Specificity of the second sound standing waves behavior in a medium with nanoparticles

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Abstract. The experimental studies of the second sound waves propagation in a resonator with a deuterium-helium gel were carried out. The latest experimental results, combined with those obtained in earlier experiments, have shown that the propagation of the second sound waves in gels leads to their significant attenuation and a decrease in the propagation velocity. This behavior differs from the case of the propagation of the sound waves of a two-component system with a strongly slow normal component and may indicate changes in the properties of superfluidity under confined geometry conditions.

1. Introduction
Impurity-helium gels have been studied since the 1960s and are still attracting the interest of researchers from different fields of science. Impurity-helium gels are a loose semitransparent substance that reminds slightly of “jelly”. It consists of clusters of impurity atoms surrounded by localized He$^4$ atoms. The attractive forces are determined by the induced polarization of neutral He$^4$ atoms by an impurity due to Van der Waals interaction. The sizes of nanoclusters formed depend on the impurity nature and can vary from several Å to several µm. The investigation of the properties of these gels is of interest for scientists in different areas of fundamental researches, for example, in astrophysics, since the mechanism of nanocluster formation can take place in an interstellar gas, the temperature of which is slightly below 3 K.

Since the pores of impurity nanoclusters in helium are soaked with a superfluid, one can observe interesting phenomena in these systems. For example, when the counterflow of normal and superfluid He$^4$ components (the second sound or heat flows) is excited, the case of the strong retardation of a normal component against the nanopore walls is realized, whereas a superfluid component passes through them freely. That is, this is the case of the second sound passing to the fourth sound. Another unusual and poorly studied phenomenon in these structures is bounded expanse superfluidity that, in particular, manifests itself in a decrease in the temperature of superfluid He$^4$ transition when He$^4$ contains nanoparticles. One can observe this change, for example, having measured the velocity of the second sound waves propagation in a resonator with a gel at different temperatures or measured the change of the resonant mode amplitudes at a fixed temperature. In the present work, we will describe the results obtained using the second method.
Figure 1. The left side is the device in the gel condensation regime (the mixture flux passes through filling pipe (3)). The right side is in the regime of measuring the second sound waves propagation in the resonator. (1) is a lift rod with heater (5) fixed at its end; (2) is a branch pipe for supplying a He^4 + (2÷4%) D2 mixture; (4) is a helium dewar with superfluid helium (9); (7) is a quartz resonator with gel (6); (8) is a superconducting bolometer; (10) is a cryopump

2. Experimental technique and method
In the present work, deuterium was used as an impurity. A deuterium-helium mixture was prepared in a tank with a capacity of 50 L and pressure slightly below the atmospheric one. The concentration of the impurity was about 2-4 %. An experimental setup was a helium cryostat in which there were a cylindrical resonator with the length L≈30 mm and diameter D≈15 mm, placed into a special cup, and a filling pipe through which the mixture was supplied laminarly. The upper end of the resonator was placed into the lower end of the pipe, which allowed all condensed gel to be gathered in the resonator. A superconducting bolometer was placed on the lower end of the resonator. It was a tin bronze thin film sputtered onto a quartz plate. The superconducting transition of the bolometer was shifted to the desired temperature range using a magnetic field generated by a superconducting solenoid placed under the bolometer. The upper end of the resonator was closed with a cover using a special rod after filling with a gel. A heater was placed on the inside of the cover. As the heater, a nonsuperconducting tin bronze film was used on which current strips were drawn in the form of a meander. This created a quasi-one-dimensional heat flow in the resonator. The operating capacity of this construction was tested by measuring the resonator characteristics after each opening and closure of the top cover.
Figure 2. Three successive measurements of the Q-factor and resonant frequency of the resonator with pure He$^4$ after the closure of the top cover of the resonator. The 6-th resonance, $T = 1.69$ K, $U_G = 5$ V.

3. Results

Before measuring the second sound waves attenuation in the resonator with a gel, the modes of the resonator with pure He were measured. The results are shown in Fig. 3.

The measurements were taken at the 6-th resonance and $T = 1.65$ K. In the vicinity of this temperature, the second sound velocity changed slightly with a temperature change and was about 20 m/s. Correspondingly, the resonant frequencies did not change either at this temperature.

After filling the resonator with a deuterium-helium gel, it was attempted to measure the Q-factor of the 6-th resonance. In this experiment, however, the obtained gel apparently turned out to be too non-uniform, which led to the very strong attenuation of the second sound waves. At that, the higher the number of the resonance was, the more significant the attenuation was. As a result, we did not succeed in measuring adequately the amplitudes of the resonances and comparing their attenuation degree.

However, the situation arisen contributed to us estimating well enough how much the velocity of the second sound decreases when passing through a dense deuterium-helium gel from a change of the frequency of the resonant modes. The results obtained are depicted in Fig. 4.

One can see in the plot that the frequencies (and, correspondingly, wave velocities) of each corresponding mode decreased markedly.

The second sound waves propagation in porous media was studied earlier [1, 2]. If a small pore size is present, the retardation of a normal component occurs, whereas a superfluid component passes through a porous medium without friction. At that, the velocity of heat waves increases and becomes close to the first sound velocity ($V_1 \sim 200$ m/s) at 1.5 K. In our experiments, the situation is opposite: the velocity of heat waves propagation decreases. The explanation can be related to the peculiarities of He$^4$ transition to the superfluid state in confined geometry. In this case [3], the transition to the superfluid state occurs at lower temperatures. Then, the
Figure 3. Resonant frequencies for the first 14 longitudinal resonances in pure He\textsuperscript{4}. The resonances with the highest Q-factor are marked with blue circles. $T = 1.75 \text{ K}$

Figure 4. Comparison of the frequencies of the resonator with pure He\textsuperscript{4} (blue squares) with the frequencies measured in the resonator with a gel (red squares). $T = 1.69 \text{ K}$, $U_G = 5 \text{ V}$
dependence $V_2(T)$ shifts to lower temperatures, which was observed in the experiment.

Conclusions
The experiments carried out have shown that, when introducing an impurity-helium gel (a deuterium-helium gel) to the resonator bulk, the second sound waves attenuate strongly, as might be expected when introducing a porous medium to the bulk. The result with a decrease in the velocity of the second sound waves propagation has turned out to be unexpected. The results obtained can be explained as follows. In the bulk of an individual nanopore, the fraction of a superfluid component turns out to be lower compared with the case of an unbounded liquid since the atoms on the nanocluster walls are in a “normal” state. Since the fraction of the surface is high at such small volumes, correspondingly, a normal component of a liquid occupies a higher fraction than in the absence of constraints. Because of this, bounded expanse superfluidity emerges at lower temperatures, which directly affects the value of the velocity of the second sound waves propagation. This situation differs from the case of the strong retardation of a normal component against the pore walls in that in the latter case the second sound velocity and the resonance Q-factor would have to increase, and the second sound would pass to the fourth sound. However, in this case, questions arise: how mobile is a normal component in the structure having a very large surface area and what has a decisive influence on mobility? Experiments with gels of other impurities, for example, nitrogen, can answer these questions. The structure of the frame of this impurity will be more rigid and similar to the structure of an aerogel for which the passages of the second sound to the fourth sound have been observed.

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