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THIRD SOUND IN A RESTRICTED GEOMETRY

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Bergman's general treatment of third sound waves has been extended to a (restricted) parallel plate geometry. In a parallel plate geometry two independent third sound modes can propagate: a symmetric and an antisymmetric one. Calculations show that at temperatures below 1 K the antisymmetric mode carries the most important part of the temperature amplitude. Because of the relatively strong substrate influence the temperature amplitude of the symmetric mode is suppressed. The $\Delta T/\Delta h$ versus T measurements by Laheurte et al.[1] *and of the $\Delta T/\Delta h$ versus ω measurements by Ellis* et al.[2] *are explained.*

The general theory for the propagation of third sound in helium films was presented by Bergman [3], and later by Verbeek [4], and by van Beelen and Bannink [5]. It takes account of the waves in the substrate and in the vapor, accompanying the third sound wave. Bergman considered mostly a helium film with an infinite vapor above it, but in a later review paper he also discussed the resonator geometry [6]. He admits to have some inconsistencies with the Onsager coefficients, that are connected with the exchange of mass and energy at the film-vapor interface. Van Beelen's group solved this problem, and treated in detail the low frequency limit of isothermal third sound in the restricted geometry of a long narrow capillary and its analogue in a narrow slit. We have extended Bergman's general treatment of the infinite vapor geometry to a parallel plate geometry.

In the geometry considered here, the film covers two parallel plates a distance d apart. The space between these plates is filled with helium vapor. Taking the waves in the substrate and in the vapor, accompanying the third sound wave, into consideration we solved the set of equations governing the behavior of the third sound wave in this geometry [7]. There are *two* independent solutions of these equations, a symmetric and an antisymmetric one. The symmetric solution gives thickness variations on the opposite plates moving in phase with each other while

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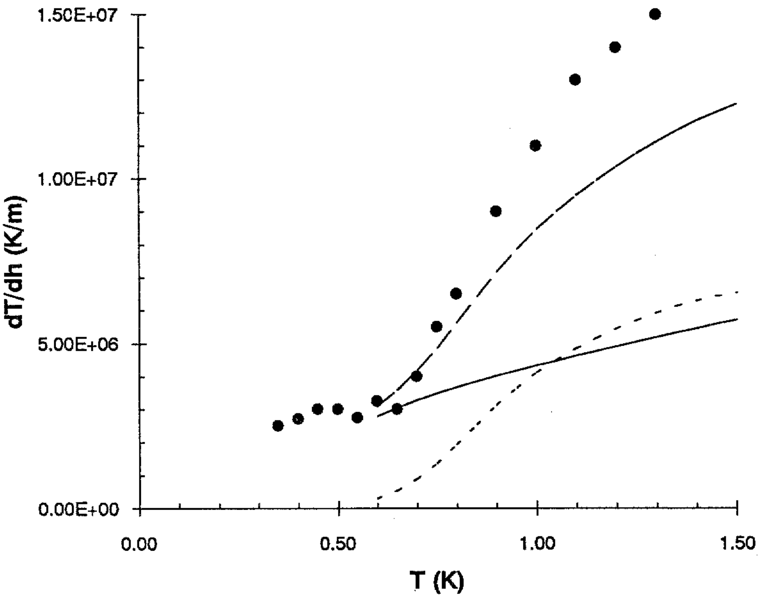

Fig. 1. Measurements of $\Delta T/\Delta h$ by Laheurte *et al.* (- - -) Symmetric mode, (——) antisymmetric mode, (— —) sum of symmetric and antisymmetric mode and (•) experimental data. The Bergman limit coincides with the antisymmetric mode. h = 8.3 at.lay., d = 5 μm, w = 4 mm.

those for the antisymmetric solution have opposite phase.

In the parallel plate geometry as well as in the infinite vapor geometry we are able to solve the general equations numerically for various frequencies ω, film thicknesses h, temperatures T, plate distances d and substrate thicknesses w in the whole range between adiabatic and isothermal boundary conditions on the outside. Especially for the symmetric mode in the restricted geometry, the acoustic waves in the vapor play a very important role. Due to their reflections the results for this mode differ considerably from those of the infinite geometry. The antisymmetric third sound waves have the same propagation speed as the symmetric ones, but they are attenuated much more strongly. The attenuation of the antisymmetric wave expresses the strong coupling between the third sound waves on the two plates. For low temperatures $T < 1$ K the damping of the antisymmetric mode decreases.

The ratio $\Delta T/\Delta h$ of the symmetric mode decreases below 1 K unlike the antisymmetric mode. Therefore the antisymmetric mode becomes more and more responsible for the temperature wave in the film. The equations loose their validity when the mean free path in the vapor becomes too large. This occurs at temperatures below about 0.6 K.

The measurements by Laheurte *et al.* [1] of $\Delta T/\Delta h$ as a function of tem-

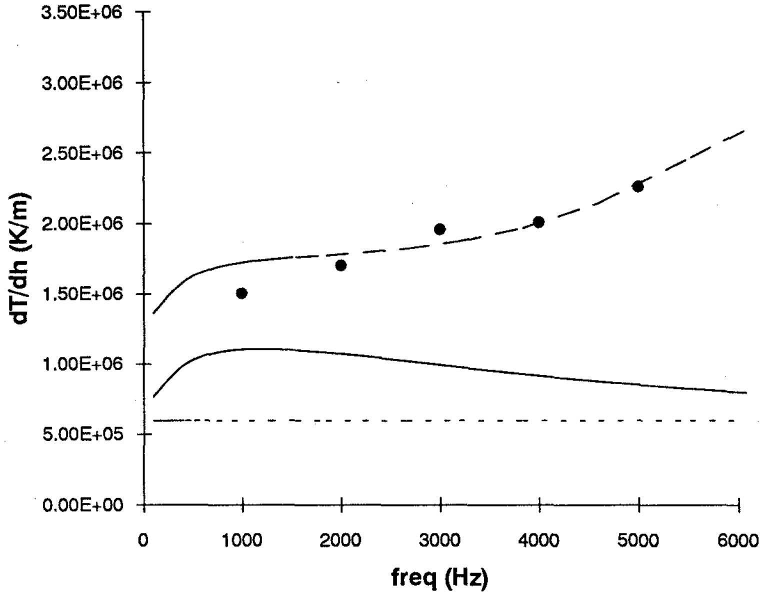

Fig. 2. Measurements of $\Delta T/\Delta h$ by Ellis *et al.* (- - -) Symmetric mode, (——) antisymmetric mode, (— —) sum of both modes after correction and (•) experimental data. T = 1.3 K, h = 14 at. lay., d = 6.35 μm, w = 2 mm.

perature show a significant departure from the Bergman limit $\Delta T/\Delta h = -f_0 T/L$ above $T = 0.7$ K (fig. 1). Our numerical calculations confirm this behaviour. In these calculations damping of the antisymmetric mode is neglected. Capacitive detection gives $2\Delta h^S$ whereas bolometric measurements give $\Delta T^S \pm \Delta T^A$ (S (A) denotes the symmetric (antisymmetric) mode). ΔT^A is usually neglected. As is remarked above, this is not correct, particularly for low temperatures. It is uncertain how much of each mode is excited in the experiments but if we assume equal amplitudes we can compare the symmetric and antisymmetric third sound solutions and their sum to the experimental values (fig. 1). The calculated values are still 25 % too low above 0.7 K. Below 0.6 K the calculations become unreliable, but it is clear, that the antisymmetric mode could be responsible for most of the measured $\Delta T/\Delta h$ in this regime!

The measurements by Ellis *et al.* [2] show an increase of $\Delta T/\Delta h$ with frequency between 1 and 5 kHz, at a film thickness of 14 at. lay (fig. 2) Our calculations for a restricted geometry show that $\Delta T^S/\Delta h$ increases indeed strongly with frequency, but only below 1 kHz. There is a maximum at about 1 kHz. $\Delta T^A/\Delta h$ is frequency independent. When the effects of a finite width of the capacitive detector are corrected for, our calculations show at frequencies above 1 kHz indeed a nearly linear increase of $\Delta T^S/\Delta h$ with frequency. The difference between the corrected calculated values and those measured by Ellis *et al.* is small.

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7. A detailed derivation of the equations for third sound in a parallel-plate-geometry will be given in a future publication.