1), so that the self-consistent equations for the renormalization function Z_n and pair potential Δ_n reduce to

$$RZ_n\Omega_n\approx i[d/l_1+dl_2]\ , \tag{2}$$

and

$$\Delta_n(E) \approx \Delta_n^{ph} - \frac{2id}{l_1}\frac{\Delta_n}{RZ_s\Omega_n} + \frac{i(\Delta_s-\Delta_n)(rE^2-\Delta_n^2)}{2RZ_s\Omega_n(E^2-\Delta_s\Delta_n+\Omega_s\Omega_n)} , \tag{3}$$

where $R=2d/\hbar v_f$, $r=(d/l_1-d/l_2)/(d/l_1+d/l_2)$, $\Omega_{n,s}=(E^2-\Delta_{n,s}^2)^{1/2}$, and Δ_s and Z_s are the pair potential and renormalization function in the absence of magnetic impurities. For the purpose of this paper, the spatial dependences of $\Delta_{n,s}$ and $Z_{n,s}$ are neglected.

Equation (3) can be rendered into the form of a polynomial. After removing an extraneous root $\Delta_n=\Delta_s$, it is

$$0=(2RZ_sE)^2\Omega_n^2(\Delta_s-\Delta_n)^2+(4Ed/l_2)^2\Delta_n^2(\Delta_s-\Delta_n)+(\Delta_s-\Delta_n)(rE^2-\Delta_n^2)^2$$
$$-8(d/l_2)\Delta_n(E^2-\Delta_s\Delta_n)(rE^2-\Delta_n^2)-4i(RZ_s\Omega_s)(\Delta_s-\Delta_n)\Omega_n^2(rE^2-\Delta_n^2) . \tag{4}$$

Equation (4) is readily solved numerically, with packaged routines. Any solutions which do not satisfy (3) well are discarded. Any remaining extraneous roots may be eliminated by requiring that $\Delta_n(E)$ be continuous, and that the integral of the density of states have approximately the same value as in the case where spin-flip scattering is absent.

The tunneling density of states is the same as Eq. (4.8) of Ref. 1, with the function $b(E)$ defined in that paper set equal to unity:

$$N_T(E)=\mathrm{Re}\left[\frac{E}{\Omega_n}+\frac{\Delta_nE(\Delta_s-\Delta_n)}{\Omega_n(E^2-\Delta_s\Delta_n+\Omega_s\Omega_n)\sinh(d/l_1+d/l_2)}\right] . \tag{5}$$

Figure 1 shows the pair potential for the case in which $d/l_1=1.0$, $\Delta_s=0.60$, $Z_s=1.0$, and $R=0.01$. With $d/l_2=0$, this case is indistinguishable from a pure BCS superconductor. However, with $d/l_2=0.05$, as shown, Δ_n is extremely depressed even though the impure layer is so thin that T_c would be hardly affected. (Of course, T_c is unaffected if the S layer is semi-infinite.) Figure 2 shows the density of states in N derived from the pair potential in Fig. 1. The structure near $E=\Delta_s$ is a remnant of the proximity-effect gap. Aside from this structure, the density of states resembles that of a bulk AG theory calculation in a material which has a much lower transition temperature. For a bulk BCS superconductor with its gap depressed as in Fig. 2, T_c would be approximately $0.44T_{c0}$.

CONCLUSIONS

A superconductor with a thin surface layer contaminated by magnetic impurities has been modeled as a proximity-effect sandwich. The limit in which AG theory holds in the contaminated layer has been considered. The

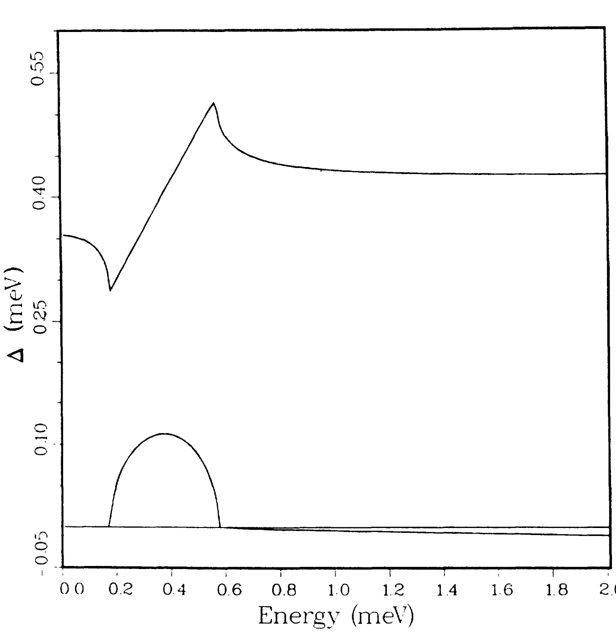

FIG. 1. Pair potential $\Delta_n(E)$ in the surface layer for $\Delta_s=0.60$ meV, $Z_s=1.0$, $d/l_1=1.0$, and $d/l_2=0.05$. Wherever $\Delta_n(E)$ has an imaginary part for $E<\Delta_s$, the density of states will be nonzero. The lower curve is the imaginary part.

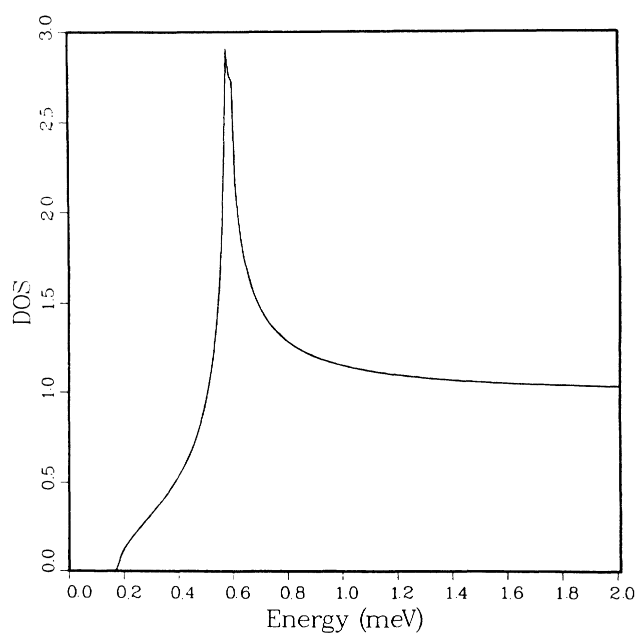

FIG. 2. Tunneling density of states calculated from the $\Delta_n(E)$ shown in Fig. 1. The structure near $E=\Delta_s$ is a remnant of the proximity-effect gap and would be smeared away in a finite-temperature experiment.

tunneling density of states for this structure resembles that of a bulk superconductor with magnetic impurities, but the transition temperature of the former is unaffected while that of the latter is extremely depressed. This effect should be kept in mind in any experiments in which contamination of the surface of a superconductor is likely.

[1]M. J. DeWeert and G. B. Arnold, Phys. Rev. B **30**, 5048 (1984).

[2]J. Zittarz, A. Bringer, and E. Muller-Hartmann, Solid State Commun. **10**, 513 (1972).

[3]M. J. DeWeert, Ph.D. thesis, University of Notre Dame, 1985 (unpublished).

[4]See, for example, G. Rickayzen, *Green's Functions and Condensed Matter* (Academic, New York, 1981).

[5]G. B. Arnold, Phys. Rev. B **32**, 3292 (1985).