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# Electric response in superfluid helium

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## ABSTRACT

We report an experimental investigation of the electric response of superfluid helium that arises in the presence of a second sound standing wave. It was found that the signal of the electric response is observed in a narrow range of second sound excitation power. The linear dependence of the signal amplitude has been derived at low excitation power, however, above some critical power, the amplitude of the signal is considerably decreased. It was established that the rapid change of the electric response is not associated with a turbulent regime generated by the second sound wave. A model of the appearance of the electric response as a result of the oscillation of electron bubbles in the normal fluid velocity field in the second sound wave is presented. Possible explanation for the decrease of the electric response are presented.

## 1. Introduction

Previous work [1,2] and recent experiments [3] showed that a wave of second sound in superfluid helium (He II) is accompanied by fluctuations in the electric potential. It has been found that the amplitude of the electric potential, $\Delta U$, in resonance is proportional to the amplitude of the temperature oscillations in the second sound wave. Such electrical activity in superfluid helium is quite unusual because the helium atom is electrically neutral, and being in the $1S_0$ ground state does not have an intrinsic dipole moment in the absence of an electric field. It should be noted that the experiments with first sound presented in [1,2] did not reveal any signs of an electrical response in He I or He II. Besides, both liquid helium He I and He II are a nonpolar dielectric and its dielectric conductivity does not demonstrate any anomalies passing through the $\lambda$-line [4].

The experiments [1,2] stimulated a great deal of theoretical research, several models were proposed to explain the occurrence of charges in He II. For example, it was suggested in [5] that helium has an ordered quadrupole moment that can be polarized in inhomogeneous superfluid flow, which causes the electric induction. The authors of [6] suggested an inertial mechanism of the polarization of helium atoms, based on the difference between the electron and the nucleus mass. A similar mechanism of polarization occurs in metals and is known as the Stewart–Tolman effect. In Ref. [7], the electrical activity was interpreted from a similar inertia effect as in Ref. [6], which arises due to the influence of a centrifugal force causing a nonuniform azimuthal rotational velocity of the superfluid component around the axis of a quantum vortex in He II. A different explanation for the electric response was recently proposed in Ref. [8]. The model is based on the thermoelectric effect whereby the potential difference appears in a capacitor due to an alternating temperature difference between the plates of a capacitor. These theoretical models are being discussed, but a satisfactory explanation for the experimental data has not yet been found.

Previous experiments [3] showed a strong correlation between the resonance frequency of the electric response and the frequency of the second sound resonance. Nevertheless, the form of second sound wave generated in the cavity transforms with an increase of the exciting power. Any influence of this transformed wave on the electric response have not yet been studied. This work is devoted to investigating the behavior of the electric response with respect to transformations in the second sound wave. We discuss the changes in the second sound wave and its influence on the electric response signal, and we propose a new approach to understanding the electric response in He II based on charged particles that may lead to the signal detected on the electrode in the second sound wave resonance.

## 2. The experiment

Experiments were performed in the cell schematically illustrated in Fig. 1. The body of the resonator is 25 mm long with an inner diameter of 7 mm and was made of epoxy. The resonator is hung on a support inside helium bath. To excite the second sound wave, we used a manganin wire heater that was placed on one end of the resonator. To detect any electrical activity in the helium, a

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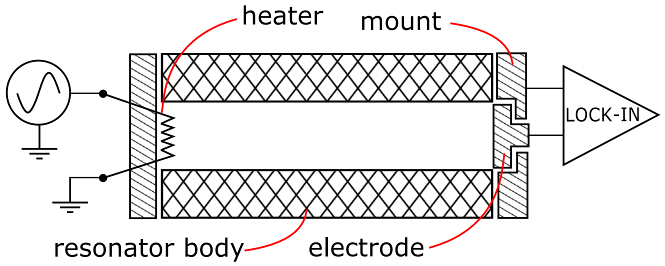

**Fig. 1.** The experimental scheme of the resonator used for generating a second sound wave and detecting the electric response. The epoxy body of the resonator is covered by a brass plate with a heater on one side and a brass mount with the electrode on the other side.

brass electrode was placed at the opposite end of the resonator. The electrode, which had a thickness of 3 mm and a diameter of 7 mm, was glued *in situ* inside the brass mount. The capacitance between the electrode and the mount was approximately 20 pF, and the total capacitance including the cables was about 260 pF. Second sound waves of various frequencies and amplitudes were generated by applying a sinusoidal signal to the heater. The signal of the electrical activity was detected by a lock-in amplifier by measuring the potential difference between the electrode and the mount. Our setup is a simple measuring circuit, and is notable due to there being no compensation of the input capacitance (for more details see Ref. [3]).

## 3. Experimental results

To study the behavior of the electric response at different amplitudes of second sound, the amplitude–frequency dependencies were measured and analyzed in the temperature range 1.7–2 K. The dependence of the peak amplitude of the first mode of second sound as a function of the ac heat flux is shown in Fig. 2(a). At low heat fluxes, the amplitude of the electric resonance is almost linearly dependent on the excitation power. Further increase of excitation power causes an irregular form of the electric response, where the peak lost the sharpness and the amplitude tends to decrease. A critical value of the heat flux, where the amplitude of the signal reaches its maximum, may change in time in a range of 3–7 × $10^{-3}$ W/cm$^2$. Taking into account the correlation of the resonance frequency of the electric response and a wave of second sound, it is reasonable to assume that the abrupt change in the electrical response may relate to a transformation of the second sound wave. The behavior of the second sound resonance with increasing of excitation power was studied in the same cavity. For this experiment, the electrode with the mount was replaced by a temperature sensor and the amplitude–frequency dependence of the second sound was measured in the same experimental range. A typical group of resonance peaks of the second sound at different heat fluxes is presented in Fig. 3. The resonance peaks have a nearly Lorentzian shape at low heat excitation power. Nevertheless, the resonance frequency of the observed peaks remains constant only below an excitation power of approximately $3 \times 10^{-3}$ W/cm$^2$ and it shows a slow decrease above this heat flux. At high heat fluxes, ~0.03 W/cm$^2$, we observed a flattening of the resonance peak. Fig. 2(b) shows the amplitude of the temperature oscillations $\Delta T$ in the resonance of second sound as a function of heat flux, *W*. The amplitude of temperature oscillations is linearly dependent on the applied power below ~$2.5 \times 10^{-3}$ W/cm$^2$. Further increasing of the heat flux led to a change of the slope of the $\Delta T(W)$ dependence. At high excitation powers, where flattening of the peaks was observed, the peak amplitude starts to be independent of heat flux.

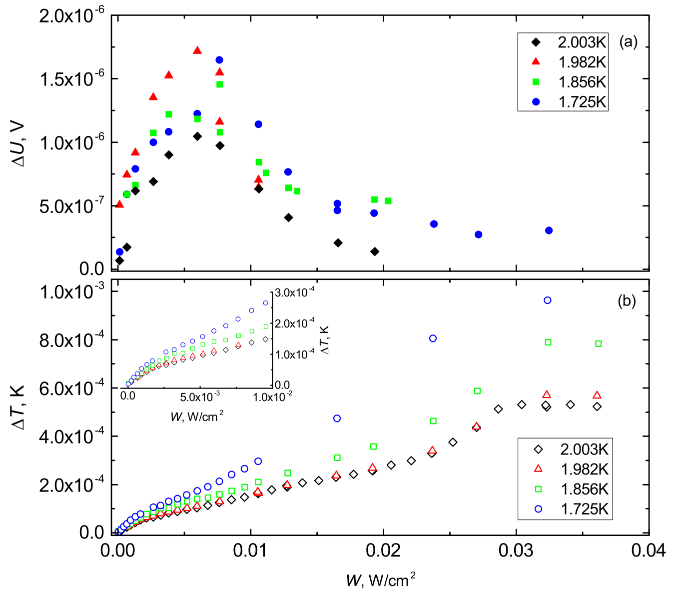

**Fig. 2.** (a) Detected potential difference in the second sound resonance as a function of excitation power in the temperature range 1.7–2 K and (b) the oscillation of temperature measured in the same resonator. The inset shows in detail the slope change of the $\Delta T(W)$ dependence at low excitation power.

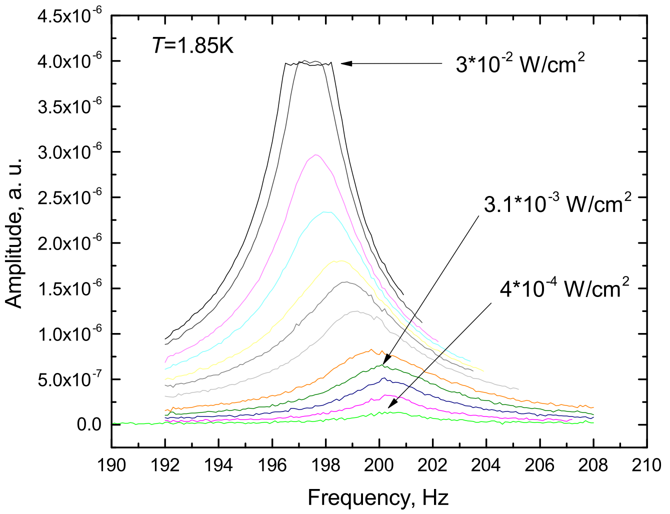

**Fig. 3.** Amplitude–frequency dependence of the first harmonic of second sound at temperature *T*=1.85 K.

## 4. Discussion

The dependence of the temperature oscillations in the second sound wave on its ac heat flux (see Fig. 2(b)) shows the following peculiarities. A purely harmonic second sound wave is observed at the lowest excitation level, where the curve has a linear dependence and the resonance frequency of the second sound is constant. The change of the slope with increasing heat flux coincides with the slow decrease of a resonance frequency of the second sound. The resonance frequency decrease can be caused by the reduction of second sound velocity due to the temperature rise inside the cavity. The estimated temperature difference between the inner space of the resonator and the bath is approximately $4 \times 10^{-3}$ K at a heat flux ~0.03 W/cm$^2$. This temperature difference is supposedly a consequence of poor heat dissipation inside the resonator [9]. On the other hand, the change of the slope of $\Delta T$