explain critical velocities.[4,12-14] It is also clear that the peak value is increasing with decreasing temperature and that it would be of considerable interest to obtain its value below 1°K which we are preparing to do. If the $\hbar/2md$ dependence is correct, then one can estimate what the upper bound on the critical velocity in films should be. Superflow has been observed in a film 2.1 layers thick below 0.8°K.[7] If the maximum in V_{sc} occurs at twice this thickness then this upper bound is 520 cm/sec.

We would like to acknowledge helpful discussions with S. J. Putterman, R. J. Donnelly, and J. P. Hulin.

*Work supported in part by the Office of Naval Research, Contract No. N00014-69-A-0200-4014, and the National Aeronautics and Space Administration, Contract No. NAS 7-100.

[1]K. R. Atkins, *Liquid Helium* (Cambridge Univ. Press, Cambridge, England, 1959), p. 198.

[2]W. M. Van Alphen, G. J. Van Haasteren, R. De Bruyn Ouboter, and K. W. Tacomis, Phys. Lett. 20, 474 (1966).

[3]R. P. Feynman, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland, Amsterdam, 1955), Vol. 1.

[4]J. S. Langer and J. D. Reppy, in *Progress in Low Temperature Physics*, edited by C. J. Gorter (North-Holland, Amsterdam, 1955), Vol. 6.

[5]A more complete description will be published elsewhere: K. Telschow, I. Rudnick, and T. Wang, to be published.

[6]M. Chester and L. C. Yang, Phys. Rev. Lett. 31, 1377 (1973).

[7]J. H. Scholtz, E. O. McLean, and I. Rudnick, Phys. Rev. Lett. 32, 147 (1974).

[8]The value used [27 (layers)^3 K] is that reported in Ref. 7 and agrees with E. S. Sabisky and C. H. Anderson, Phys. Rev. Lett. 30, 1122 (1973). The latter also find that for films thicker than about 10 atomic layers, α is a function of d. We have made such corrections using their $\alpha(d)$ for MgO which is expected to be similar to glass. E. S. Sabisky and C. H. Anderson, Phys. Rev. A 7, 790 (1973).

[9]This agreement is direct experimental evidence against the Doppler-shift expression $\pm\frac{1}{2}(\langle\rho_s\rangle/\rho)V_s$ advanced by D. Goodstein and P. G. Saffman, Proc. Roy. Soc., Ser. A 325, 447 (1971). This is discussed more completely in Ref. 5.

[10]T. Wang and I. Rudnick, J. Low Temp. Phys. 9, 425 (1972). The thicknesses plotted there must be multiplied by 0.677 to correct them for the proper value of Van der Waals constant; see Refs. 7 and 8.

[11]K. A. Pickar and K. R. Atkins, Phys. Rev. 178, 389 (1969). In their experiment third-sound pulses were seen traveling parallel and antiparallel to the film flow at all times. Thus their film may not have been flowing at critical velocity in the measurement region. Consequently their reported values for V_{sc} may be low. Also, these authors omitted the factor ρ_s/ρ in the Doppler-shift expression. If the correct expression [Eq. (1)] is used then the data they present are consistent with V_{sc} being independent of temperature for their saturated films.

[12]S. V. Iordanskii, Zh. Eksp. Teor. Fiz. 48, 708 (1965) [Sov. Phys. JETP 21, 467 (1965)].

[13]J. S. Langer and M. E. Fisher, Phys. Rev. Lett. 19, 560 (1967).

[14]R. J. Donnelly and P. H. Roberts, Phil. Trans. Roy. Soc. London, Ser. A 271, 41 (1971).

Attenuation of 9.4-GHz Acoustical Waves in Helium Films

Ch. Frénois, J. Joffrin, P. Legros, and A. Levelut
Laboratoire d'Ultrasons, Université Paris VI, 75230 Paris-Cédex 05, France*
(Received 21 February 1974)

Using a standard acoustical technique, we present new data concerning the attenuation of 9.4-GHz phonons in thin helium films. The mechanical resonance of the film is observed in the temperature range 1.4 to 2.1 K. A comparison with the bulk case is made.

Interest has grown recently concerning the lifetime and velocity of excitations in helium at different temperatures. The propagation of heat pulses in bulk[1] or in films[2] has provided new data for thermal phonons and has proved to be well suited for observing the change in their propagation characteristics. In addition, Brillouin scattering experiments[3] and the propagation of acoustical waves[4] have given some insight on the processes which govern the lifetime of phonons of low frequencies ($\nu < 1$ GHz).

In this Letter we present a new experiment which fills the gap between these two extreme frequency ranges and which also proves to be well suited for measuring several properties of thin helium films. Using standard acoustical

methods at 9.4 GHz, we have observed mechanical resonances of thin films of helium deposited on free and plane surfaces of piezoelectric materials. The parameters of the resonance line (intensity, position, linewidth) provide numerical values for the phonon attenuation and also for the Van der Waals forces of the substrate. The most noticeable results obtained from the attenuation measurements are a critical increase near T_λ and the lack of a Khalatnikov-Chernikova[5] maximum in the vicinity of 1.5 K.

A pulsed acoustical wave generated in a rhumbatron cavity travels back and forth in an X-cut quartz crystal with two polished, parallel faces. The crystal and the cavity are placed in a cell where it is possible to change the pressure of the helium gas and the temperature. For a pressure P less than the equilibrium pressure P_0 at T_0, an unsaturated film covers the walls of the cell and also the faces of the crystal. $\Delta p = P_0 - P$ is directly measured with a capacitor differential-pressure meter. The resonance of the film is observed when the thickness d is equal to $\frac{1}{4}n\lambda$, where λ is the phonon wavelength in the helium film and $n = 1, 3, 5, \ldots$. The thickness is varied by slowly pumping the cell containing the crystal or by leaking helium gas into this space. At 9.4 GHz, $\frac{1}{4}\lambda$ is of the order of 60 Å. With the geometry used in the cell, the saturated thickness of the film is about 150 Å; therefore, only the fundamental resonance can be seen ($n = 1$). The usual acoustical echo pattern can be observed on the screen of an oscilloscope, and the amplitude of one of the echoes is recorded as a function of pressure. As a result of the short lifetime of phonons in helium, the resonance occurs as an absorption line. In spite of the mismatch of the acoustical impedance between the solid substrate and the helium, the sensitivity of the method is high if the path of the acoustical pulse is long; for each round trip in the crystal, the acoustical wave interacts twice with the helium film: once at each opposite end of the crystal. Typically, we have recorded the amplitude of the tenth echo, and the signal as a function of Δp is given in Fig. 1.

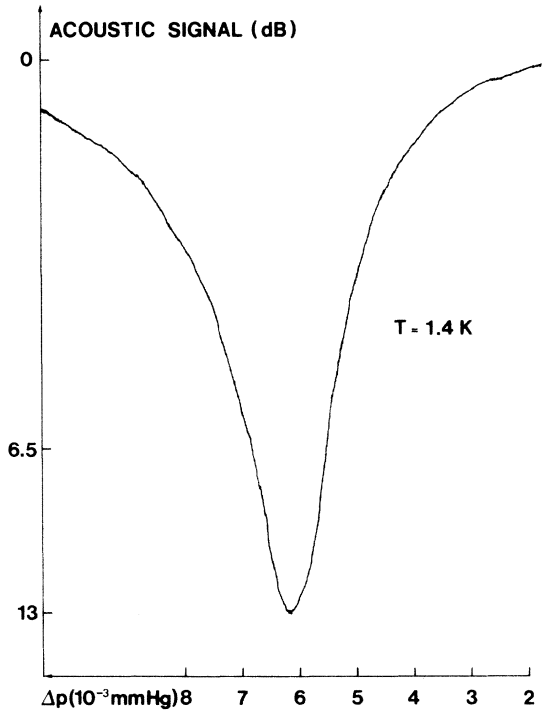

FIG. 1. Record of the tenth acoustical echo intensity as a function of $\Delta p = P_0 - P$. It corresponds to a wave which has interacted twenty times with a helium film; therefore, the ordinate measures, in decibels, the quantity R^{20}.

Several features of this curve have to be emphasized and may be explained easily.

(1) The amplitude of the dip is sensitive to the temperature T_0. The attenuation of phonons in helium is deduced from the formula which gives the reflection coefficient R of the acoustical energy on a film in terms of imaginary and real parts of the wave vectors, k' and k'' (the substrate is assumed to have no absorption in comparison to that of the helium):

$$R = 1 - \frac{4z_0[\cos\theta \sinh(2k''d) - \sin\theta \sin(2k'd)]}{(1+z_0^2)\cosh(2k''d) + (1-z_0^2)\cos(2k'd) + 2z[\cos\theta \sinh(2k''d) - \sin\theta \sin(2k'd)]}, \quad (1)$$

where

$$z_0 = \rho_{He} v_{He}/\rho_{sol} v_{sol}, \quad k''/k' = \tan\theta, \quad k' = (\omega/v_{He})\cos\theta,$$

and θ is a parameter characteristic of the phonon losses. In our temperature range, we have kept $z_0 = 22\times10^{-4}$, obtained from $\rho_{He} = 0.145$ g/cm^3, $v_{He} = 23\times10^3$ cm/sec, $\rho_{sol} = 2.7$ g/cm^3, and $v_{sol} = 5.7\times10^5$ cm/sec. With these numerical values, formula (1) has been computed for different θ; by comparison

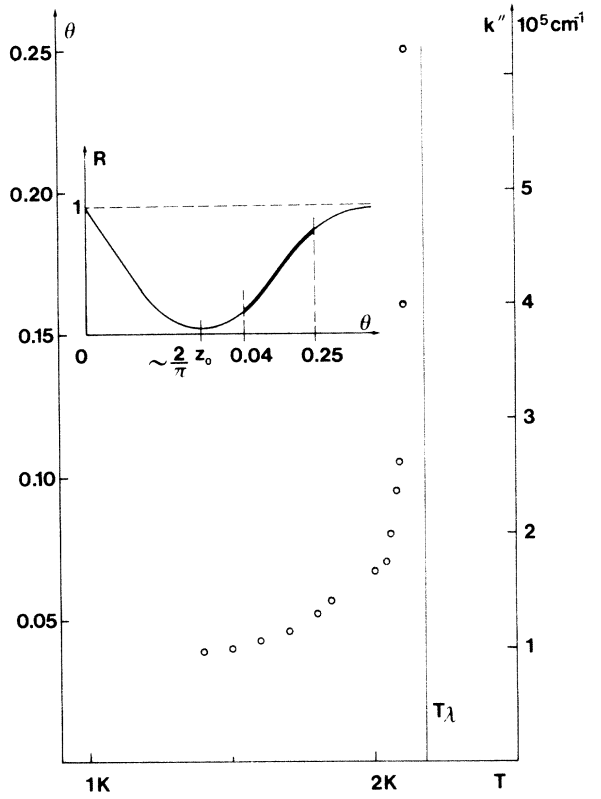

FIG. 2. Attenuation as a function of temperature. It is measured by the imaginary part of the wave vector (right ordinate) and by the parameter θ (left ordinate). The inset shows schematically the correspondence between R and θ; the region of interest for our experiment is shown by the thick line: θ increases when R increases.

with the attenuation at resonance, experimental values of θ are deduced and plotted as a function of temperature in Fig. 2. As long as θ is not too large, k'' and k' have a clear meaning.

(2) The curve in Fig. 1 looks asymmetrical, with a larger slope on the high-pressure (larger-thickness) side. This is due to two facts: First, the pressure scale is not linearly related to the thickness d because of the form of the Van der Waals potential which governs the equilibrium of the film. At a given temperature T_0, Δp and d are related to within a good approximation by

$$\Delta p = P_0 - P = \alpha P_0/d^3 k_B T_0, \qquad (2)$$

where α is the Van der Waals coefficient. Secondly, formula (1) itself is not symmetrical in d around the resonance value ($k'd \simeq \pi/2$) because θ is not very small.

(3) The linewidth $\Delta p_{1/2}$ is strongly dependent on T_0 essentially because in formula (2) P_0/T_0 changes by more than an order of magnitude when the temperature increases from 1.4 to 2.1 K. The contribution of the surface imperfections to the linewidth $\Delta p_{1/2}$ is difficult to evaluate. The strong temperature dependence indicates, however, that it is probably negligible.

(4) Once θ has been determined for each temperature, the linewidth of the recorded signal, measured in the pressure interval Δp, depends only on the Van der Waals coefficient α; the same value of α, (18 ± 2) (layers)^3 K, fits all the curves. This method could be used to measure the Van der Waals coefficient α for different materials. Our value for quartz is small in comparison with other experimental results given in the literature[6]: 39 (Ref. 6a) and 26 (Ref. 6b). This discrepancy is as yet unexplained.

(5) We have carefully checked that the absorption peak is proportional to the number which labels the different acoustical echoes observed on the oscilloscope. This point is not trivial: It may be shown that to the first approximation during emission and detection the helium film has to be credited with only one half of the attenuation in comparison with the pure reflection attenuation. The fundamental reason for this effect is that the source (and the receiver) of the acoustical wave is the face of the piezoelectric crystal, which radiates both in the quartz and in the helium.

We have also verified that the attenuation remained insensitive to the power of the acoustical pulses; thus, there is no burning of the film due to energy losses.

From the physical point of view, the following remarks may be made:

(a) Our value of θ at 9.4 GHz must be compared with the value given by the experiments of Imai and Rudnick[4] and Commins.[7] They measured an attenuation coefficient of 1100 cm^{-1} at 1.4 K, corresponding in our notation to $\theta \simeq 4 \times 10^{-4}$. Their value is 2 orders of magnitude smaller than our result, but their frequency was 1 order of magnitude smaller. Thus, it is reasonable to assume, as they did, that the attenuation of phonons varies as the square of the frequency in the superfluid region up to 10 GHz. However, we have not been able to observe any maximum of attenation around 1.5 K, corresponding to the Khalatnikov-Chernikova relaxation process.[5] As can be seen from Fig. 2, θ varies continuously from 1.4 to 2.1 K, increasing sharply in the vicinity of T_λ, an effect related to critical attenuation in helium. The calculation of Khalatnikov-Cherniko-

va has been made for bulk helium. In our case, the thickness of the film is smaller than the wavelength. Because the component of wave vectors perpendicular to the film cannot be defined with a greater precision than $\Delta k \sim d^{-1}$, some usually forbidden processes may occur and the selection rules become less severe.

(b) The question arises whether or not some energy flows from the helium film into the helium gas. As is well known from acoustics, when the thickness d is of the order of $\lambda/4$, the matching conditions between the substrate and the gas are fulfilled when the acoustic impedances of the solid, Z_S, of the liquid, Z_L, and of the gas, Z_G, are such that

$$Z_S Z_G / Z_L{}^2 = z_1 = 1. \quad (3)$$

From the kinetic theory of gases, z_1 decreases monotonically with temperature from $z_1 \simeq 0.5$ at 2 K to 0.025 at 1.4 K: It should give a large change in the signal which we do not observe. In fact in our (T, P) conditions, the meaning of Z_G is questionable because the wavelength Λ of 10-GHz phonons in helium gas is smaller than the mean free path l of the helium atoms: at 2 K, $\Lambda = 60$ Å, $l = 200$ Å; l rapidly increases as T is lowered. Thus, formula (3) is no longer convenient to estimate the coupling to the gas. We are in a situation more or less similar to that described by Andres, Dynes, and Narayanamurti: The heating of the film due to the acoustical wave produces evaporation of atoms. But in contrast to the behavior in temperature-wave experiments or with direct heating of the film, this mechanism is probably small in our case (density wave).

(c) Rather than the geometrical resonance condition $d = \lambda/4$, it would be better to consider a phase shift of $\pi/2$ through the film; this takes into account the elastic inhomogeneities of the film, due to the Van der Waals attraction on the first layers.

(d) Finally we would like to list some differences with the experiments of Anderson and Sabisky.[9] First of all, in their experiment, they observe the influence of the film on a population of phonons with the same frequency but with very different wave vectors k in the substrate. Even if most of the phonons, because of the severe mismatch, flow in the film with a small angle, their measured linewidth may be obscured by this fact. This is especially so if we remember that the angle of refraction may be widened if we take into account the absorption in the substrate of phonons propagating parallel to the surface.[10] Secondly, with our method, it seems easy to observe Van der Waals forces with either piezoelectric or nonpiezoelectric crystals by bonding another crystal on the piezoelectric generator. Moreover, it is possible to compare accurately these forces when recordings of the echo reflected on the free surface of the bounded crystal and of the echo reflected on the free end of the piezoelectric crystal are made simultaneously (this method has given us clear evidence of the contribution of a film on each crystal face). Thirdly, and this is probably the major advantage, the experimental setup is simple, convenient for any type of crystal, and able to give absolute values of the acoustical attenuation in helium with pure single modes. These experiments are now being extended to still higher frequencies and are designed to study helium film properties.

We gratefully thank C. H. Anderson and I. Rudnick for helpful comments and N. Machorine and G. Vandenberghe for carefully polishing the quartz crystals.

---

*Associated with the Centre National de la Recherche Scientifique.

[1]R. C. Dynes, V. Narayanamurti, and K. Andres, Phys. Rev. Lett. 30, 1129 (1973).

[2]B. L. Blackford, Phys. Rev. Lett. 28, 414 (1972).

[3]G. Winterling, F. S. Holmes, and T. J. Greytak, Phys. Rev. Lett. 30, 427 (1973).

[4]J. Imai and I. Rudnick, Phys. Rev. Lett. 22, 694 (1969).

[5]I. M. Khalatnikov and D. M. Chernikova, Zh. Eksp. Teor. Fiz. 49, 1957 (1965) [Sov. Phys. JETP 22, 1336 (1966)], and 50, 411 (1966) [23, 274 (1966)].

[6a]M. Chester, L. C. Yang, and J. B. Stephens, Phys. Rev. Lett. 29, 211 (1972).

[6b]E. S. Sabisky and C. H. Anderson, Phys. Rev. Lett. 30, 1122 (1973).

[7]D. E. Commins, University of California at Los Angeles Technical Report No. 34, 1972 (unpublished).

[8]K. Andres, R. C. Dynes, and V. Narayanamurti, Phys. Rev. B 8, 2501 (1973).

[9]C. H. Anderson and E. S. Sabisky, Phys. Rev. Lett. 24, 1049 (1970).

[10]M. Vuorio, J. Low Temp. Phys. 10, 781 (1973).