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# Quantum zero sound in liquid helium-3

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**Abstract**

In his early paper on Fermi liquids, Landau predicted that a new regime of propagation for density waves sets in at very low temperature $T$ when the frequency $\omega$ of the waves becomes larger not only than the inverse of the quasiparticles relaxation time (zero sound regime) but also larger than the temperature (quantum zero sound regime). In these last conditions the attenuation $\alpha$ is frequency dependent, thus distinguishing QZS from ZS. By measuring simultaneously the absolute values of $\alpha(\omega, T)$ at three different frequencies (85, 250, 420 MHz) and in the 10 mK range we have verified the Landau predictions.

## 1. Introduction

L.D. Landau has predicted that a new regime of propagation for density waves in a Fermi liquid, called "quantum zero sound", takes place when the frequency of the acoustical wave exceeds not only the inverse of the quasi-particle relaxation time but also the temperature. To check Landau's theory we have measured the ultrasonic wave attenuation, for different frequencies (84, 254, 422, 592 MHz), from 7 to 300 mK, in normal liquid $^3$He. Our results agree with his theoretical predictions [1].

## 2. Theoretical aspects

Landau's model uses the concept of the quasiparticle. The quasiparticle term stands for a particle surrounded by a cloud of virtual excitations. This "dressed particle" description successfully leads to the prediction of thermodynamic quantities at equilibrium (specific heat, spin susceptibility, etc.), and collective modes (sound modes, spin-wave modes, etc.) at low temperature [2].

For low, but non-zero temperature, it is a well-known result that the number of collisions is proportional to the temperature square and the corresponding relaxation time to $T^{-2}$. Sending an ultrasonic wave disturbs the liquid equilibrium; however, as long as $\tau < \omega^{-1}$ (high temperature range), the quasiparticles have time to recover their local equilibrium during compressional and dilatational periods. This is typical for the hydrodynamic regime; ordinary sound propagates with an attenuation $\gamma_1$ given by

$$\gamma_1 = \frac{K^2}{c_1^3}\omega^2\tau \rightarrow \gamma_1 = A_1\frac{\omega^2}{T^2}, \qquad (1)$$

where $c_1$ stands for the velocity of first sound, $K$ is a coupling coefficient and $A_1$ a coefficient of proportionality.

As the temperature decreases, $\tau$ increases. When $\tau$ becomes larger than $\omega^{-1}$, the local equilibrium of the liquid is no longer ensured by quasiparticle collisions: the new fluctuation of density is called zero sound (ZS). The quasiparticle collisions are still responsible for the ultrasonic attenuation. The attenuation coefficient being

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proportional to the number of collisions, we have to distinguish between two conditions for the collision integral.

On the one hand, if the inequality $\hbar\omega \ll kT$ is fulfilled (low frequency range), the classical calculation of the collision integral results in a frequency independence and a temperature square dependence of the attenuation $\gamma_{ZS}$:

$$\gamma_{ZS} = A_0 T^2, \tag{2}$$

where $A_0$ is a coefficient of proportionality.

On the other hand, for $\hbar\omega \gg kT$ (high frequency range), called quantum zero sound (QZS), quantum effects appear in the collision integral. Landau's calculations lead to an attenuation $\gamma_{QZS}$ varying as

$$\gamma_{QZS} = \gamma_{ZS}\left(1 + \left(\frac{\hbar\omega}{2\pi kT}\right)^2\right),$$

$$\gamma_{QZS} = A_0 T^2\left(1 + \left(\frac{\hbar\omega}{2\pi kT}\right)^2\right). \tag{3}$$

The peculiarity of the QZS attenuation is its frequency dependence in $\omega^2$, and the vanishing influence of the temperature when extrapolating $T$ to zero.

Finally, when considering the attenuation of the density waves and taking into account quantum effects, one obtains

$$\gamma(\omega, T) = \frac{A_0 A_1 (\omega T)^2}{A_1\omega^2 + A_0 T^4}\left[1 + \left(\frac{\hbar\omega}{2\pi kT}\right)^2\right]. \tag{4}$$

We note that Eq. (4) is the same as the usual expression found for an attenuation due to a process of relaxation time $\tau$ without quantum effect:

$$\gamma(\omega, T) = \sqrt{A_0 A_1}\,\frac{\omega^2\tau}{1 + \omega^2\tau^2}, \tag{5}$$

with

$$\tau = \sqrt{\frac{A_1}{A_0}}\,\frac{1}{T^2}.$$

## 3. Experimental

The experiment is designed to distinguish between Eqs. (5) and (4). The attenuation in $^3$He is measured inside a small cavity defined by the end-faces of two X-cut quartz crystals separated by a 74 μm wide spacer. Longitudinal acoustical waves are generated by the piezoelectric effect in a transducer (thin $NbLiO_3$ crystal) sticked to the first quartz. The output signal (detected by inverse piezoelectric effect at the transducer on the second quartz) is amplified in a logarithmic amplifier, displayed and measured with a digital oscilloscope. The ampli-log output signal is calibrated directly in dBm. The standard error measurement has been determined from the scatter of the points realised at constant attenuation; it is amplitude and frequency independent, and evaluated at $\pm 0.2$ dB. Taking into consideration the different sources of the amplitude attenuation of the output signal (electromagnetic/acoustic conversion factors, matching of impedance at the helium/quartz interfaces, signal to noise ampli-log ratio, etc.), the maximum attenuation in $^3$He, we could detect, is estimated at 40 dB. Low temperatures are reached in a $^3$He/$^4$He dilution cryostat, that is able to cool the cell (Fig. 1) down to 7 mK in continuous mode of operation. Temperatures are determined with a calibrated $RuO_2$ resistor immersed in the liquid $^3$He.

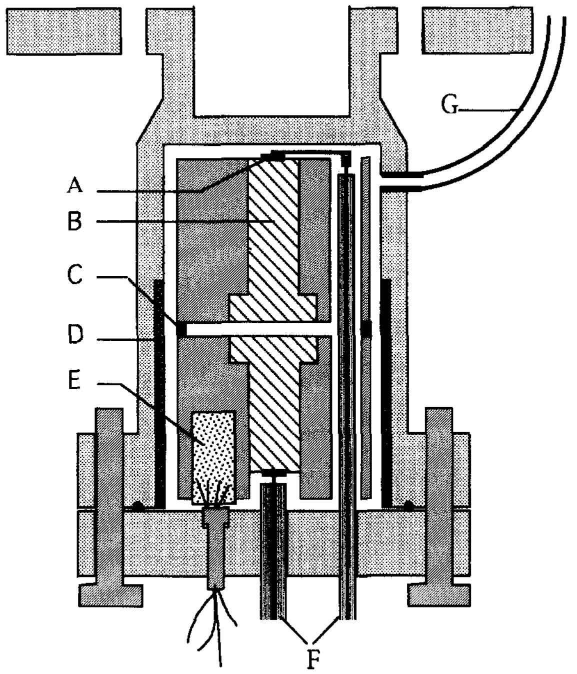


Fig. 1. Design of the $^3$He cell. A, transducer; B, quartz; C, spacer (74 μm); D, sintered Ag; E, $RuO_2$ resistance; F, coaxial cables; G, He-3 filling capillary.

## 4. Results

For 84 MHz (contrary to 254 MHz and higher frequencies), even at 7 mK, quantum effects are negligible; we use this theoretical fact to determine the parameters $A_0$ and $A_1$, respectively, at low and high temperature:

$$A_0 = 1.25 \times 10^6\ (\mathrm{K^{-2}\,cm^{-1}}),$$

$$A_1 = 3.01 \times 10^{-18}\ (\mathrm{s^2\,K^2\,cm^{-1}}).$$

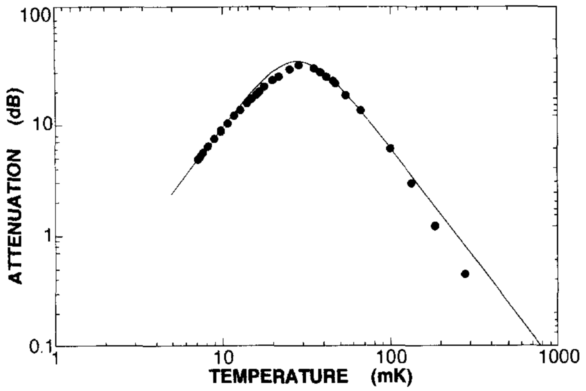


Fig. 2. Attenuation in $^3$He versus temperature at 84 MHz. Points: experimental results; curve: Eq. (4).

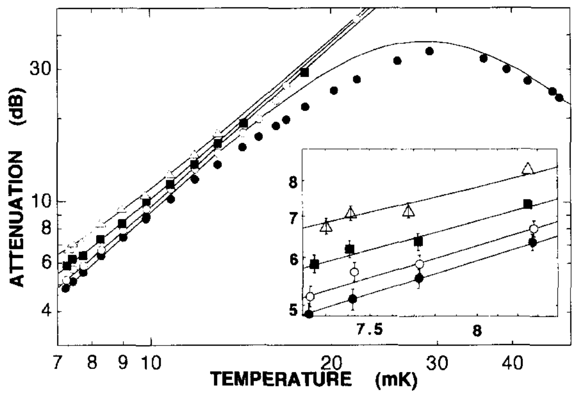


Fig. 3. Attenuation in $^3$He at different frequencies versus temperature. Points: experimental results. (●) 84 MHz; (○) 254 MHz; (■) 422 MHz; (△) 592 MHz; curves: Eq. (4).

We note here that the accuracy of our temperature measurements implies that attenuation coefficients above 200 mK are subject to error and hence should not be seriously taken into consideration.

Fig. 2 shows the agreement between the curve calculated with these two parameters and our measurements. As already mentioned in previous works [2], the theoretical curve of Eq. (4) overestimates by about 10% of the maximum attenuation at the peak ($\omega\tau = 1$).

The signal level for quantum zero sound is plotted in Fig. 3. Each point shown on the graph is the average of several data points obtained during two runs. Three hours were required to reach a new temperature equilibrium, and we waited 10 min between each measurement at different frequencies, with a repetition rate for acoustical pulses of 80 Hz, to avoid the heating of the liquid.

Eq. (4) assumes that the higher the frequency of the propagating wave, the more pronounced the QZS effect, but in return, the output signal amplitude is submitted to a greater attenuation in addition to the desired one in $^3$He, mainly due to non-parallelism between the two quartz crystals, which has constituted an experimental threshold (signal losses due to non-parallelism effect are theoretically investigated in Ref. [3]).

## 5. Conclusions

In comparison with the earlier experimental attempt of Ref. [4], we have observed with a better accuracy the quantum effect predicted by Landau. The reliable measurements performed with the four frequencies used in the present experiment, have been sufficient to demonstrate the existence of the phenomenon of QZS propagation in liquid $^3$He.

## References


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