Optical Measurement of the Non-linear Focusing of Sound in Liquid Helium 4

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We have measured the amplitude of 1MHz acoustic waves focused in liquid helium 4. Our resolution is 10 nanoseconds in time and 15 micrometers in space. The waves are focused onto a flat glass plate. We measure the reflection of light at the glass/helium interface, which depends on the refractive index of the liquid, consequently on its density which we could measure with an accuracy of $\pm 10^{-4} g/cm^3$*. At large amplitude, strong non-linear effects are observed, in good agreement with a numerical calculation.*

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1. INTRODUCTION

We are studying nucleation with 1 MHz sound waves[1,2]. These waves are emitted by a hemispherical transducer whose geometry induces a focusing at its center. We reach very high intensities (10 kW/cm^2, i.e. 200 dB). Here, we describe the optical method which allowed us to measure the sound intensity directly. We analyze the reflection of light at a glass/helium interface (Section 2). Details of our calibration are given in Section 3. In Section 4, we briefly compare our measurements with a numerical calculation of the focusing of sound waves, which accounts for strong non-linear effects.

2. EXPERIMENTAL SETUP

The transducer radius is 8 mm and its thickness is 2 mm. It is immersed in 300 cm^3 of liquid He, inside the experimental cell, which is attached to

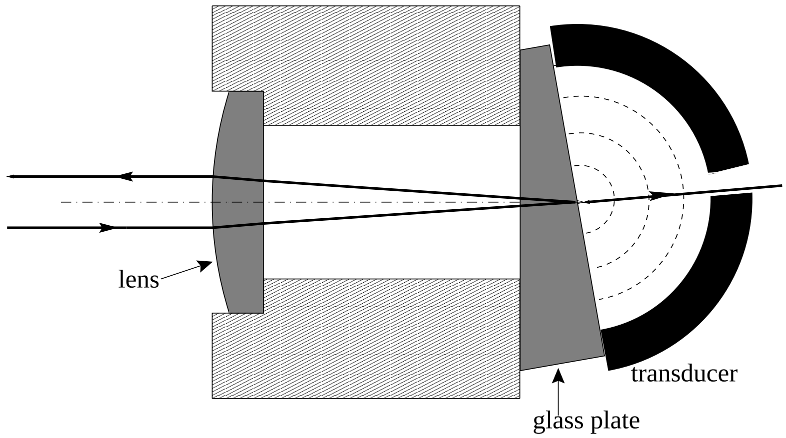

Fig. 1. The optical setup inside the experimental cell.

the mixing chamber of a dilution refrigerator. We can run the experiment between 30 mK and 1.5 K, at static pressures from 0 to 25 bar. Fig.1 shows our optical setup: a brass piece holds a plano-convex lens with a 20 mm focal length (21.8 mm in liquid He) and a wedged glass plate (20 mm in diameter, $\approx$ 2 mm thick). The transducer is hemispherical and pressed against the plate by bronze clamps. All the space inside is filled with liquid He. Thanks to the lens, the radius of the laser waist is reduced from 320 μm to 7 μm. This means that the spatial resolution is about 14 μm, the diameter of the optical focal region. It is small compared to the size of the acoustic focal region which is set by the acoustic wavelength at 1 MHz: from 240 μm at 0 bar to 360 μm at 25 bar. The distance of the lens to the glass plate has been carefully adjusted to have the laser focussed at the glass/helium interface, on the transducer side. This was checked from the parallelism of the reflected beam. The 2 degrees wedge of the glass plate avoids interferences with reflections on its front face. A 1.7 mm hole in the transducer allows the transmitted light to be analyzed on the other side of the cryostat (see fig.2).

We use a single mode Ar^+ laser (20 mW maximum output power at 514.5 nm). It is operated around 10 mW where its stability is best. In front of the laser is an absorber which reduces the light entering the cell (fig.2). We use the reflection on the front face of the absorber to monitor possible drifts of the laser power, but its stability is better than 0.5 % per day. For low temperature measurements, we reduced the dissipation in the cell with a small electromechanical shutter; it was synchronized by the pulse generator so that the cell was illuminated during 10 msec only, around the arrival time of each acoustic pulse on the glass plate. Two moving mirrors allow us to translate the laser beam vertically and horizontally. The last

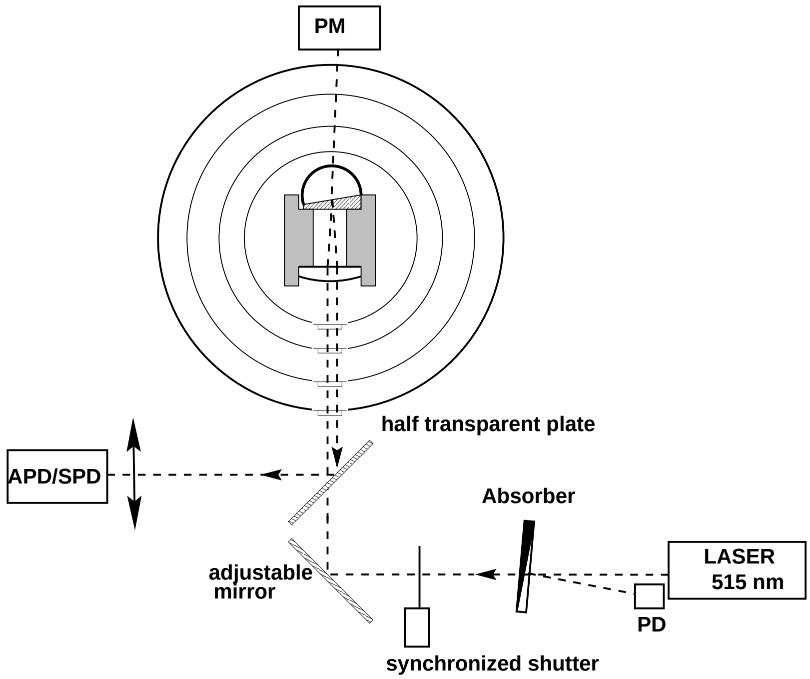

Fig. 2. A schematic view of the optical table.

mirror is mounted on a rotating plate, so that the angle of incidence of the beam can be adjusted as well. These rotations correspond to translations of the optical focus in the focal plane of the lens. By successive operations, the laser spot is brought to the center of the acoustic focal region. The final adjustment is obtained by maximizing the modulation of the reflected signal by the acoustic wave.

The cryostat and the optics are attached to a 1000 kg optical table. The experimental cell is surrounded by five thermal shields whose respective temperatures are 300K, 77K, 4K, 1K and 50 mK. The glass windows at 300K and 77K are treated antireflection, as well as the sapphire window on the cell. The windows at 77K and 4K are infrared filters to reduce the incoming radiation from the outside world. Due to all these windows, only 40% of the incident beam arrives at the glass/helium interface. The transmitted light is collected by a photomultiplier and used to detect nucleation events one by one. The light which is reflected at the glass/helium interface is separated from the incident beam by means of a semi-transparent plate and directed towards a photodiode. We used either a Hamamatsu C5331-03 avalanche photodiode (the"APD"), for the detection of the ac-modulation of the reflected beam, or a Hamamatsu S1406 silicon photodiode (the"SPD") for the detection of the dc-component. The APD gain is $G_{APD} = 15.5$ kV/W (at 514.5 nm) in its frequency bandwidth (4 kHz to 100 MHz). The SPD has a gain $G_{SPD} = 2.35$ kV/W (at 514.5 nm) and behaves as a low pass filter with a cutoff around 400 kHz. The output from the photodiodes is digitized with a LeCroy 9344 CM oscilloscope at 1 GS/s with 8-bit resolution (6.5 effective bits due to the clock jitter at 1 GS/s).

The ac-component of the signal is related to the modulation of the helium density by the acoustic wave, and is at most a few percent of the dc part which is related to the static density. In order to achieve a 1% accuracy on the wave amplitude, we reduced the noise by averaging on 10000 bursts at a rate of 1 to 10 Hz. There are two main sources of noise. The first one is photon noise in the reflected light. For a 5 μW power, this quantum noise is typically 10 nW, much more than the resolution we need. The other noise source is the ocilloscope jitter and has a comparable amplitude.

3. CALIBRATION

The intensity of the reflected light is proportional to the normal reflectance R at the glass/helium interface:

$$R = \left(\frac{n_g - n}{n_g + n}\right)^2 \tag{1}$$

where $n_g = 1.5205$ is the refractive index of glass for 514.5 nm green light. As for the index n of helium it is given by the Clausius Mossoti relation:

$$\frac{n^2 - 1}{n^2 + 2} = \frac{4\pi\rho\alpha_M}{3M} \tag{2}$$

where M = 4.0026 g, ρ is the helium density, and $\alpha_M = 0.1245\ cm^3 mol^{-1}$ is the molar polarizability for the same green light. Note that the α_M increases slightly as a function of frequency from its zero frequency value $\alpha_{M0} = 0.1233$ $cm^3 mol^{-1}$, as explained by successive authors[4].

We proceed as follows. We first measure the static pressure in the cell. Knowing the equation of state $P(\rho)$, we obtain the static density[5,6]. From the static density, we calculate the normal reflectance in the absence of modulation by the wave. This is our reference. We then measure the ratio of the ac- to the dc-component of the reflected light, and obtain the amplitude of the density modulation in the acoustic wave. Unfortunately, we could not do this with a single diode, so that we had to calibrate the ratio of the respective gains of our two photodiodes. This was achieved in the overlap of their bandwidths, with the help of an acousto-optic modulator operated at 200 kHz. We obtained $G_{APD}/G_{SPD} = 6.60 \pm 0.05$. We also had to check

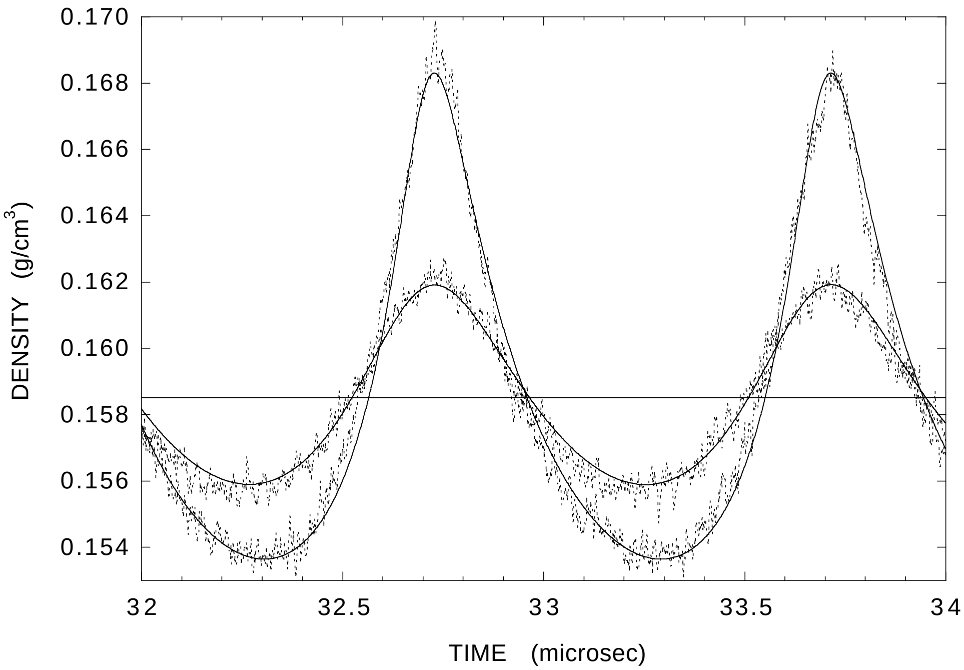

Fig. 3. Two recordings of sound wave amplitudes respectively corresponding to excitation voltages 9.05 and 20.4 V on the transducer. The static density is ρ=0.15851 g/cm^3 (horizontal line). The measurements are compared with numerical calculations (solid lines). Evidence for non-linear effects is found from the asymmetry of the large amplitude oscillations.

the linearity of the APD. Its gain was found constant up to incoming powers of 6 μW where it started decreasing. At 8.5 μW, the gain was reduced by 2 %. Most of the time, we used the APD in its linear regime; otherwise, a small correction was applied.

We finally had the following sources of uncertainties: the static density could be known within 2 to $4.10^{-5}\,g/cm^3$. About the same uncertainty came from the determination of the base line of the APD signal. Uncertainties in the gain ratio and in the APD measurement led to a 1% uncertainty in the wave amplitude. We could finally check our calibration by studying heterogeneous nucleation of bubbles on the glass plate. We observed various nucleation mechanisms. One of them occured at saturated vapor pressure ($P_{sv} = 0$ bar in the low temperature limit) where the liquid density is 0.14513 g$/cm^3$. In a series of measurement at a static pressure $P_{stat} = 4.30$ bar, we found cavitation at 0.14515 g$/cm^3$; in another series of measurements at $P_{stat} = 2.95$ bar, we found cavitation at 0.14512 g$/cm^3$. This illustrates the final uncertainty in our measurements.

4. NON LINEAR EFFECTS

Fig.3 shows two recordings obtained at 0.1K with respective excitation amplitudes of 9.05 and 20.4 V on the transducer. In the cell, the static pressure was 9.80 bar, corresponding to a static density $\rho = 0.15851$ g/cm^3. The density oscillation was found asymmetric at large amplitude: negative swings are broader with a smaller amplitude than positive swings. Moreover, the negative swings are not symmetric in time. We show this recording at intermediate pressure and moderate amplitude so that the signal shape is not modified by any nucleation of crystals or bubbles.

We have compared the experimental recordings with numerical calculations of the focusing[3]. These calculations showed that the main source of non-linearities is the shape of the equation of state: the sound velocity depends on pressure. This is particularly true when the negative swing approaches the spinodal limit where the sound velocity vanishes. In this limit, the calculation becomes difficult, due to the formation of shocks in the focal region. The adjustment was made on the central oscillation only. Indeed, in the experiment, the transducer is excited with an electrical burst of six oscillations. Since the transducer has a finite quality factor $Q \approx 50$, the amplitude of the sound wave increases during six periods and slowly decreases afterwards. The calculation was performed for a continuous wave. It had only one adjustable parameter, the effective displacement of the transducer surface, which we found to be $2.95 \pm 0.1\mathring{A}/V$. We have not yet studied the possible effect of sound attenuation on the non-linearities, at higher temperature.

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