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## High frequency critical attenuation of sound in pressurized $^4\text{He}$ near $T_\lambda$

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**Résumé.** — Nous avons mesuré l'atténuation critique du son à 1,1 GHz dans de l'hélium 4 sous pression jusqu'à 20,4 bars. Au-dessus de la transition  $\lambda$  les résultats sont analysés avec la même fonction d'échelle pour des fréquences allant du kHz au GHz. Pour l'hélium sous pression de vapeur saturante, nos résultats sont en bon accord avec la récente théorie de Ferrell et Bhattacharjee.

**Abstract.** — We have measured the critical attenuation of sound at 1.1 GHz in pressurized helium 4 up to 20.4 bars. Above the  $\lambda$  transition, the results are scaled from kHz to GHz frequencies with the same function. For saturated vapour pressure helium our data are in good agreement with the recent theory of Ferrell and Bhattacharjee.

**1. Introduction.** — Recent experimental measurements of the critical attenuation of sound in pure  $^4\text{He}$  at saturated vapour pressure (S.V.P.), at both low [1, 2] and high frequencies [3, 4] have made it possible to clarify the behaviour of the critical dynamics around the  $\lambda$  transition.

Above the transition ( $T > T_\lambda$ ), the ultrasonic attenuation is due to the fluctuations of the order parameter; in accordance with scaling ideas and mode-mode coupling arguments the data are scaled as

$$\alpha(T, \omega) = \alpha(T_\lambda) f(\omega\tau_F) \quad (1)$$

where  $\alpha(T_\lambda)$  is a function of the frequency  $\omega/2\pi$  and  $\tau_F$  ( $\tau_F = \tau_0 t^{-x}$ ;  $t = T/T_\lambda - 1$ ) is a characteristic time of the fluctuations; the exponent  $x = 1.13 \pm 0.05$  is determined from both low and high frequency data [5].

Below the transition, in addition to the fluctuations of the order parameter, its relaxation contributes to the attenuation. At low frequencies ( $\sim 1$  MHz) the two contributions are of the same order of magnitude; but at high frequencies ( $\sim 1$  GHz) the fluctuations become the main contribution [3] ( $\gtrsim 90\%$ ); high frequency data can be scaled in the same form as (1) but with another function  $f$ .

A test of universality at the  $\lambda$  transition consists of adding to the system an inert variable such as  $^3\text{He}$

concentration or pressure  $P$ . Measurements of the attenuation of sound, above  $T_\lambda$ , at both low [1, 2] and high frequencies [5] in  $^3\text{He}$ - $^4\text{He}$  mixtures have shown that experimental data are well scaled from 2.3 kHz to 1.1 GHz (for concentration less than 24 %). For pressurized helium 4 along the  $\lambda$  line there exist systematic measurements at low frequencies [6] and preliminary results at 50 MHz [7]. The purpose of this letter is to complete the experimental investigation with high frequency ultrasonic measurements (1.1 GHz).

**2. Experimental results.** — **2.1 DIRECT EXPERIMENTAL RESULT.** — The acoustical transmission techniques and experimental set up have already been described in a previous work [3]. The accuracy of our temperature measurements is 1 mK and the pressure in the cell is measured with an accuracy better than 0.1 bar; the corresponding uncertainty of the temperature  $T_\lambda(P)$  of the transition would then be about 1 mK, but due to the uncertainty in the curve  $T_\lambda(P)$  [6], the accuracy  $\Delta T = |T - T_\lambda(P)|$  is even worse ( $\sim 3$  mK). In the table I we give the different values of  $T_\lambda(P)$  as well as the temperature  $T_{\max}(P)$  of the small maximum (due to the contribution of the relaxation) observed below the transition.

The first part concerns the dispersion of sound; the accuracy of our velocity measurements ( $\sim 0.2$  ms, i.e. 0.1 %) permits us to give neither a frequency nor

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Table I. — Pressure dependence of the temperature  $T_\lambda$  of the transition and  $T_{\max}$  of the small maximum below the transition;  $\alpha_{B\lambda}$  is the non-critical attenuation at the transition;  $\alpha_{\max c}$  and  $\alpha_{\lambda c}$  are the attenuations at  $T = T_{\max}$  and  $T = T_\lambda$ .

P	S.V.P.	1.0	9.2	15.2	20.40	bars
$T_\lambda$	2.172	2.160	2.072	1.995	1.921	K
$T_{\max}$	2.169	2.157	2.069	1.994	1.915	K
$\alpha_{B\lambda}$	980	865	460	355	310	cm <sup>-1</sup>
$\alpha_{\max c}$	1 490	1 280	1 270	1 220	1 390	cm <sup>-1</sup>
$\alpha_{\lambda c}$	1 280	1 190	1 120	1 180	1 140	cm <sup>-1</sup>

a pressure dependence; but we can give a value of the dispersion at the  $\lambda$  transition

$$(u(\omega, T_\lambda)/u(0, T_\lambda)) - 1 = (10 \pm 1) \cdot 10^{-3}$$

for our frequency and pressure range; this result is in agreement with light scattering measurements at 500 MHz [8].

In figure 1 we present our attenuation data at 1.1 GHz for a pressure of 15.2 bars.

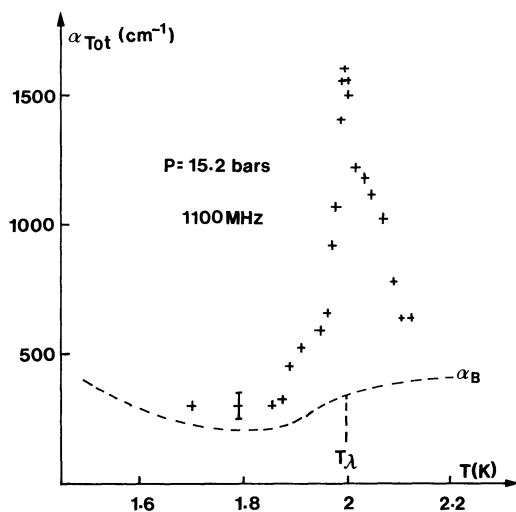


Fig. 1. — Crosses show the variations of the total attenuation at 1 100 MHz for  $P = 15.2$  bars; the dashed line is the background  $\alpha_B$ .

2.2 ESTIMATES OF THE NON-CRITICAL ATTENUATION. — In order to extract from such data the critical attenuation of sound we have to subtract a background attenuation  $\alpha_B$ :  $\alpha_B$  is due to classical losses such as shear viscosity  $\eta$ , second viscosity and for  $T > T_\lambda$  thermal conductivity. At frequencies around 15 MHz [9] the critical region is very narrow ( $|t| \lesssim 0.01$ ) and attenuation measurements give an  $\alpha_B$  which has the expected hydrodynamic behaviour ( $\alpha_B \sim \omega^2$ ); unfortunately these values are only given away from  $T_\lambda$  ( $|t| > 0.1$ ). We therefore use the following semi-empirical method to estimate  $\alpha_B$ :

(i) for  $|t| > 0.1$ , we scaled the 15 MHz experimental results with a  $\omega^2$  law;

(ii) for  $|t| < 0.1$ , we first interpolate the previous experimental data and then we take into account the contribution due to the critical variation of the shear viscosity [10] and thermal conductivity.

The resulting  $\alpha_B$  is shown in figure 1 for  $P = 15.2$  bars; the values of  $\alpha_B(T_\lambda)$  at  $T_\lambda$  for different pressures are given in the table.

2.3 CRITICAL ATTENUATION. — The values  $\alpha_{\lambda c}$  of the critical attenuation at the transition and the values  $\alpha_{c \max}$  of the small maximum of the attenuation below  $T_\lambda$  are shown in the table. As opposed to the strong variations in  $\alpha_{c\lambda}$  and  $\alpha_{c \max}$  for concentration changes in  $^3\text{He}$ - $^4\text{He}$  mixtures, we find a weak decrease with pressure changes; this was also observed at low frequencies [1, 2]. Observe that our value of the attenuation,  $\alpha_{B\lambda} + \alpha_{\lambda c} = 1\,450 \text{ cm}^{-1}$  at 20.4 bars, is in reasonable agreement with the only existing data for pressurized helium [8]:  $\alpha_{B\lambda} + \alpha_{\lambda c} = 1\,300 \text{ cm}^{-1}$  at 0.98 GHz and 23.1 bars.

Above the transition we now have to compare our results with expression (1). Using the same procedure as in the case of  $^4\text{He}$  and  $^3\text{He}$ - $^4\text{He}$  mixtures [2], we fit our results at 1.1 GHz with those at lower frequencies [6, 7]; for the pressures investigated we find that the critical exponent  $x$  is almost pressure independent,  $x = 1.1 \pm 0.1$ . Moreover, if we plot the relative attenuation  $\alpha_c/\alpha_{\lambda c}$  against the reduced temperature  $t = T/T_\lambda(P) - 1$  for all pressures, one can see in figure 2 that within experimental accuracy the data fall on the same curve; this means that for both sides of the transition the value  $\tau_0$  ( $\tau_F = \tau_0 t^{-x}$ ) is pressure independent. This result above the transition was also quoted at low frequencies [6]; we should mention that in  $^3\text{He}$ - $^4\text{He}$  mixtures,  $\tau_0$  is concentration dependent.

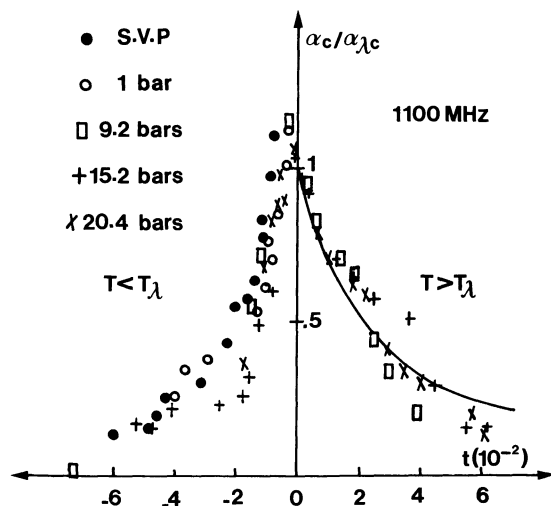


Fig. 2. — Scaling plot  $\frac{\alpha_c}{\alpha_{\lambda c}}$  versus  $t = \frac{T - T_\lambda}{T_\lambda}$  at 1 100 MHz for different pressures. The curve for  $T > T_\lambda$  corresponds to the new (F. and B.) theory at S.V.P. [11, 13].

**3. Discussion.** — At this point it is necessary to recall what we state in the introduction : for  $T > T_\lambda$  our experimental data can be scaled with equation (1) not only for S.V.P.  $^4\text{He}$  but also for  $^3\text{He}$ - $^4\text{He}$  mixtures and now for pressurized  $^4\text{He}$ . This presentation of the data is valid from kHz to GHz frequencies. For  $T < T_\lambda$  there are two contributions to the attenuation due to relaxation and fluctuation of the order parameter ; the last one is dominant at high frequencies, and the value of  $\tau_0$  for  $T < T_\lambda$  is pressure independent. From the theoretical point of view, during past years, there was no way to calculate a scaling function.

Recent theoretical work of Ferrell and Bhattacharjee [11] on the dynamic scaling of the ultrasonic at the  $\lambda$  point uses a new approach to the problem. The authors (F. and B.) first apply dynamic scaling ideas to the thermodynamics of the system (Pippard-Buckingham-Fairbank relation) and then they use previous work [12] on the thermal conductivity to find the characteristic frequency of the dynamic phenomena. The main results [11] first concern the dispersion and the attenuation at the transition and secondly, in a first step towards a complete theory, they give the appropriate scaling function. In pure  $^4\text{He}$  at S.V.P. and for  $T = T_\lambda$  the authors predict a dispersion of  $10^{-2}$  at 1.1 GHz (Fig. 1 of Ref. [11]), in agreement with our rough measurement. The expected attenuation at the transition is  $1\,250\text{ cm}^{-1}$ , in remarkably good agreement with the value of  $1\,280\text{ cm}^{-1}$  we measure at S.V.P.

For  $T > T_\lambda$ , if we try to plot our experimental results at 1.1 GHz as in figure 2 of reference [11], we must employ [13] the experimental value of the specific heat instead of the purely logarithmic temperature dependence assumed in [11] : the remaining curve [13] is drawn in figure 2 for S.V.P. helium.

The agreement is rather good. If we use our old scaling plot [5] based on equation (1) the agreement is also good. The (F. and B.) theory will have to explain why such a presentation of the results using equation (1) is relevant.

For  $T < T_\lambda$ , the authors announce in a forthcoming paper how the two contributions are mixed, and they also contradict the usual assertion, commonly used at low frequencies, that the two processes are purely additive ; in any case, we can expect that at high frequencies the fluctuation process would be dominant.

**4. Conclusion.** — We have measured the high frequency critical attenuation in pressurized  $^4\text{He}$ . These results and those obtained previously in  $^3\text{He}$ - $^4\text{He}$  mixture clearly show :

i) Above the transition, for both  $^3\text{He}$ - $^4\text{He}$  mixtures and pressurized  $^4\text{He}$ , all the experimental results depend only on the variable  $\omega t^{-x}$  over 5 decades in frequency. For S.V.P. helium, our data are also well fitted with the scaling function of the recent (F. and B.) theory.

ii) Below the transition, high-frequency data seem to be in major part due to fluctuations of the order parameter.

iii) At the  $\lambda$  transition (where the characteristic time is infinite) our measurements of the dispersion and attenuation of sound for pure  $^4\text{He}$  at S.V.P. are in good agreement with the recent theory of Ferrell and Bhattacharjee.

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