

# Ultrasonic study on superconducting $\text{HoNi}_2\text{B}_2\text{C}$ and $\text{Ho}_{0.75}\text{Y}_{0.25}\text{Ni}_2\text{B}_2\text{C}$

Miki Suetake <sup>a</sup>, Yoko Takahashi <sup>a</sup>, Masaru Suzuki <sup>a,1</sup>, Kohji Abe <sup>a</sup>, Kichizo Asai <sup>a</sup>,  
Kazuhiko Kuroki <sup>a</sup>, Susumu Isida <sup>b</sup>, Hiroyuki Takeya <sup>b</sup>

<sup>a</sup> *The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan*

<sup>b</sup> *National Institute for Materials Science, 1-2-1 Sengen, Tsukuba, Ibaraki 305-0047, Japan*

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## Abstract

We performed ultrasonic measurements for  $\text{HoNi}_2\text{B}_2\text{C}$  and  $\text{Ho}_{0.75}\text{Y}_{0.25}\text{Ni}_2\text{B}_2\text{C}$  single crystals between 1.7 and 80 K under various magnetic field. In zero field,  $C_{66}$  for  $\text{HoNi}_2\text{B}_2\text{C}$  decreases continuously on lowering temperature in a wide temperature region below 80 K, and showed a discontinuous softening and recovering at 5.5 and 3.8 K, respectively. In contrast,  $(C_{11} - C_{12})/2$  remained almost constant in the whole temperature region. In the field applied along the  $b(a)$ -axis, the softening of  $C_{66}$  was largely suppressed, which suggests that the softening is magnetic in origin. A similar softening of  $C_{66}$  was also observed for  $\text{Ho}_{0.75}\text{Y}_{0.25}\text{Ni}_2\text{B}_2\text{C}$ .

*Key words:* ultrasonic study; elastic constant;  $\text{HoNi}_2\text{B}_2\text{C}$ ;  $\text{Ho}_{1-x}\text{Y}_x\text{Ni}_2\text{B}_2\text{C}$

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The properties of quaternary intermetallic superconductors  $R\text{Ni}_2\text{B}_2\text{C}$  ( $R = \text{Y}$  and rare-earth ions) have attracted a great deal of attention because of the competition between superconductivity and magnetism.  $\text{HoNi}_2\text{B}_2\text{C}$  appears to be one of the most interesting members of the system. This material shows rather complicated magnetic transitions and a reentrant behavior in superconductivity. The specific heat  $C_p$  and the magnetic susceptibility  $d\chi_T/dT$  indicated three successive magnetic transitions around 5 K in zero field.[1] Neutron scattering measurements[2] revealed that two incommensurate ( IC ) and one antiferromagnetic ( AF ) orders develop at about the same temperature, but only the AF order remains at the lowest temperature.

Up to the present, a number of studies for  $\text{HoNi}_2\text{B}_2\text{C}$  have been performed by means of the magnetic measurements. However, the investigation of the lattice

dynamics in this material, which will be related closely with the magnetic orders and the superconducting state, is scarce. One of us ( H. T. ) succeeded in growing a large single crystal of  $R\text{Ni}_2\text{B}_2\text{C}$ , which enables us to perform the ultrasonic measurements of  $\text{Ho}_{1-x}\text{Y}_x\text{Ni}_2\text{B}_2\text{C}$ .

Large single crystals of  $\text{HoNi}_2\text{B}_2\text{C}$  and  $\text{Ho}_{0.75}\text{Y}_{0.25}\text{Ni}_2\text{B}_2\text{C}$  were grown by a floating zone method.[3] These crystals were cut for several experiments. For the ultrasonic measurements, cubic samples of  $\sim 3$  mm were prepared. Faces of the samples were polished carefully, and 10 MHz longitudinal or transverse  $\text{LiNbO}_3$  transducers were bonded to both ends of the sample with silicone adhesive.

The sound velocity and attenuation were measured precisely by the phase-sensitive detection of the pulse echo. The echo signals multiplied by the in-phase and quadrature phase cw references gave a phase difference between the echo and the reference. Here, the difference depends on the sound velocity. In the measurements, the phase of the reference was controlled to keep the difference constant, and the change of the sound

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<sup>1</sup> Corresponding author. Department of Applied Physics and Chemistry, The University of Electro-Communications, 1-5-1 Chofugaoka, Chofu, Tokyo 182-8585, Japan. E-mail: suzuki@phys.uec.ac.jp

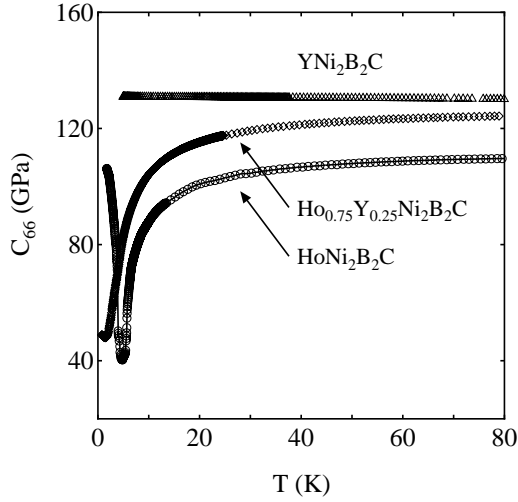


Fig. 1. Variation of elastic constants of  $C_{66}$  for  $\text{HoNi}_2\text{B}_2\text{C}$  and  $\text{Ho}_{0.75}\text{Y}_{0.25}\text{Ni}_2\text{B}_2\text{C}$ , together with  $\text{YNi}_2\text{B}_2\text{C}$ .

velocity was obtained from the phase of the reference. The absolute value of the velocity was determined separately using the time-of-flight method.

We measured the sound velocity and attenuation of these samples from 80 K down to 1.7 K. The elastic constants  $C$  were obtained from the sound velocity  $v$  and the mass density  $\rho$  as  $C = \rho v^2$ . Figure 1 shows the variation of  $C_{66}$  for these samples, together with  $\text{YNi}_2\text{B}_2\text{C}$ . [4] It was found that  $C_{66}$  of  $\text{HoNi}_2\text{B}_2\text{C}$  shows a remarkable softening from temperatures higher than 80 K and takes a minimum value around 5 K. In contrast,  $(C_{11} - C_{12})/2$  of  $\text{HoNi}_2\text{B}_2\text{C}$  remained almost constant in the whole temperature region (not shown).

The difference in  $C_{66}$  between  $\text{HoNi}_2\text{B}_2\text{C}$  and  $\text{YNi}_2\text{B}_2\text{C}$  suggests that the huge softening in the former arises from the magnetic order of Ho moments. Kreyssig et al. [5] reported the lattice distortion in the AF phase based on the neutron-diffraction experiment: Accompanied with the AF order, the tetragonal to orthorhombic crystallographic phase transition takes place. Thus, the remarkable softening of  $C_{66}$  is understood as due to coupling of the mode with the AF order. Although the AF order was not reported for  $\text{Ho}_{0.75}\text{Y}_{0.25}\text{Ni}_2\text{B}_2\text{C}$ , [6] the large softening of the sample observed in the present study suggests a strong AF correlation of Ho atoms in this material.

We measured  $C_{66}$  for  $\text{HoNi}_2\text{B}_2\text{C}$  under the magnetic field. In zero field,  $C_{66}$  showed a discontinuous softening at 5.5 K and recovered at 3.8 K. As the magnetic field along the  $b$ -axis increased, this softening was largely suppressed, as shown in Fig. 2. In contrast, this softening is little affected by the field along the  $c$ -axis (not shown). From these measurements, it is concluded that  $C_{66}$  is strongly coupled with the arrangement of Ho moments.

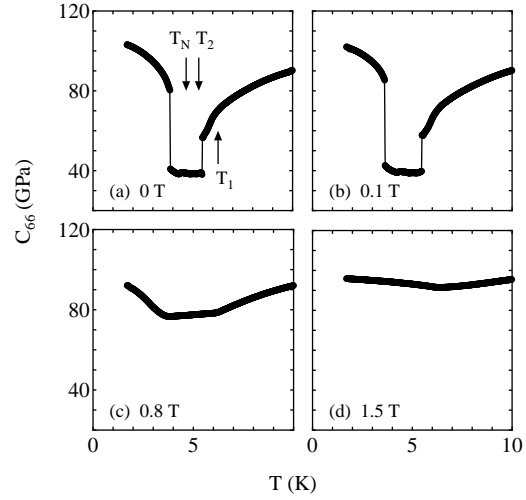


Fig. 2. Constant field, temperature-dependent sweeps of  $C_{66}$  for  $\text{HoNi}_2\text{B}_2\text{C}$  ( $k \parallel a$ -axis,  $p \parallel b$ -axis,  $H \parallel b$ -axis). The arrows in (a) denote three peaks of the specific heat  $C_p$ .

It is interesting to compare the temperature dependence of  $C_{66}$  with that of the specific heat  $C_p$ . In zero field, three peaks of  $C_p$  were clearly observed in this sample, and correspond to three magnetic transition temperatures  $T_1$ ,  $T_2$  and  $T_N$ , as indicated in Fig. 2 (a). Here,  $T_1$ ,  $T_2$  and  $T_N$  are thought to be the transition temperatures for an IC spiral state with the propagating vector along the  $c$ -axis, an IC state with the vector along the  $a$ -axis, and an AF order, respectively. It should be noted that the discontinuous increase in  $C_{66}$  at 3.8 K coincides with *none* of these magnetic transitions, and is close to the reentrant temperature of superconductivity for this sample.

In summary, we performed the ultrasonic measurements for  $\text{Ho}_{1-x}\text{Y}_x\text{Ni}_2\text{B}_2\text{C}$  single crystals.  $C_{66}$  in zero field showed a remarkable softening, and this softening depended strongly on the magnetic field and its direction. Thus, it is concluded that  $C_{66}$  is strongly coupled with the arrangement of the Ho moments.

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