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Point-contact spectroscopy of the nickel borocarbide superconductors RNi$_2$B$_2$C (R = Y, Dy, Ho, Er, Tm, Lu)

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Abstract

An overview of the recent efforts in point-contact (PC) spectroscopy of the nickel borocarbide superconductors RNi$_2$B$_2$C in the normal and superconducting (SC) state is given. The results of measurements of the PC electron–boson(phonon) interaction spectral function are presented. Phonon maxima and crystalline-electric-field (CEF) excitations are observed in the PC spectra of compounds with R = Dy, Ho, Er and Tm, while for R = Y a dominant phonon maximum around 12 meV is characteristic. Additionally, non-phonon and non-CEF maxima are observed near 3 meV in R = Ho and near 6 meV in R = Dy. Directional PC study of the SC gap gives evidence for the multi-band nature of superconductivity in R = Y, Lu. At low temperature the SC gap in R = Ho exhibits a standard single-band BCS-like dependence, which vanishes above $T_c^* \simeq 5.6$ K $< T_c \simeq 8.5$ K, where a specific magnetic ordering starts to play a role. For R = Tm ($T_c \simeq 10.5$ K) a decrease of the SC gap is observed below 5 K.

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Keywords: Nickel borocarbides; Point-contact spectroscopy; Superconducting gap; Electron–phonon interaction; CEF

The RNi$_2$B$_2$C (R is mainly rare earth, Y or Sc) family of ternary superconductors discovered in 1994 has become attractive to study fundamental questions in superconductivity [1]. The interest is because the critical temperature in RNi$_2$B$_2$C is relatively high, their superconducting (SC) properties exhibit often unconventional behavior and depending on the rare earth element magnetism and superconductivity co-exist in these materials in a wide range of temperatures. Last but not least there is continuous progress in synthesis of high purity single crystal samples. However in spite of dozens of publications some fundamental issues as to the nature of Cooper pairing and attractive interaction are still under debate for the borocarbides.

By point-contact (PC) research both the SC gap and the PC electron–phonon(boson) interaction (EP(B)I) function $\alpha^2_{PC}F(\omega)$ can be determined from the first and second derivatives of the $I(V)$ characteristic of PC's [2]. The second derivative of $I(V)$ contains straightforward information as to the PC EP(B)I spectral function $\alpha^2F(\omega)$ [2]. Knowing $\alpha^2F(\omega)$ one can elucidate the nature of the attractive interaction and characteristic bosons. Unique is that with the same PCs driven to the superconducting state the SC gap can be measured. Thus the PC spectroscopy is a powerful method to study both the EP(B)I spectra and the SC gap behavior.

At first we start with the discussion of PC EP(B)I spectra in RNi$_2$B$_2$C presented in Figs. 1 and 2. The most detailed spectra are measured for HoNi$_2$B$_2$C. Here, most of the maxima correspond to those in the phonon DOS of the

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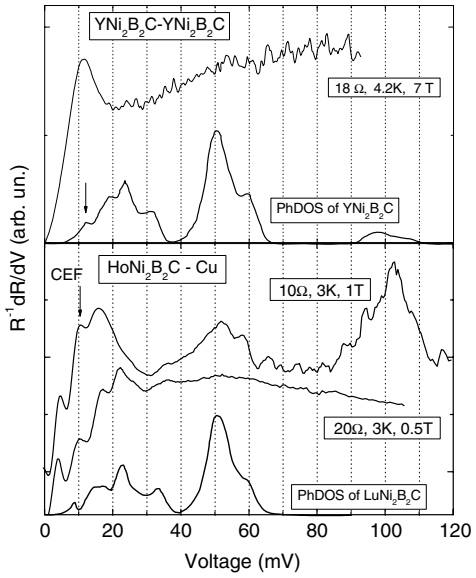

Fig. 1. PC spectra of RNi$_2$B$_2$C (R = Y, Ho) in comparison with the phonon DOS for YNi$_2$B$_2$C and LuNi$_2$B$_2$C [3]. The superconductivity which causes huge features in the low bias region is suppressed by a magnetic field. For the Ho compounds two kind of spectra are shown.

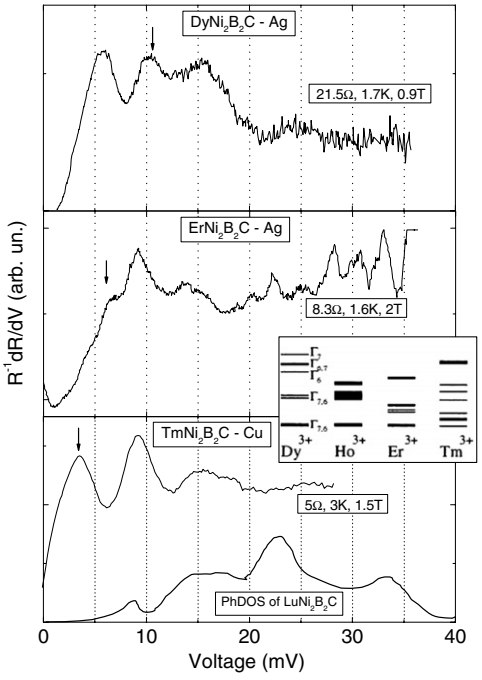

Fig. 2. Low energy part of the PC spectra of RNi$_2$B$_2$C (R = Dy, Er, Tm) in comparison with the phonon DOS for LuNi$_2$B$_2$C [3]. The superconductivity is suppressed by a magnetic field. The arrows show approximate position of the first exited CEF level for each compound according to the CEF scheme from [6] shown in the inset.

isostructural compound LuNi$_2$B$_2$C [3]. The upper Ho-spectrum displays also expressed high energy maxima around 50 and 100 mV which were not so clearly resolved so far in the PC spectra of other nickel borocarbides. The low energy maxima around 3 mV in R = Ho and 6 mV in R = Dy (Fig. 2), not present in the phonon DOS, have non phonon origins. The 3-mV maximum in R = Ho can be suppressed by a magnetic field (Fig. 3) pointing to its "magnetic" origin as discussed in [4,5]. The 6-mV peak in R = Dy vanishes with increasing T above 15 K, has probably a similar "magnetic" origin. The first maximum in R = Tm and R = Er corresponds in position to the first exited crystal-electric-field (CEF) level [6]. CEF contributes apparently also to the 10-mV peak in R = Ho and Dy compounds. In the former case this is seen from the modification of the 10-mV peak in a magnetic field (Fig. 3). Most of the PC spectra in R = Ho (not shown) demonstrate a prominent 10-mV peak while other phonon maxima are completely smeared. This points to the importance of the CEF excitations in the charge transport as well as in the SC properties of HoNi$_2$B$_2$C and other R = Dy, Er and Tm borocarbides. Thus the contribution of the 10-mV peak in the EP(B)I constant λ_{PC} for R = Ho is evaluated as 20–30%, while the contribution to λ_{PC} of the high frequency modes at 50 and 100 meV amounts up to 10% for each maximum.

The spectra of the nonmagnetic YNi$_2$B$_2$C show a dominant maximum at about 12 mV and a broad shallow maximum or a kink positioned close to 50 mV (Fig. 1). These features have a counterpart in the phonon DOS of YNi$_2$B$_2$C. To summarize: a clear coupling to the low energy modes has been shown in the PC spectra of the title compounds. In R = Dy, Ho, Er and Tm compounds the CEF excitations contribute to the EP(B)I function. For R = Ho the contribution of two high energy modes are also notable. The 50-mV mode can be also resolved for other compounds, but it looks very smeared as shown in Fig. 1 for R = Y. In this context, we note that the electronic mean free path is shortened with increase of the bias voltage due to the EP(B)I. In this case if the EP(B)I is strong enough, it results in a violation of the ballistic condition (with voltage increase) necessary for energy resolved spectroscopy by PCs. On the other hand the high energy modes involve vibration of light B and C ions. As it is known, the physical properties of nickel borocarbides, including the superconductivity, are sensitive to small variations in the crystal

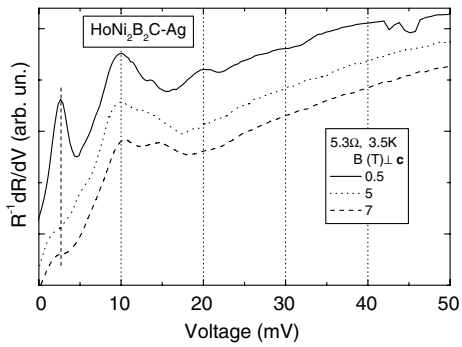

Fig. 3. PC spectra of a HoNi$_2$B$_2$C–Ag contact which demonstrate pronounced 3 and 10 mV maxima and their modification in a magnetic field.