Zero- and first-sound damping in NaF observed by inelastic neutron scattering

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Angaben zur Veröffentlichung / Publication details:

Loidl, Alois, J. Daubert, H. Jex, and E. Schedler. 1976. "Zero- and first-sound damping in NaF observed by inelastic neutron scattering." *Physics Letters A* 56 (2): 139–41. https://doi.org/10.1016/0375-9601(76)90174-2.

ZERO- AND FIRST-SOUND DAMPING IN NaF OBSERVED BY INELASTIC NEUTRON SCATTERING☆

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The frequency and temperature dependence of the damping of transverse acoustic modes with $0.06 \leqslant q/q_{\mathrm{max}} \leqslant 0.25$ in NaF was determined by means of inelastic neutron scattering. The results clearly show a transition from the Akhiezer to the Landau–Rumer regime.

In anharmonic crystals the velocity and the damping of sound depend on the relation between the applied frequency Ω and the averaged inverse lifetime $\bar{\Gamma}$ of the thermal phonons in the crystal. In the region $\Omega \ll \bar{\Gamma}$ the sound waves travel at adiabatic or first-sound velocities, in the opposite case $\Omega \gg \bar{\Gamma}$ at zero-sound velocities, which are expected to be slightly higher [1,2]. The most striking effects appear in the damping of the modes. The hydrodynamic equations predict a damping of first sound proportional to the square of the frequency, whereas the damping of zero sound, obtained from ordinary perturbation theory of phonons, becomes linear in the frequency [2,3]. Also the temperature dependence in the two regimes is quite different. In the collision-dominated region $\Omega \ll \bar{\Gamma}$ the damping exhibits a T^{-1} behaviour in the range $T \ll \Theta_{\mathrm{D}}$ and is temperature independent at $T \gg \Theta_{\mathrm{D}}$. In the collision-less region the damping is proportional to T independent of the Debye-temperature Θ_{D} [3]. Usually the low-frequency regime is investigated by ultrasonic measurements and the high-frequency regime by inelastic neutron scattering. However since the transition between zero and first sound itself is shifted towards higher frequencies with increasing temperatures, in some favourable cases it was possible to measure also in the transition region by ultrasonic techniques [4–6], by Brillouin scattering [7] and by means of inelastic neutron scattering [8].

In inelastic neutron scattering experiments the damping is related to the width of the measured neutron groups. Therefore experimental data of the widths as a function of frequency and temperature provide information about the region the measured frequencies belong to and in addition about the order of magnitude of the averaged inverse lifetime of the thermal phonons in the crystal.

We performed our inelastic neutron scattering experiment in NaF on the triple-axis spectrometer IN3 at the Hihg-Flux-Reactor Grenoble. We used an incident energy of 14.6 meV, produced by an (111)-Bragg reflexion from a copper monochromator and filtered by a pyrolytic graphite filter to remove higher orders. A germanium (111) crystal was used as analyser. We installed two Soller-type collimators between the sample-furnace and the analyser crystal, which limited the horizontal and the vertical divergence to 0.7°. For the incident beam both divergences were 0.4°. The experiments were performed in a wave-vector region $0.06 \leqslant q/q_{\mathrm{max}} \leqslant 0.25$ at 295, 500, 600 and 700 K in the [ξ00]TA and [ξξ0]$\mathrm{T_2A}$ branches. Except for 700 K the whole set of measurements was done twice, in the heating-up process as well as cooling down. The experimental half-widths of the neutron groups differed for equivalent phonons less than 4%. In the [ξ00]TA branch we measured the instrumental resolution even at 700 K, indicating that the half-width at half-maximum (HWHM) Γ due to the damping of the TA-phonons is

☆ Research supported by the Bundesministerium für Forschung und Technologie.

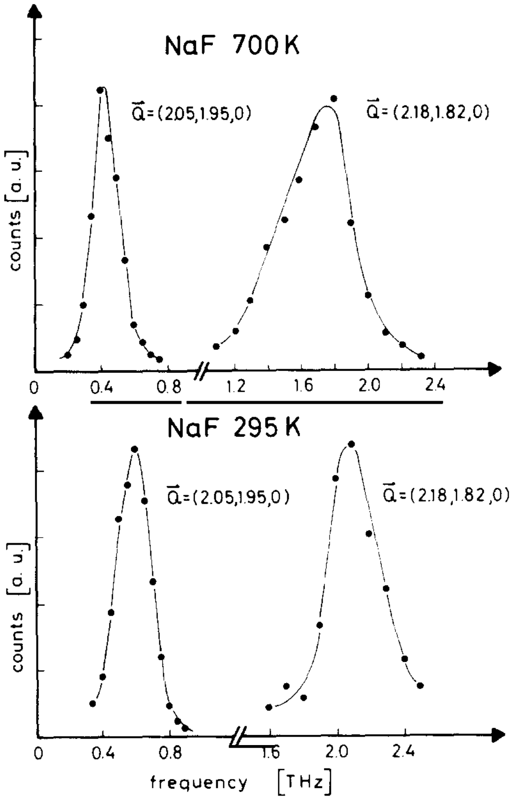

Fig. 1. Two representative neutron groups out of the temperature runs at 295 and 700 K.

negligible against the resolution of the instrument. However the widths of the neutron groups which belong to the mode with a velocity proportional to $(c_{11}-c_{12})^{1/2}$ exhibit a weak temperature dependence at room temperature and a strong one at 700 K. In fig. 1 two representative neutron groups out of these two temperature runs demonstrate this behaviour. In fig. 2 we plotted the change of the HWHM of T_2A-phonons with the temperature against the frequency. The differences of the squares of the widths were chosen in order to get rid of the instrumental resolution. An interpolation between neighbouring points out of a temperature run was necessary to take account of the temperature shifts of equivalent phonons at the same $\boldsymbol{q}$. The presentation of our data in a frequency scale favours a direct comparison with the theories. The number of plotted points equals the number of measured neutron groups. The data clearly demonstrate an increasing frequency dependence of the

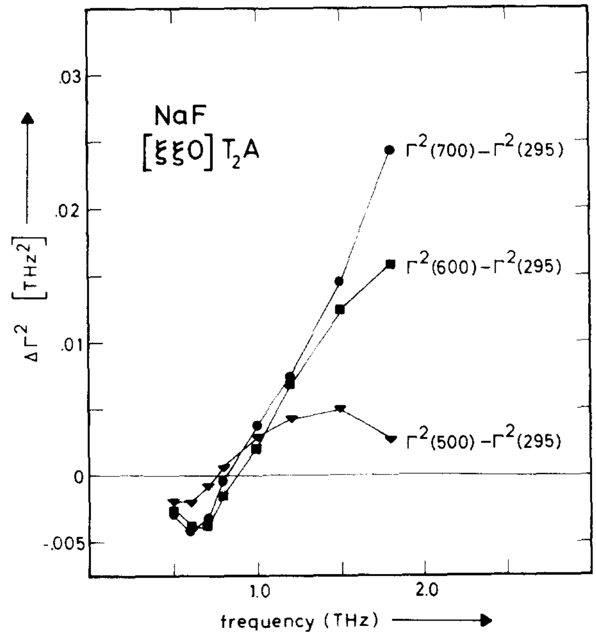

Fig. 2. Change of the half-widths at half-maximum of T_2A phonons with the temperature against the frequency. The lines are drawn to guide the eye.

widths with rising temperature and a different temperature dependence at low and at high frequencies.
At frequencies below 1 THz the change in the damping is rather small or negative, while at higher frequencies the increase is striking. This behaviour is well understood with the expected damping of transverse branches [3], where in the first-sound regime we have Akhiezer's result

$$\Gamma \sim \omega^2/T\,, \quad T \ll \Theta_D\,,$$

$$\Gamma \sim \omega^2\,, \quad T \gg \Theta_D\,,$$

and in the zero-sound regime the result of Landau–Rumer

$$\Gamma \sim \omega T\,, \quad T \ll \Theta_D\,, \quad T \gg \Theta_D\,.$$

The Debye-temperature of NaF is 440 K.

We see that negative changes in the damping are possible below the Debye-temperature, whereas at higher temperatures the damping should remain nearly temperature independent if our data cover the transition region near first sound. This effect is already indicated by the 600 and 700 K shifts, where only at the highest measured phonon-frequency the damping is significantly different.

We believe, that at temperatures above 700 K it should be possible to measure temperature independent first-sound damping and to varify the squared frequency dependence. Theoretical calculations are performed at present and measurements at higher temperatures are planned for the near future.

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