Resistivity and electron-phonon coupling in YNi$_2$B$_2$C single crystals

R.S. Gonnelli$^a$, V.A. Stepanov$^b$, A. Morello$^a$, G.A. Ummarino$^a$, G. Behr$^c$, G. Graw$^c$, S.V. Shulga$^c$ and S.-L. Drechsler$^c$

$^a$INFM - Dipartimento di Fisica, Politecnico di Torino, c.so Duca degli Abruzzi 24, 10129 Torino, Italy
$^b$P.N. Lebedev Physical Institute, Russian Academy of Sciences, SU-117924 Moscow, Russia
$^c$Institut für Festkörper- und Werkstofforschung Dresden, Postfach 270016, D-01171 Dresden, Germany

In this work, we present the results of precise measurements of the resistivity of YNi$_2$B$_2$C single crystals with $T_c = 15.5$ K as a function of the temperature, and analyze the experimental data in the framework of the Bloch-Grüneisen theory and electron-phonon coupling. The transport electron-phonon spectral function that best fits the resistivity data is then inserted in the real-axis Eliashberg equations, which are directly solved to determine the normalized tunneling conductance both in $s$- and $d$-wave symmetry.

1. INTRODUCTION

The discovery of superconducting quaternary rare-earth borocarbide intermetallic compounds RNi$_2$B$_2$C ($R$=rare earth) have aroused great interest because, even though they are layered materials like high-$T_c$ cuprates, band-structure calculations predict a three-dimensional electronic structure. Most of the experimental and theoretical results tend to support a conventional BCS-Eliashberg descriptions of the superconducting properties in these materials [1]. Some peculiar features of the upper critical field of YNi$_2$B$_2$C have been recently explained in the framework of Migdal-Eliashberg theory by considering the presence of two bands, one of them being more deeply involved in the transport properties of the compound [2].

In the present work we show that the resistivity measurements in YNi$_2$B$_2$C are in complete agreement with the predictions of the theory for the strong electron-phonon (e-p) interaction, and we obtain a value of the transport e-p coupling constant in agreement with previous experimental and theoretical results.

2. EXPERIMENT

The resistivity of YNi$_2$B$_2$C single crystals with $T_c = 15.5$ K has been accurately measured as a function of the temperature by using the standard four-probe technique. The crystals were grown by using the rf - zone melting process [3]. We directly soldered the current leads to the lateral sides of the samples, while very small gold voltage leads were glued by a conducting paste to their surface. In order to improve the sensitivity of the measure we injected in the crystals an AC current (typically 10 mA at 133 Hz) and detected the voltage by the standard lock-in technique. Figure 1 shows the resistivity $\rho(T)$ of one of the YNi$_2$B$_2$C crystals. It is important to notice that a very slow cooling down procedure allowed us to collect nearly three thousand resistivity values between 4.2 and 300 K, but only few points are reported in the figure. As observed in previous experiments [4], the resistivity shows a perfect Bloch-Grüneisen (BG) behaviour with a linear high-temperature part ($d\rho/dT = 0.12 \, \mu\Omega\cdot cm/K$) and a small residual value $\rho(0)= 3 \, \mu\Omega\cdot cm$, indicating the high quality and low impurity content of the samples. We obtained quite similar results in various YNi$_2$B$_2$C samples.

3. DISCUSSION

According to the Matthiessen’s rule for the resistivity in a normal Fermi-liquid metal, one can write: $\rho(T)=\rho_0+\rho_{ph}(T)$, $\rho_0$ and $\rho_{ph}(T)$ being the residual and the phonon resistivities, respectively. In the framework of the BG theory, the high-temperature part of $\rho_{ph}(T)$ is well represented by a linear behaviour: $\rho_{ph}(T)=(2\pi e_0 k_B/h\omega_p^2)\lambda_{tr}T$.
where \( \lambda_{tr} = 2 \int_{0}^{\infty} [\alpha_{tr}^{2} F(\Omega)/\Omega] d\Omega \) is the transport e-p coupling constant, \( \omega_{p} \) is the plasma frequency and \( \alpha_{tr}^{2} F(\Omega) \) is the transport e-p spectral function. From the linear part of the resistivity of Fig. 1 \((T > 100 \text{ K})\) and the experimental value of the plasma energy \( \hbar \omega_{p} = 4.25 \text{ eV} \) determined by means of reflectance and EELS measurements \[5\], we extracted the transport coupling constant \( \lambda_{tr} = 0.53 \).

In order to obtain additional information on the e-p coupling in YNi\(_{2}\)B\(_{2}\)C, we can fit the resistivity of Fig. 1 in the whole temperature range by using the most general expression for \( \rho_{\text{ph}}(T) \), according to the BG theory:

\[
\rho_{\text{ph}}(T) = (4\pi\varepsilon_{0}k_{B}/\hbar\omega_{p}^2) \int_{0}^{\Omega_{\text{max}}} [\alpha_{tr}^{2} F(\Omega)/\Omega] \\
\cdot [\hbar\Omega/2k_{B}T \sinh(\hbar\Omega/2k_{B}T)]^2 d\Omega.
\]

Actually, we used for \( \alpha_{tr}^{2} F(\Omega) \) the phonon spectral density \( G(\Omega) \) determined by inelastic neutron scattering \[6\] multiplied by a multistep weighting function. As a first approximation, we considered a two-step function, whose constant values for \( \Omega < 37.5 \text{ meV} \) and \( 37.5 < \Omega < 70 \text{ meV} \) (corresponding to the two well-distinguishable structures of the \( G(\Omega) \)) were determined by the fit. As shown in Fig. 1, the results of the fit are extremely good: the theoretical BG curve fits so perfectly the experimental \( \rho(T) \) that the relative deviations \( (\rho - \rho_{\text{FTT}})/\rho \) never exceed \( \pm5\% \) (see the inset of Fig. 1). The spectral function \( \alpha_{tr}^{2} F(\Omega) \) obtained from the fit is shown in the inset of Fig. 2. Of course, the resulting \( \lambda_{tr} \) coincides with that previously obtained from the linear part of \( \rho(T) \).

As a first approximation, since \( \lambda \approx \lambda_{tr} \), we used \( \alpha_{tr}^{2} F(\Omega) \) to calculate the YNi\(_{2}\)B\(_{2}\)C quasiparticle density of states by directly solving the real-axis Eliashberg equations both in s- and d-wave symmetry. The resulting tunneling conductances at 4.2 K are shown in Fig. 2. Actually a value \( \lambda = 0.57 \) slightly greater than \( \lambda_{tr} \) is necessary to explain both \( T_{c} \) and the superconducting gap \( \Delta \approx 2 \text{ meV} \) as determined in tunneling experiments \[7\]. The comparison of the curves of Fig. 2 with the experimental data \[7\] suggests a possible s-wave symmetry for the YNi\(_{2}\)B\(_{2}\)C. Finally, the value of \( \lambda_{tr} \), here determined from the resistivity is consistent with the value used in Ref. 2 for the discussion of the properties of YNi\(_{2}\)B\(_{2}\)C in the framework of the isotropic single-band model.

**REFERENCES**

1. S.-L. Drechsler *et al*., Physica C 317–318 (1999) 117.
2. S.V. Shulga *et al*., Phys. Rev. Lett. 80 (1998) 1730.
3. G. Behr *et al*., J. Crystal Growth 198–199 (1999) 642.
4. I.R. Fisher *et al*., Phys. Rev. B 56 (1997) 10820.
5. K. Widder *et al*., Europhys. Lett. 30 (1995) 55.
6. F. Gompf *et al*., Phys. Rev. B 55 (1997) 9058.
7. T. Ekino *et al*., Phys. Rev. B 53 (1996) 5640.