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High frequency critical attenuation of sound in He³-He⁴ mixtures near T_λ

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Résumé. — Nous avons mesuré l'atténuation critique du son à 1,1 GHz dans des mélanges He³-He⁴ de concentrations molaires d'He³ : 0,06, 0,20 et 0,24. Les résultats au-dessus de la transition de phase normale-superfluide sont analysés avec les mêmes fonctions d'échelle que celles utilisées dans l'He⁴ pur à des fréquences dans la gamme du kHz.

Abstract. — We have measured the critical attenuation of sound at 1.1 GHz in He³-He⁴ mixtures of 0.06, 0.20 and 0.24 molar He³ concentrations. The results above the superfluid-normal transition are scaled with the same scaling function used in the kHz frequency range for pure He⁴.

Recent experimental results on the critical attenuation of sound in pure helium 4 around T_λ , at both low frequencies [1, 2] ⁽¹⁾ ($\nu \leq 1$ MHz) and high frequencies [3] (~ 1 GHz) have helped specify the different contributions to the attenuation. At GHz frequencies the main contribution comes from the order parameter fluctuations. On both sides of the transition, these fluctuations contribute to the attenuation in a form which is not symmetric in temperature relative to T_λ . This contribution takes the form :

$$\alpha_F = \alpha_\lambda \frac{\omega\tau}{c + \omega\tau} \quad (1)$$

with a characteristic time $\tau = \tau_0 t^{-x}$, $t = |1 - T/T_\lambda|$ and c is a constant. Such an expression fits the experimental data from 2.3 kHz to 1.2 GHz, for $T > T_\lambda$.

In He³-He⁴ mixtures the He³ concentration acts as an inert variable (as the pressure along the λ line), thus it becomes interesting to test the universality of the scaling function (1) for different mixtures. This was done recently at low frequencies [1, 4] ($\nu < 45$ MHz). The purpose of this paper is to extend these measurements up to 1.1 GHz; this high frequency offers an especially good opportunity to study the contribution of the fluctuation mechanism to the attenuation [3].

The acoustical transmission technique used and the method by which we relate the transmitted signal to the attenuation, have already been described in previous articles [3]. Because we use thin samples (~ 5 to 10μ), no gravity corrections are needed.

The first results of our measurements concern the dispersion of sound velocity : within the accuracy of our measurements (~ 0.2 m/s), we see no critical dispersion at any concentration; this result is in agreement with our previous result in pure He⁴ [3] and with the fact that the critical dispersion is expected to decrease with increasing concentration [1, 4].

Before analysing the critical attenuation α_c , we have to subtract the non critical attenuation α_B from the measured attenuation. For $T > T_\lambda$, we take into account the contribution of the shear viscosity and of the thermal conductivity; the increase of α_B with the He³ concentration is connected with the decrease of the density and of the velocity of sound. For $T < T_\lambda$, the problem is more complicated : the elementary excitations (phonons and rotons) contribute to the attenuation; this contribution is well known in pure He⁴ [4], it peaks at 1.5 K for 1 GHz. In He³-He⁴, this contribution is completely unknown at GHz frequencies. Therefore it is not possible for us to extract the critical attenuation for $T < T_\lambda$ at this frequency.

The λ transition temperature $T_\lambda(X)$ is deduced from the He³ molar concentration (see table) with a maximum error of 10 mK. The accuracy of our temperature measurement is better than 1 mK; but due to the error in the determination of $T_\lambda(X)$, our total accuracy is worse. Also shown in the table is the

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⁽¹⁾ References [1] and [2] correspond respectively to results on He³-He⁴ mixtures and pressurized He⁴. Each of these papers enables results for pure He⁴ at $P = 0$ to be obtained.

temperature $T_{\max}$ of the small apparent maximum of the attenuation just below the transition.

Table. — X is the molar He^3 concentration of the mixture; T_λ , the temperature of the normal superfluid transition [1, 4, 6]; $T_{\max}$, the temperature of the small maximum of the attenuation below the transition temperature $T_\lambda(X)$; $\tau_0(X)$ is the value which gives the best fit to the data (see text).

X	0	0.06	0.20	0.24
T_λ	2.172	2.085	1.875	1.805 K
$T_{\max}$	2.169	2.070	1.860	1.775 K
$\tau_0(X)$	1.5	2.2	4.0	5.2×10^{-12} s

Later on we only present experimental results for the normal phase. The value of the critical attenuation at the transition $\alpha_{\lambda c}$ is a decreasing function of X . We present in figure 1 experimental value $\alpha_c/\alpha_{\lambda c}$, for

Fig. 1. — The full lines are theoretical curves (see Eq. (1)) with $x = 1.13$, $c = 0.5$ and respectively $\tau_0(X) = 2.2 \times 10^{-12}$ s and $\tau_0(X) = 4.1 \times 10^{-12}$ s for $X = 0.06$ and $X = 0.20$ mixtures.

$T > T_\lambda$ for two different He^3 - He^4 mixtures. In previous papers [3], we analysed our data with the characteristic time τ_2 of a relaxation mechanism; exp. (1) is then used with $\tau \equiv \tau_2$, $\tau_{20} = 2 \times 10^{-12}$ s and $x = 1.062$; c , which is a free parameter, is determined

as $c = 0.5 \pm 0.05$ for $T > T_\lambda$. Here we follow the procedure of reference [4] (Fig. 7) and we determine, with the experimental data from kHz [1] to 1.1 GHz [3], the exponent x : for pure He^4 we find $x = 1.13 \pm 0.05$. Using eq. (1) with $c = 0.5$, we determine

$$\tau_0 = (1.5 \pm 0.2) \times 10^{-12} \text{ s}$$

in accordance with previous experiment [2]. We present in figure 2 the values of $\alpha_c/\alpha_{\lambda c}$ versus $(2\pi/\omega) t^{-x}$

Fig. 2. — Scaling plot $\alpha_c/\alpha_{\lambda c}$ versus $\frac{\omega}{2\pi} t^{-x}$ with $x = 1.13$ for $T > T_\lambda$ and $X = 0$; the frequencies are 600 kHz [1], 10.2 MHz [7], 90 MHz [7], 775 MHz [3] and 1 GHz [5].

with $x = 1.13$; this scaling plot illustrates the satisfactory collapsing of the data onto one curve. The small scattering of the data is due to many causes such as: (i) different techniques of attenuation measurements (especially at 1 GHz), (ii) different estimations of non-critical attenuation α_B , (iii) oscillations of α_c (see for example the data at 90 MHz) due to the variations of the sound velocity.

We use the same procedure for He^3 - He^4 mixtures; for instance our results at 1.1 GHz for $X = 0.06$, are fitted with the results for $X = 0.07$ [1] and $X = 0.05$ [4] at lower frequencies with an exponent $x = 1.13 \pm 0.05$. It has been mentioned [4] that this exponent slightly increases with X (e.g. 1.19 ± 0.05 for $X = 0.366$); we are not able to determine this small increase in our experiment event at $X = 0.20$; at least this small increase is of the order of magnitude of the accuracy. The exponent we use to fit our data is then $x = 1.13$ for all concentrations ($X = 0$; $X = 0.06$; $X = 0.20$; $X = 0.24$); the corresponding values of $\tau_0(X)$ which best fit the data are given in the table. In figure 1, the full lines represent the value of the scaling function (1) for the corresponding mixtures: these scaling functions are in reasonable agreement with the experimental data. Finally we have to mention that in He^3 - He^4 mixtures another dissipation process may contribute to the attenuation of sound: it is the mass

diffusion (α_D) for which we have no theoretical expression in the critical regime. In pure He^4 , where there is no mass diffusion, we analyse our data with a fluctuations contribution. In $\text{He}^3\text{-He}^4$ mixtures it is possible to analyse the data in the same way. Therefore we can say that it is possible to make the assumption [4] that the mass diffusion contribution, if it exists, can

be described by a function of the same form as the fluctuations.

Conclusion. — We have measured the critical attenuation of sound at 1.1 GHz in $\text{He}^3\text{-He}^4$ mixtures. Above the transition, the data are fitted with the same scaling function from 2.3 kHz to 1.1 GHz.

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