The Superconducting Gap Behavior in the Antiferromagnetic Nickel-Borocarbide Compounds $R\text{Ni}_2\text{B}_2\text{C}$ ($R=\text{Dy, Ho, Er, Tm}$) Studied by Point-Contacts Spectroscopy

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Abstract. An general survey of the superconducting (SC) gap study in the title compounds by point-contact (PC) spectroscopy is presented. The SC gap was determined from $dV/dI$ of PCs employing the well-known theory of conductivity for normal metal-superconductor PCs accounting Andreev reflection. The theory was modified by including pair-breaking effects considering the presence of magnetic rare-earth ions. A possible multiband structure of these compounds was also taken into account. The PC study of the gap in the Er–compound ($T_N \simeq 6 \text{ K} < T_c \simeq 11 \text{ K}$) gives evidence for the presence of two SC gaps. Additionally, a distinct decrease of both gaps is revealed for $R=\text{Er}$ in the antiferromagnetic (AF) state. For $R=\text{Tm}$ ($T_N \simeq 1.5 \text{ K} < T_c \simeq 10.5 \text{ K}$) a decrease of the SC gap is observed below 4–5 K, while for $R=\text{Dy}$ ($T_N \simeq 10.5 \text{ K} > T_c \simeq 6.5 \text{ K}$) the SC gap has a BCS-like dependence in the AF state. The SC gap for $R=\text{Ho}$ ($T_N \simeq 5.2 \text{ K} < T_c \simeq 8.5 \text{ K}$) exhibits below $T^* \simeq 5.6 \text{ K}$ a single-band BCS-like dependence vanishing above $T^*$, where a specific magnetic order occurs. The difference in the SC gap behavior in the title compounds is attributed to different AF ordering.

1. Introduction

The $R\text{Ni}_2\text{B}_2\text{C}$ ($R=\text{Dy, Ho, Er, Tm}$) family of ternary superconductors attracts attention [1] because superconductivity and long-range antiferromagnetic (AF) order compete in these materials and their superconducting (SC) properties exhibit often unconventional behavior. It turned out also that a multiband approach is required to describe properly SC properties of $R=\text{Y}$ and Lu nickel borocarbides as it was shown in [2]. Additionally, the AF order has its own specific features in each of the title compounds, e.g., along with different Néel temperature $T_N$ the AF order can be in- or commensurate [1]. The manifestation of the mentioned extraordinary behavior of $R\text{Ni}_2\text{B}_2\text{C}$ is intimately dependent on the chemical composition and crystal perfectness, therefore continuous progress in synthesis of high quality single crystal samples leads to deeper understanding of their fundamental physics. In this paper we overview
the efforts in point-contact (PC) studies of the SC gap in the title compounds based on very recent research (see [3, 4, 5, 6] and Refs. therein). The PC method [7] allows to study the directional, temperature and magnetic field dependence of the SC gap which can provide insight into the SC ground state of RNi$_2$B$_2$C and its interplay with magnetic order.

2. Experimental

Here we will focus on results measured on the best single crystals reported so far. HoNi$_2$B$_2$C ($T_N \approx 5.2$ K $< T_c \approx 8.5$ K) and TmNi$_2$B$_2$C ($T_N \approx 1.5$ K $< T_c \approx 10.5$ K) crystals were grown by a floating zone technique with optical heating at IFW Dresden, while ErNi$_2$B$_2$C ($T_N \approx 6$ K $< T_c \approx 11$ K) and DyNi$_2$B$_2$C ($T_N \approx 10.5$ K $> T_c \approx 6.5$ K) were grown at Ames Laboratory (USA) by a Ni$_2$B high-temperature flux growth method. PCs were established at the liquid helium temperature by standard "needle-anvil" methods [7], using as a "needle" a sharpened piece of Cu or Ag. The SC gap was evaluated from the measured $dV/dI(V)$ dependences of PCs applying both the standard BTK theory and an akin theory (in the case of Er), which considered the pair-breaking effect of magnetic impurities [8].

Figure 1. Gap behavior in HoNi$_2$B$_2$C (circles) [4] and DyNi$_2$B$_2$C (squares) [9] established by a BTK fit of PC dV/dI curves. Inset: example of a dV/dI curve (symbols) at 3 K fitted by BTK theory (thin curve).

Figure 2. Gap behavior in TmNi$_2$B$_2$C established by a BTK fit of PC dV/dI curves. The dashed curve shows qualitatively the $B_{c2}$ behavior in TmNi$_2$B$_2$C along the c-axis. Inset: example of a dV/dI curve at 1.6 K.

3. Results and discussion

The SC gap $\Delta_0$ manifests itself on the $dV/dI$ characteristic of a normal metal-superconductor PC by pronounced minima symmetrically placed at $V \approx \pm \Delta_0/e$ if $T << T_c$ (see inset in Fig. 1). The measured $dV/dI$ of the title compounds exhibit one pair of minima as in the case of single gap superconductors [7], therefore a single gap approach is usually used to fit experimental data. It is seen from the inset in Fig. 1 that the one-gap fit reasonably describes $dV/dI$ for $R$=Ho. The same is true for $R$=Dy [9] (not shown). The obtained $\Delta_0(T)$ in Fig. 1 exhibits a BCS-like $T$-dependence in both cases, however, $\Delta_0(T)$ vanishes at $T^* \approx 5.6$ K for $R$=Ho, a few K below the bulk critical temperature $T_c \approx 8.5$ K. It was suggested in [4] that superconductivity in the

1 The theory [8] was used to fit $dV/dI(V)$ for $R$=Er PCs. In this case instead of the SC gap the SC order parameter (OP) $\Delta$ is evaluated while the SC gap $\Delta_0 = \Delta(1-\gamma^2/3)^{3/2}$, here $\gamma$ is pair-breaking parameter. Forasmuch as $\gamma$ variates at our OP evaluation below 0.1, the gap has similar behavior like OP, shown in Fig. 3 for $R$=Er. Therefore, for uniformity we used definition "one-gap" or "two-gap" fit, although in the case of $R$=Er a notation "two-OP" fit is more adequate.
commensurate AF phase in the $R=$Ho compound survives at a special nearly isotropic Fermi surface sheet, while the gap suppression at $T^*$ may be caused by a peculiar magnetic order developing in this compound above the AF state at $T_N \approx 5.2$ K.

Interesting peculiar behavior of $\Delta_0(T)$ in TmNi$_2$B$_2$C (Fig. 2) was found recently \[5\]. The SC gap has a maximum around 4-5 K and further decreases at lowering temperature. This is in accord with the behavior of the upper critical field along the c-axis. Apparently, AF fluctuations occurring above the magnetically ordered state at $T_N = 1.5$ K are responsible for the decrease of the SC gap observed at low temperatures.

As it was shown in \[6\], the "one-gap" approach to fit the measured high-quality $dV/dI$ curves\[2\] for ErNi$_2$B$_2$C results in a clear discrepancy between the fit and the data at the minima position and at zero bias. At the same time, a "two-gap" approach allows a better fit of $dV/dI$ for ErNi$_2$B$_2$C \[6\]. As it was mentioned above, the upper critical field $H_{c2}(T)$ of nonmagnetic borocarbides $R=Y$ and Lu \[2\] can be properly described only by a two-band model. Therefore, the detection of two SC gaps in magnetic ErNi$_2$B$_2$C (with about the same magnitude as in $R=$Lu \[3\]) from one hand testifies for similarities in the electronic band structure of the mentioned compounds, from the other hand it points to the fact that superconductivity and magnetism develop in ErNi$_2$B$_2$C in different bands.

![Figure 3. Temperature dependence of the larger OP (circles) and the smaller OP (squares) for ErNi$_2$B$_2$C: open symbols – c-direction, solid – ab-plane. Inset: example of a $dV/dI$ curve at 1.46 K for c-direction \[6\].](image)

From the $T$-dependence of the SC order parameter (OP) in ErNi$_2$B$_2$C (Fig. 3) is clearly seen that both OPs start to decrease by approaching or below $T_N$. A similar decrease of the SC gap in ErNi$_2$B$_2$C in the AF state was reported by STM measurements in \[10\] and, recently, by laser-photoemission spectroscopy \[11\]. Such a gap decrease in the AF state is also in line with the Machida theory \[12\] in which spin-density-wave ordering competes with superconductivity.

On the other hand, $\Delta(T)$ in ErNi$_2$B$_2$C above $T_N$ is close to the BCS-like behavior, only the steep vanishing of the larger OP at $T_c$ is rather unexpected. It turned out \[6\] that the contribution of the larger OP to $dV/dI$ is also temperature dependent decreasing with increasing temperature and containing only about 10% close to $T_c$. Therefore, it seems that the larger OP disappears at $T_c$ due to a "shrinking" of the corresponding SC part of the Fermi surface.

It should be noted that the magnetic structure in $R=$Er and Tm compounds is given by an incommensurate spin density wave. As it is seen from Fig. 2, $\Delta_0(T)$ for TmNi$_2$B$_2$C deviates from

\[2\] High quality means that $dV/dI$ looks like a smooth curve with pronounced AR minima (see inset in Fig. 3) while some irregularities like e.g. spike-like structures above the minima (see inset in Fig. 1) are absent.
the BCS behavior approaching $T_N$. Contrary, Ho and Dy compounds with commensurate AF order display a BCS-like gap. Of course, in the case of $R=$Tm measurements below $T_N \approx 1.5$ K are very desirable to trace similarity with the Er compound.

Fig. 4 summarizes the measured SC gap/OP by PCs in the title compounds. In general, the SC gap/OP values are close to the BCS value $\Delta_0=1.76 \, k_B T_c$ taking into account the multiband behavior in the Er-compound and the vanishing of the SC gap in $R=$Ho at $T^* \approx 5.6$ K. For comparison, also the SC gaps of the nonmagnetic compounds $R=Y$ and Lu are presented in Fig. 4. A two-gap state is established for $R=Lu$ and a strong anisotropy of the gap (probably due to multiband state) is observed for $R=Y$. It is seen that the OPs in Er and Lu compounds have close values, but in the case of Er the larger OP contribution to $dV/dI$ dominates at low temperature. However, then this contribution decreases (by a factor 5) with increasing temperature, while for $R=Lu$ a similar behavior is observed for the smaller OP.

4. Conclusions
The SC gap (SC OP) was studied using normal metal-superconductor PCs for a series of magnetic rare-earth nickel borocarbide superconductors. For the first time, the existence of two SC OPs in the magnetic compound ErNi$_2$B$_2$C has been shown. Moreover, a distinct decrease of the both OPs is observed as the temperature is lowered below $T_N$. For the $R=$Ho and Dy compounds with commensurate AF order, the SC gap has a BCS like behavior in the AF state, while for $R=$Tm the gap starts to decrease by approaching a magnetic state with incommensurate AF order. Note that the $R=Er$ compound has an incommensurate AF order and the OPs also start to decrease slightly above $T_N$ at lowering temperature. Thus, the discrepancy in the magnetically ordered state between $R=$Ho, Dy (commensurate state) and $R=Er$, Tm (incommensurate state) results in a different SC gap (or OP) behaviors. More extensive directional PC measurements for $R=Ho$, $Ho$ and Tm are desirable to check the presence of multi-gap superconductivity in these compounds as well.

5. Acknowledgments
The authors thank P. C. Canfield, K.-H. Müller, K. Nenkov, M. Schneider, D. Souptel, L. V. Tyutrina for the long term collaboration in the field of rare-earth nickel borocarbides investigations, sample preparation and experimental assistance. Two of us, Yu. G. N. and O. E. K., thank Prof. L. Schultz and the Alexander von Humboldt Foundation for support.

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