Thermal conductivity of RNi$_2$B$_2$C (R=Y,Ho)

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Thermal conductivity of $\text{RNi}_2\text{B}_2\text{C}$ ($R=\text{Y, Ho}$) single crystals

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We have studied the thermal conductivity $\kappa$ of high-quality single crystals of $\text{YNi}_2\text{B}_2\text{C}$ and $\text{HoNi}_2\text{B}_2\text{C}$. In both compounds, $\kappa$ in the normal state at low temperatures is dominated by electrons. In $\text{YNi}_2\text{B}_2\text{C}$, $\kappa$ shows a pronounced enhancement around 4 K well below the superconducting transition temperature $T_c=15.6$ K. It may be due to the increase of the phonon contribution below $T_c$ as a result of the decrease of the number of normal electrons as scattering centers of phonons. This enhancement is suppressed largely by applying the magnetic field at high temperatures and under the magnetic field was measured by the AuFe-Chromel thermocouple and two Cernox thermometers, respectively. The electrical resistivity $\rho$ was measured by the usual four-probe method. The error bar of the absolute value of $\kappa$ and $\rho$ is about 10–15 % and 20–30 %, respectively, depending on the sample size. The residual resistivity of $\text{YNi}_2\text{B}_2\text{C}$ samples 1 and 2 and $\text{HoNi}_2\text{B}_2\text{C}$ are $\sim 2.0$, 4.1, and 3.1 $\mu\Omega$ cm, respectively. The de Haas–van Alphen effect was observed in the samples of $\text{YNi}_2\text{B}_2\text{C}$ sample 1 cut from the same ingot. The magnetoresistivity was measured by the three terminal capacitance method. The specific heat was measured by the usual adiabatic heat pulse method for the same $\text{HoNi}_2\text{B}_2\text{C}$ crystals as those used in the $\kappa$ and $\rho$ with a weight of 56 mg.

Figure 1 shows the temperature dependence of the thermal conductivity $\kappa$ of $\text{YNi}_2\text{B}_2\text{C}$ sample 1. The inset shows the temperature dependence of the reduced Lorenz number $L/L_0$ of the same sample which was derived from the observed $\kappa$ and $\rho$. Here, $L_0 = 24.5 \text{ nW K}^{-2}$ is the Sommerfeld value and $L = \kappa \rho / T$. Along the $a$ axis, $L/L_0$ is nearly 1 at low temperatures below $\sim 20$ K in the normal state. The absolute values of $\kappa$ of $\text{YNi}_2\text{B}_2\text{C}$ sample 2 at $T=20$ K are 110 and 103 mW/K cm along the $a$ and $c$ axes, respectively. The difference of the absolute value of $\kappa$ at low temperatures between samples 1 and 2 by a factor of two is almost the same as that of the residual resistivities between these samples. These results indicate that in the normal state at low temperatures, $\kappa$ is limited by the impurity scattering, i.e., the elastic scattering of electrons by impurities is dominant and heat current is carried mainly by electrons. Rough estimation of the electronic thermal conductivity $\kappa_e$ at low temperature...
by using the results of the electronic specific heat (Ref. 6) and the electrical resistivity is consistent with the observed result. $\kappa$ shows a small but clear decrease at $T_c=15.6$ K and a pronounced enhancement around 4 K which is clearly seen in an expanded scale in Fig. 2. This characteristic behavior is observed also in sample 2 with twice larger residual resistivity. At high temperatures above $40$ K, $\kappa$ shows the anisotropic behavior, i.e., $\kappa$ with heat current $J$ parallel to the $a$ axis is larger than that parallel to the $c$ axis. This anisotropic behavior of $\kappa$ at high temperatures is common to YNi$_2$B$_2$C samples 1 and 2 and HoNi$_2$B$_2$C, while their electrical resistivities are almost isotropic. $\kappa$ parallel to the $c$ axis of YNi$_2$B$_2$C sample 2 does not show a peak as is seen in sample 1 which may be due to a large residual resistivity in this sample. With the increase of temperature, $L/L_0$ once becomes smaller than 1, again increases and becomes larger than 1 above $\sim 50$ K. The fact that $L/L_0 > 1$ at high temperatures above $\sim 50$ K indicates an increase of the phonon contribution to $\kappa$. The fact that $L/L_0 < 1$ in the intermediate-temperature region indicates the existence of the inelastic scattering for electrons. While the effect of the scattering of electrons by long-wavelength acoustic phonons on $\rho$ is small, the thermal conductivity is largely affected through the vertical transition. Different from $\kappa$ parallel to the $a$ axis, in the case parallel to the $c$ axis, $L/L_0$ is smaller than 1 in a wide range of temperature. This situation is common to all the samples studied here, which reflects the anisotropic behavior of $\kappa$ as mentioned above. Further studies are necessary to understand this anisotropy.

Figure 2 shows the temperature dependence of $\kappa$ parallel to the $a$ axis in the zero magnetic field and under the longitudinal magnetic field of 4 kOe. The thermal conductivity in the zero magnetic field shows the characteristic behavior, i.e., an anomaly at $T_c$, and a pronounced maximum at $\sim 4$ K as mentioned above. On the other hand, the thermal conductivity under the magnetic field of 4 kOe shows a rapid decrease below $T_c (H=4$ kOe), which is common to conventional superconductors in which heat current is carried mainly by electrons. Figures 3(a) and 3(b) show the longitudinal magnetic-field dependence of the thermal conductivity parallel to the $a$ axis of YNi$_2$B$_2$C sample 1. The $\kappa$ value is largely suppressed by applying a small magnetic field corresponding to $H_{c1}$ and, with further increase of the magnetic field, it is restored to the normal-state value above $H_{c2}$. The hysteresis is observed below $H_{c1}$, which is shown in the result at $T=4.3$ K. The similar results are observed also in $\kappa$ parallel to the $a$ axis under the transverse magnetic field parallel to the $c$ axis. The rapid suppression of the thermal conductivity at $H>H_{c1}$ indicates that heat current is suppressed largely by the existence of vortices. The inset in Fig. 2 shows the temperature dependence of the difference of the thermal conductivities normalized at $T_c (H)$ between under $H=0$ and $H=4$ kOe. This indicates that the contribution from carriers of heat current except electrons to $\kappa$ increases below $T_c$ in the zero magnetic field because in this temperature region electrons are dominated by the elastic scattering as mentioned above. Considering that this enhancement of $\kappa$ below $T_c$ is suppressed by introducing vortices and the temperature dependence of $\kappa$ under $H=4$ kOe is similar to that of the conventional superconductor whose heat current is carried mainly by electrons, it is natural to ascribe the origin of the enhancement of $\kappa$ below $T_c$ in the zero magnetic field to the increase of the phonon contribution. We simply assume that the total thermal conductivity is expressed as the sum of the phonon and electron contributions, i.e., $\kappa_{tot} = \kappa_{ph} + \kappa_e$. The temperature dependence of the difference of the temperature dependence of $\kappa$ normalized at $T_c (H)$ between under $H=0$ and 4 kOe shown in the inset in Fig. 2 originates from $\kappa_{ph}$. $\kappa$ under $H=4$ kOe mainly originates from $\kappa_e$. In the zero magnetic field, the phonon mean free path becomes large below $T_c$ due to the decrease of the number of normal electrons which act as scattering centers of phonons above $T_c$. This increase of the phonon mean free

FIG. 1. Temperature dependence of the thermal conductivity with heat current $J$ parallel to the $a$ and $c$ axes of YNi$_2$B$_2$C, sample 1. The inset shows the temperature dependence of the reduced Lorenz number $L/L_0$ of sample 1. See the text in detail.

FIG. 2. Temperature dependence of the thermal conductivity with heat current $J$ parallel to the $a$ and $c$ axes of YNi$_2$B$_2$C sample 1 under the longitudinal magnetic field. The inset shows the temperature dependence of the difference of the temperature dependence of the thermal conductivities $\kappa_e$ normalized at $T_c (H)$ between under $H=0$ and $H=4$ kOe.
path causes the additional contribution to \( \kappa \) below \( T_c \) and this suggests the existence of a large electron-phonon coupling in this material. It is noted that such an enhancement of \( \kappa \) below \( T_c \) is not observed in Ba\(_{1-x}\)K\(_x\)BiO\(_3\) with a relatively high \( T_c \) which is considered as the phonon-mediated strong-coupling superconductor.\(^\text{12}\)

Next, we discuss the magnetic-field dependence of \( \kappa \). The phonon thermal conductivity \( \kappa_{ph} \) enhanced below \( T_c \) in the zero magnetic field is largely suppressed by vortices introduced at \( H>H_c1 \) because the phonon mean free path decreases as a result that phonons are scattered by vortices. In turn, the electron contribution becomes important with further increase of magnetic field. The schematic picture of the magnetic-field dependence of \( \kappa_{ph} \) and \( \kappa_e \) together with \( \kappa_{tot} \) below \( T_c \) is shown in inset (1) of Fig. 3(b). At low temperatures, the negative curvature of the \( d\kappa/dH \) vs \( H \) curve is observed, which suggests the possible existence of low-energy excitations in the superconducting state. The temperature dependence of \( \kappa \) under the magnetic field of 4 kOe shows \( T^2 \) behavior in a wide temperature region below \( T_c \). At present, it is difficult to separate the electron contribution \( \kappa_e \) from \( \kappa_{tot} \) in the superconducting state. Further studies are necessary to understand the magnetic field and temperature dependence of \( \kappa \) below \( T_c \).

The magnetization curve shows the peak effect just below \( H_c2 \) (Ref. 13) which are also observed in UPd\(_2\)Al\(_3\) and CeRu\(_2\) (Ref. 14) and has attracted much attention in relation to the possible existence of the Fulde-Ferrell-Larkin-Ovchinnikov state. Inset (2) of Fig. 3(b) shows the longitudinal magnetostriction along the \( c \) axis in a magnetic field region around \( H_{c2} \).

FIG. 3. Magnetic-field dependence of the thermal conductivity with heat current \( J \) parallel to the \( a \) axis of YNi\(_2\)B\(_2\)C sample 1 under the longitudinal magnetic field (a) in a temperature region up to 18 K and (b) in a low-temperature region below 4.3 K. \( H_{c1} \) and \( H_{c2} \) are the lower and upper critical field. Inset (1) shows a schematic picture of \( \kappa_{tot} \), \( \kappa_{ph} \), and \( \kappa_e \). See the text in detail. Inset (2) shows the longitudinal magnetostriction along the \( c \) axis in a magnetic field region around \( H_{c2} \).

FIG. 4. Temperature dependence of (a) the thermal conductivity, (b) electrical resistivity, and (c) specific heat of HoNi\(_2\)B\(_2\)C at low temperatures. \( T^2 \) and \( T^4 \) are the higher and lower superconducting transition temperatures, respectively, and \( T_m \) and \( T_N \) are the incommensurate and commensurate antiferromagnetic transition temperatures, respectively.
nearly zero at the higher superconducting transition temperature $T_c^h \sim 6.6$ K and after recovering to the normal state value at $\sim 5.3$ K, it becomes zero at the lower superconducting transition temperature $T_c^l \sim 3.6$ K. A small but clear decrease of $\rho$ is observed at 4.6 K. The specific heat shows a small peak at $T_m = 5.3$ K and a large and sharp peak at $T_N = 4.6$ K which correspond to the incommensurate and commensurate antiferromagnetic ordering temperature (Ref. 15), respectively. The large short-range order effect is observed. These results are similar to the reported ones (Refs. 16 and 17) apart from slightly lower transition temperatures in the present sample.18 At high temperatures, the anisotropic behavior of $\kappa$ is observed as in YNi$_2$B$_2$C and the temperature dependence of $L/L_0$ is also similar to those of YNi$_2$B$_2$C. However, low-temperature behavior of $\kappa$ is different. At higher superconducting transition temperature $T_c^h = 6.6$ K, we could not observe an anomaly in $\kappa$. A small but clear increase is observed in $\kappa$ at $T_N$. This increase of $\kappa$ originates from the decrease of $\rho$ accompanying with the decrease of the magnetic scattering of electrons in the antiferromagnetic state. The clear decrease is observed in $\kappa$ below $T_c^l \sim 3.6$ K.

At present, we do not know whether the heat current is dominated by phonons or electrons in the superconducting state in this compound. In order to clarify it, further studies are necessary at lower temperatures and under the magnetic field.

In conclusion, we have studied the thermal conductivity $\kappa$ of high-quality YNi$_2$B$_2$C and HoNi$_2$B$_2$C single crystals. The results of YNi$_2$B$_2$C show the followings. The heat current is mainly carried by electrons at low temperatures in the normal state and in the superconducting state, is mainly carried by phonons which may be due to the decrease of the phonon mean free path as a result of the decrease of the number of normal electrons below $T_c$. However, this phonon contribution is easily suppressed by introducing vortices at $H > H_{c1}$ and the electron contribution becomes dominant above $H_{c1}$. The thermal conductivity of HoNi$_2$B$_2$C shows a clear increase just below the Neél temperature 4.6 K and a clear decrease below $T_c^l \sim 3.6$ K.17,18

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13 K. Kadowaki et al. (unpublished).
18 H. Takeya et al. (unpublished).