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Magnetotransport in the magnetic-superconductor $HoNi_2B_2C$

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The electrical resistivity and the magnetization of single crystalline $HoNi_2B_2C$ have been measured at several magnetic fields. In the paramagnetic region, the magnetization is nicely reproduced by calculations that take the crystal electric field (CEF) into consideration. The magnetoresistance is negative at a wide temperature range, and is strongly dependent on the magnetization. It is interpreted by the reduction of spin-disorder scattering as the moments are polarized.

1 Introduction The borocarbides, RNi$_2$B$_2$C (R= Dy-Lu, Y) are an interesting series of compounds because of the interplay between superconductivity and magnetism[1]. The structure is a varient of $ThCr_2Si_2$ type, a body-centered tetragonal crystal structure which consists of alternating layers of HoC planes and Ni_2B_2 slabs. The compounds of this series are magnetic superconductors for most of the heavy rare earth elements; superconductivity and antiferromagnetism have been found to coexist for the rare earth elements Dy, Ho, Er and Tm.

$HoNi_2B_2C$ is particularly interesting because superconductivity are observed at T_{SC}= 8.5 K to coexist with several complex magnetic phases[2,3]. A magnetic phase diagram is described by the results of magnetoresistance, mangetization and heat capacity, indicating a complex magnetic structure at low temperature and magnetic field[4–6]. In the paramagnetic phase at high temperature, on the other hand, the magnetic properties of $HoNi_2B_2C$ is dominated by Ho^{3+} ion, which is influenced not only by the total angular momentum but also by the crystal electric field (CEF).

The temperature dependence of electrical resistivity also depends strongly on magnetic field in the paramagnetic state[7,8]. Such behavior has been observed in some heavy-fermion compounds, where several kinds of interactions such as RKKY interaction, the Kondo effect and CEF effect are competing each other[9,10]. In the present work, we made an attempt to measure the temperature dependence of the electrical resistivity and the magnetization of $HoNi_2B_2C$ at different magnetic field in detail to clarify the relation between the electrical transport and the magnetic property in the paramagnetic state.

2 Experimental A single crystal of $HoNi_2B_2C$ was grown via high temperature flux growth. The details of the preparation were reported previously[2]. Both the electrical resistivity and the magnetization were measured at a magnetic field along a-axis. The dc magnetization was measured in the temperature range 2.0-300 K using a Quantum Design MPMS-5 superconducting quantum interference device magnetometer. Electrical resistance was measured using standard four-probe method in the direction parallel to a-axis and perpendicular to magnetic field.

3 Results Figure 1 shows the temperature dependence of magnetization of $HoNi_2B_2C$ at several magnetic fields along the a-axis. At 0.5 T, no negative magnetization is observed reflecting the diamagnetism due to superconductivety since $H_{c2} < 0.5$ T above 2 K. $M(T)$ shows a small kink and a sharp peak at T_N= 4.4 K and T^*= 5.4 K, respectively. Both T_N and T^* decreases as in-

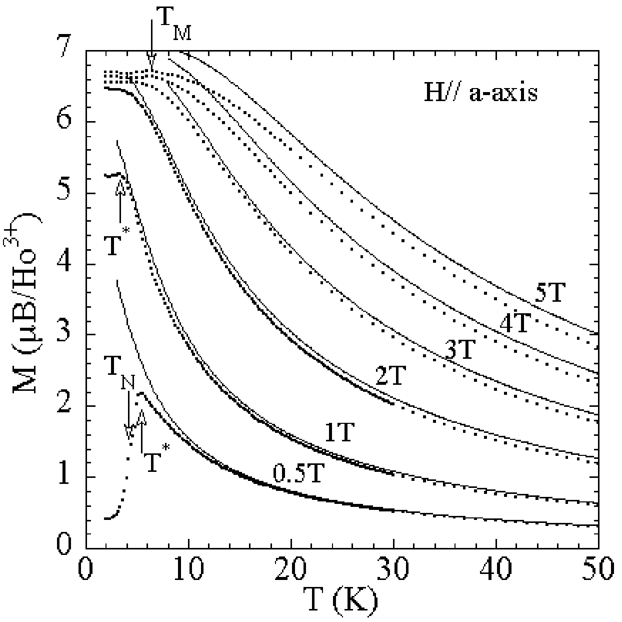

Figure 1 Temperature dependence of magnetization of $HoNi_2B_2C$ at several magnetic fields along the a-axis. The circles and broken lines are the results of experimental and CEF calculations, respectively. T_N, T^* and T_M are the magnetic phase transitions.

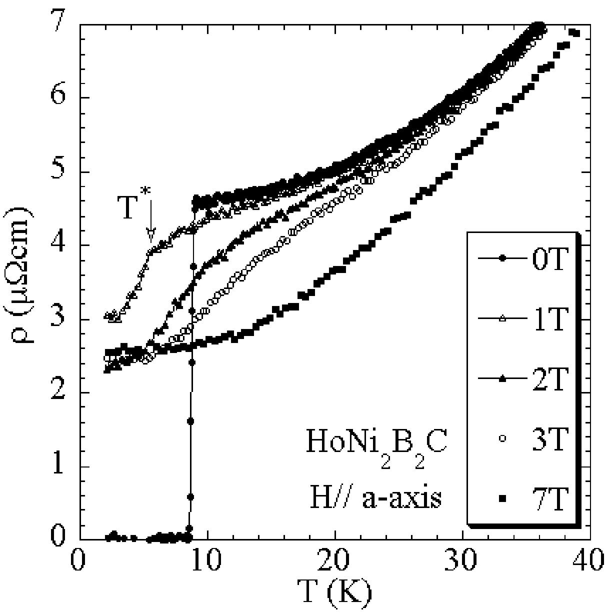

Figure 2 The $\rho(T)$ curves at various magnetic fields. T^* is the magnetic phase transition.

creasing magnetic field, and disappear at H= 1 T and 2 T, respectively. Although there are three magnetic transitions (T_N, T^*, T_M) in the neutron scattering and specific heat measurements[3,4], no anomaly is observed near the paramagnetic-antiferromagnetic transition temperature T_M $\sim$ 6 K. Because of the large value of $|dM/dT|$ due to Curie-weiss law, it may be difficult to detect an anomaly near T_M at low magnetic field. On the other hand, a brood maximum appears around T_M above 4 T, where an anomaly is observed in the results of the specific heat[4].

Above 10 K in the paramagnetic region, the magnetization decreases monotonically as increasing temperature. Moreover, at low magnetic field below 3 T, the magnetization is nicely reproduced by calculations that take CEF effect into consideration by using the parameters taken from the previous report[11]. At low temperature, on the other hand, the calculated values deviate from the experimental ones since a magnetic interaction relies on the magnetization. At high magnetic fields the CEF description is not so good, either.

In figure 2, the electrical resistivity at various magnetic fields are summarized in a wide temperature range up to 40 K. At H= 0 T, ρ decreases with decreasing temperature and shows a sudden drop to 0 at 8.7 K (=T_C) due to the superconducting transition. At 1 T, where the superconducting transition disappears, a kink is found in the $\rho(T)$ curve at T^*= 5.5 K due to magnetic phase transition.

4 Discussion Here we discuss the temperature dependence of ρ in paramagnetic state when we apply magnetic fields. We defined the magnetoresistance as $\Delta\rho(H,T) = \rho(H,T) - \rho(0,T)$, which is shown in figure 3 at various magnetic fields. $\Delta\rho$ has negative value for a wide temperature range, and the magnitude of $|\Delta\rho|$ decreases monotonically as increasing temperature. This results are similar to other heavy fermion compounds and qualitatively consistent with a reduction of spin-disorder scattering as the moments are polarized.

In figure 4, the value of $\Delta\rho(H,T)$ of $HoNi_2B_2C$ is plotted as a function of M. It is noted that a universal curve is found in this plot at several magnetic fields in the wide temperature range in paramagnetic state. Our results follow the expression

$$\frac{\Delta\rho(H,T)}{\rho(0,T)} = -\beta[M(H,T)]^{\alpha}, \qquad (1)$$

where α= 2.5 and β= 0.013.

In general, $\Delta\rho/\rho(0)$ of typical heavy fermion compounds form a universal curve when plotted by using the magnetic field H and the temperature T. At the low-field limit of the magnetization where the magnetic susceptibility is described Curie-Weiss law, the equation (1) is described as

$$\frac{\Delta\rho(H,T)}{\rho(0,T)} = -\beta'\left(\frac{H}{T-\Theta}\right)^{\alpha}. \qquad (2)$$

For spin-disorder scattering $\Delta\rho$ is proportional to $\langle S\rangle^2$, where $\langle S\rangle$ is the normalized thermal-average spin moment[12]. Since $\langle S\rangle$ is proportional to the magnetization

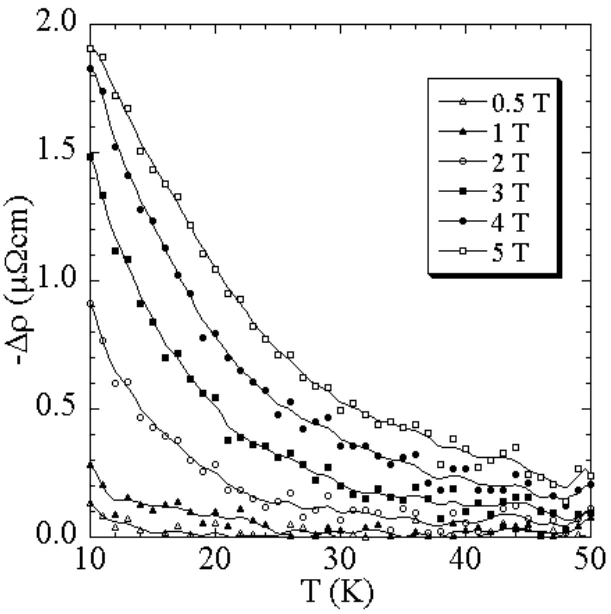

Figure 3 Temperature dependence of magnetoresistance $\Delta\rho$ of $HoNi_2B_2C$ in the paramagnetic state between 10 K and 50 K at several magnetic fields.

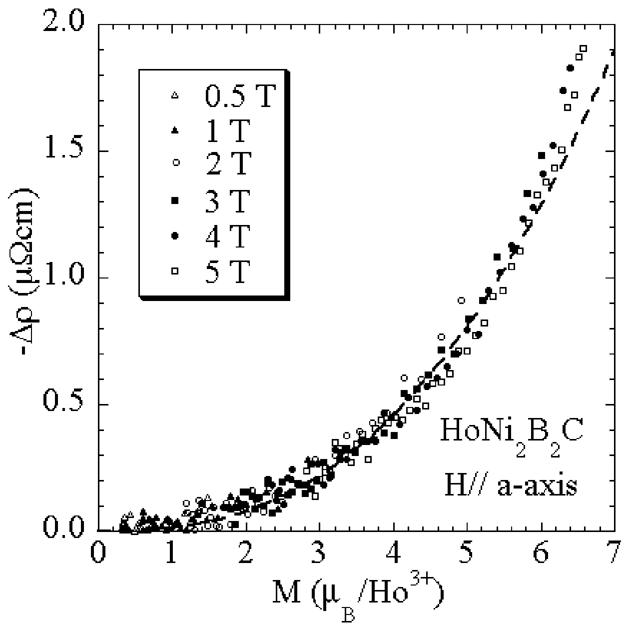

Figure 4 The normalized transverse megnetoresistance plotted as a function of M. Dashed line is a fit to the equation (1), where α ∼2.5 and β ∼0.013 (see in the text).

M, $\Delta\rho$ should follow the expression of the equation (1) or (2) where α=2. For example, the value of α is close to 2 in $CeNiGe_2$ (α=1.9)[14] and YbPtSn (α=1.8)[15]. On the other hand, UBe_{13} has small value of α=1.6[16]. Unfortunately, the α for $HoNi_2B_2C$ is larger than 2. Similar behavior is observed in $YbNi_2B_2C$ (α= 2.8)[17].

5 Summary We have measured the electrical resistivity and the magnetization of $HoNi_2B_2C$ single crystal along a-axis. The calculated magnetization, using the CEF parameters, shows good agreement with experimental data. The electrical resistivity is strongly dependent on the magnetization at the several magnetic fields and high temperatures in the paramagnetic state. The magnetoresistance is negative at a wide temperature range and is possible to scale these data by taking account of a reduction of spin-disorder scattering as the magnetic moments are polarized.

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