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Superconducting and normal state properties of $Y_{1-x}Pr_xNi_2B_2C$ ☆

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Abstract

Electrical resistivity, magnetoresistance and magnetic susceptibility have been studied for $Y_{1-x}Pr_xNi_2B_2C$ samples with $0 \leqslant x \leqslant 1.0$. The increase of Pr concentration x results in a rapid suppression of superconductivity, $|dT_c/dx| = 35$ K. No indication on superconductivity was observed for $PrNi_2B_2C$ down to $T = 0.35$ K. The absence of superconductivity for $PrNi_2B_2C$ and the large superconductivity suppression rate $|dT_c/dx|$ for $Y_{1-x}Pr_xNi_2B_2C$ correlate with the anomalously high Néel temperature of $PrNi_2B_2C$ ($T_N \approx 4$ K). Possible reasons for the absence of superconductivity in $PrNi_2B_2C$ and the large $|dT_c/dx|$ value for $Y_{1-x}Pr_xNi_2B_2C$ are discussed.

Keywords: Borocarbides; Substitution effects; Electrical resistivity; Magnetoresistance

Intensive study of quaternary borocarbides RNi_2B_2C (R = Y, rare earth) has revealed a unique possibility given by this system for investigations of the interplay between superconductivity and magnetism. Recently it was reported [1,2] that some properties of $PrNi_2B_2C$ (Pr1221) deviates considerably from those of other magnetic borocarbides. Here we describe results of our investigation of the $Y_{1-x}Pr_xNi_2B_2C$ system.

Polycrystalline $Y_{1-x}Pr_xNi_2B_2C$ samples were prepared by arc-melting in Ar atmosphere and subsequent careful annealing [3]. Powder X-ray diffractometry has shown that the samples are essentially single phase. The lattice parameters of Pr1221 were found to be $a = 3.7002$ Å and $c = 9.974$ Å which is in good agreement with Refs. [4–6]. The lattice parameters of $Y_{1-x}Pr_xNi_2B_2C$ vary approximately linearly with increase of the Pr concentration x (see Fig. 1).

Results of electrical resistivity measurements for $Y_{1-x}Pr_xNi_2B_2C$ samples with various x are shown in Fig. 2. For Pr1221 a gradual but pronounced drop in resistivity was found below ~10 K [1,2]. A magnetic field $H = 50$ kOe only slightly shifts the $\rho(T)$ curve for Pr1221. The $\rho(T)$ dependence for Pr1221 at $T < 10$ K and the influence of H on $\rho(T)$ has an anomalous character with respect to other magnetic borocarbides. The drop in $\rho(T)$ found for Pr1221 is connected with some peculiarities in scattering of conduction electrons by Pr ions at low temperatures rather than with AFM ordering because the drop in $\rho(T)$ develops

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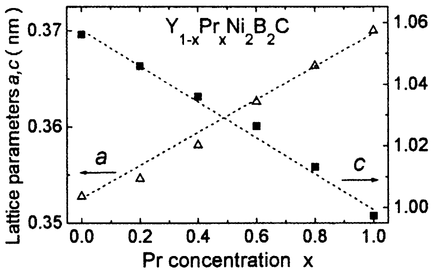

Fig. 1. Lattice parameteres vs. Pr concentration x for $Y_{1-x}Pr_xNi_2B_2C$.

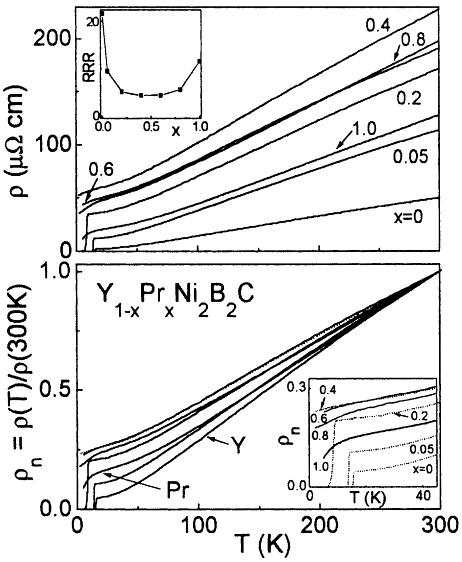

Fig. 2. Resistivity vs. T (upper part) and normalized resistivity $\rho_n(T) = \rho(T)/\rho(300\ K)$ (lower part) for $Y_{1-x}Pr_xNi_2B_2C$. The numbers correspond to the Pr concentration x. Insets: RRR vs. x and low temperature part of ρ_n vs. T.

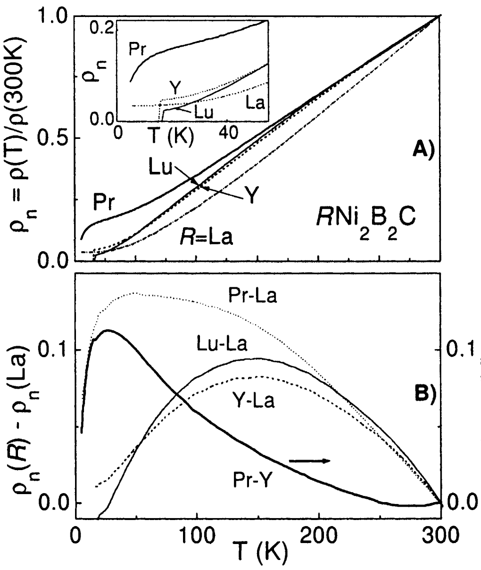

Fig. 3. (A) Normalized resistivity $\rho_n(T) = \rho(T)/\rho(300\ K)$ vs. T for a Pr1221 polycrystal in comparison with the results for Y1221, Lu1221 and La1221. Inset: Low temperature part of ρ_n vs. T. (B) The difference between ρ_n of R1221 (R = Pr, Lu, Y) and La1221 (left axis) and between ρ_n of Pr1221 and Y1221 (right axis).

at $T \gg T_N$ [1,2]. The anomaly in $\rho(T)$ gradually disappears with decrease of x. Noteworthy is the nonmonotonic variation of the electrical resistivity, normalized resistivity and residual resistance ratio (RRR) with increase of x (see Fig. 2). This behavior seems to be connected with lattice distortions developing in the pseudoquaternary $Y_{1-x}Pr_xNi_2B_2C$ system due to the difference in the ionic radii of Y^{3+} and Pr^{3+} ions. The resistivity has maximum values for the samples with x close to 0.5 for which maximal lattice distortions can be expected.

The contribution of Pr ions to the scattering of conduction electrons can be estimated by comparison of the resistivity for different borocarbides, (see Fig. 3A). Unexpectedly it was found that, for $200 < T < 300$ K, $\rho_n(T)$ of Pr1221 is very similar to that of Y1221 and Lu1221 and is significantly different from $\rho_n(T)$ of nonsuperconducting La1221. Consequently, to obtain the contribution in $\rho_n(T)$ from the Pr ions it is more appropriate to use, as a nonmagnetic reference Y1221 or Lu1221 rather than La1221. The difference $(\rho_n(\mathrm{Pr}) - \rho_n(\mathrm{Y}))$ is shown as solid curve in Fig. 3B). Magnetic scattering increases with decreasing T and has a pronounced maximum at $T \approx 25$ K. Such a behavior is typical for some heavy-fermion systems (see, e.g., Ref. [7]). Therefore, the absence of superconductivity in Pr1221 can be connected with the increased scattering of conduction electrons by Pr ions at low T.

The magnetoresistance (MR) of a Pr1221 polycrystalline sample is plotted in Fig. 4 for various temperatures. At high T, MR is positive at all magnetic fields H. With decrease of T, MR becomes negative, the $\rho(H)$ dependencies start to

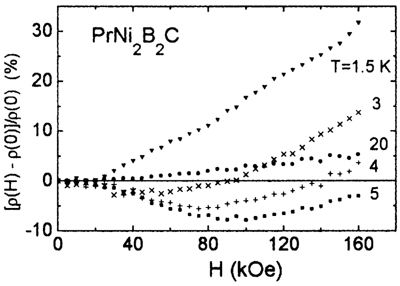

Fig. 4. MR of $PrNi_2B_2C$. Only some representative curves are shown.

have minima at some H. The positions of these minima shift to lower H with decrease of T. At $T = 1.5$ K, MR becomes positive at all H again. It should be noted that the behavior of resistivity and MR of Pr1221 deviates considerably from that for other magnetic borocarbides R1221 (R = Gd–Tm). At the same time the observed anomalies are rather similar to those reported [8,9] for Yb1221 with heavy fermion behavior and may be connected with some 4f-conduction electron hybridization in Pr1221.

Analyzing the influence of the Ni–Ni distance and the de Gennes factor on T_c of borocarbides one could expect $T_c \approx 4$ K in the case of the "normal" Pr behavior in Pr1221. Our measurement of $\rho(T)$ has shown that there is no indication of superconductivity at T down to 0.35 K. $|dT_c/dx|$ for $Y_{1-x}Pr_xNi_2B_2C$ is about 35 K (see Fig. 5), which is about 20 times larger than could be expected from the de Gennes scaling for $(Y_{1-x}Gd_x)$1221. Partially this rapid suppression of T_c is connected with the difference in the ionic radii of Y^{3+} and Pr^{3+} ions. Nevertheless, after the correction for this difference [10], the pure magnetic contribution to $|dT_c/dx| \approx 18$ K is still about nine times larger than expected from the de Gennes scaling. This correlates with the value of $T_N \approx 4$ K [6,1] which for Pr1221 is about four times larger than expected from the de Gennes scaling. The observed simultaneous deviations of T_N and $|dT_c/dx|$ from the expected values can be considered as a further manifestation of 4f-conduction electron hybridization in Pr1221.

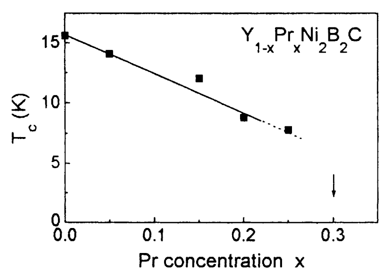

Fig. 5. Superconducting critical temperature of $Y_{1-x}Pr_xNi_2B_2C$ samples as a function of x.

The substitution of Y by Pr in $Y_{1-x}Pr_xNi_2B_2C$ leads not only to a rapid suppression of T_c but also to a pronounced decrease of upper critical magnetic fields. For instance, the shift of the superconducting transition curve in a magnetic field $H = 1$ kOe is about three times larger for the sample with $x = 0.2$ than for pure YNi_2B_2C (see Fig. 6).

In conclusion, it was found that the behavior of $\rho(T)$ and MR for $Y_{1-x}Pr_xNi_2B_2C$ deviates considerably from that of "normal" magnetic borocarbides R1221 (R = Gd–Tm). The values of $|dT_c/dx|$ for $(Y_{1-x}Pr_x)$1221 and T_N for Pr1221 are found to be considerably larger than could be expected from the de Gennes scaling. This gives an evidence for the increased (with respect to "normal" R1221) exchange interaction between Pr 4f states and

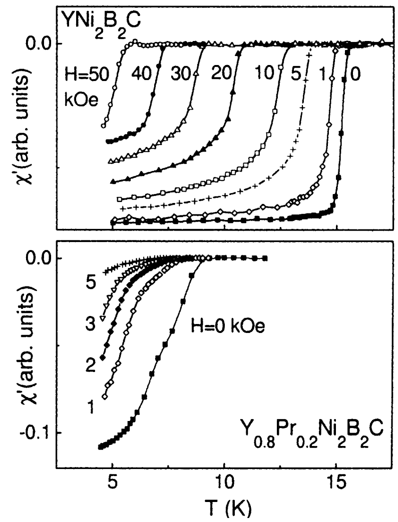

Fig. 6. Real part of the ac susceptibility of YNi_2B_2C (upper part) and $Y_{0.8}Pr_{0.2}Ni_2B_2C$ (lower part) samples vs. T at various fields H.

conduction electrons. Both anomalous scattering of conduction electrons by Pr ions and the influence of lattice distortions should be taken into account in describing the behavior of $Y_{1-x}Pr_xNi_2B_2C$ system.

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