HYPERSONIC ABSORPTION IN LIQUID HELIUM

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We have measured by a new optical method the hypersonic attenuation in liquid He^4 at a frequency of about 650 MHz. In this high-frequency range absorption data are presented between 1.2 and 4.2°K, including the vicinity of the λ point. The results are compared with the previous low-frequency measurements.

The attenuation of ultrasonic waves in liquid He^4 at low frequencies (10^5-10^7 Hz) has been investigated so far in several experiments.[1] In contrast, the absorption at GHz frequencies is still much less known[2,3] because of the considerable difficulties of conventional ultrasonic techniques in this frequency range. With a novel optical-pulse method described below we have been able to measure the hypersonic attenuation at about 650 MHz between 1.2 and 4.2°K, including the region of the λ point. Our main results are the following: Above the λ point the absorption corresponds to an ω^2 extrapolation from earlier low-frequency data. In particular, for $T > 2.8$°K the attenuation can be explained by the classical contributions of viscosity and thermal conductivity only. At the λ point the absorption has a broad maximum. However, the magnitude of this maximum and its location relative to the λ point cannot be understood by the relaxation theory of Landau and Khalatnikov.[4] Between 1.2 and 1.6°K the attenuation shows an almost temperature-independent behavior. This result is in agreement with previous measurements of Woolf, Platzman, and Cohen[2] using an optical continous wave method but disagrees with the theoretical treatment by Khalatnikov and Chernikova.[5]

Our experimental arrangement, as already previously described,[6] makes use of two consecutive light pulses from a Q-switched ruby laser. The first strong pulse (peak power, 5 MW; duration, 24 nsec) is focused by a lens (focal length 25 cm) inside a helium Dewar and generates coherent hypersonic phonons of about 650 MHz in the focal volume by stimulated Brillouin scattering.[7] The second pulse of much smaller intensity is delayed (delay time 42 nsec) relative to the first pulse and enters the focal region in exactly the same way as the first pulse. Each pulse is backscattered by the phonons in the focal volume and the reflected intensities can be detected separately. While the backscattered first (stimulated) pulse is a measure of the number of phonons created, the (spontaneous) backscattered second pulse is a measure of the number of phonons "left over" after the fixed delay time. The ratio of the intensity of the backscattered second pulse relative to that of the first one varies with temperature. It is largest at a temperature of 1.95°K, which corresponds to a minimum of the hypersonic absorption. From this observed ratio the phonon lifetime can be evaluated at any temperature relative to its value at 1.95°K, assuming an exponential phonon decay. The phonon lifetime at 1.95°K and at 674 MHz (being the Brillouin shift at 1.95 °K) has a value of nearly 70 nsec according to an ω^2 extrapolation from measurements at 30 MHz[8] and, independently, from experimental data by Woolf, Platzman, and Cohen.[2] By referring our results to this known value of the lifetime at 1.95 °K we have established, over the entire temperature range studied, the absolute values of the absorption reported here.

In our measurements the stimulated optical Brillouin pulses had a peak power of about 0.5 MW and a width of 12 nsec. Assuming an effective focal volume of 10^{-3} cm^3 the amplitude of the created sound wave can be estimated to be $\Delta\rho/\rho \cong 10^{-3}$. This high value required an investigation of a possible amplitude dependence of the absorption. We therefore decreased the stimulated Brillouin intensities by a factor of 3. At these lower phonon intensities we observed at $T = 1.45$°K and $T_\lambda - T = 1$ mdeg the same phonon lifetime as before within our experimental uncertainty of ±10%. The high value of $\Delta\rho/\rho$ also required an estimate of the local overheating in the focal region by the Brillouin phonons. In the vicinity of the λ point this overheating amounts to considerably less than 10^{-4} °K. Therefore our determination of the temperature near the λ point[9] with an accuracy of $\pm 10^{-4}$ °K is still meaningful. At lower temperatures the local overheating is, of course, larger but still only amounts to less than 5×10^{-4} °K at 1.4°K.

Figure 1 shows the hypersonic absorption for a fixed frequency of 674 MHz[10] between 1.2 and 4.2 °K. The data in the He I region were taken when

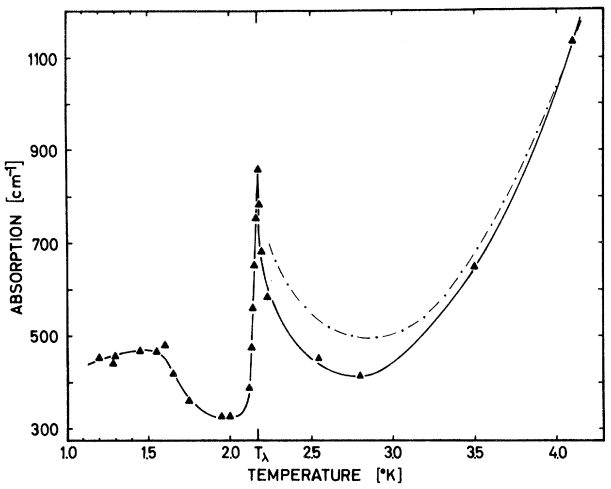

FIG. 1. Hypersonic (amplitude) absorption in liquid helium at 674 MHz versus temperature (saturated vapor pressure). Each point represents the mean value of several single measurements. The dash-dotted curve corresponds to an ω^2 extrapolation from previous data at 15 MHz [see J. R. Pellam and C. F. Squire, Phys. Rev. 72, 1245 (1947)].

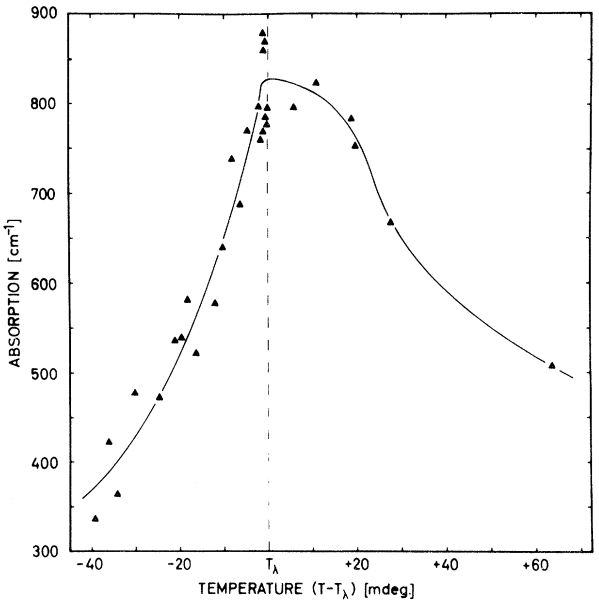

FIG. 2. Hypersonic (amplitude) absorption at 653 MHz versus temperature near the λ point (saturated vapor pressure). Each point corresponds to a single measurement. The error in temperature is about ±3 mdeg above the λ point and about ±0.1 mdeg below the λ point. In the region between 0.1 and 1 mdeg below T_λ data were taken in temperature steps of 0.2 mdeg (see also Fig. 3).

cooling down. The most interesting feature of our results in He I and in the vicinity of the λ point ($T-T_\lambda \geq 20$ mdeg) is the satisfactory agreement with an ω^2 extrapolation from data at the much lower frequencies of 15 and 12 MHz,[11,12] as can be seen from Figs. 1 and 3. For $T > 2.8$°K our results can be well accounted for by the classical contributions of viscosity and heat conduction. The increase of the attenuation, however, when approaching the λ-point is not understood in detail at present.

The absorption near the λ point is presented in Fig. 2. It is obvious from our data that the absorption has its highest value very close to the λ point ($|T_\lambda - T| \leq 2$ mdeg). As already observed at low frequencies the absorption at 653 MHz (being the Brillouin shift at T_λ) also shows clearly an asymmetry in the temperature dependence below and above T_λ. The measured absorption at the λ point is about six times larger than the contribution from the normal viscosity η_n (see Fig. 3). The contribution of heat conduction just above T_λ ($T-T_\lambda \geq 0.1$ mdeg) is still much smaller than the observed absorption and thus negligible.

At low frequencies the absorption just below the λ point[12,13] can be explained, according to the theory of Landau and Khalatnikov,[4] by a relaxation between ρ_n and ρ_s characterized by a relaxation time θ which increases linearly as $T_\lambda - T$. For a frequency of 653 MHz this theory would lead us to expect an absorption maximum of about $\alpha/\omega^2 = 1.2\times10^{-17}$ sec²/cm at a temperature of approximately 40 mdeg below T_λ, where $\omega\theta = 1$. Our results do not agree with this prediction (see Fig. 3): Firstly there is no absorption peak at 40 mdeg below T_λ, and secondly, the maximum absorption is about four times stronger than expected. It should be pointed out that for 653 MHz the critical damping[14] of second sound {when the second-sound wavelength λ_{II} approaches the correlation length[15] $\xi = \xi_0[T_\lambda/(T_\lambda - T)]^{2/3}$} occurs at about 40 mdeg below the λ point, just the position of the Landau-Khalatnikov peak. Also at lower frequencies (10^5-10^7 Hz) the position of the Landau-Khalatnikov peak coincides with the temperature for which $\lambda_{II} = 2\pi\xi$.

For temperatures closer to the λ point ($T_\lambda - T < 40$ mdeg at 653 MHz) the second-sound wavelength would become smaller than the correlation length. In this region Swift and Kadanoff[16] have estimated the absorption to vary as $(T_\lambda - T)^{-2/3}$ as indicated in Fig. 3 by a straight line. This prediction is only valid for the temperature interval for which $\lambda_{II} < 2\pi\xi < \lambda_I$ with λ_I being the first-sound wavelength. Both limits are indicated

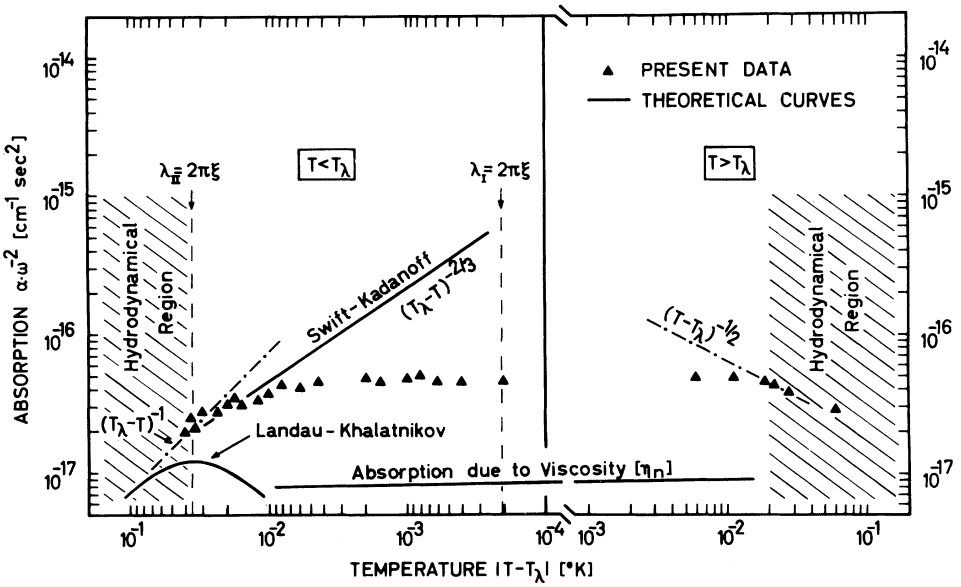

FIG. 3. Hypersonic (amplitude) absorption at 653 MHz versus temperature below and above the λ point. The dash-dotted lines represent earlier 12-MHz measurements by Chase (see Ref. 12). λ_I and λ_{II} refer to the wavelengths of first and second sound, respectively, and ξ to the temperature-dependent correlation length.

by vertical dashed lines (Fig. 3). It is obvious that our data are not in good agreement with this theory for $T_\lambda - T \leq 5$ mdeg. Sufficiently far above the λ point ($T - T_\lambda > 20$ mdeg) the absorption α/ω^2 at 653 MHz agrees with the low-frequency values[12] represented by the dash-dotted line on the right-hand side of Fig. 3. However, closer to the λ point there is a significant deviation from the low-frequency data. Evidently, the temperatures above and below the λ point at which the deviation from the hydrodynamical frequency dependence ($\alpha \propto \omega^2$) becomes apparent are symetrically located to the λ point.

Below 1.95°K our results show a similiar temperature dependence as earlier measurements by Woolf, Platzman, and Cohen,[2] who used an optical cw method. As can be seen from Fig. 1 the absorption becomes almost temperature independent below 1.6°K although theoretically a relaxation peak is expected at a temperature near 1.4°K for which the ultrasonic frequency ω equals the phonon-roton relaxation rate.[5] Below 1.4°K the hypersonic period becomes longer than the phonon-roton relaxation time,[5] and the hypersonic wave loses energy mainly to those thermal phonons which are collinear with the hypersonic wave. If at low enough temperatures the thermal contact of this small group of collinear phonons with the other excitations becomes too weak, an overheating of the collinear phonons by a hypersonic wave of sufficient intensity will occur.[5] This overheating, however, amounts to less than 30 mdeg in our case at 1.2°K. It therefore leads only to a very small additional absorption and cannot explain the temperature independent plateau of absorption observed between 1.2 and 1.6 °K.

Finally it should be mentioned that the threshold power for stimulated Brillouin scattering, which is always considerably lower than the threshold power for optical breakdown, shows an unexpected temperature dependence. While the threshold for stimulated Brillouin scattering remains constant between 4.2 and 1.3°K,[7] it increases rapidly below 1.3°K without any noticeable shift of the Brillouin frequency.

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[9]The temperature near the λ point was measured by an immersed carbon resistor [$R(T_\lambda) \simeq 6$ kΩ]. The λ point itself was identified by a short stop in the warming rate of the resistor followed by a rapid overheating.

[10]In backward Brillouin scattering the wavelength of the created phonons is approximately temperature independent; the frequency varies, of course, with temperature like the velocity of first sound. In order to obtain a useful diagram the measured absorption $1/\alpha = 2v_s(T)\tau(T)$ was scaled with ω^2 to 674 MHz (phonon frequency at 1.95°K). v_s and τ refer to the velocity of first sound and the lifetime of the created phonons, respectively.

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THEORY OF LIQUID He⁴ AT ZERO TEMPERATURE*

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We present a linked-cluster expansion for the ground state of a many-boson system which permits an exact treatment of particle conservation without introducing a chemical potential. We then propose a program of partial summations designed to permit accurate calculations with realistic He-He potentials. This theory treats the depletion effect in a fully consistent manner.

Twenty years after Bogoliubov's classic paper,[1] there is still no satisfactory microscopic theory of the ground and low excited states of liquid He⁴. The simplest qualitative features of superfluid behavior were explained by Bogoliubov on the basis of a weak repulsive interaction. Lee, Huang, and Yang[2] extended this theory to a low-density system with hard-sphere interactions, and Brueckner and Sawada[3] extended the latter model to high densities. Huang[4] has included an attractive interaction beyond the repulsive core, but his treatment is restricted to low densities. To this day, all methods which have dealt quantitatively with realistic interactions and densities have been based upon trial wave functions and the variational principle. A fully satisfactory theory should not have to rely on this technique.

We now present a theory to handle interactions with a strong short-range repulsion followed by an attraction of finite range. The attractive part must be strong enough to bind the system, so that it has a finite density at zero pressure. This need not be a low density. Our theory is based on partial summations of a linked-cluster perturbation expansion. It therefore amounts to a systematic refinement of the Brueckner-Sawada theory. All of the new features are very straightforward analogs of refinements that we have introduced previously[5] for the Brueckner-Bethe-Goldstone theory of nuclear matter.

Up to now, there has been no fully systematic linked-cluster expansion for the ground state of a many-boson system.[6] The difficulty has been that the "condensate weights" for diagrams with more than one linked part are not simply a function of the structure of each linked part by itself.[7] This is illustrated by diagram (a) of Fig. 1, where the total "condensate weight" is $N(N-1) \times (N-2)(N-3)$. However, a linked-cluster result can only be obtained if this quantity factorizes into a product of terms such as $[N(N-1)] \times [N(N-1)]$, one factor of $N(N-1)$ being associated with each of the linked parts in diagram (a). Some authors[7,8] have circumvented this problem by introducing a chemical potential μ. We wish to avoid this artifice, since we believe that the ground state should be properly understood before any thermodynamic or particle-nonconserving features are added.

A similar problem arises for fermion systems,