PRESSURE STUDIES OF REENTRANCE BEHAVIOR IN $\boldsymbol{H}_{\mathbf{c2}}$ OF $HoNi_2B_2C$*

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(Received July 10, 2002)

We have investigated pressure dependence of the superconductivity of $HoNi_2B_2C$ using high quality single crystals. Upon applying pressures, T_c was slightly suppressed unlike T_N taken from $M(T)$ data that increases gradually with pressures. At the same time, reentrance behavior found in H_{c2} gets subdued and disappears altogether above 8.3 kbar. Our experimental findings can be understood in terms of the Ginzburg–Landau type analysis.

PACS numbers: 74.25.Dw, 75.62.Fj, 74.23.Ha

1. Introduction

The discovery of superconductivity and magnetism in rare earth nickel borocarbides has revived the very old field of research on how to understand a possible interplay between superconductivity and magnetism [1]. Although $4f$ electrons of rare earth elements are responsible for the magnetism while conduction electrons, probably $3d$ bands of Ni, participate in the superconducting transition, there may well be interactions between the two different types of electrons coupling the two order parameters of superconductivity and magnetism. This kind of an interplay between the two order parameters can be responsible for somewhat anomalous behavior observed in $(Ho_{1-x}Dy_x)Ni_2B_2C$, where T_c shows an abrupt change near

* Presented at the Strongly Correlated Electron Systems Conference, Kraków 2002
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$x = 0.2$ and becomes x independent for larger Dy concentrations although T_N does still follow the de Gennes scaling behavior [2]. Another noticeable point is that $HoNi_2B_2C$ shows reentrance behavior in the temperature dependence of H_{c2}. The anomalous features in the H_{c2}(T) of $HoNi_2B_2C$ have been subject to theoretical studies. There have been so far two theoretical scenarios for these anomalies [3, 4]. The main purpose of our work is to explore how the electron-phonon coupling can affect the suppression of superconductivity and to understand the mechanism of the reentrance behavior in H_{c2}(T) of $HoNi_2B_2C$. We note that there are similar pressure experiments [5] on $HoNi_2B_2C$ published before us, but we believe that our work addresses directly the problem of reentrance behavior in H_{c2} with theoretical calculations.

2. Experimental details

We have grown single crystals using the Ni_2B high-temperature flux growth method as described elsewhere [2]. Magnetization measurements were performed using a commercial SQUID magnetometer (Quantum Design, MPMS7) with fields up to 7 Tesla. Electrical resistivity measurements were performed using a standard four-probe DC method with current on the *ab* plane, perpendicular to the magnetic field, from 1.8 to 20 K. Hydrostatic pressure was generated up to 12 kbar at room temperature by using a Cu–Be cylinder cell [6].

3. Results and discussion

Figure 1(a) shows the temperature dependence of reduced resistivity for $HoNi_2B_2C$ at several magnetic fields applied along the *c*-axis and at two pressures. At ambient pressure, the resistivity drops rapidly to zero at the upper superconducting transition temperature and does not show an anomaly at the antiferromagnetic transition temperature as seen in other polycrystalline samples [7]. However, even a very small magnetic field of 50 Oe is seen to destroy the superconducting state at the antiferromagnetic transition temperature near 5.6 K before recovering a superconducting state at lower transition temperature. With increasing magnetic fields, both upper and lower superconducting transition temperatures get suppressed. On the other hand, the antiferromagnetic transition temperature remains almost the same up to 4 kOe which is in accord with our magnetization data. Interestingly enough, with increasing pressures the superconducting transition moves toward lower temperatures whereas the antiferromagnetic transition temperature increases slightly. One note that at 9.8 kbar the upper superconducting state is very sensitive to magnetic fields. For example,

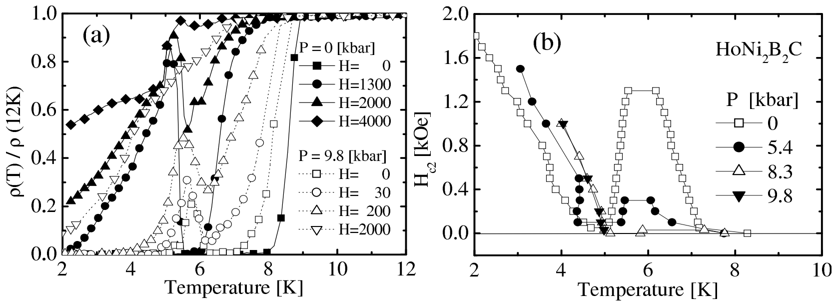

Fig. 1. Temperature dependence of the resistivity of $HoNi_2B_2C$ for several magnetic fields at ambient pressure (closed symbols) and 9.8 kbar (open symbols). Temperature dependence of H_{c2} for several pressures.

we found that it is destroyed even by applying 30 Oe, the smallest magnetic field we can control with our set-up. It then means that H_{c2} is very small for 9.8 kbar from 5 to 8 K. This observation is in sharp contrast with the data taken at ambient pressure. For example, at ambient pressure the upper superconducting state is not destroyed up to 1.3 kOe. The very strong field dependence of the upper superconducting phase at 9.8 kbar is very unusual and the nature of this upper superconducting state needs to be further understood.

From the resistivity data, we can obtain the temperature dependence of upper critical fields H_{c2} for several pressures and investigate pressure effects on the superconductivity. H_{c2}, determined as zero-resistivity temperature for a given field, is shown in Fig. 1(b) for four different pressures. As reported previously [8], at ambient pressure H_{c2} increases rapidly below T_c and shows a pronounced peak around 6 K before falling sharply. Below 5 K, H_{c2} begins to increase again. This unusual feature is often called reentrance behavior in $H_{c2}(T)$. With increasing pressures, the reentrance feature gets rapidly suppressed although the superconducting transition temperature is reduced very little. At the same time, the H_{c2} line below 5 K moves towards higher temperatures, *i.e.* higher H_{c2} for a given temperature at higher pressure. For pressures bigger than 8.3 kbar, this anomalous peak in $H_{c2}(T)$ seems to disappear.

In order to understand the pressure dependence of H_{c2}, we also carried out model calculations using the Ginzburg–Landau scheme [3]. For our calculations, we used two magnetic order parameters: antiferromagnetic order and spiral order, and two superconducting order parameters as described in Ref. [3]. Here we include the pressure effect by adopting pressure dependent T_N which originates from the pressure induced enhancement of J_{sf} due to the pressures [9]. According to our theoretical results explaining the

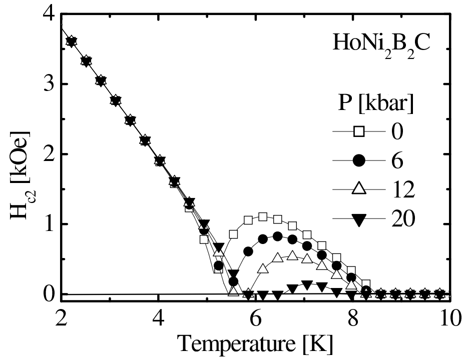

Fig. 2. Theoretical calculations have been made using the model given in Ref. [3] of the temperature dependence of H_{c2} for $HoNi_2B_2C$ for several pressures (see the text).

experimental results even at a quantitative level, it is found that possible mutual interaction between the antiferromagnetic order and the superconducting order plays an important role in having such an anomalous pressure effect on H_{c2}. However, we note that there are some disagreements in details between the experimental results and the theoretical calculations. Further studies about these disagreements will follow.

Works at SungKyunKwan University were supported by the nuclear R & D program of the Ministry of Science and Technology and Korea Research Foundation Grant (KRF-2000-015-DP0111).

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