Competition of multiband superconducting and magnetic order in ErNi$_2$B$_2$C observed by Andreev reflection

N. L. Bobrov$^1$, V. N. Chernobay$^1$, Yu. G. Naidyuk$^{1(a)}$, L. V. Tyutrina$^1$, D. G. Naugle$^2$, K. D. D. Rathnayaka$^2$, S. L. Bud'ko$^3$, P. C. Canfield$^3$ and I. K. Yanson$^1$

$^1$ B. Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine
47 Lenin Ave., 61103, Kharkiv, Ukraine

$^2$ Department of Physics, Texas A&M University - College Station, TX 77843-4242, USA

$^3$ Ames Laboratory, Department of Physics and Astronomy, Iowa State University - Ames, IA 50011, USA

received 6 March 2008; accepted in final form 6 June 2008
published online 8 July 2008

PACS 74.45.+c – Proximity effects; Andreev effect; SN and SNS junctions

PACS 74.50.+r – Tunneling phenomena; point contacts, weak links, Josephson effects

PACS 74.70.Dd – Ternary, quaternary, and multinary compounds (including Chevrel phases, borocarbides, etc.)

Abstract – Point contacts (PC) Andreev reflection $dV/dI$ spectra for the antiferromagnetic ($T_N \approx 6$ K) superconductor ($T_c \approx 11$ K) ErNi$_2$B$_2$C have been measured for the two main crystallographic directions. The observed retention of the Andreev reflection minima in $dV/dI$ up to $T_c$ directly points to an unusual superconducting order parameter (OP) vanishing at $T_c$. The temperature dependence of the OP was obtained from $dV/dI$ using the recent theory of Andreev reflection including the pair-breaking effect. For the first time the existence of two superconducting OPs in ErNi$_2$B$_2$C is shown. A distinct decrease of both OPs as temperature is lowered below $T_N$ is observed.

Copyright © EPLA, 2008

Introduction. – The family of quaternary nickel borocarbides superconductors RNi$_2$B$_2$C, where $R$ is a rare-earth element or Y, has attracted worldwide attention both because of a relatively high critical temperature $T_c$, up to 16 K for $R = \text{Lu}$, and especially from the point of view of competition between superconducting and magnetic ordered states in the case of $R = \text{Tm, Er, Ho, Dy}$, where energy scales for the antiferromagnetic and superconducting order can be varied over a wide range (see, e.g., refs. [1,2] and further references therein). The compound with $R = \text{Er and} \, T_c \approx 11$ K is interesting for two reasons [1]: below ($T_N \approx 6$ K) incommensurate antiferromagnetic order with spin density wave occurs and weak ferromagnetism develops below $T_{\text{WFM}} \approx 2$ K [3]. Both phenomena are, in general, antagonistic to superconductivity, so that competition between superconducting and the magnetic states should take place in this compound. Additionally, the superconducting ground state in borocarbide superconductors is expected to have a multiband nature [4,5] with a complex Fermi surface and different contributions to the superconducting state by different Fermi surface sheets. Therefore, determining the influence of these magnetic states on a possible multiband superconducting ground state or multiband order parameter (OP) in ErNi$_2$B$_2$C is a challenge.

Previous tunneling (STM/STS) and point contact (PC) spectroscopy results have left some open questions regarding the coexistence of superconductivity and magnetism in ErNi$_2$B$_2$C. STM/STS measurements of ref. [6] show a small feature, namely, the decrease of the superconducting gap below $T_N$ nearly within error bars, which was not reproduced in subsequent experiments [7]. Early PC data on polycrystalline samples [8] indicated that the superconducting gap has roughly a BCS dependence with only a shallow dip around $T_N \approx 6$ K. Very recent laser-photoemission spectroscopy data [9] show the SC gap decrease (with remarkably large error bars) below the Neel temperature, but, at present the laser-photoemission spectroscopy has not enough resolution to go deeper in to details.

In this paper we report our detailed directional PC Andreev reflection measurements on single crystal ErNi$_2$B$_2$C along the $c$-axis and in the $ab$-plane. Our results show for the first time the presence of two
dominating OPs in ErNi$_2$B$_2$C, which differ by a factor of about two, and an appreciable depression of both OPs by the antiferromagnetic transition is found.

**Experimental details.** — We have used single crystals of ErNi$_2$B$_2$C grown by the Ames Laboratory Ni$_2$B high-temperature flux growth method [10]. PCs were established both along the c-axis and in the perpendicular direction by standard “needle-anvil” methods [11]. The ErNi$_2$B$_2$C surface was prepared by chemical etching or cleavage as described in [12]. As a counter electrode, edged thin Ag wires ($\varnothing=0.15\text{mm}$) were used to improve mechanical stability of PCs in comparison to using a bulk Ag piece. We have measured the temperature dependence of $dV/dI(V)$ characteristics of such N-S PCs (here N denotes a normal metal and S is the superconductor under study) in the range between 1.45K and $T_c$ for several contacts oriented both along the c-axis and in the ab-plane. In the paper we demonstrate results of analysis of 60 $dV/dI(V)$ along the ab-plane measured for the same PC at different temperatures between 1.45K and 11 K and of 46 $dV/dI(V)$ along the c-direction for another PC (see footnote\(^1\)) in the same temperature range.

**Results and discussion.** — To determine the OP from the measured differential resistance curves $dV/dI(V)$ we used the recent theory [13] of Andreev reflection in PC, which includes the pair-breaking effect by magnetic impurities. The last assumption is reasonable, because of the presence of the local magnetic moments of Er ions. The fit of the measured curves using equations as (1) in [14] has been performed. As fit parameters the superconducting OP $\Delta$ (see footnote\(^2\)), the pair-breaking parameter $\gamma=1/(\tau_s\Delta)$ (here $\tau_s$ is the spin-flip scattering time) and the dimensionless barrier parameter $Z$ have been used. Although the $dV/dI$ curves shown in fig. 1 exhibit one minimum for each polarity, as in the case of ordinary one-gap superconductors [11,15], to fit $dV/dI$ in full we had to use a two-OP (gap) approach\(^3\), adding the corresponding conductivities as made in [12] for LuNi$_2$B$_2$C. The contributions of these conductivities account for the part of the Fermi surface containing a particular OP. Thus, for the two-OP model, experimental curves are fitted\(^4\) by the following expression:

$$\frac{dV}{dI} = K \frac{S}{\tau_V^\Delta(\Delta_1,\gamma_1, Z_1)+(1-K)\tau_V^\Delta(\Delta_2,\gamma_2, Z_2)}.$$

Here, the coefficient $K$ reflects the contribution of the part of the Fermi surface having the OP $\Delta_1$, $S$ is the scaling factor to match the amplitude of the calculated and the experimental curves.

Before discussing the fitting results, we point out the unusual specific behavior of the measured $dV/dI$ curves.\(^5\)

---

\(^1\)The PC resistance is 36$\Omega$ along the c-axis and 10.5$\Omega$ in the ab-plane. The PC diameter estimated by the Wexler formula (see [11], pp. 9, 31) is about 7 nm and 14 nm, respectively, using $\rho l \approx 10^{-11}\text{cm}^2/\text{mV}$ [4]. At the same time a mean free path $l$ is 28 nm, using $\rho \approx 3.5-4.0\Omega$ cm [10] just above $T_c$. Therefore, the mentioned PCs are close to the ballistic limit $d<l$.

\(^2\)Assuming that pair breaking is by magnetic impurities, the energy gap $\Delta_0$ and the OP $\Delta$ are related as follows: $\Delta_0 = \Delta(1-\gamma^2/3)^{1/2}$ [13].

\(^3\)Not only does the one-OP approach give a worse fit (especially at minima position and at maximum, see insets in fig. 2) of the experimental data such that the rms deviation is 2–3 times higher compared to the two-OP fit, it also requires a varying $Z$ parameter. On the contrary, at the two-OP fit $Z$ parameters remain constant, equal to 0.77 and 0.6 for the ab-plane and c-direction, respectively. This is important because there is no physical reason for the barrier parameter $Z$ to be temperature dependent.

\(^4\)Before the fit, $dV/dI$ curves were normalized to the $dV/dI$ curve measured above $T_c$ and symmetrized. The fit was done between $\pm 8\text{mV}$, to avoid contribution from the phonons seen, e.g., as an inflection point around 10 mV for some curves in fig. 1. The fit was done in two stages. At first we keep both $\gamma_1, \gamma_2$ coefficients equal to zero. As a result of such fit, $\Delta_1, \Delta_2$ values shown in fig. 3 were obtained, while the variation of $Z$ and $K$ was within 10%. If we hold $K$ on this stage strictly constant, it will result only in more scatter (noise) for $\Delta_1, \Delta_2$, but their overall behavior remains the same. To improve the fit on the second stage, we used the obtained $\Delta_1, \Delta_2$ and variable $\gamma_1, \gamma_2$ and $K$. As a result, the obtained $K$ and $\gamma_1, \gamma_2$ are shown in figs. 4 and 5. After this, the theoretical curves were almost indistinguishable from the experimental ones (see insets in fig. 2).

---

37003-p2
Competition of multiband superconducting and magnetic order in ErNi$_2$B$_2$C

Fig. 2: (Color online) Reduced position of the minima in the raw dV/dI curves for ErNi$_2$B$_2$C and that for LuNi$_2$B$_2$C from [12]. Insets: comparison of two OPs (solid line) and one-OP (dashed line) fitting of the reduced experimental dV/dI (symbols) at 1.45 K.

(see footnote\textsuperscript{5}) (see fig. 1). First, the distance between dV/dI minima shown in fig. 2, which is often taken as a rough estimation of the superconducting gap value, increases with temperature before decreasing on approaching $T_c$ — a quite different behavior from the nonmagnetic LuNi$_2$B$_2$C. Second, the dV/dI minima for ErNi$_2$B$_2$C persist up to temperatures close to $T_c$ (see fig. 2, upper panel) though with a small amplitude, leading to a suppression of the presence of the second OP. From these direct observations, a nontrivial behavior of the superconducting OP parameters is expected in ErNi$_2$B$_2$C.

Indeed, from the two-band model fitting both OPs $\Delta_1$ (large) and $\Delta_2$ (small) diminish on entering the antiferromagnetic state around 6 K (see fig. 3). Qualitatively the same behavior has the OP determined by the one-OP fit (fig. 3, triangles). This is qualitatively consistent with the temperature dependence of the superconducting gap determined by tunneling in [6], by laser-photoemission spectroscopy data [9] and also with the upper critical field [2,16] and the superconducting coherence length behavior [17] in the vicinity of $T_N$. The theories of coexistence of superconductivity and antiferromagnetic state also predict such OP suppression below $T_N$, [18] e.g., by an antiferromagnetic molecular field [19].

Further, the large-OP $\Delta_1(T)$ may be described by a BCS dependence above $T_N \simeq 6$ K in the paramagnetic state with extrapolated $T^*_c \simeq 14.5$ K, close to that of nonmagnetic RNi$_2$B$_2$C ($R =$ Lu, Y). On the other hand, retention of the Andreev reflection minima in dV/dI up to $T_c$ (see fig. 2) results in unconventional abrupt $\Delta_1(T)$ vanishing near $T_c$. Note, that to fit experimental curves, not only the OP but also the large-OP relative contribution $K$ (see eq. (1)), must be temperature dependent (see fig. 4). Shown in fig. 4, the decrease of $K$ with

\textsuperscript{5}The PCs presented in the paper have survived about 36 hours (c-direction) and 50 hours (ab-plane) of measurements. The dV/dI temperature series for these PCs are the fullest; therefore they were presented in the paper. Of course, there were other PCs with dV/dI of lower quality or which did not survive the temperature sweep in the whole range between 1.45 K and $T_c$. Nevertheless, there were a few of the PCs which had dV/dI similar to those presented in the paper, supporting our observations.
appears that $\gamma_1$ is always larger than $\gamma_2$ above 2 K, that is the pair-breaking effect is stronger in the band with the largest OP. This is in line with the conclusion, that the different bands are differently affected by magnetic order, made in [5,20] by band structure analysis of the coexistence of superconductivity and magnetism in the related antiferromagnetic superconductor DyNi$_2$B$_2$C, i.e., some bands provide a basis for superconductivity while others are important for the magnetic interactions. Here we should add that the $S$ parameter in (1) has a maximal value of 0.5 at low temperature, the same value as the normalized zero-bias tunnel conductivity obtained by the STS study of ErNi$_2$B$_2$C [7]. So, both observations suggest that nearly half of the total Fermi surface (or bands) is nonsuperconducting in ErNi$_2$B$_2$C. The formation of a superzone gap at the antiferromagnetic transition seen in transport measurements [16] may be responsible for this.

From fig. 5 it is also seen that $\gamma$ has maxima at temperature close to $T_N$ and also close to the appearance of weak ferromagnetism around 2 K, which is reasonable. At both of these temperatures an increase in pair breaking is expected due to increasing spin fluctuations accompanying the corresponding transitions.

**Conclusion.** – This study demonstrates that the two-band approximation with two OPs, including pair-breaking effects, suits better for describing the PC Andreev reflection spectra in ErNi$_2$B$_2$C pointing for the first time to the presence of multiband superconducting OP in this compound. The values and the temperature dependences of the large and the small OPs have been estimated for the $ab$-plane and in the $c$-direction. It is found that in the paramagnetic state both OPs can be described by BCS dependence, but the formation of the antiferromagnetic state below $T_N \simeq 6$ K leads to a decrease of both OPs. The pair-breaking effect is found to be different for the large and the small OPs indicating that the different bands are affected differently by magnetic order. This may be the reason for the observed abrupt vanishing of the larger OP at $T_c$. It is interesting that the extrapolation of the largest OP by “conventional” BCS behavior above $T_N$ results in $T_c^* \approx 14.5$ K, similarly to nonmagnetic YNi$_2$B$_2$C, so that $2\Delta_{BCS}(0)/k_B T_c^* \approx 4.25$ and 4.7 for the $ab$-plane and $c$-direction, respectively. BCS extrapolation gives for the small-OP $2\Delta_{BCS}(0)/k_B T_c \approx 4.1$ ($ab$-plane) and 3.5 ($c$-direction), while for the one-OP fit $2\Delta_{BCS}(0)/k_B T_c \approx 4.6$ ($ab$-plane) and 4.5 ($c$-direction) pointing, in general, to a moderately anisotropic and strongly coupled superconducting state in ErNi$_2$B$_2$C.

***

The support by the State Foundation of Fundamental Research of Ukraine (project Φ16/448-2007), by the Robert A. Welch Foundation (Grant No. A-0514, Houston, TX), and the National Science Foundation (Grant No. DMR-0422949) is acknowledged. Ames
Competition of multiband superconducting and magnetic order in ErNi$_2$B$_2$C

Laboratory is operated for the U.S. Department of Energy by Iowa State University under Contract No. W-7405-Eng-82.

REFERENCES

[1] MÜLLER K.-H., SCHNEIDER M., FUCHS G. and DRECHSLER S.-L., Handbook on the Physics and Chemistry of Rare Earths, edited by Gschneidner Karl A. jr., Bünzli Jean-Claude and Pecharsky Vitalij K., Vol. 38 (North-Holland) 2008, sect. 239.

[2] CANFIELD P. C., GAMMEL P. L. and BISHOP D. J., Phys. Today, 51, issue No. 10 (1998) 40; CANFIELD P. C. and BUD’KO S. L., C. R. Phys., 7 (2006) 56.

[3] CANFIELD P. C., BUD’KO S. L. and CHO B. K., Physica C, 262 (1999) 249.

[4] SHULGA S. V., DRECHSLER S.-L., FUCHS G., MÜLLER K.-H., WINZER K., HEINECKE M. and KRUG K., Phys. Rev. Lett., 80 (1998) 1730.

[5] DRECHSLER S.-L., SHULGA S. V., MÜLLER K.-H., FUCHS G., FREUDENBERGER J., BEHR G., ESRHIG H., SCHULTZ L., GOLDEN M. S., VON LIPS H., FINK J., NAROZHNII V. N., ROSNER H., ZAHN P., GLADUN A., LIPP D., KREYSSIG A., LOEWENHAUPT M., KOEPERNIK K., WINZER K. and KRUG K., Physica C, 317-318 (1999) 117.

[6] WATANABE TADATAKA, KITAZAWA KOICHI, HASEGAWA TETSUYA, HOSSEIN ZAKIR, NAGARAJAN RADHAKRISHNAN and GUPTA LAXMI CHAND, J. Phys. Soc. Jpn., 69 (2000) 2708.

[7] CRESPO M., SUDEROW H., VIEIRA S., BUD’KO S. and CANFIELD P. C., Phys. Rev. Lett., 96 (2006) 027003.

[8] YANSON I. K., Rare Earth Transition Metal Borocarbides (Nitrides): Superconducting, Magnetic and Normal State Properties, edited by MULLER K. H. and NAROZHNII V., Vol. 14 (Kluwer Academic, Dordrecht) 2001, p. 95.

[9] BABA T., YOKOVA T., TSUDA S., KISS T., SHIMOJIMA T., ISHIZAKA K., TAKEYA H., HIRATA K., WATANABE T., NOHARA M., TAKAGI H., NAKA N., MACHIDA K., TOGASHI T., WATANABE S., WANG X.-Y., CHEN C. T. and SHIN S., Phys. Rev. Lett., 100 (2008) 017003.

[10] CHO B. K., CANFIELD P. C., MILLER L. L., JOHNSTON D. C., BAYERMANN W. P. and YATSKAR A., Phys. Rev. B, 52 (1995) 3684.

[11] NAIDYUK YU. G. and YANSON I. K., Point-Contact Spectroscopy, Vol. 145 (Springer Science+Business Media, Inc.) 2005.

[12] BOBRNOV N. L., BELOBORO'DKO S. I., TYUTRINA L. V., CHERNOYAB V. N., YANSON I. K., NAUGLE D. G. and RATHNAYAKA K. D. D., Low Temp. Phys., 32 (2006) 489 (Fiz. Nizk. Temp., 32 (2006) 641).

[13] BELOBORO'DKO S. I., Low Temp. Phys., 29 (2003) 650 (Fiz. Nizk. Temp., 29 (2003) 868).

[14] BOBRNOV N. L., BELOBORO'DKO S. I., TYUTRINA L. V., YANSON I. K., NAUGLE D. G. and RATHNAYAKA K. D. D., Phys. Rev. B, 71 (2005) 014512.

[15] NAIDYUK YU. G., VON LOHNEYSEN H. and YANSON I. K., Phys. Rev. B, 54 (1996) 16077.

[16] BUD’KO S. L. and CANFIELD P. C., Phys. Rev. B, 61 (2000) R14932.

[17] GAMMEL P. L., BARBER B. P., RAMIREZ A. P., VARMA C. M., BISHOP D. J., CANFIELD P. C., KOGAN V. G., ESKILDSEN M. R., ANDERSEN N. H., MORTESEN K. and HARADA K., Phys. Rev. Lett., 82 (1999) 1756.

[18] Various theories of antiferromagnetic superconductors including the effect of spin fluctuations, molecular field, and impurities on the $\Delta$ behavior (see, e.g., Chi H. and NAGI A. D. S., J. Low Temp. Phys., 86 (1992) 139 and references therein) in support of our observation will be discussed in a forthcoming extended publication.

[19] KAZUSHIGE MACHIDA, KAZUO NOKURA and TAOKE MATSUBARA, Phys. Rev. B, 22 (1980) 2307.

[20] SHORIKOV A. O., ANISIMOV V. I. and SIGRIST M., J. Phys.: Condens. Matter, 18 (2006) 5973.