Ultrasound velocity measurements in the vortex-state of \( \text{YNi}_2\text{B}_2\text{C} \)

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Abstract. We performed ultrasound velocity measurements in single-crystalline \( \text{YNi}_2\text{B}_2\text{C} \) \((T_c = 15.6\ \text{K})\) in the vortex state. The elasticity of the flux line lattice was probed in temperature and magnetic-field dependence of the ultrasound velocities. Magnetic-field dependence of the ultrasound velocities revealed elastic anomalies due to a first-order 45º reorientation transition of the hexagonal flux line lattice, and a second-order hexagonal-to-square lattice transition of the flux line lattice.

1. Introduction
The borocarbide \( \text{RNi}_2\text{B}_2\text{C} \) \((R = \text{Y}, \text{Lu})\) has attracted much interest due to the occurrence of unconventional superconductivity with the nodal gap function despite the \( s \)-wave symmetry. A number of experiments provided the compelling evidence for the anisotropic \( s \)-wave gap function with point nodes along [100] and [010] directions of the tetragonal crystal \([1-10]\). Another interesting feature of this compound is that the flux line lattice (FLL) undergoes magnetic-field-induced structural transitions. With the magnetic field applied parallel to the \( c \) axis, \( H \parallel c \), the small-angle neutron scattering (SANS) experiments revealed the occurrence of a first-order 45º reorientation transition of the hexagonal FLL, and a second-order hexagonal-to-square FLL transition \([11-14]\). It is considered that these FLL transitions are relevant to the underlying anisotropy of the superconducting gap as well as the Fermi surface. Thus it is crucial to study the FLL structure for understanding the electronic structure in the vortex state in \( \text{RNi}_2\text{B}_2\text{C} \).

Ultrasound velocity measurement is a unique tool for the study of the FLL structure. In the vortex state, this tool can examine the FLL elasticity in addition to the conventional crystal-lattice elasticity, since the sound wave with the propagation \( \mathbf{k} \) and the polarization \( \mathbf{u} \) can couple to the FLL via the Lorentz force in the configuration of \( \mathbf{u} \perp \mathbf{H} \) \([15]\). The FLL elasticity provides important information of the electronic structure in the vortex state.

In this study, we report results of ultrasound velocity measurements in single-crystalline \( \text{YNi}_2\text{B}_2\text{C} \) \((T_c = 15.6\ \text{K})\) in the vortex state with \( H \parallel c \). We investigated the FLL elasticity focusing on the magnetic-field induced FLL structural transitions in \( \text{YNi}_2\text{B}_2\text{C} \).

2. Experimental
A large single crystal of \( \text{YNi}_2\text{B}_2\text{C} \) was grown by the floating zone method. For the ultrasound velocity measurements, the single crystal was cut into cuboid shape with dimensions of \( 3.5 \times 3.6 \times 3.1 \ \text{mm}^3 \).
Mirror surfaces of the sample were prepared by careful polishing using the 1 μm diamond slurry because the ultrasound measurements are quite sensitive to the roughness of the sample surface. The ultrasound velocity measurements were performed using the phase comparison technique which can measure the relative change in the ultrasound velocities with high resolution of about 1 ppm. The ultrasounds were generated and detected by LiNbO$_3$ transducers glued on the parallel mirror surfaces of the sample by the epoxy adhesive. The ultrasound velocities were measured in temperatures ($T$) from 2 K to 100 K with magnetic field ($H$) up to 7 T. For the FLL elasticity, there are three symmetrically independent elastic modes: compression modulus $C_{11}^{\text{FLL}}$, tilt modulus $C_{44}^{\text{FLL}}$, and shear modulus $C_{66}^{\text{FLL}}$, as illustrated in Figs. 1 (a), (b), and (c), respectively. We performed ultrasound velocity measurements in all of these elastic modes in the vortex state with $H || c$. The configuration of propagation $k$ and polarization $u$ of the sound wave for each elastic mode is summarized in Table 1.

Table 1 Elastic modulus of crystal lattice and flux line lattice with $H||c$ in YNi$_2$B$_2$C, and the corresponding configuration of sound wave with propagation $k$ and polarization $u$.

| Elastic modulus | Magnetic field $H$ | propagation $k$ | polarization $u$ |
|-----------------|------------------|----------------|----------------|
| (a) Compression modulus | $C_{11}^{\text{FLL+CL}}$ | [001] | [100] | [100] |
| (b) Tilt modulus | $C_{44}^{\text{FLL+CL}}$ | [001] | [001] | [100] |
| (c) Shear modulus | $C_{66}^{\text{FLL+CL}}$ | [001] | [100] | [010] |

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3. Results and discussion

Figures 2(a), (b), and (c) show temperature dependence of the ultrasound velocities in $C_{11}$, $C_{44}$, and $C_{66}$, respectively. In the normal state, $C_{44}(T)$ and $C_{66}(T)$ exhibit softening with decreasing temperature, which is most likely attributed to the Fermi surface nesting [16]. $C_{11}(T)$ in the normal state, on the other hand, exhibits ordinal hardening with decreasing temperature. In the superconducting state with $H = 0$, $C_{44}(T)$ and $C_{66}(T)$ exhibit a discontinuous change of slope at $T_c$ and harden below $T_c$ with...
decreasing temperature, while $C_{11}(T)$ exhibits no superconductivity-driven anomaly. The elastic properties mentioned here imply that the nesting-sensitive elastic modes, $C_{44}$ and $C_{66}$, couple to the superconducting order parameter much stronger than the nesting-insensitive mode $C_{11}$.

In the vortex state, the measured elasticity $C_{ij}$ should consist of the crystal elasticity in the normal state (the background) $C_{ij}^0$, the superconductivity-driven change of the crystal elasticity $\Delta C_{ij}^{\text{CL}}$, and the FLL elasticity $\Delta C_{ij}^{\text{FLL}}$, $C_{ij} = C_{ij}^0 + \Delta C_{ij}^{\text{CL}} + \Delta C_{ij}^{\text{FLL}}$. As shown in Fig. 2 (a), $C_{11}(T)$ at 2 T and 4 T exhibits gradual hardening below $T_c$ with decreasing temperature. Since $C_{11}(T) = 0$ manifests $\Delta C_{11}^{\text{CL}} \approx 0$, this hardening below $T_c$ only in the vortex state should be due to the hardening of the FLL elasticity $\Delta C_{11}^{\text{FLL}}$.

In contrast to $C_{11}(T)$, the hardening below $T_c$ in $C_{44}(T)$ and $C_{66}(T)$ with $H = 0$, as shown in Figs. 2 (b) and (c), manifests the presence of the $\Delta C_{ij}^{\text{CL}}$ component in these elastic modes. Thus the hardening below $T_c$ in $C_{44}(T)$ and $C_{66}(T)$ at 2 T and 4 T should in part arise from the hardening in $\Delta C_{ij}^{\text{CL}}$. However, the measured $C_{44}(T)$ and $C_{66}(T)$ at 2 T and 4 T are harder than the components of $C_{ij}^0 + \Delta C_{ij}^{\text{CL}} + \Delta C_{ij}^{\text{FLL}}$ in $C_{44}$ and $C_{66}$ which are estimated in assumption of $\Delta C^{\text{CL}} (T = 0) \propto T_c$, as shown in Figs.2 (b) and (c). Thus the measured elasticity in $C_{44}$ and $C_{66}$ in the vortex state should contain the component of the FLL elasticity $\Delta C_{ij}^{\text{FLL}}$. And we conclude that all elastic modes measured in the present study probe the FLL elasticity $\Delta C_{ij}^{\text{FLL}}$.

Figures 3(a), (b), and (c) show the low-field ultrasound velocities at 2 K in $C_{11}$, $C_{44}$, and $C_{66}$ as a function of magnetic field, respectively. Elastic-mode dependent anomalies are observed at $H_1^* \approx 0.1$ T and $H_2^* \approx 0.15$ T: a sudden jump at $H_1^*$ in $C_{44}(H)$, a cusp at $H_2^*$ in $C_{44}(H)$, and a cusp at $H_1^*$ in $C_{66}(H)$. It is noteworthy that $H_1^*$ and $H_2^*$ respectively correspond to the first-order 45° reorientation transition of hexagonal FLL, and the second-order hexagonal-to-square FLL structural transition which were observed in SANS experiments [14]. Thus the observed elastic anomalies at $H_1^*$ and $H_2^*$
should be attributed to these FLL structural transitions. Taking into account that the measured elasticity $C_{ij}$ contains the contribution of the FLL elasticity $\Delta C_{ij}^{\text{FLL}}$ in all the elastic modes, as mentioned above in conjunction with Figs. 2, the elastic anomalies at $H_1^*$ and $H_2^*$ most likely arise in the FLL elasticity $\Delta C_{ij}^{\text{FLL}}$. Thus the present results suggest that the first-order $45^\circ$ reorientation transition of the hexagonal FLL gives rise to the elastic anomalies in the in-plane elastic modes of the compression modulus $C_{11}^{\text{FLL}}$ and the share modulus $C_{66}^{\text{FLL}}$, while the hexagonal-to-square FLL structural transition gives rise to the elastic anomaly in the out-of-plane elastic mode of the tilt modulus $C_{44}^{\text{FLL}}$.

4. Summary
In summary, ultrasound velocity measurements in the vortex state in YNi$_2$B$_2$C probed the FLL elasticity and discovered the elastic anomalies due to the low-field FLL structural transitions. Further detailed ultrasound velocity measurements, analysis, and discussion could explain the correlation between the FLL elasticity and the electronic state in the vortex state in YNi$_2$B$_2$C.

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