Magnetic-field dependence of conductance in microjunctions employing nonhomogeneous superconducting electrodes

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Zero bias anomaly phenomena in conductance spectra relative to superconductor/normal metal–constriction–normal metal (S_1/N_1-c-N_2) junctions are interpreted in terms of the proximity effect. Attention is focused in particular on the influence of the magnetic field on the conductance in point contact junctions and microjunctions with nonhomogeneous base electrodes (S_1/N_1). We find that the highly transmissive nature of the N_1-c-N_2 interface is fundamental in determining the weak dependence of zero bias conductance on the applied magnetic field. The predictions of our model are compared with experimental data on Nb based junctions by Xiong *et al.* [Phys. Rev. Lett. **71**, 1907 (1993)], supplying helpful information on the actual morphology of the structures.

I. INTRODUCTION

Normal metal (N) [semiconductor (Sm)]–superconductor (S) heterostructures are the objects of an active interest for two main reasons. First, they are a powerful probe to investigate the nature of superconductivity in the material employed in the junction, including high-T_c (HTCS),[1] heavy fermions (HF),[2] and organic superconductors.[3] Moreover, they represent an important step toward the realization of several electronic devices, ranging from mesoscopic S-Sm three terminal devices[4] to some types of interferometers.[5] As pointed out by several theories,[6–9] the nature of the interface between the N and S layers in the junction and the level of the disorder in the N layer plays a primary role in the definition of transport phenomena, laying some basic physics in the interplay of Andreev[10] reflections and quantum coherent impurity scattering. However, some problems relative to the interpretation of the observed phenomenology,[7,9,11,12] such as the dependences of conductance on voltage (V), temperature (T), and magnetic field (H), are open. Among the others, a basic issue, presently debated, is the appearance of a zero centered conductance peak and its dependence on magnetic field and temperature.

In the present work we consider within certain approximations the occurrence of proximity effects[13] and their influence on the conductance spectra in point contact (PCJ) and high transmittance microjunction spectroscopy in the presence of an external magnetic field. In this regard the configuration of a spatially nonhomogeneous base electrode gives the possibility to point out interesting aspects of proximity effects. Following some experimental evidence,[9,14] a nonhomogeneous electrode may be modeled in several cases as an S_1/N_1 bilayer, where the two slabs S_1 and N_1 are weakly coupled. The configuration we will discuss is, therefore, of the type S_1/N_1-c-N_2, where c stands for the constriction between the two sides of the junction.

Our model based on proximity effect reliably restores some experimental phenomenology[3,12,15] of a zero bias peak usually reported as a zero bias anomaly (ZBA), which is among the most significative deviations from the classical results of Bonder, Tinkham, and Klapwijk[6] (BTK) and Arnold.[16] Furthermore we find that the zero bias anomaly is almost insensitive to the magnetic field. Conversely the bump which corresponds to the gap value of the S electrode ($eV=\Delta_{BE}$) significantly depends on the magnetic field. According to the model, the physical origin of ZBA can be related to the base electrode and more precisely to the weakly coupled nature of the interface between S_1 and N_1 of the bilayer (transmission probability $\alpha \ll 1$). On the other hand, Andreev reflection processes at the metallic N_1-N_2 interface (between the needle and the normal part of the base electrode) seem to be crucial in determining the weak dependence of the conductance on the magnetic field. This has been experimentally observed for various types of junctions.

II. MODEL: BASIC CONCEPTS AND MAIN FORMALISM

A. Point contact junctions: Nonhomogeneous base electrode

We first briefly report on the conductance behavior in the simple superconductor–constriction–normal metal (S_1-c-N_2) configuration and in the more complicated case of S_1/N_1-c-N_2, where the nonhomogeneous base electrode is represented by the S_1/N_1 bilayer. Afterwards we discuss the solution of the model equations as an external magnetic field is applied to the structure.

Based on the technique of the exact Green function, Arnold[16] found a general expression of the current in a PCJ, which in the case of S_1-c-N_2 configuration reduces to the following:

$$I(V,T)=\int_0^\infty dE[G_{\rm QP}(E,T)+G_{\rm sup}(E,T)]\{f(E-eV,T)-f(E+{\rm eV},T)\}, \tag{1}$$

where

$$G_{\rm QP}(E,T)=\left[\frac{2e}{\pi}\right]\sum_{k_\parallel}\frac{[(1+2Z^2){\rm Re}\{A(E,T)\}+\frac{1}{2}(1+|A(E,T)|^2-|B(E,T)|^2)]}{|D(E,T)|^2},$$

$$G_{\rm sup}(E,T)=\left[\frac{2e}{\pi}\right]\sum_{k_\parallel}\frac{|B(E,T)|^2}{|D(E,T)|^2}.$$

The explicit forms of the functions $A(E,T)$, $B(E,T)$, and $D(E,T)$ are

$$A(E,T)=\frac{|E|}{i\sqrt{\Delta_{\rm BE}(E,T)^2-E^2}},\quad B(E,T)=\frac{|\Delta_{\rm BE}|}{i\sqrt{\Delta_{\rm BE}(E,T)^2-E^2}}\quad \text{for } |E|\leqslant{\rm Re}\{\Delta_{\rm BE}(E,T)\},$$

$$A(E,T)=\frac{|E|}{\sqrt{E^2-\Delta_{\rm BE}(E,T)^2}},\quad B(E,T)=\frac{\Delta_{\rm BE}(E,T){\rm sgn}(E,T)}{\sqrt{E^2-\Delta_{\rm BE}(E,T)^2}}\quad \text{for } |E|>{\rm Re}\{\Delta_{\rm BE}(E,T)\},$$

$$D^R(E,T)=(1+2Z^2)+A^R(E,T),$$

respectively, where $\Delta_{\rm BE}(E,T)$ is the order parameter of the base electrode. The parameter Z takes into account the resistance at the interface between the needle and the base electrode.[6,16]

$G_{\rm QP}(E,T)$ represents the usual quasiparticle current through the junctions; $G_{\rm sup}(E,T)$ contributes also to voltages below the gap value of S.

The expression of the current [Eq. (1)] is obtained under the assumptions that the barrier is ideal and structureless and the entire voltage drop occurs across the barrier. Furthermore quasiparticles in the electrodes distribute according to the equilibrium distribution function in each electrode.[16]

In the simplest case we can depict the nonhomogeneous base electrode as formed by two spatially homogeneous regions, which are weakly coupled. As a consequence Δ exhibits a steplike shape. According to such a scheme, we use the order parameter expression of the McMillan tunneling proximity model[13] for $\Delta_{\rm BE}(E,T)$ in the formalism previously presented, through $A(E,T)$ and $B(E,T)$.[9]

In the McMillan theory, the order parameters in the bilayer basically depend on the order parameters $\Delta^{\rm ph}_{N,S}(T)$, characteristic of the "bulk" materials, and on two parameters $\Gamma_{N,S}$, characteristic of the whole assembly:[13]

$$\Delta_{N,S}(E,T)=\left[\Delta^{\rm ph}_{N,S}(T)+\frac{i\Gamma_{N,S}\Delta_{S,N}(E,T)}{\sqrt{E^2-\Delta^2_{S,N}(E,T)}}\right]\times\left[1+\frac{i\Gamma_{N,S}}{\sqrt{E^2-\Delta^2_{S,N}(E,T)}}\right]^{-1}. \tag{2}$$

The indices N and S refer to the side of the bilayer facing the counterelectrode, respectively. For the configuration S_1/N_1-c-N_2, we are mainly interested in the case $\Delta_{\rm BE}(E,T)=\Delta_{N_1}(E,T)$. In particular, $\Gamma_{N,D}=\mathbf{h}\nu_{FN,FS}\alpha/(2\pi B d_{N,S})$, where α is the transmission probability coefficient at the S/N interface, B is basically a constant value, $\nu_{FN,FS}$ indicate the Fermi velocities in N and S, and $d_{N,S}$ are the respective thicknesses of the normal and superconducting layers.[13] As is well known, the model is valid in the weak coupling regime ($\alpha\ll 1$) and the conditions $\xi_{N,S}\gg d_{N,S}$ have to be fulfilled,[14,17,18] where ξ_N and ξ_S are the coherence lengths in N and S, respectively, and can depend in general on H (Ref. 19).

B. Point contact and microjunctions in a magnetic field

The effect of a magnetic field, applied parallel to the junction, on the quasi-particle current has been widely considered in the literature.[19–22] In the S_1/N_1-c-N_2 configuration, the external magnetic field can basically influence the order parameter of the bilayer[21,22] and the Andreev reflection mechanisms.[19] At an S/N interface, characterized by a low barrier transmittance, the Andreev reflection probability is sensitively affected even at low magnetic fields H of the order of $H^*=\Phi_0(v_0)^{1/2}/[2\pi\lambda\xi_N(\Delta)]$,[19] where λ is the London penetration depth, Φ_0 the magnetic flux quantum, and v_0 a characteristic voltage determining the width of the conductance peak at zero bias. In the case of a highly transmissive S/N interface, the Andreev reflection probability is not substantially affected by H (Ref. 19). Within such a framework, Volkov, Zaitsev, and Klapwijk (VZK) (Ref. 19) studied the magnetic dependence of the conductance of an SN-N' structure in the limit in which SN and NN' interfaces are weakly coupled ($\alpha \ll 1$). Their model properly predicts the strong magnetic dependence of the zero bias conductance $\sigma(V=0,H)$ for S-semiconductor (Sm) junctions.[11] On the other hand, measurements on structures based on highly transmissive interfaces give different results such as $\sigma(V=0,H)$ almost independent of H (Ref. 12).

Therefore, some questions are still open and it seems interesting to consider other aspects of the problem, which are more closely related to the actual nature of the junction. In particular, it might be of interest to consider the metallic regime of a point contact or microjunction ($Z \approx 0$) using our approach. As a matter of a fact, in such a system, corrections to Andreev reflection probability at the metallic interface N_1N_2, due to the magnetic field, are negligible. It is therefore necessary to take into account the effect of the magnetic field on the order parameters Δ_{N_1} and Δ_{S_1} of the base electrode. These give complete information about the weakly coupled S_1/N_1 bilayer ($\Delta_{N_1} \ll \Delta_{S_1}$) and its interface. The magnetic behavior of the conductance $\sigma(H)$ will finally depend on the modified value of $\Delta_{N_1}(H)$ basically related to $\Delta_{S_1}(H)$, through the McMillan model.

In order to determine $\Delta_{S_1}(H)$and $\Delta_{N_1}(H)$, we first guess a magnetic dependence of the order parameter in the bulk materials S and N [$\Delta_S^{\mathrm{ph}}(H)$ and $\Delta_N^{\mathrm{ph}}(H)$, respectively] and then solve self-consistently the coupled equations. Afterwards we introduce this expression in Eq. (1) to obtain conductance spectra as a function of H. As far as the magnetic dependence of $\Delta_{S,N}^{\mathrm{ph}}$ is concerned, it can be approximated according to general theories in tunnel junctions,[17,22] in analogy to the case of dilute magnetic alloys in a proximity system[23] and on the basis of the main concepts of depairing mechanisms. In the case of a normal metal we have $\Delta_N^{\mathrm{ph}}(0)=0$, while Δ_S^{ph} vs H is given by the expression

$$\Delta_S^{\mathrm{ph}}(H,E,T)=\Delta_S^{\mathrm{ph}}(0,E,T)[1-(H/H_c)^2]^{1/2}, \quad (3)$$

where H_c is the critical magnetic field of the superconductor. Such classic dependence of Δ on H is strictly valid in the case of a ratio d/λ of the thickness d of the superconductor to penetration depth λ close to 0 (Ref. 21). Our results on ZBA, as we discuss further on, are not sensitively affected by a different choice of the magnetic dependence Δ_S^{ph}or by other values of the ratio d/λ. Differences due to type-I or type-II superconductivity are neglected as a first approximation.

III. CONDUCTANCE SPECTRA: DEPENDENCE ON PROXIMITY PARAMETERS AND MAGNETIC FIELD

The conductance was computed according to the model presented in the previous section as a function of the proximity parameters and magnetic field H, at different temperatures. We first review the dependence of the conductance $\sigma(V)$ on proximity parameters. In Fig. 1 conductance σ is reported as a function of normalized energy [energies are divided by $\Delta_S^{\mathrm{ph}}(0)$] for the following values of the proximity parameters: $\Gamma_N=0.1$ meV and $\Gamma_S=0.05$ meV (crosses), $\Gamma_N=0.1$ meV and $\Gamma_S=0.01$ meV (circles), $\Gamma_N=0.1$ meV and $\Gamma_S=0.001$ meV (triangles), $\Gamma_N=0.01$ meV and $\Gamma_S=0.0001$ meV (squares), respectively, with $\Delta_S^{\mathrm{ph}}(0)=1.0$ meV, $\Delta_N^{\mathrm{ph}}(0)=0$ meV, $T=0.5$ K, and $Z=0$. Through this choice of the parameters, a situation, in which effects due to proximity are relevant, is reached: the presence of a zero centered structure can be noticed differently from BTK and from Arnold's results. The bump in correspondence to the gap value of S obviously becomes sharper by increasing the thickness of the superconducting layer d_S (with d_N a constant). Moreover, a reduction of a factor 10 of the barrier transparency at the S_1/N_1 interface of the base electrode determines a decrease of the zero centered structure and a lowering of the bump at finite voltage,[9] as evident from curves indicated by the triangles and squares in Fig. 1, respectively. For $d_N \to 0$ the BTK limit is obviously restored.

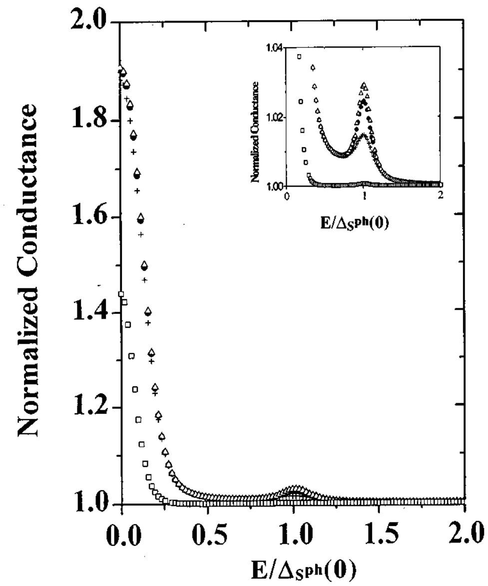

FIG. 1. Conductance vs normalized energy [energies are divided by $\Delta_S^{\mathrm{ph}}(0)$] calculated according to the proposed model for the set of parameters: $\Gamma_N=0.1$ meV and $\Gamma_S=0.05$ meV (crosses), $\Gamma_N=0.1$ meV and $\Gamma_S=0.01$ meV (circles), $\Gamma_N=0.1$ meV and $\Gamma_S=0.001$ meV (triangles), $\Gamma_N=0.01$ meV and $\Gamma_S=0.0001$ meV (squares), respectively, with $\Delta_S^{\mathrm{ph}}(0)=1.0$ meV, $\Delta_N^{\mathrm{ph}}(0)=0$ meV, $T=0.5$ K, and $Z=0$. The presence of a zero centered structure, along with a bump in correspondence to the gap value of S layer of the bilayer S/N, can be noticed.

As far as the zero bias conductance is concerned, significant deviations from BTK appear in Fig. 2, where $\sigma(V=0)$ is reported as a function of T/T_c for various proximity parameters [BTK (triangles): $\Gamma_N=1$ meV, $\Gamma_S=1$ meV (circles); $\Gamma_N=0.1$ meV, $\Gamma_S=1$ meV (squares); $\Gamma_N=0.05$ meV, $\Gamma_S=1$ meV (crosses); $\Gamma_N=0.01$ meV, $\Gamma_S=1$ meV (stars), respectively] and is compared with relevant experimental results (full circles) from high transmission microjunctions from Xiong *et al.*[12] From this study we deduce that an increase in the thickness of the normal layer causes a severe reduction of the zero bias conductance. It is worth noticing that experimental data fall in a regime where effects due to proximity are relevant (see below).

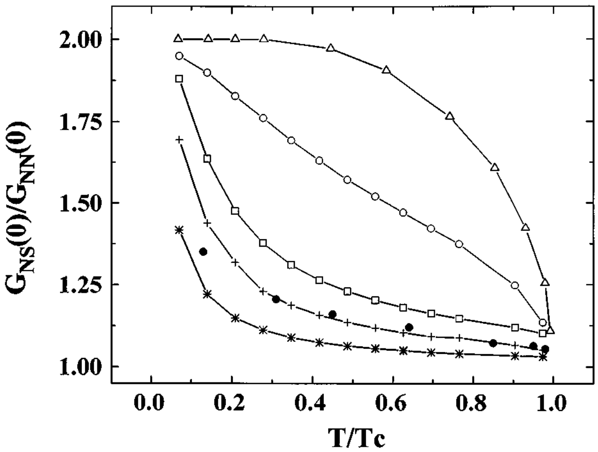

FIG. 2. Zero bias conductance $\sigma(V=0)$ vs reduced temperature T/T_c at $Z=0$, for the following proximity parameters: BTK (triangles): $\Gamma_N=1$ meV, $\Gamma_S=1$ meV (circles); $\Gamma_N=0.1$ meV, $\Gamma_S=1$ meV (squares); $\Gamma_N=0.05$ meV, $\Gamma_S=1$ meV (crosses); $\Gamma_N=0.01$ meV, $\Gamma_S=1$ meV (stars), respectively. Increasing the effect of proximity, i.e., reducing Γ_N, produces remarkable differences from BTK. Experimental results from Ref. 12 are reported by full circles.

In Fig. 3 conductance vs normalized energy [energies are divided by $\Delta_S^{\mathrm{ph}}(0)$] of a junction of the type S_1/N_1–constriction (c)–N_2 is reported in the metallic regime $(Z=0)$ at different values of the magnetic field H ($H=0$ squares, $H=0.2\ H_C$ diamonds, $H=0.4\ H_C$ crosses, respectively) for the proximity parameters $\Gamma_N=0.1$ meV, $\Gamma_S=0.01$ meV ($d_S\approx 10\ d_N$; d_N is of the order of one thousand angstroms for a typical transmission probability $\alpha\approx 0.1$), being $T=0.5$ K. Zero bias conductance is almost insensitive to the magnetic field. In the metallic regime, this behavior has been verified in a wide range of proximity parameters up to the opposite case $d_N\approx 20 d_S(\Gamma_N=0.05$ meV, $\Gamma_S=1.0$ meV), which for the same α value implies d_N of the order of the micron. Such behavior has been also obtained for higher values of the magnetic field. Moreover, the bump at finite voltage is significantly affected by the magnetic field only for $d_N<d_S$. This is in agreement with the fact that, when $d_N \gg d_S$, the conductance structures relative to the superconducting properties of S are too weak to be significantly dependent on H. As shown in Fig. 4, similar results are obtained also for less transmissive interfaces $(Z=0.5)$, where the other parameters used in the computation have the same values used in the computation of Fig. 3.

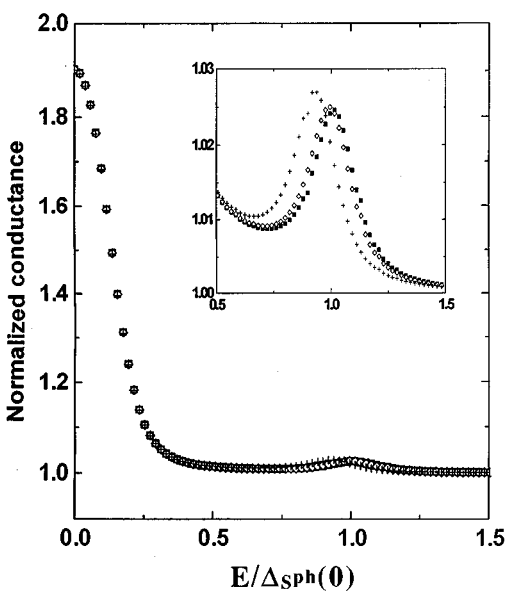

FIG. 3. Conductance vs normalized energy [energies are divided by $\Delta_S^{\mathrm{ph}}(0)$] of a junction of the type S_1/N_1–constriction (c)–N_2 in the metallic regime $(Z=0)$ is reported at different values of the magnetic field H: $H=0$ (squares), $H=0.2\ H_C$ (diamonds), $H=0.4\ H_C$ (crosses), respectively, for the proximity parameters $\Gamma_N=0.1$ meV, $\Gamma_S=0.01$ meV at $T=0.5$ K. In the inset is shown the behavior of the bump of the conductance at finite voltage for the same values of the magnetic field.

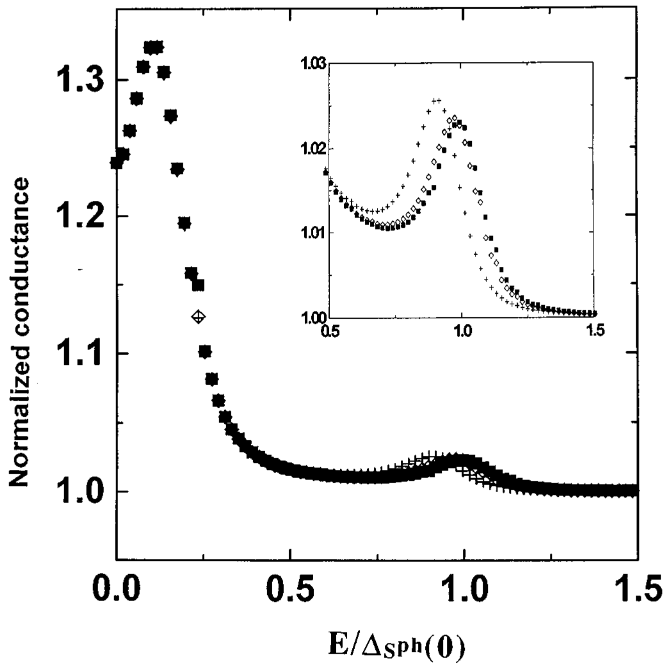

FIG. 4. Conductance vs normalized energy [energies are divided by $\Delta_S^{\mathrm{ph}}(0)$] of a junction of the type S_1/N_1–constriction (c)–N_2 in a metallic regime $(Z=0.5)$ is reported at different values of the magnetic field H: $H=0$ (squares), $H=0.2\ H_C$ (diamonds), $H=0.4\ H_C$ (crosses), respectively, for the proximity parameters $\Gamma_N=0.1$ meV, $\Gamma_S=0.01$ meV at $T=0.5$ K. In the inset is shown the behavior of the bump of the conductance at finite voltage for the same values of the magnetic field.

IV. COMPARISON WITH EXPERIMENTAL DATA

In conductance measurements on several different junctions employing S/N interfaces, there is clear evidence of ZBA and of various structures related to the gap of the superconductor S. In contrast to the case of Sm/S interfaces, the zero bias conductance does not shown significant variations by applying a magnetic field (Refs. 1, 3, and 12) in point contact and microjunctions involving S/N interfaces. By using our model we will give an interpretation of some experimental results.[1,3,12]

Structures employing traditional superconductors as electrodes: Nb-Ag (Al) microjunctions

Nb-Ag(Al) microjunctions are formed near the edge of an Nb film.[12] Two different types of structures were realized: in some structures the Ag (Al) counterelectrode was directly deposited on the edge and on the top of the Nb film, while in others, the topside of Nb was protected by a layer of Nb_2O_5 before the counterelectrode deposition. Depending on this step of the fabrication process, two different behaviors were observed. In particular, in the case of Nb covered by a thick oxide layer, BTK-like conductance was observed, in contrast to the case of bare Nb. In the latter type of junction conductance spectra exhibit significant deviations from the classical BTK behavior that could be explained by our model. In particular ZBA, basically independent of the magnetic field, were observed, along with a dependence of the Nb gap structure[12] on magnetic field. A possible interpretation of experimental data in terms of our approach needs reasonable arguments to depict the edge Nb-Ag microjunction as a $S/N\text{-}c\text{-}N'$ structure.

As a matter of fact, such a configuration can occur when considering the overlap region and the possibility that superconductivity is weakly induced in Ag(N) by proximity effect due to the presence of Nb(S). Moreover, as revealed by BTK-like spectra of the junctions employing a thick oxide layer, the edge geometry, with a width of the Ag lead much shorter than the total contact width,[12] is such as to determine a constriction where N' is represented by the normal Ag lead. The whole structure is reported in Fig. 5(a). We therefore suggest the idea that subgap currents strongly depend on the layout of the electrodes. This was also proposed by Hekking and Nazarov[4] in a different picture.

In this context, the transition from BTK-like behavior to the ZBA regime can be qualitatively explained as follows: without direct top contact between Nb and Ag [see Fig. 5(b)], the region of Ag, where superconductivity is induced, is too small to determine evident deviations from BTK. In the other case the normal region of Ag, which is superconducting because of proximity effect (Ag_S) is much wider because of the top contact. We expect that in a diffusive regime[12] electrons in average probe a longer region of Ag_S and the effect of induced superconductivity in Ag especially on the subgap current is the more relevant the longer d' is (where d' is the width of the Ag overlap on the Nb top surface and its value is of the order of magnitude of a few microns, regime of the type $\Gamma_N=0.05$ meV, $\Gamma_S=1.0$ meV). This is confirmed by $\sigma(V=0)$ vs T/T_C (Fig. 2), where effects due to the strong depression of S properties ($\Gamma_N<\Gamma_S$ and therefore $d_N>d_S$) should be related, in our framework, to the experimental parameters $d'>d_{Nb}$. We also predict that current paths, which do not pass through the Ag overlap region, give a significant contribution to conductance at voltages of the order of the Nb gap. This results in a relevant magnetic dependence of the Nb gap structure.

The idea of proximity effects developed in this paper does not exclude the arguments of Ref. 12, based on phase coherence and Andreev reflection in disordered mesoscopic junctions. As a matter of fact they contain concepts that could be linked together in a more general approach.

Finally it has to be noticed that Arnold[24] retrieved the McMillan order parameter expression even in a N/S bilayer, where the N and S slabs are strongly coupled and N is characterized by relevant scattering. This confirms that the McMillan approach can be a reasonable approximation to describe proximity effect in the investigated problem in a diffusive regime. Spatial dependence of Δ in each side of the bilayer could also be taken into account.[25]

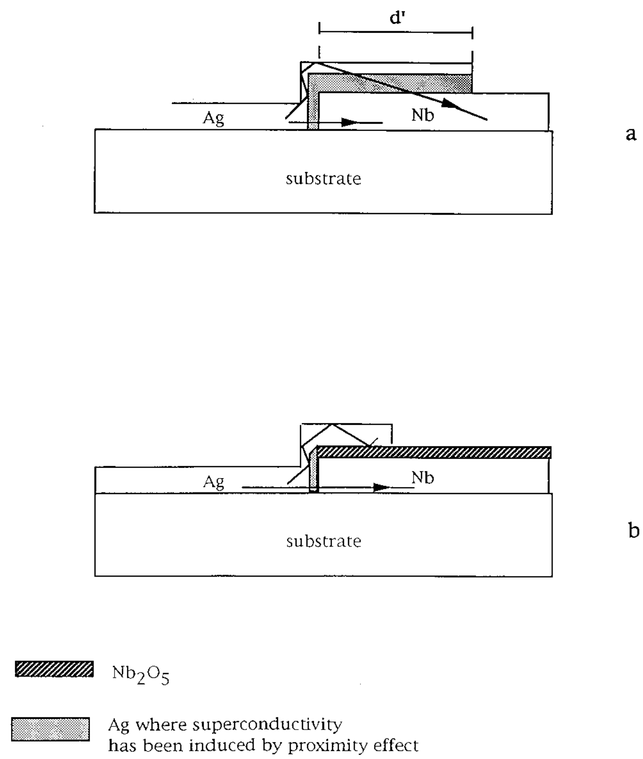

FIG. 5. Scheme of a Ag-Nb microjunction without (a) and with (b) a thick Nb_2O_5 top layer, respectively. Part of Ag is weakly superconducting because of the proximity effect. In the former case (a) electrons can move diffusively in the Ag superconducting part along the top side, differently from the latter (b). As revealed by BTK-like spectra of the junctions employing a thick oxide layer, the edge geometry, with a width of the Ag lead much shorter than the total contact width, is such as to determine a constriction where N' is represented by the normal Ag lead.

Junctions employing unconventional superconductors

As far as some measurements on unconventional superconductors are concerned, it is by far beyond the aims of the present work to enter into the debate of the nature of superconductivity in such materials.[26] We simply observe that a particular spatial dependence of Δ, due mainly to proximity effect, allows to explain some conductance anomalies without invoking unconventional superconductivity mechanisms.

For instance it has been experimentally observed in point contact spectroscopy on HTCS and organic superconductors [α_t-(BEDT-TTF)$_2I_3$] that ZBA is insensitive to the magnetic field H, while the structure, conventionally related to the superconducting gap, is strongly affected by H.[1–3,27] The magnetic field will move the peak in correspondence to the gap structure towards lower voltages, until this last merges completely in the zero centered conductance peak. Such behaviors are in agreement with the predictions of our model. It has to be noticed that spin flip and Kondo type scattering[28] have been neglected in the present investigation. Therefore no comparisons can be carried out with data from junctions with barriers, which favor such processes.

V. CONCLUSIONS

Some phenomenology related to zero bias conductance and to the superconducting gap structures in S-N microjunctions is discussed in the frame of a proximity approach, extended to the case of nonzero external magnetic field (H). Some typical features experimentally observed, like for example the appearance of ZBA, its dependence on the temperature and its stability with respect to the applied magnetic field, are explained by the proximity model we propose. Such an analysis further enlights the actual roles that the morphology of the interface and the phenomenology of proximity effect play to determine conductivity in the various investigated structures.

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