Heat-capacity and magnetic measurements on the Y(Ni$_{2-x}$Co$_x$)B$_2$C system

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We have performed field- and temperature-dependent magnetization, resistivity, and heat-capacity measurements on polycrystalline samples of the Y(Ni$_{2-x}$Co$_x$)B$_2$C system with 0.0≤x≤0.4. Values of $T_c$, $x_0$, $H_{c2}$, $\Theta_D$, $\lambda$, and $N(E_f)$ were determined for various samples. We observe that $\Theta_D$ increases with $x$, while all the other parameters decrease with $x$. The $T_c$ vs $x$ data can be described using the BCS theory and the measured values of $N(E_f)$ and $\Theta_D$. The results suggest that the decrease in $T_c$ is due to the decrease in $N(E_f)$, in agreement with the results from band structure calculations.

**INTRODUCTION**

The discovery of superconductivity in the RNi$_2$B$_2$C (R = Sc, Y, Lu, Er, Tm, Ho) system has generated widespread interest among experimentalists and theorists alike. This system forms a filled variant of the ThCr$_2$Si$_2$ structure having alternating YC and Ni$_2$B$_2$ layers, similar to the high-$T_c$ oxides. Unlike the high-$T_c$ oxides, these materials appear to be traditional electron-phonon coupled superconductors. It is believed that superconductivity exists in this system due to a large density of electronic states at the Fermi level and a moderately strong electron-phonon interaction. There is a systematic decrease in $T_c$ with increasing magnetic moment of the rare earth ions, scaling roughly with the deGennes factor. This behavior indicates that $T_c$ decreases due to weak magnetic interactions between the rare earth ions and the conduction electrons. Mattheiss et al. put forth the idea that the superconductivity is highly correlated with the Ni-B-Ni bond angle. Changing the angle, by increasing the size of the rare earth ion, changes the density of states at the Fermi level, accounting for the decrease in $T_c$ and the eventual disappearance of superconductivity.

Band structure calculations predict a peak in the density of states at the Fermi level for YNi$_2$B$_2$C and LuNi$_2$B$_2$C, with a large contribution coming from the 3$d$ nickel bands. Similar calculations on LuCo$_2$B$_2$C predict that the density of states at the Fermi level lies in a valley, explaining the lack of superconductivity in this compound. Assuming a rigid band model and BCS superconductivity, even small amounts of Co doped into the Ni site could lead to large reductions in $T_c$ due to a shift in the value of the density of states. Previous doping studies on polycrystalline samples indicate that Co alloying destroys superconductivity with 20% substitution of Co for Ni.$^{10-12}$ Possible explanations for this change are a reduction in the density of states at the Fermi level and/or a change in the electron-phonon coupling strength. To study these effects further we present low temperature heat capacity measurements on samples in the system Y(Ni$_{2-x}$Co$_x$)B$_2$C with $x = 0.02, 0.2, 0.4$ and magnetization and electron transport measurements on samples with $x = 0.00, 0.05, 0.10, 0.15, 0.20, 0.25, 0.35$.

**EXPERIMENTAL DETAILS**

Samples were made by melting high purity Y(Ames Lab), Ni(99.998%), Co(99.9975%), B(99.999%), and C(99.9%) on a standard water cooled copper hearth in a zirconium gettered argon atmosphere. The button was turned over and remelted three times to ensure sample homogeneity. Mass losses for the samples ranged between 0.3% and 1%. The samples were wrapped in tantalum foil, vacuum sealed in quartz tubes and annealed at 1050 °C. Samples used for magnetization and electrical resistivity studies were approximately 0.2 g and annealed for 2 days. Samples used for heat capacity were approximately 5 g and were annealed for 9 days.

All samples were characterized by powder x-ray diffraction using Cu $K\alpha$ radiation in a Siemens D500 diffractometer. Lattice parameters were determined using a standard least squares fit. The majority of samples were single phase. Magnetization samples with $x = 0.05, 0.15, 0.25$ had impurities that could be identified as YNi$_2$B and YNiBC with impurity levels under 3%; heat capacity samples with $x = 0.02$ and 0.04 had impurities that could be identified as YB$_2$C$_2$ with impurity levels under 3% as well.

Magnetization and resistivity studies were performed on rectangular samples with dimensions approximately 1×1×3 mm. Resistivity measurements were done using a standard four-probe technique. Magnetization measurements were done in a commercial superconducting quantum interference device (SQUID) magnetometer.$^3$

Heat capacity data were taken in fields of 0 and 7 T using

**TABLE I.** Superconducting transition temperature, upper critical field, and lattice parameters for compounds in the system Y(Ni$_{2-x}$Co$_x$)B$_2$C. (*) Determined from heat capacity. (**) Measurement was not performed.

<table>
<thead>
<tr>
<th>$x$</th>
<th>$T_c$ (K)</th>
<th>$\Delta T_c$ (K)</th>
<th>$H_{c2}(0)$</th>
<th>$\alpha$ (nm)</th>
<th>$c$ (nm)</th>
</tr>
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<tr>
<td>0.00</td>
<td>14.5</td>
<td>1.0</td>
<td>5.9</td>
<td>0.352 60</td>
<td>1.0533</td>
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<td>2.0</td>
<td>4.3</td>
<td>0.352 56</td>
<td>1.0529</td>
</tr>
<tr>
<td>0.05</td>
<td>11.0</td>
<td>2.0</td>
<td>3.2</td>
<td>0.352 56</td>
<td>1.0530</td>
</tr>
<tr>
<td>0.10</td>
<td>9.5</td>
<td>1.2</td>
<td>2.3</td>
<td>0.352 55</td>
<td>1.0530</td>
</tr>
<tr>
<td>0.15</td>
<td>7.5</td>
<td>2.0</td>
<td>1.6</td>
<td>0.352 55</td>
<td>1.0524</td>
</tr>
<tr>
<td>0.20</td>
<td>5.7</td>
<td>5.0</td>
<td>**</td>
<td>0.352 45</td>
<td>1.0515</td>
</tr>
<tr>
<td>0.25</td>
<td>5.0</td>
<td>1.5</td>
<td>**</td>
<td>0.352 45</td>
<td>1.0515</td>
</tr>
<tr>
<td>0.30</td>
<td>2.7</td>
<td>2.0</td>
<td>**</td>
<td>0.352 44</td>
<td>1.0514</td>
</tr>
<tr>
<td>0.35</td>
<td>2.0</td>
<td>2.0</td>
<td>**</td>
<td>0.352 44</td>
<td>1.0514</td>
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<tr>
<td>0.40</td>
<td>1.6*</td>
<td>1*</td>
<td>**</td>
<td>0.352 34</td>
<td>1.0502</td>
</tr>
</tbody>
</table>
FIG. 1. Superconducting transitions for samples of the Y(Ni$_{2-x}$Co$_x$)B$_2$C system in a field of 5 Oe.

A semiadiabatic heat pulse technique. The heat capacity data are accurate to within 2% in zero field and 4% at 7 T.

RESULTS AND DISCUSSION

The structural space group for the entire Y(Ni$_{2-x}$Co$_x$)B$_2$C series is $I4/mmm$. The lattice parameters decrease slightly with increasing Co concentration, the decrease for both $a$ and $c$ is less than 0.5% over the superconducting region. The values for $a$ and $c$ are listed in Table I. These values are consistent with the results of Braun$^9$ and Gangopadhyay.$^{11}$

The transition temperature $T_c$ was taken to be the midpoint of the superconducting transition (Fig. 1) in a field of 5 Oe. All of the samples have transition widths less than 2 K, except for $x = 0.25$ which has $\Delta T_c = 5$ K, with superconducting volume fractions that are consistent with 100% shielding. The onset temperature for the $x = 0.0$ sample was 15.2 K consistent with values reported in the literature.$^{1,10,11,14,15}$ A plot of $T_c$ versus $x$ is shown in Fig. 2. The measurements of the superconducting transition temperatures from heat capacity and magnetization agree very well. The transition temperature is a strong nonlinear function of Co concentration, with $T_c$ going from 14.5 K at $x = 0.0$ to 1.6 K; at $x = 0.4$.

The upper critical field $H_{c2}$ is determined from resistance vs temperature measurements at various fields. The critical temperature at a specified field is given by the midpoint of the superconducting transition. Figure 3 plots the critical temperature versus the specific field $H_{c2}$ for 0.0 $x$ 0.2. A value for $H_{c2}(0)$ can be estimated using the Werthamer, Helfand, and Hohenberg (WHH) equation: $^{16}$

$$H_{c2}(0) = -0.69T_c \frac{dH_{c2}(T)}{dT} \bigg|_{T=T_c}.$$  

Values for $H_{c2}(0)$ are listed in Table I. The results show that the upper critical field decreases nonlinearly with $x$.

The heat capacity results for both 0 and 7 T are plotted in Figs. 4(a) and 4(b), and 4(c) for $x = 0.0, 0.2, 0.4$. The superconducting state was completely suppressed using a 7 T field for the samples with $x = 0.0$ and $0.2$. The $x = 0.4$ sample is normal to below 2 K so it was not deemed necessary to measure the sample in a field. The normal state data below 10 K were fit to the form:

$$C_p = \gamma T + \beta T^3,$$  

where $\gamma T$ is the electronic heat capacity and $\beta T^3$ is the lattice heat capacity. An estimate of the Debye temperature can be determined from values of $\beta$ using the following equation:

$$\Theta_D = \left[ \frac{12\pi^4 r_N k_b}{5\beta} \right]^{1/3},$$  

where $k_b$ is the Boltzmann constant, $r$ is the number of atoms per molecule, and $N$ is the number of molecules. As the Co concentration is varied, $\Theta_D$ increases slightly with increasing $x$. The quantitative values derived from these fits of the data are listed in Table II.

The $\gamma$ term is related to the density of states at the Fermi level by the following relation:

$$\gamma = \frac{1}{3} \pi^2 k_b^2 N^* (E_f),$$  

where $N^*$ is the density of states at the Fermi level.
where \( N^*(E_f) \) is the enhanced density of states. The density of states is enhanced due to electron-phonon interactions, which effectively increase the mass of the electron. This in turn increases \( N(E_f) \) so that

\[
N^*(E_f) = \frac{m^*}{m} N_b(E_f) = (1 + \lambda) N_b(E_f), \tag{5}
\]

where \( N_b(E_f) \) is the density of states in the absence of electron-phonon interactions or the bare density of states, \( m^* \) is the effective mass of the electron, and \( \lambda \) is the electron-phonon coupling constant. There is a strong nonlinear decrease in both \( \gamma \) and \( N^*(E_f) \) as \( x \) increases. The results are listed in Table II.

Estimates for \( \lambda \) and \( N_b(E_f) \) were obtained using Eq. (5) and measurements of the temperature independent dc magnetic susceptibility, \( \chi_0 \). A value for \( \chi_0 \) was obtained by fitting the susceptibility vs temperature data to the equation

\[
\chi = \chi_0 \frac{C}{(T - T_c)}, \tag{6}
\]

where \( \chi_0 \) is the temperature independent susceptibility and \( C/(T - T_c) \) is assumed to be due to the weak paramagnetism of magnetic impurities. Values for \( \chi_0 \) obtained from fitting the data are listed in Table II. The temperature in dependent dc magnetic susceptibility is the sum of the core diamagnetism, Landau diamagnetism, and the Pauli paramagnetism:

\[
\chi_0 = \chi_{\text{core}} + \chi_{\text{Landau}} + \chi_{\text{Pauli}}. \tag{7}
\]

The value for \( \chi_{\text{core}} \) was determined from standard tables and is estimated to be \( 3.6 \times 10^{-5} \) emu/mole; \( \chi_{\text{Landau}} \) and \( \chi_{\text{Pauli}} \) are given by the following equations:

\[
\chi_{\text{Landau}} = -\frac{1}{3} \left( \frac{1}{\lambda} \right) \chi_{\text{Pauli}} \quad \text{and} \quad \chi_{\text{Pauli}} = 2 \mu_B^2 N_b(E_f). \tag{8}
\]

Thus

\[
\chi_0 - \chi_{\text{core}} = 2 \mu_B^2 \left( 1 - \frac{1}{3} \left( \frac{1}{\lambda} \right)^2 \right) N_b(E_f). \tag{9}
\]

Because \( \chi_0 - \chi_{\text{core}} \) and \( N^*(E_f) \) are determined experimentally, \( \lambda \) and \( N_b(E_f) \) can be determined experimentally, \( \lambda \) and \( N_b(E_f) \) can be calculated by solving Eq. (5) and Eq. (8) simultaneously. The results are listed in Table II. The values for \( N_b(E_f) \) are quite large, ranging between 0.334 and 0.212 (states/eV atom spin); values for \( \lambda \) range between 1.10 and 0.34. These results are consistent with the superconductivity being due to a moderate electron-phonon coupling and a large \( N(E_f) \). The values for \( N(E_f) \) and \( \lambda \) decrease sharply with Co substitution indicating that there is a peak in the density of states in agreement with band structure calculations.

There is evidence that the borocarbides are conventional BCS superconductors. For a BCS superconductor, the transition temperature is proportional to the quantity \( T_c \approx \Theta_D \exp[-1/N(E_f)\sqrt{V}] \) where \( V \) is a parameter describing the electron-phonon coupling strength. In this expression, the transition temperature is very sensitive to changes in \( N(E_f) \) or \( V \) and only moderately sensitive to changes in \( \Theta_D \). Based on our results, the variation of \( \Theta_D \) as Co is substituted for Ni can be expressed by the equation \( \Theta_D \approx 480 \times \lambda \). Similarly,
Assuming a rigid band model, cobalt, which has one less 3d electron than nickel, will decrease the position of the Fermi energy, moving \( N(E_f) \) away from the peak. A rigid band model appears to be valid because the lattice parameters are essentially unchanged as Co is doped into the material and because Co and Ni are neighbors having similar electronic structure and atomic size. Thus the borocarbides appear to be conventional superconductors. Experimentally, \( T_c \) and \( N(E_f) \) do decrease with Co doping. Furthermore, the decreasing \( N(E_f) \) lowers the \( T_c \) as described by the BCS equation.

**CONCLUSION**

In summary, we have performed measurements of \( T_c, H_{c2}, \chi_0, \Theta_D \), and \( \gamma \) from which we determined \( N(E_f) \) and \( \lambda \). The results show that there is a peak in \( N(E_f) \) verifying predictions from band structure calculations. This implies that the electronic contributions, especially the 3d nickel electrons, are very important to the superconductivity in these materials. The decrease in \( T_c \) with \( x \) can be explained by the cobalt concentration dependence of \( \Theta_D, N(E_f) \), and the BCS theory. This is further confirmation that the superconductivity in the borocarbides is conventional BCS in nature. The large \( N(E_f) \) and the moderate electron phonon coupling strength lead to the rather high transition temperatures.

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