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AMPLITUDE-DEPENDENT SOUND ATTENUATION IN bcc $^3$He CRYSTALS WITH $^4$He IMPURITIES

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Abstract.- The attenuation of longitudinal sound wave at 10 MHz was investigated in bcc $^3$He crystals with $^4$He impurities at a molar volume of 24.4 cm$^3$/mole. The attenuation became amplitude-dependent after the crystals were cooled below the phase separation temperature. Namely, the amplitude dependence appeared at 86 mK and 98 mK for $^4$He concentrations $x_4 = 480$ ppm and 1600 ppm, respectively, and disappeared at 350 mK irrespective of $x_4$. The critical amplitude above which the attenuation increased was independent of $x_4$ and $T$. It is proposed that screw dislocations which were multiplied in the course of the phase separation were responsible for the effect. The critical resolved shear stress is estimated to be $\tau_c = 5 \times 10^{-5} \mu$ from the critical amplitude, where $\mu$ is the shear modulus. The value of $\tau_c$ is considerably lower than the Peierls stress so that the dislocations possibly tunnel the Peierls barrier.

It is well known that a solid solution of $^3$He and $^4$He undergoes a phase separation at a temperature $T_{PS}$. The phase separation curve is well described by the regular solution theory, but it is slightly asymmetrical due to the difference between $^3$He and $^4$He atoms in the amplitude of the zero-point vibration. We report here the first ultrasonic measurements on bcc $^3$He crystals with $^4$He impurities which are cooled below the phase separation temperature.

The concentration of $^4$He in the sample gas, $x_4$, was determined by a mass-spectrometer-type leak detector (Shimadzu Model MS-E) with an accuracy of 5%. All the crystals were grown at a constant pressure of 33 atm. The corresponding solidification temperature was 0.7 K and the molar volume was 24.4 cm$^3$/mole. After the solidification the filling capillary was blocked and the attenuation and velocity of the longitudinal sound at 10 MHz were measured at the constant volume.

Amplitude dependence of the attenuation was found when the crystals were cooled below a temperature $T_A (\leq 100$ mK). Figure 1 shows the attenuation in crystal No.8 with 480 ppm $^4$He at two temperatures above and below $T_A$ on a cooling run at input amplitudes, $I$, between 10 and 60 dB. The input amplitude of RF-pulses was varied by a step attenuator and the amplitude of the sound signal was read on the oscilloscope. A 20-dB attenuator was inserted between the
receiver transducer and the amplifier to avoid distortion of large signals, if necessary. The relative attenuation in Fig. 1 was calculated by assuming $\alpha = 0$ dB at $T = 114$ mK and $I = 20$ dB.

The attenuation at 114 mK is essentially independent of the input amplitude. At 77 mK, on the other hand, a distinct amplitude dependence is observed: the attenuation below 30 dB is constant and its value is the same as at 114 mK (low-amplitude plateau), $\alpha$ increases with $I$ between 30 and 50 dB (transition region) and $\alpha$ is constant above 50 dB (high-amplitude plateau).

We define a critical amplitude $I_c$ as the amplitude at which the transition region begins. We find $I_c = 32$ dB from the data at 77 mK in Fig. 1.

Figure 2 shows how the amplitude dependence varies on a warming run. At 190 mK we still observe the amplitude dependence and it disappears at 350 mK. The critical amplitude does not change with temperature from 67 to 190 mK. The variation of $I_c$ from crystal to crystal is also negligible (Table I). We may therefore take $\alpha$'s at $I = 20$ dB and 50 dB as representatives for the low- and high-amplitude plateaus, respectively. The attenuation increment is defined as

$$\Delta \alpha = \alpha(50\text{ dB}) - \alpha(20\text{ dB}).$$

Figure 3 shows $\alpha(20\text{ dB})$ and $\alpha(50\text{ dB})$ for crystal No. 9. On the first cooling (run 1) $\alpha(50\text{ dB})$ rose at $T_A = 86$ mK and reached 6 dB at 78 mK. Then the crystal was warmed up to 600 mK (run 2). $\alpha(50\text{ dB})$ at first remained constant, decreased gradually above 200 mK and
diminished at \( T_B = 350 \) mK. On the second cooling (run 3) the variation of \( \alpha(50 \, \text{dB}) \) was similar to the first cooling. In this run the temperature was lowered down to 72 mK but no appreciable change was observed below 78 mK. The attenuation at 20 dB was independent of temperature within \( \pm 1 \) dB during the measurement.

Figure 4 shows a similar plot for crystal No.14 with \( x_4 = 1600 \) ppm. At first the crystal was cooled to 60 mK (run 1). Then it was warmed to 150 mK (run 2) and cooled to 60 mK (run 3). The second warming was up to 460 mK (run 4), followed by the cooling down to 62.5 mK (run 5). Finally the temperature was carefully raised to 140 mK (run 6). It was found that \( T_A = 98 \) mK from \( \alpha(50 \, \text{dB}) \) on the cooling runs. On warming there were two stages of recovery in \( \alpha(50 \, \text{dB}) \). The first occurred between 90 and 110 mK and the second was between 200 and 350 mK. The first stage of recovery was never observed in crystals with \( x_4 = 480 \) ppm. The hysteresis of \( \alpha(50 \, \text{dB}) \) was reproducible when the crystal was warmed above \( T_B = 350 \) mK.

In Fig. 4 \( \alpha(20 \, \text{dB}) \) also shows a hysteresis which is, however, amplitude-independent.

The observed values of \( I_C, \Delta \alpha, T_A \) and \( T_B \) and the sound velocity \( v_0 \) are summarized in Table I. As seen from this table, \( T_A \) increases with \( x_4 \) and \( \Delta \alpha \) is also an increasing function of \( x_4 \), so that we may suppose that the appearance of the amplitude dependence is related to the phase separation. The curve in Fig. 5 represents the phase
separation temperature $T_{PS}$ as a function of $x_4$, which is obtained from the specific heat data with the aid of the regular solution theory\(^1\) and is given by

$$T_{PS} = 0.76 \frac{1-2x_4}{\ln((1-x_4)/x_4)} [K]. \quad (2)$$

We find $T_{PS} = 99$ and 117 mK for $x_4 = 480$ and 1600 ppm, respectively, which are higher than $T_A$ at corresponding concentrations. This result seems to be reasonable because of the following reasons: (1) $T_{PS}$ is determined by warming the specimen while $T_A$ is determined by cooling; (2) several minutes are required for phase separation; (3) some supercooling may be possible; and (4) phase separation should proceed to some extent before the amplitude dependence appears.

It seems at first sight that the amplitude dependence of the attenuation is caused by the clusters of $^4$He atoms formed as a result of phase separation. However, it is not the case because the amplitude dependence is stable at much higher temperatures than $T_A$ and $T_{PS}$, where the phase-separated state cannot exist.

Amplitude-dependent attenuation is usually caused by dislocations.\(^4\) A large number of dislocations are possibly introduced in the crystals by the phase separation because of a sizable local deformation accompanied. The molar volume of a pure bcc $^3$He crystal at 33 atm is 24.4 cm$^3$/mole while that of a pure hcp $^4$He crystal is 20.4 cm$^3$/mole at the same pressure. Strain field around the clusters of

<table>
<thead>
<tr>
<th>Crystal</th>
<th>$T_m$ (mK)</th>
<th>$P_m$ (atm)</th>
<th>$V_m$ (cm$^3$/mole)</th>
<th>$x_4$ (ppm)</th>
<th>$V_0$ (m/s)</th>
<th>$T_A$ (mK)</th>
<th>$T_B$ (mK)</th>
<th>$T_{PS}$ (mK)</th>
<th>$I_c$ (dB)</th>
<th>$\Delta \alpha$ (dB)</th>
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<tr>
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<td>—</td>
<td>350</td>
<td>102</td>
<td>32</td>
<td>12.4</td>
</tr>
<tr>
<td>No.8</td>
<td>703</td>
<td>32.8</td>
<td>24.39</td>
<td>480</td>
<td>490</td>
<td>—</td>
<td>350</td>
<td>99</td>
<td>32</td>
<td>6.7</td>
</tr>
<tr>
<td>No.9</td>
<td>703</td>
<td>32.8</td>
<td>24.39</td>
<td>480</td>
<td>475</td>
<td>86</td>
<td>350</td>
<td>99</td>
<td>30</td>
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</tr>
<tr>
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<td>24.40</td>
<td>1600</td>
<td>472</td>
<td>96</td>
<td>350</td>
<td>117</td>
<td>31</td>
<td>11.4</td>
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<tr>
<td>No.14</td>
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<td>32.9</td>
<td>24.38</td>
<td>1600</td>
<td>501</td>
<td>98</td>
<td>340</td>
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</table>
almost pure hcp $^4\text{He}$, which are formed by the phase separation, should be relaxed by plastic deformation in the matrix of bcc $^3\text{He}$.

In a previous paper$^5$) we reported amplitude dependences for hcp $^4\text{He}$ crystals containing 30 and 300 ppm $^3\text{He}$. It was attributed to un-pinning of the edge dislocations in the basal plane from $^3\text{He}$ impurities because the critical amplitude $I_C$ depended upon temperature and $^3\text{He}$ concentration. In the present case, on the other hand, $I_C$ depends neither on temperature nor on $^4\text{He}$ concentration. Therefore the dislocations in the bcc $^3\text{He}$ crystals are of screw type and their obstacles are not $^4\text{He}$ impurities but the Peierls potential.

The stress amplitude $\sigma_C$ which corresponds to $I_C=30\text{dB}$ is estimated to be $3\times10^3\text{ dyn/cm}^2$. The resolved shear stress is given by $\tau = R\sigma$, where $R$ is the Schmid factor and $R \leq 1/2$. We then obtain the normalized critical resolved shear stress $\tau_C/\mu \leq 5\times10^{-5}$ using $\mu = 3\times10^7\text{ dyn/cm}^2$ as the appropriate shear modulus.

The depth of the Peierls potential $\Delta V$ or equivalently the Peierls stress $\tau_P$ can be estimated by several ways. The normalized Peierls stress is $\tau_P/\mu = (3\div6)\times10^{-3}$ in most bcc metals. In the case of bcc $^3\text{He}$ the zero-point energy of a straight dislocation is much lower on the hill of the Peierls potential than in the valley of the potential so that $\Delta V$ is reduced at least by a factor of 15 in a crude estimate.$^6$) Hence $\tau_P/\mu \leq 4\times10^{-4}$. Experiments on the plastic deformation in bcc $^3\text{He}$ at 54 atm$^7$) suggests that $\tau_P/\mu$ is of the order of $5\times10^{-4}$, which gives an upper bound to $\tau_P/\mu$ at 33 atm. If the estimations are correct, $\tau_C$ is an order of magnitude smaller than $\tau_P$. As $I_C$ is independent of temperature, the possibility of thermal activation is excluded. Therefore, we may conclude that a dislocation penetrates the Peierls potential barrier by tunneling under an applied stress which is higher than $\tau_C$.

We are preparing a new equipment for the plastic-deformation measurement at temperatures down to 0.3 K in order to get a more reliable value of $\tau_P$.

References
6) H. Suzuki: to be published.