Sound velocity and attenuation in nuclear-ordered U2D2 solid ^{3}He

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Abstract

We studied sound properties of nuclear-ordered U2D2 solid ^{3}He crystal with a single magnetic domain along the melting curve. We measured temperature dependences of sound velocities and attenuations for a longitudinal and two transverse sounds between the sound frequency f, 3 and 50 MHz below the nuclear-ordered transition temperature T_N. The sound velocity v changes as $\Delta v/v = a(T/T_N)^4$ and the attenuation α approximately as $\Delta\alpha = cf^3(T/T_N)^9$. The coefficients a and c depend on crystal orientations and sound modes. Assuming the tetragonal symmetry of U2D2 crystal, we determined 6-independent elastic constants of nuclear spin system from $\Delta v/v$.

Key words: Solid ^{3}He ;ultrasound ;nuclear magnetism ;U2D2 solid;

At ultra-low temperatures, nuclear magnetism of solid ^{3}He is described by the multiple spin exchange model[1]. The results suggested theoretically that more than 6-body exchange processes are needed to describe the nuclear magnetism of solid ^{3}He[2]. Recently, a new model of the nuclear magnetism was proposed, which is based upon the nuclear-spin exchange interaction through the dipolar interaction of electronic spins caused by correlated zero point motion of ^{3}He atoms[3]. Since the spin exchange process strongly depends on the molar volume, the ultrasound is strongly coupled to the nuclear spin system and is very useful for investigating the nuclear magnetism of solid ^{3}He. The coupling between the sound and the nuclear spin can be studied through the anisotropy of sound velocity and attenuation against crystal orientations. The nuclear-spin contribution to the longitudinal sound velocities in U2D2 solid ^{3}He was measured and the Grüneisen constant for the spin exchange constant was obtained [4]. In this report, we measured both longitudinal and transverse sound velocities and attenuations in single crystals of nuclear-ordered solid ^{3}He with an almost single magnetic domain along the melting curve. We grew a crystal in superfluid ^{3}He in a narrow space between 3 mm-separated parallel transducers. One of them was Z-cut-$LiNbO_3$ for longitudinal wave and the other X-cut-$LiNbO_3$ for transverse wave. The design of sample cell was the same with that described in Ref. [4].

The relative changes of sound velocity $\Delta v/v$ were measured from the phase changes between sound echoes using a phase sensitive detector and the resolution of $\Delta v/v$ was about 10^{-5}. The absolute values of the sound velocity v were determined by the time of flight of sound between echoes and the resolution was about 0.5 %. We measured cw-NMR where the magnetic field was applied along the sound propagation direction. We determined crystal orientation and temperature from cw-NMR. We grew about 30 crystals and the results for 13 crystals with an almost single magnetic domain (more than 70 % of the crystal was occupied by one domain) are reported. We could simultaneously observe a longitudinal and two transverse sounds for each sample but sometimes one of the transverse signals was missed, depending on the crystal orientation. We calculated the elastic constants from the absolute velocities and obtained c_{11}=0.221, c_{12}=0.184, c_{44}=0.108 [$\times$ 10^9 g/cm s^2] for bcc ^{3}He at

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the melting pressure. These values were in very good agreement with Wanner[5].

The temperature dependences of the relative changes of sound velocity below T_N for three sound modes are proportional to T^4 and analyzed as

$$\Delta v/v = a(T/T_N)^4. \quad (1)$$

where the coefficient a depends on sound mode and crystal orientation. The anisotropy of the coefficient a was reported in Ref. [4] but the temperature dependence of the sound velocity was analyzed by the spin wave approximation for an isotropic medium of spin system. Due to the improved accuracy of the measurement and the large number of samples measured, we could determine the anisotropic contribution of nuclear spins to the sound velocity for the U2D2 ^{3}He which has the tetragonal symmetry. The elastic constants are divided into two parts, c_{ij}=c^L_{ij}+c^S_{ij}. The c^L_{ij} is the lattice part and c^S_{ij} is the nuclear-spin part. The c^L_{ij} is about 10^5 times larger than c^S_{ij} but is independent of temperature for a constant molar volume below 1 mK. We subtracted the change of the sound velocity of the lattice part due to the molar volume change ΔV along the melting curve as follows,

$$\Delta v/v|_{Lattice} = -(\gamma_L - 1/3)\,\Delta V/V, \quad (2)$$

where V is the molar volume, γ_L=2.2 is the Grüneisen constant for Debye temperature[5]. The contribution of $\Delta v/v|_{Lattice}$ to $\Delta v/v|_{Spin}$ is in the order of 10 % in the ordered solid. We obtained $\Delta v/v|_{Spin}$ as,

$$\Delta v/v|_{Spin} = \Delta v/v - \Delta v/v|_{Lattice} = b(T/T_N)^4. \quad (3)$$

The coefficient b depends on sound mode and crystal orientation and we fit $\Delta v/v|_{Spin}$ to the orientational dependence for tetragonal symmetry by using 6 independent elastic constants. In this analysis, we used c^L_{ij} determined by the absolute values of sound velocity. In Fig. 1, we show b (obs) observed vs. b (cal) calculated for longitudinal and transverse sounds for 13 samples, where c^S_{11}=5.6, c^S_{33}=7.7, c^S_{12}=3.7, c^S_{13}=8.5, c^S_{44}=2.1, and c^S_{66}=2.9 [$\times$ $10^4(T/T_N)^4$ g/cm s^2] (1:xx,2:yy,3:zz,4:yz,5:zx,6:xy $\hat{z}\|\hat{l}$, where $\hat{l}$ is the anisotropy axis) with 20 % error. The inset is the similar plot of b (obs) vs. b (cal) for bcc symmetry. The fit is poor for bcc symmetry and the orientational dependence of the sound velocity in the nuclear-ordered U2D2 solid is better explained for tetragonal symmetry.

The spin part of elastic constant for compressional distortion along $\hat{l}$, c^S_{33}, is larger than that perpendicular to $\hat{l}$, c^S_{11}, and elastic constant for the shear distortion along $\hat{l}$, c^S_{44}, is smaller than that perpendicular to $\hat{l}$, c^S_{66}, while c_{33}=c_{11}, c_{44}=c_{66} and c_{13}=c_{12} for bcc symmetry.

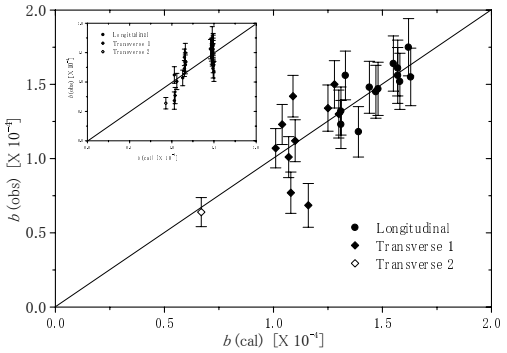

Fig. 1. The coefficients of $\Delta v/v|_{Spin}$, b (obs), are plotted against the calculated ones b (cal) with tetragonal symmetry. The inset is the same plot with cubic symmetry.

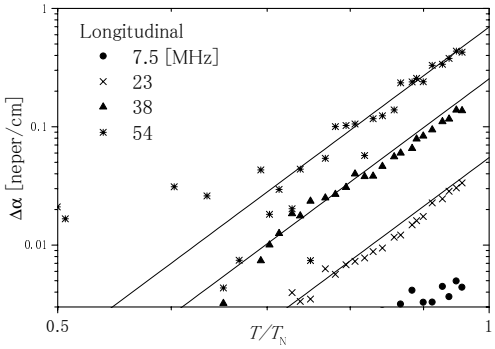

Fig. 2. The temperature dependences of attenuation $\Delta\alpha$ for longitudinal sound in nuclear-ordered U2D2 solid below T_N. The solid line is the fit to $\Delta\alpha(T)$=$cf^3(T/T_N)^9$.@The crystal orientation against the sound propagation is {85.2^o , <u>64.8^o</u>, 25.7^o} .The underlined is the anisotropy axis of dominant magnetic domain.

The sound absorption α was measured for several frequencies 7.5, 23, 38, 54 MHz for longitudinal and 14, 24, 33, 43 MHz for transverse sounds. We subtracted the temperature-independent part α_0 from α, and the temperature-dependent part of attenuation $\Delta\alpha(T)$ is shown in Fig. 2 for a longitudinal sound. The straight line is the fit to $\Delta\alpha(T)$=$cf^3(T/T_N)^9$ with c=4.5×10^{-6} [MHz^{-3}cm^{-1}]. The coefficient c depends on sound mode and crystal orientation. The attenuation mechanism has not been known yet.

References

[1] For instance M. Roger, J. H. Hetherington, J. M. Delrieu Rev. Mod. Phys. **55** (1983) 1.

[2] D. M. Ceperley, G. Jacucci, Phys. Rev. Lett. **58**, 1648 (1987); Phys. Rev. Lett. **59** (1987) 380.

[3] N. Gov, E. Polturak, J. Low Temp. Phys. **121** (2000) 683

[4] R. Nomura, *et. al* Phys. Rev. Lett. **85** (2000) 2977.

[5] R. Wanner, Phys. Rev. A **3** (1971) 448.