Anomalous pressure effect on the superconducting transition temperatures and critical fields of Ho_{1-x}Y_xNi_2B_2C

Gendo Oomi^1,2, Yukio Sakikawa^2, Mio Ohmura^2, Masashi Ohashi^3, P.C.Canfield^4 and B.K.Cho^5

^1Department of Education and Creation Engineering, Kurume Institute of Technology, Kamitsu-machi, Kurume, Fukuoka 830-0052, Japan
^2 Department of Physics, Kyushu University, Fukuoka 812-8581, Japan
^3 Faculty of Environmental Design, Kanazawa University, Kanazawa 920-1192, Japan
^4 Ames Labo.,Iowa State Univ., Ames, IA 50011,USA
^5 Center for Frontier Materials and Development of Materials Science and Engineering, Gwangju Institute of Science and Technology, Gwangju, South Korea

E-mail: geomi@cc.kurume-it.ac.jp

Abstract. The superconducting transition temperatures \( T_C \) and upper critical fields \( H_{C2} \) of borocarbides Ho_{1-x}Y_xNi_2B_2C have been measured under high pressure up to 3 GPa. It is found that \( T_C \) of these compounds decreases with increasing pressure but the pressure derivatives have a maximum near \( x = 0.7 \), where the magnetic ordering temperature \( T_N \) becomes 0. The pressure coefficients of \( H_{C2} \) show also a maximum near \( x = 0.7 \). The possible origins of these anomalies are briefly discussed in connection with the instability of antiferromagnetism.

1. Introduction
The borocarbides RNi_2B_2C (R: rare earth element) have been studied extensively because the antiferromagnetism(AF) coexists with superconductivity(SC)[1]. It is a typical example to explore a new origin of superconductivity. The structure of this material is a variant of the ThCr_2Si_2 type, which consists of alternating layers of RC planes and Ni_2B_2 slabs. Among these compounds, the most interesting material is R=Ho, in which the superconductivity is observed around \( T_C = 9 K \), reenters normal conducting state near 5K due to antiferromagnetic ordering around \( T_N = 5 K \) and then shows a reentrant superconducting behavior below 5K. The interplay of AFM and SC is the most significant in this material because of the large value of \( T_N/T_C \) of about 0.63[2]. It has been revealed that as pressure increases, \( T_C \) decreases but \( T_N \) increases[3,4].

In the system of Ho_{1-x}Y_xNi_2B_2C the ratio is easily controlled by changing x because the sample of \( x = 1 \) is superconductor with \( T_C = 16 K \) and the \( T_N \) decreases with x followed by a disappearance of AFM around \( x = 0.6 \) [5]. The effect of pressure on the \( T_C \) reflects the stability of superconductivity: the value of pressure coefficient of \( T_C \) of \( x = 0 \) is extremely larger than that of \( x = 1 \)[6,7], which indicates that the interplay of AFM and SC is closely related to the magnitude of pressure coefficient.

In the present work we attempted to measure the effect of pressure on the \( T_C \) and the upper critical field \( H_{C2} \) of Ho_{1-x}Y_xNi_2B_2C by measuring the electrical resistivity under high pressure and high magnetic field in order to clarify the interplay of AFM and SC in this system. Anomalous pressure effect on the \( T_C \) and \( H_{C2} \) near \( x = 0.7 \) is found and the possible origins will be briefly discussed.
2. Experimental procedure
Single crystals were grown by a Ni$_2$B flux method. The details of sample preparation and characterization were reported previously [8]. High pressure was generated by using a piston-cylinder method up to 3 GPa. The pressure was kept constant throughout the experiment by controlling the load of hydraulic press. The electrical resistance was measured by using standard four-probe method and the current was in the ab plane. The magnetic field was generated by using a superconducting magnet and applied parallel to the ab plane. The details of present high pressure apparatus were published elsewhere [9].

3. Results and discussion

3.1. Effect of pressure on the $T_C$
Figure 1 shows the $T_C$ as a function of Y concentration $x$ at ambient pressure. In this figure the $T_N$ is also shown for comparison [5]. It is found that the $T_C$ increases almost linearly with $x$ while $T_N$ decreases with $x$ and seems to disappear around $x = 0.7$. This result indicates that the SC competes with AFM, i.e., the SC is stabilized with increasing $x$ although the AFM becomes unstable. The $T_C$ of all samples decreases with increasing pressure but the decreasing rate depends on $x$: the value of $\partial T_C/\partial P$ of $x = 0$ is about -0.4K/GPa while that of $x=1$ is almost 0 [4,7].

Figure 2 shows the pressure dependence of $T_C$ as a function of $x$. It is found that the magnitude of $-\partial T_C/\partial P$ decreases with increasing $x$ below $x = 0.5$ but increases quickly above that followed by a peak around $x = 0.7$, i.e., $-\partial T_C/\partial P$ does not show a linear dependence against $x$ such as $T_C$. As mentioned above, the value of $x$ showing the peak agrees well with that where the AFM disappears. In other words, the peak observed in the concentration dependence of Y is closely related with the disappearance of AFM.

3.2 Effect of pressure on the upper critical fields $H_{C2}$
Figure 3 shows the upper critical field $H_{C2}$ at 4.2K as a function of $x$ at ambient pressure. The $H_{C2}$ of $x = 0$ at 4.2K is 0.2T and that of $x=1$ is larger than 5T, which is not shown in Fig.3. $H_{C2}$ increases with $x$, i.e., the sign of $\partial H_{C2}/\partial x$ is positive. The increasing rate of $H_{C2}$ changes between $x=0.6$ and 0.7: the value of $\partial H_{C2}/\partial x$ above 0.6 is about 5.5 times larger than that below 0.5. The concentration $x = 0.6$ showing the anomaly mentioned above is nearly the same as that showing the disappearance of AFM as illustrated in Fig.1.

Next we consider the pressure dependence of $H_{C2}$. It was reported [3,4,7] that the $H_{C2}$ of $x = 0$ at 7K decreases with pressure having a rate, $\partial H_{C2}/\partial P=-0.14$ T/GPa, which is different from that of the re-entrant SC phase below 5K[2,6,10]. Figure 4 shows the values of $\partial H_{C2}/\partial P$ at 4.2K as a function of $x$.
It is found that the value increases with increasing $x$ and shows a peak around $x = 0.7$, where the AFM disappears as shown in Fig. 1.

Figure 3. The upper critical field $H_{C2}$ at 4.2K as a function of $x$.

Figure 4. Pressure derivatives of $H_{C2}$ at 4.2K.

From these results, it is suggested that the instability of AFM state is closely related with the pressure dependence of $T_C$ and $H_{C2}$ as was mentioned in 3.1. Near $x = 0.7$, a large antiferromagnetic fluctuation may be induced at low temperature. The application of pressure is expected to suppress the fluctuation effect, which gives rise to a large pressure effect on the electronic and magnetic properties in this system. This consideration explains qualitatively the anomalies near $x = 0.7$ observed in the present work.

Finally we comment the lattice properties of this system. It should be noted that the $x$ dependence of the unit cell volume and the compressibility in Ho$_{1-x}$Y$_x$Ni$_2$B$_2$C show an anomaly near $x = 0.7$, which suggests that some kind of lattice instability exists near 0.7[11]. The peak in the pressure derivatives of $T_C$ and $H_{C2}$ may be partly due to this anomaly. We pointed out previously the close relation between superconductivity and the compressibility in high $T_c$ superconductors and UGe$_2$[12,13,14]. However in order to clarify this point, more information about lattice properties of this system such as thermal expansion measurements under high pressure are highly desired.

4. Conclusions

In this work we have measured the electrical resistance of ternary borocarbides Ho$_{1-x}$Y$_x$Ni$_2$B$_2$C under high pressure and magnetic fields. The main results are summarized as follows.

1) The superconducting transition temperatures of this system decrease with increasing pressure. The pressure derivatives show a peak around $x = 0.7$.
2) The upper critical fields $H_{C2}$ increase with $x$ while the increasing rate changes around $x = 0.7$.
3) The pressure dependence of $H_{C2}$ shows a peak around $x = 0.7$ same as that of $T_C$.
4) These results indicate that the antiferromagnetic fluctuation plays an important role in the behaviour of the superconducting properties under high pressure.

References

[1] Canfield P C, Gammel P L, Bishop D J, 1998 Phys. Today 51 40
[2] Oomi G, Masaoka D, Kagayama T, Kuroda N, Cho B K, Canfield P C, 2003 Physica C 388-389 177
[3] Uwatoko Y, Oomi G, Canfield P C, Cho B K, 1996 Physica B 216, 329
[4] Akiyama H, Kaji S, Oomi G, Cho B K, Canfield P C, 2006 J.Alloys and Compd. 408-412 226
[5] Eversmann K, Handstein A, Fuchs G, Cao L, Müller K -H, 1996 Physica C 266, 27
[6] Oomi G, Matsuda N, Kagayama T, Cho B K, Canfield P C, 2003 Intern.J.Mod.Phys.B 17 3664
[7] Oomi G, Takeya H, Kadowaki K, 1998 Rev. High Pressure Sci. Technol. 7 592
[8] Canfield P C, Cho B K, Johnston D C, Finnemore D K, Hundley M F, 1994 Physica C 230, 397
[9] Honda F, Kaji S, Ohashi M, Oomi G, Eto T, Kagayama T, 2002 J. Phys.: Condens. Matters 14 11501
[10] Oomi G, Kagayama T, 1998 Materia Japan 37 397 (in Japanese)
[11] Sakigawa Y, 2006 Master Thesis, Department of Physics, Kyushu University
[12] Suenaga K, Oomi G, 1991 J. Phys. Soc. Jpn 60 1189
[13] Kagayama T, Oomi G, 1999 J. Materials Processing Technology 85 229
[14] Oomi G, Ohashi M, Honda F, Haga Y, Onuki Y, 2003 J. Phys.: Condens. Matters 15 S2039