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Effect of pressure on the superconducting properties and magnetism in $HoNi_2B_2C$

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Abstract

The electrical resistance of a single crystal of $HoNi_2B_2C$ has been measured as a function of temperature (T) and magnetic field (H) under high pressure (P). As pressure increases, T_C decreases with the rate of $\partial T_C/\partial P = -0.62$ K/GPa but T_N increases with $\partial T_N/\partial P = 0.41$ K/GPa. This implies that the superconductivity above T_N competes with antiferromagnetism. The re-entrant superconducting temperature coexisting with the antiferromagnetic phase is increased by applying pressure. The present result indicates that T_C coincides with T_N near 3.2 GPa.

Keywords: Borocarbide; High pressure; Superconductivity; Antiferromagnetic order; Electrical resistance

PACS: 74.25.Fy; 75.50.Ee; 74.62.Fj

1. Introduction

The family of the rare earth borocarbides having the formula RNi_2B_2C (R: rare earth elements) contains a few representatives of the magnetic superconductors [1]. For R = Tm, Er, Ho and Dy, the coexistence between superconductivity and antiferromagnetic ordering has been observed at low temperatures. The structure is tetragonal $ThCr_2Si_2$ type, which consists of alternating layers of HoC planes and Ni_2B_2 slabs. For $HoNi_2B_2C$, the two transition temperatures lie in the same temperature range 5–8 K. This compound has two different superconducting phases; the one co-exists with the antiferromagnetic order and the other nonmagnetic superconducting phase. It has been reported that T_C decreases and T_N increases by applying pressure up to 2 GPa [2,3]. This means that the pressure effect on the two superconducting phases are different, i.e., the superconductivity in antiferromagnetic phase becomes stable but the nonmagnetic one unstable under pressure. This result suggests that T_C coincides with T_N at high pressure.

In the present work, we made an attempt to measure the temperature-dependent electrical resistance of a single crystal of $HoNi_2B_2C$ up to 3 GPa, in order to examine the interplay of the superconductivity and antiferromagnetism at high pressure.

2. Experimental procedures

The samples were grown using the Ni_2B flux technique [1]. The electrical resistance was measured by using standard dc four-probe method. The current was in the *ab*-plane. A magnetic field was applied parallel to *ab*-plane using superconducting magnet. Hydrostatic pressure up to 3 GPa was generated using piston-cylinder method.

3. Experimental results

Fig. 1 shows the temperature-dependent electrical resistivity $\rho(T)$ at various pressures up to 3 GPa. The resistance at

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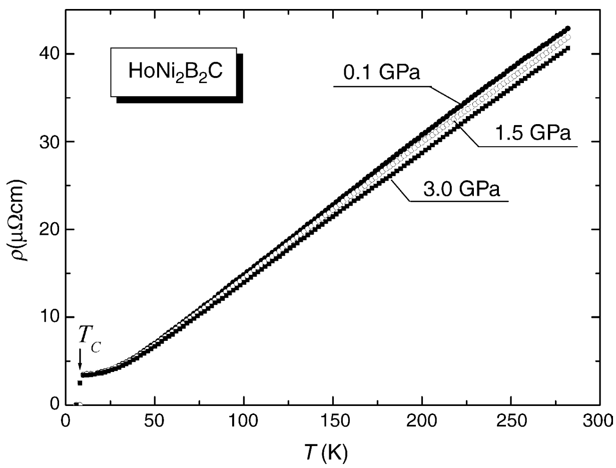

Fig. 1. Temperature dependence of the electrical resistivity of $HoNi_2B_2C$ at high pressures up to 3 GPa.

room temperature decreases with increasing pressure with the rate $(1/R)\partial R/\partial P = -1.7 \times 10^{-2}\,\mathrm{GPa}^{-1}$. The $\rho(T)$ curves show a smooth decrease with decreasing temperature without any discontinuities, followed by a sudden decrease at T_C, due to a superconducting transition.

Fig. 2 shows a detail of the $\rho(T)$ curves at low-temperature below 10 K at various pressures. At 0.1 GPa, the superconducting transition begins around 9.2 K and is complete at 8.8 K. Above 2.5 GPa a re-entrant peak is observed in $\rho(T)$ around 6 K, while it is not seen below 2.5 GPa. The maximum of $\rho(T)$ is enhanced by applying pressure more but is suppressed near 3 GPa. This behavior is considered to be due to the competing pressure effect between the nonmagnetic superconducting phase and magnetic ordered phase.

We defined five characteristic temperatures, the onset of transition as (1) T_C (onset), the offset of transition as (2) T_C (offset), a maximum of the re-entrant peak as (3) T_N and the temperatures showing $R = 0$ in the re-entrant phase as (4) T_{C1}^{AF} and (5) T_{C2}^{AF}, the former is below T_N and the latter above T_N, respectively. These are shown in the inset of Fig. 2. As pressure increases, T_C (onset) and T_C (offset) decrease but T_N increases, and the superconducting transition no longer completes above T_N at 3 GPa because a finite resistivity remains between 6.7 and 7.1 K. This fact means that there is no paramagnetic superconducting state above 3 GPa. It should be noted that the shape of $\rho(T)$ curves is changed by increasing pressure; at low pressures (below 2 GPa) the resistivity becomes zero sharply but by further pressurizing, a tail just above T_C (offset) is developed and the width of the transition becomes large.

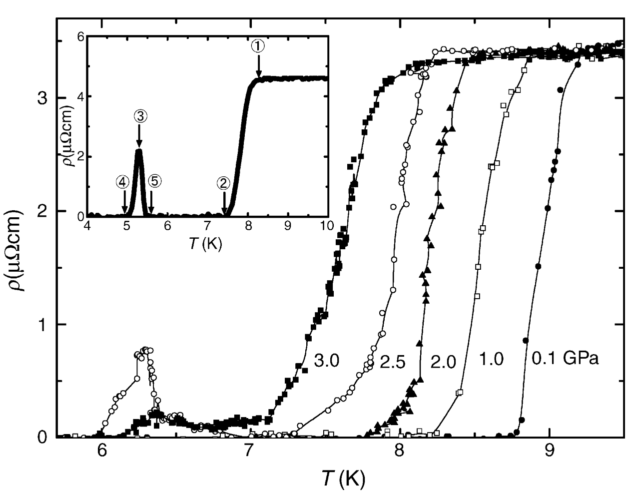

Fig. 2. Temperature-dependent electrical resistivity between 5.5 and 9.5 K at high pressures. The arrows in the inset: (1) T_C (onset), (2) T_C (offset), (3) T_N, (4) T_{C1}^{AF} and (5) T_{C2}^{AF}.

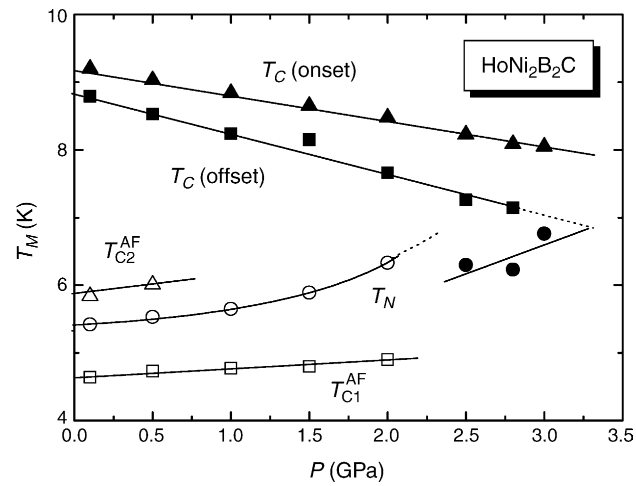

Fig. 3. Pressure dependence of T_C (onset), T_C (offset), T_{C1}^{AF}, T_{C2}^{AF} and T_N. Open circles show T_N at a magnetic field $H = 1.5$ kOe and filled circles show T_N at zero field. Filled triangles and squares show T_C (onset) and T_C (offset) at zero field. Open squares and triangles show T_{C1}^{AF} and T_{C2}^{AF} at a magnetic field $H = 1.5$ kOe, respectively. The solid lines are guide of eye.

Fig. 3 displays the pressure dependence of T_C (onset), T_C (offset), T_{C1}^{AF}, T_{C2}^{AF} and T_N. Below 2.5 GPa, the re-entrant peak in the $\rho(T)$ curve does not appear at $H = 0$, but is seen at small applied magnetic field, $H = 1.5$ kOe [4]. T_N, T_{C1}^{AF} and T_{C2}^{AF} are obtained at $H = 1.5$ kOe. Above 2.5 GPa, it was difficult to obtain T_N from the re-entrant peak at 1.5 kOe because the peak in $\rho(T)$ due to antiferromagnetic ordering merged into the superconducting transition. So we use the data of T_N at 1.5 kOe below 2.5 GPa and T_N at $H = 0$ above 2.5 GPa. The magnetic field dependence on T_N was negligibly small. At 3 GPa, the transition did not complete but the temperature extrapolated to $R = 0(\sim 7\,\mathrm{K})$ is slightly above T_N. T_C (offset) and T_N are close each other, which gives rise to a strong interaction between superconductivity and antiferromagnetism. Both T_C (onset) and T_C (offset) decrease with increasing pressure with the rates, $\partial T_C(\mathrm{onset})/\partial P = -0.40$ K/GPa and $\partial T_C(\mathrm{offset})/\partial P = -0.62$ K/GPa, respectively. T_N increases with pressure, $\partial T_N/\partial P = +0.41$ K/GPa. Compared with the previous data [2,4], $\partial T_C(\mathrm{offset})/\partial P = -0.46$ to -0.50 K/GPa and $\partial T_N/\partial P = 0.70$–$0.84$ K/GPa, the present results show that the pressure derivative of T_C (offset) is nearly the same but that of T_N is different. The origins of the difference are partly due to an experimental error but not clear now. There are also sample dependence of pressure dependence of T_N and T_C.

4. Discussion

4.1. Temperature dependence of ρ above T_C (onset)

To examine the temperature dependence of electrical resistivity above T_C (onset), we assume the following power law [5]:

$$\rho(T) = \rho_0 + AT^n, \tag{1}$$

where ρ_0 and A are the residual resistivity and the constant depending on pressure. Fig. 4 shows the plot of $(\rho(T) - \rho_0)$ as a function of T at 0.1 and 2.5 GPa in the logarithmic scale, in which the gradients correspond to the value of n. ρ_0 is estimated by extrapolating resistivity above T_C (onset) to $T = 0$. It is found that there is no difference between 0.1 and 2.5 GPa within experimental error and we obtain $n = 2.0 \pm 0.2$. This result indicates the electronic state above T_C (offset) is described by normal Fermi liquid, which is stable under high pressure at least up to 3 GPa. The values of ρ_0 are also nearly constant below 3 GPa. The value of A is about $8.0 \times 10^{-4}\ \mu\Omega\,\mathrm{cm\,K^{-2}}$, which is almost constant against pressure. This result means the effect of pressure on spin fluctuation is small because A is related to the magnitude of spin fluctuation. The magnitude of A is smaller than the value $A = 3.0 \times 10^{-3}\ \mu\Omega\,\mathrm{cm\,K^{-2}}$, which is expected from Kadowaki–Woods plot and by using the value $\gamma = 17.5\,\mathrm{mJ/mol\,K^2}$ [6,7].

The coefficient A is proportional to the square of the density of state of conduction electrons at Fermi level $N(0)$ [8].

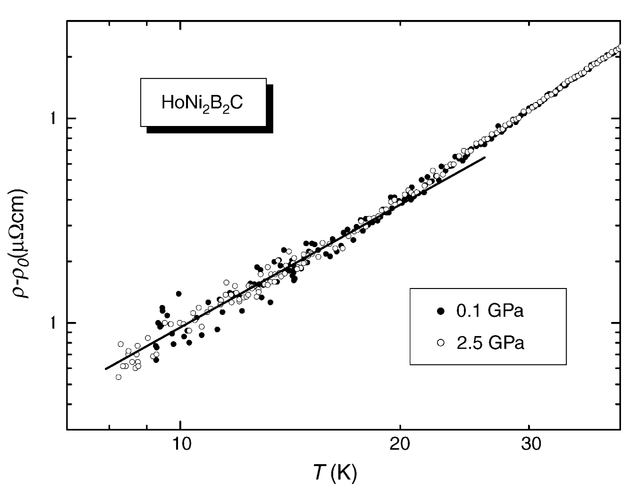

Fig. 4. $(\rho(T) - \rho_0)$ as a function of T at 0.1 and 2.5 GPa at zero field in logarithmic scale. Filled and open circles show the data at 0.1 and 2.5 GPa, respectively.

T_C is represented by following equation:

$$T_C = 1.14\Theta_D \exp\left(-\frac{1}{N(0)V_{ph}}\right), \tag{2}$$

where Θ_D and V_{ph} are Debye temperature and electron–phonon interaction energy, respectively. The volume dependence of T_C is described as

$$\frac{\partial \ln T_c}{\partial \ln V} = \frac{\partial \ln \Theta_D}{\partial \ln V} + \ln\left(\frac{1.14\Theta_D}{T_c}\right)\frac{\partial \ln N(0)}{\partial \ln V} + \ln\left(\frac{1.14\Theta_D}{T_c}\right)\frac{\partial \ln V_{ph}}{\partial \ln V}. \tag{3}$$

Since A and Θ_D are almost independent of pressure as mentioned in the foregoing paragraph, the first and second term may be 0. We obtained $\Gamma[T_C(\text{offset})] = -\partial \ln T_C(\text{offset})/\partial \ln V = -13.6$, which is relatively large compared with normal superconductors [9]. Taking into account these results, the pressure dependence of T_C is originated mainly from the pressure effect on electron–phonon interaction. The value of $(1/V_{ph})\partial V_{ph}/\partial P$ is estimated to be $-1.9 \times 10^{-2}\,\mathrm{GPa^{-1}}$ by using Eq. (3), which is the same order of magnitude as that of $TmNi_2B_2C$ [10].

4.2. Coexistence of antiferromagnetism and superconductivity

The re-entrant peak appears above 2.5 GPa at $H = 0$ but it is not seen below it. This is caused by the antiferromagnetic correlation of 4f-electrons enhanced by applying pressure to give magnetic interaction to overcome the superconductivity. Compressibility of this compound has large anisotropy; linear compressibility of c-axis is two times larger than that of a-axis [4]. This fact implies that the distance between layers shrinks more than that in the layers. Consequently, the application of pressure strengthens antiferromagnetic correlation but weakens the superconductivity in nonmagnetic phase.

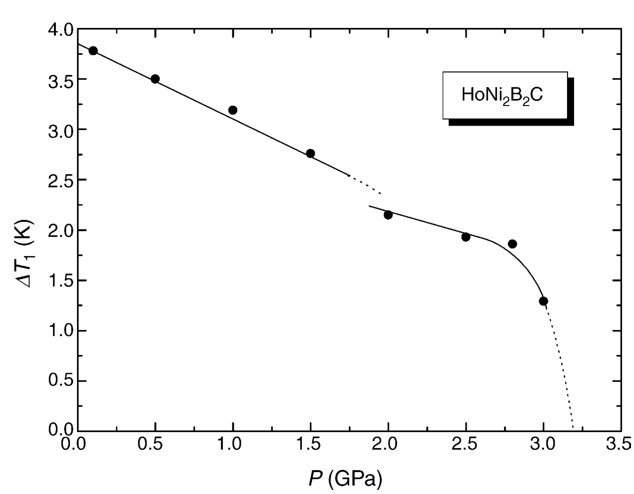

Fig. 5. $\Delta T_1 = T_C(\text{onset}) - T_N$ as a function of pressure.

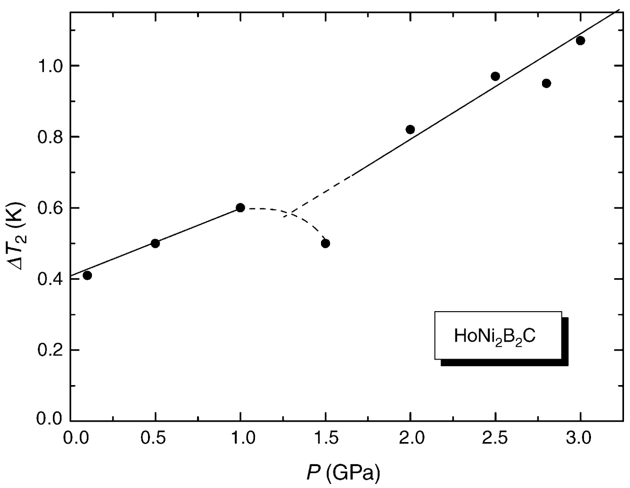

Fig. 6. Pressure dependence of the width of superconducting transition, $\Delta T_2 = T_C(\text{onset}) - T_C$ (offset).

Measurements of H_{C2} indicate that there is a drastic dip in H_{C2} data around T_N [1]. A previous study reported that the dip of H_{C2} smears to zero by applying pressure [11]. The sudden appearance of the re-entrant peak at 2.5 GPa is due to the fact that pressure dependence of T_N is larger than that of T_{C1}^{AF} as shown in Fig. 3.

To investigate the effect of pressure on T_C and T_N, we define, $\Delta T_1 = T_C(\text{onset}) - T_N$, ΔT_1 is plotted in Fig. 5 as a function of pressure. The pressure dependence of ΔT_1 is found to change in near 2 GPa. This is caused by a rapid increase of T_N with increasing pressure above 2 GPa. Considering that the re-entrant peak appears above 2 GPa, the antiferromagnetic interaction among Ho^{3+} ions may be especially enhanced by pressure around 2 GPa, i.e., the interaction between T_C (onset) and T_N may become strong as both temperatures are close. ΔT_1 is extrapolated to 0 around 3.2 GPa.

The width of superconducting transition, ΔT_2, defined as $\Delta T_2 = T_C$ (onset)-T_C (offset) is plotted in Fig. 6. ΔT_2 increases linearly with pressure but the point at 1.5 GPa deviates downward. Then it increases again by further pressurizing. It is caused by a tail on the superconducting transition just above T_C (offset). Pressure inhomogeneity sometimes makes the width of the transition broad. But the tail in $\rho(T)$ at 3 GPa is shorter than that at 2.5 GPa. Considering this fact, it should be ruled out as an origin of long tail. This long tail is reminiscent of behavior of vortex at magnetic field in another borocarbide compound such as YNi_2B_2C [12]; a magnetic field changes the vortex solid due to field-enhanced pinning. The anomalous behavior above 2 GPa suggests that pressure affects a motion of vortex in a similar fashion as the effect of a magnetic field mentioned above. But the details of mechanism of the tail above 2.5 GPa are not known at present.

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