

Influence of the interplay between helicoidal magnetic ordering and superconductivity on the differential conductance in $\text{HoNi}_2\text{B}_2\text{C}/\text{Ag}$ junctions

I N ASKERZADE^{1,2}

¹Department of Physics, Ankara University, Tandogan 06100, Ankara, Turkey

²Institute of Physics, Azerbaijan National Academy of Sciences, Baku 370143, Azerbaijan

Email: iaskerzade@yahoo.com

MS received 17 October 2002; accepted 23 January 2003

Abstract. The point contact spectra of magnetic superconductor $\text{HoNi}_2\text{B}_2\text{C}/\text{Ag}$ -based junctions is analysed in the framework of Blonder–Tinkham–Klapwijk (BTK) theory. The anomalous behavior in the dI/dV curves above the Neel temperature ($T_N \sim 5$ K) is attempted to be explained by the partial suppression of superconducting gap parameter of the prevailing helical incommensurate structure.

Keywords. Andreev reflection; differential conductivity; NS junctions; helicoidal magnetic ordering.

PACS Nos 74.80.Fp; 74.80.Dm; 74.25.Fy

1. Introduction

Eight years after the discovery [1] of rare earth transition metal borocarbides(nitrides) $RT\text{BC}(\text{N})$ with $T = \text{Ni, Pd, Pt}$ transition metals, the place of $RT\text{BC}(\text{N})$ compounds within the family of more or less exotic superconductors is still under debate. For this class of exotic superconductors there are several properties which taken together might be interpreted also as hints for unconventional (d -wave or p -wave) superconductivity. For example, d -wave superconductivity has been proposed for $\text{YNi}_2\text{B}_2\text{C}$ and $\text{LuNi}_2\text{B}_2\text{C}$ compounds [2]. Phase-sensitive experiments [3] and the observation of Andreev bound state near appropriate surfaces [4] must await to confirm or disprove the predicted d -wave scenario.

It is well-known [5,6] that the measurement of the differential conductivity of superconductor–insulator–normal metal (SC/I/N) junctions is a very sensitive method to probe the superconducting properties. Point-contact spectroscopy studies on borocarbide compounds are motivated by the possibility of a detailed investigation of the anisotropy of the gap parameter and the coexistence of superconductivity and magnetism in magnetic borocarbides. Andreev reflection spectroscopy for non-magnetic borocarbides $\text{Y}(\text{Lu})\text{Ni}_2\text{B}_2\text{C}$ is known to yield superconducting energy gap peaks [7,8]. The magnetic borocarbides with Dy and Er gap-like features in the Andreev reflection spectrum have also

been seen. In the Dy compound superconductivity develops in the presence of antiferromagnetic ordering with $T_N = 10.5$ K and it is the only borocarbide with Neel temperature greater than the superconducting transition temperature, viz. $T_N > T_c = 6$ K. For instance, the Er compound with $T_c = 10.8$ K exhibits antiferromagnetic (AFM) ordering [9] below $T_N = 5.9$ K. HoNi₂B₂C compounds are marked by a complex magnetic structure [10]. In these compounds, the AFM structure develops below the Neel temperature $T_N \sim 5$ K which is related [11] to the c -axis modulated commensurate magnetic structure with wave vector $Q_{AF} = c^* = 2\pi/c$. Other magnetic structures have been observed in the temperature region $T_N < T < T_m = 6$ K, spiral (helical) c -axis modulated incommensurate with wave vector $Q_c = 0.91c^*$ and a -axis modulated incommensurate with wave vector $Q_a = 0.55a^*$. In HoNi₂B₂C re-entrant or almost re-entrant superconductivity was detected over a large range manifesting magnetic ordering [12]. Experimental point contact study was conducted by Rybaltchenko *et al* [13] but the explanation of the suppression of Andreev peculiarities are mostly unexplored.

Our primary aim is to discuss the influence of the helicoidal structure on the $G_{NS}(V)$ curve of HoNi₂B₂C/Ag junctions in the framework of Blonder, Tinkham and Klapwijk [6] (BTK) formalism.

2. Basic equations

First, we shall discuss the effect of a helicoidal structure on superconductivity. This question has been originally considered by Morosov [14] and also more recently in application to Ho borocarbides [15]. As it was shown [14,15] using Bogoliubov transformations the gap parameter in the spectrum of electron quasiparticles becomes strongly anisotropic and vanishes at the boundaries of the breaks in the Fermi surface due to the Bragg planes generated by the magnetic ordering (i.e. when the Bragg planes intersect the Fermi surface).

Transport through NS junctions has successfully been investigated using the Bogoliubov–de Gennes (BdG) equation [6]. In the BdG formalism, the quasiparticles in SC are represented by a two-element column vector

$$\psi(\mathbf{x}) = \begin{pmatrix} u(\mathbf{x}) \\ v(\mathbf{x}) \end{pmatrix}, \quad (1)$$

where $u(\mathbf{x})$ and $v(\mathbf{x})$ are the electron and hole components of the quasiparticle excitations, and obey the BdG equations

$$Eu(\mathbf{x}) = H_0u(\mathbf{x}) + \int d\mathbf{x}' \Delta(\mathbf{x}, \mathbf{x}')v(\mathbf{x}'), \quad (2)$$

$$Ev(\mathbf{x}) = -H_0v(\mathbf{x}) + \int d\mathbf{x}' \Delta(\mathbf{x}, \mathbf{x}')u(\mathbf{x}'), \quad (3)$$

where $H_0 = -(\nabla^2/2m) + V(\mathbf{x}) - \mu$ is the single-particle Hamiltonian with μ being the Fermi energy, $V(\mathbf{x})$ and $\Delta(\mathbf{x}, \mathbf{x}')$ are the ordinary potential and pair potential, respectively. We assume that the superconducting order parameter is not degraded by the normal metal, and thus neglect the proximity effect, i.e. for the NS interface (at $x = 0$) problem we can write

$$\Delta(\mathbf{x}) = \Delta\Theta(x), \quad (4)$$

where $\Theta(x)$ is a step function. As a result of calculations, the formula for the differential conductance of the junction normal metal-isotropic superconductor was obtained [6].

The BTK theory [6] for isotropic superconductors can be extended to the anisotropic case by including the momentum \mathbf{k} dependence of the superconducting energy gap $\Delta(\mathbf{k})$ in the expression for Andreev reflection probability $A(\varepsilon, \Delta(\mathbf{k}))$ and the normal reflection probability $B(\varepsilon, \Delta(\mathbf{k}))$. Then, the differential conductance G_{NS} of an NS junction normalized to the normal state value G_{NN} at $T = 0$ can be written as

$$\frac{G_{\text{NS}}}{G_{\text{NN}}} = \frac{\partial I_{\text{NS}}/\partial V}{\partial I_{\text{NN}}/\partial V} = \frac{(\partial/\partial V) \int d^3\mathbf{k} v_z [1 + A(\varepsilon, \Delta(\mathbf{k})) - B(\varepsilon, \Delta(\mathbf{k}))]}{(\partial/\partial V) \int d^3\mathbf{k} v_z [1 - Z^2/(1 + Z^2)]}, \quad (5)$$

where Z is the barrier height, which can be introduced phenomenologically and v_z is the positive velocity component perpendicular to the interface of NS junction. As mentioned above, in this approximation the proximity effect is not taken into account, although the symmetry of the gap parameter strongly influences the behavior at the surface in the case of pure d -wave or p -wave symmetry.

Calculation of the differential conductance based on eq. (1) for an N/d -wave superconductor has been performed by Tanaka *et al* [16] and for a ferromagnet/ d -wave superconductor by Zhu *et al* [17]. Dependence of the subgap structure on d -wave parameters and orientation to the NS boundary are presented. It is necessary to note calculations [18] in the framework of BTK formalism for possible p -wave gap parameter in Sr_2RuO_4 . For the heavy fermion systems [19] UPt_3 similar calculations were performed by introducing odd-parity gap parameter. In all these cases the anisotropy of the gap parameter leads to a transformation of the plateau at $(-\Delta, \Delta)$ to triangular peak of the conductance in the subgap region.

As pointed out by Morosov [15], the gap parameter of a superconductor in the presence of helical structure may be written as

$$\Delta(\mathbf{k}, T) = (u_{\mathbf{k}}^2 - v_{\mathbf{k}}^2)\Delta(T), \quad (6)$$

where

$$u_{\mathbf{k}}^2 - v_{\mathbf{k}}^2 = \left(\frac{(\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{k}+\mathbf{Q}})^2}{(\varepsilon_{\mathbf{k}} - \varepsilon_{\mathbf{k}+\mathbf{Q}})^2 + I^2 S^2} \right)^{1/2}, \quad (7)$$

in which I is the exchange interaction integral, S the average ion spin, $\varepsilon_{\mathbf{k}}$ the dispersion relation in the paramagnetic phase and

$$\Delta(T) = \int_0^\omega d\varepsilon \frac{\Delta(T)(1 - 2n_{\mathbf{k}})}{\varepsilon^2 + \Delta^2(T)} \left(\int_{\text{MFS}} \frac{dS'}{(2\pi)^3} \frac{(u_{\mathbf{k}'}^2 - v_{\mathbf{k}'}^2)^2}{|\nabla_{\mathbf{k}'} \tilde{\varepsilon}_{\mathbf{k}'}|} \right), \quad (8)$$

where $\tilde{\varepsilon}_{\mathbf{k}}$ is the new dispersion relation [15] and $n_{\mathbf{k}}$ takes into account the occupation of the electronic state. The last equation corresponds to the usual BCS self-consistent gap equation with an effective parameter $\lambda_{\text{eff}}(T)$ defined as the term in brackets. $\lambda_{\text{eff}}(T)$ depends on the underlying magnetic state through the Bogoliubov coefficients and the slope of the magnetic Fermi surface.

3. Results and discussions

Since all the anomalous magnetic wave vector dependencies come from the region where Fermi surface intersects the Bragg planes, the difference $\Delta\lambda(T) = \lambda - \lambda_{\text{eff}}(T)$ between the actual electron–phonon interaction λ and its effective value, we can expand quantities in terms of IS/ε_F . Using the results of band structure calculations [11] for borocarbide compounds the difference $\Delta\lambda(T)$ is estimated by Amici, Thalmeier and Fulde [20] as $\Delta\lambda(T=0)/\lambda = 0.12$. This result has been employed in the explanation of the main anomaly (re-entrant behavior) of the upper critical field $H_{c_2}(T)$.

The experimental data for $\text{HoNi}_2\text{B}_2\text{C}/\text{Ag}$ junctions show [13] insensitivity of the shape of $G_{\text{NS}}(V)$ curve to the orientation of the contact plane with respect to the crystal axis. This fact confirms the isotropic character of the electronic structure of these compounds. Thus, the possibility of d -wave or p -wave gap parameter in helical superconductors is eliminated. Evaluation of the shape of the $G_{\text{NS}}(V)$ curve for an NS junction by changing the parameter Z is analysed by Blonder, Tinkham and Klapwijk [6]. It is clear that the subgap plateau at $Z = 0$ transforms to two peaks at $\pm\Delta$ when the barrier height is increased. For the $\text{HoNi}_2\text{B}_2\text{C}/\text{Ag}$ contact at $T < 5$ K, where helicoidal structure transforms into the antiferromagnetic phase, a double-peak structure is obtained [13].

However, in the temperature region $5 < T < 8$, 1 K, or equivalently $\Delta T/T \sim 3/8 \approx 0.4$, gapless behavior is observed (we remark that the corresponding value of the same parameter in $\text{ErNi}_2\text{B}_2\text{C}$ compound [9] is about ~ 0.2). In our opinion, the broadening character and the gapless behavior are related by the partial suppression of the order parameter in the presence of helical structure. As mentioned by Amici, Thalmeier and Fulde [20], reduction of $\Delta\lambda/\lambda \sim 0, 12$ is not sufficient for the total elimination of superconductivity and transition to the normal state. On the other hand, in calculating the $G_{\text{NS}}(V)$ curve using eq. (1), we must take into account an additional reduction factor of $u_{\mathbf{k}}^2 - v_{\mathbf{k}}^2$. Because this latter factor is greater than unity, when averaged over the Fermi surface, we obtain an additional suppression of the gap parameter.

Thus, the broadening character of gapless behavior in $G_{\text{NS}}(V)$ curve at temperatures close to T_c for $\text{HoNi}_2\text{B}_2\text{C}/\text{Ag}$ junctions can be explained by the suppression of the gap parameter. Total suppression does not occur because the experiments of Rybaltchenko *et al* [13] were conducted for a highly pure Ho compound. It follows from the experimental data [12] (resistive measurements) that in the region where helicoidal structure exists we have small (but not zero) gap parameter. As shown in [15] nonmagnetic impurities play an important role in suppressing superconductivity in systems with helical magnetic structure. To put it in another way, due to the helical magnetic structure developing Andreev double maximum structure is ‘delayed’ in comparison with other magnetic borocarbides.

Acknowledgements

This work was partially supported by the Scientific and Technical Research Council of Turkey (TUBITAK). The author also thanks B Tanatar and I O Kulik for useful discussions.

References

- [1] R Nagarajan, C Mazumdar, Z Hossain, S K Dhar, K V Gopalakrishnan, L C Gupta, C Godart, B D Padalia and R Vejayaraghavan, *Phys. Rev. Lett.* **72**, 274 (1994)
- [2] G Wang and K Maki, *Phys. Rev.* **B58**, 6493 (1998)
- [3] D A Wollman, D J Van Harlingen, W C Lee, D M Ginzberg and A J Leggett, *Phys. Rev. Lett.* **71**, 2134 (1993)
- [4] C-R Hu, *Phys. Rev. Lett.* **72**, 1526 (1994)
- [5] A F Andreev, *Sov. Phys.-JETP* **19**, 1228 (1964)
- [6] G E Blonder, M Tinkham and T M Klapwijk, *Phys. Rev.* **B25**, 4515 (1982)
- [7] Y E Wilde, M Iavarone, W Welp, V Metlushko, A E Koshelev, L Aranson and G W Grabtee, *Phys. Rev. Lett.* **78**, 4273 (1997)
- [8] T Eskino, H Fujii, M Kosugi, Y Zeutrani and J Akimitsu, *Phys. Rev.* **B53**, 5640 (1995)
- [9] I K Yanson, in *Symmetry and pairing in superconductors* edited by M Ausloos and S Kruchinin (Kluwer Academic Publisher, 1999) pp. 271–285
- [10] A I Goldman, S Stassis, P C Canfield, J Zarestky, P Dervenages, B K Cho, D C Johnston and B Sternlieb, *Phys. Rev.* **B50**, 9668 (1994)
- [11] S L Drechsler, S V Shulga, K H Muller, G Fuchs, J Freudenberger, G Behr, H Eschrig, L Schultz, M S Golden, H von Lips, J Fink, V N Narozhnyi, H Rosner, P Zahn, A Gladun, D Lipp, A Kreyssig, M Loewenhaupt, K Koepemik, K Winzer and K Krug, *Physica* **C317–318**, 117 (1999)
- [12] K Krug, H Heinecke and K Winzer, *Physica* **C26**, 7321 (1996)
- [13] L F Rybaltchenko, A G M Jansen, P Wyder, L V Tjutrina, P C Canfield, C V Tomy and D McK Pau, *Physica* **C319**, 189 (1999)
- [14] A I Morosov, *Sov. Phys. Solid Stat.* **22**, 1974 (1980)
- [15] A I Morosov, *Sov. Phys.-JETP* **83**, 1048 (1996)
- [16] Y Tanaka and S Kashiwaya, *Phys. Rev. Lett.* **74**, 3451 (1995)
- [17] J-X Zhu, B Freidman and C S Ting, *Phys. Rev.* **B59**, 9558 (1999)
- [18] C Honeramp and M Sigrist, *J. Low Temp. Phys.* **111**, 895 (1998)
- [19] G Goll, C Bruder and H V Lohneysen, *Phys. Rev.* **B52**, 6801 (1995)
- [20] A Amici, P Thalmeier and P Fulde, *Phys. Rev. Lett.* **84**, 1800 (2000)