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A study on the reversibility of electric response induced by second sound in superfluid helium

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The reversibility of the electric response induced by second sound in helium II, the so-called "reverse effect", was examined. Two different cylindrical cavities were used to provide a different direction of the electric field and to check the significance of the interruption of longitudinal flow from the copper mesh electrode. The ability to reproduce the normal electric response induced by second sound was verified and compared with a previously performed experiment. No indications of the reverse effect were found. The results show that the reverse effect was absent or within a lower limit of the measurement in the order of nano-volts regardless of temperature.

Keywords: superfluid helium, second sound, electric activity, electric response, reverse effect.

1. Introduction

Heat distribution in helium II happens by second sound, a temperature wave which can be explained by the two-fluid model in helium II. When second sound is confined in a cavity, the amplitude of the temperature oscillation shows a maximum at the associated resonance frequencies. Rybalko [1] reported the first experiment of electric response induced by the second sound in helium II. He excited a second sound wave at one end of a cavity and observed the voltage response on a pair of electrodes placed at the other end of the cavity. Sweeping the frequency of the second sound, he observed a voltage peak at the resonance frequency of the second sound being generated by a heater. This effect was observed in helium II, but not in helium I.

This is a stunning result due to the chemically inert and electrically inactive nature of liquid helium. Related experiments have been carried out [2,3] in different ways, showing the effect is intrinsic to helium II no matter the experimental setup. Experiments to confirm this effect were carried out by other two laboratories [4,5] so far, and similar results were obtained. Hereafter, we call this phenomenon "normal effect".

Rybalko [1] also searched for the "reverse effect". This means that an electric field is applied to the electrodes at one end of the cavity and a temperature oscillation was observed by a thermal sensor placed at the other end of the cavity. In his paper, he mentioned briefly that a second sound wave could be excited in this way, but no experimental data or consequent graphs were shown.

As Rybalko's findings on this reversibility of second sound excitation have yet to be reproduced, it is imperative that the experiment be repeated by other laboratories. The aim of this research is to give an answer as to the reverse effect of the electric response induced by second sound in helium II.

2. Experimental

2.1. Setup and cavities

Figure 1 shows a schematic of the measurement system for the second sound reverse effect. Figure 2 shows the experimental cells that are immersed in a superfluid helium bath during the experiments. Their temperature is regulated by controlling the vapour pressure. The methodology of this experiment is similar to that of experiments performed pre-

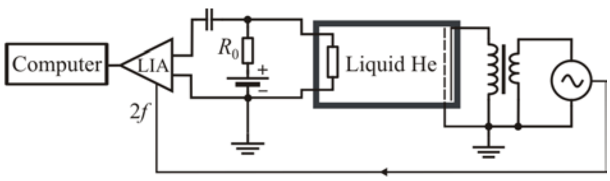

Fig. 1. The circuit used for measurement of the second sound reverse effect. The cavity represented here is cavity A (see Fig. 2).

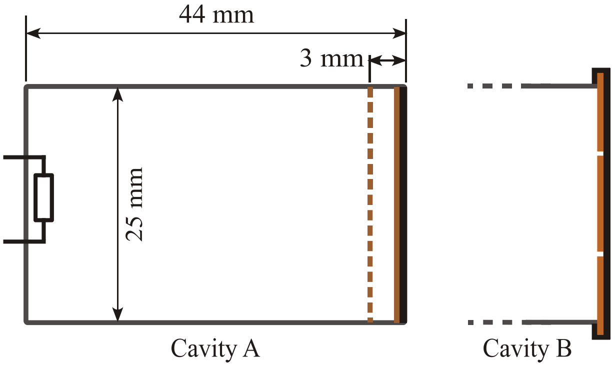

Fig. 2. (Color online) The cavities used for the experiments. Cavity A, on the left, uses a pair of electrodes consisting of a copper plate and a mesh. The right half of cavity B, using a Corbino-type electrode, is shown on the right. The left half is the same as that of cavity A. The outer electrode is grounded when it is used in the circuit of Fig. 1. In both cavities, the backside of the electrodes is covered by a grounded aluminium foil for better electric shielding.

viously on second sound in the same laboratory [5]. There are, however, a few key differences in order to measure the reverse effect.

As shown in Fig. 2, two slightly different cavities were used. The cavity A in Fig. 2 was the same as the cavity used in Ref. 5. The pair of electrodes was composed of a copper plate and a copper mesh, similar to that used in Ref. 5. The copper mesh electrode was located inside the cavity so that helium atoms could go through, retaining the electrical shielding it exhibits. A voltage of 52 V was applied to the electrodes, equivalent to an electric field of $1.7 \cdot 10^4$ V/m. The other end of the cavity was a plastic plate with manganin wire wound around it, functioning as a heater. This heater is not shown in the figure, but it was used to reproduce the second sound electrical activation, *i.e.*, the normal effect. This cavity was the same as the one used in Ref. 5.

The cavity B in Fig. 2 contained a pair of concentric electrodes (Corbino-type, where the diameters of the inner and outer electrodes are 12 and 30 mm, respectively), similar to the electrodes used in Refs. 1, 4, 6. These electrodes were used to prevent any interruption of the longitudinal helium flow along the axis of the cavity, as such an interruption was anticipated to occur in between the electrodes with a copper mesh. Furthermore, the direction of the electric field is no longer parallel to the length of the cavity, as with cavity A, but it also contains radial components between the inner and the outer electrodes. The voltage applied for this cavity was 48 V. The other end of the cavity was covered by a plastic plate.

Both cavities had a thermal sensor placed on the opposite end of the electrodes to pick up the signal. This thermal sensor was a temperature-sensitive ruthenium oxide (RuO_2) resistance whose nominal resistance was 10 kΩ in room temperature, its resistance increasing as the temperature decreased. It was approximately 29 kΩ at 2.1 K and 38 kΩ at 1.5 K. The electric cables outside the cavity were shielded by aluminium foil to supress interference and noise. A large 9 MΩ resistance R_0 was connected in series to a 9 V battery to keep the electric current nearly constant at 1 μA. Due to this constant current I, the measured voltage U_a can be converted to a root-mean-square (rms) temperature oscillation T_a using

$$T_a = \left|\frac{dR}{dT}\right|^{-1} \frac{U_a}{I}, \qquad (1)$$

where R is the resistance, and T is the temperature. The derivative $|dR/dT|$, which represents the sensitivity of the thermal sensor, is shown in Fig. 3 as a function of the temperature. The sensitivity at 1.5 K is roughly twice as large as that at 2.1 K.

As shown in Fig. 1, the reference frequency of the lock-in-amplifier (LIA) was set to $2f$ where f is the frequency of the signal sent out into the cavity. This is because the electric field reaches its maximum value at both the maxima and minima of an ac voltage applied to the electrodes, meaning that the second sound produced by the electrodes has twice the frequency of the voltage applied to it.

2.2. Experimental procedure

Before the experiment regarding the reverse effect, a test was done using the similar setup described in Ref. 5 to compare the data with. Here, power was applied to the heater, and the resultant voltage induced in the electrodes was measured. As mentioned before, the frequency of the induced signal was twice that of the resonance frequency of the cavity.

The experiment to measure the reverse effect was carried out using the setup of Fig. 1 which is in a reverse fashion of Ref. 5. The sinusoidal wave voltage 0.5 V produced by a generator was amplified to 50 V by a transformer. This voltage caused an electric field to be present in the liquid helium inside the cavity. If the phenomenon of electric response due to the second sound is reversible, a tem-

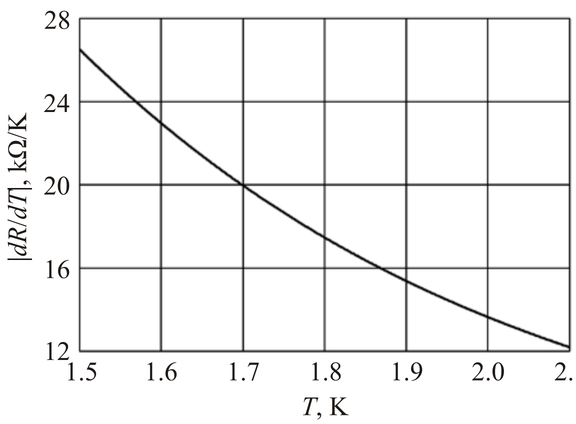

Fig. 3. The sensitivity data for the RuO_2 thermal sensor. The temperature oscillation T_a can be converted from the measured voltage U_a putting these data in Eq. (1).

perature wave should be induced due to the electric field, and this temperature wave could then be picked up by the thermal sensor at the other end of the cavity.

3. Results and discussion

For both cases of measurements, normal effect and reverse effect, the resonance peak would appear as a standing wave at a frequency f given by the equation

$$2f = \frac{nv_2}{2L}, \tag{2}$$

where v_2 is the velocity of second sound and L is the length of the cavity. Note that the factor 2 appears on the left, because the frequency of the second sound is twice that of the excitation frequency f, as mentioned above.

3.1. Normal effect

Before measuring the normal effect, a preliminary experiment to observe the resonance of the second sound was performed to determine the resonance frequency. Power was applied to the heater and the temperature oscillation was measured as a function of frequency. The peak at the second resonance of the second sound was found to be 232 Hz.

In the normal effect measurements, power was applied to the heater in cavity A and the response of the electrodes at the other end of the cavity was measured. For this measurement, the 1st to 6th order peaks were observed, but the second order resonance showed the clearest peak as it was accompanied by the lowest number of spurious peaks. For more information on this experiment, one should refer to Ref. 5 for which the experimental setup was the same except that an FET amplifier was omitted in the present experiment to eliminate any experimental uncertainties.

Figure 4 shows the result of normal effect measurements of the second resonance. The charge oscillation q was converted from the induced voltage V by the equation $q = CV$, where C is an input capacitance of 280 pF for the present setup. The apparent peak of the electric oscillation of the second resonance is seen at 232 Hz. The resonance frequency 227 Hz calculated from Eq. (2) shows a deviation from the measured peak frequency 232 Hz. This disagreement often happens due to the so-called open end correction as mentioned in Ref. 5. However, it has readily been confirmed that the frequency of the peak 232 Hz in Fig. 4 is the exact same as that of the resonance frequency of the second sound in the preliminary experiment, showing that the peak is indeed caused by the second sound.

3.2. Reverse effect

Figure 5 shows the temperature oscillation measured by the thermal sensor of cavity A when the power is applied to the electrodes. The frequency was swept with a step of 0.1 Hz in the same range as for Fig. 4 in order to detect a peak more precisely. Should the reverse effect be present, a peak is anticipated at the same frequency 232 Hz as the peak in Fig. 4. However, no peak is seen in the data.

Figure 6 shows the results of cavity B under the same conditions, except the frequency sweep range is wider, ranging from 100 to 700 Hz with a step of 1 Hz for 3 different temperatures. The expected resonance frequencies calculated from Eq. (2) are indicated by arrows for each temperature. However, the data in Fig. 6 do not show any peaks for the 3 different temperatures.

As mentioned in the Sec. 1, Rybalko [1] reported the presence of the reverse effect. However, in our measurements, neither cavity showed the reverse effect signal. The reason for this discrepancy is not clear, but it might be due to the difference in the sensitivity of the setup or the noise level. In the present experiment, as shown in Figs. 5 and 6, the average noise levels for 1.5 K were of the order of 8 nV

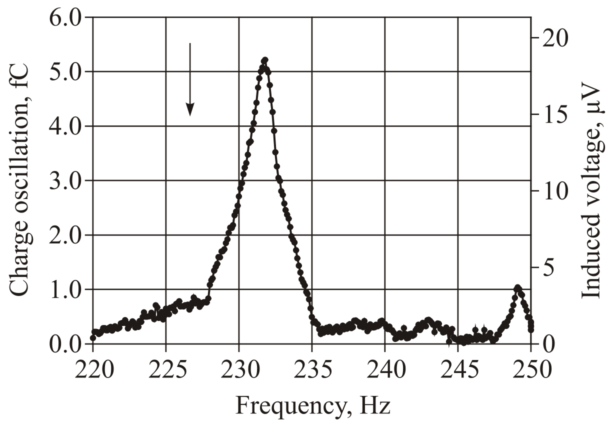

Fig. 4. Result of the normal effect measurements. The electric charge oscillation was measured at the electrodes of cavity A while sweeping the frequency of the voltage applied to the heater at 1.5 K. Note that the setup used here is that of previous experiments [5]. The frequency of the peak is 232 Hz, corresponding to the calculated 227 Hz. Their discrepancy is due to the open end correction.

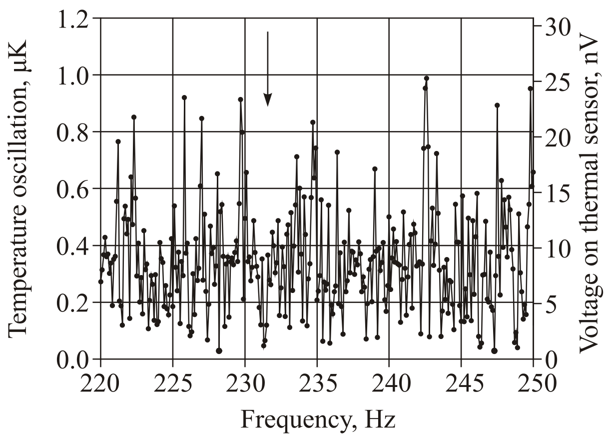

Fig. 5. Result of the reverse effect measurements in cavity A. The temperature oscillation was measured by the thermal sensor while sweeping the frequency of the voltage applied to the electrodes at 1.5 K. The setup used here is that of Fig. 1. The arrow shows the frequency 232 Hz corresponding to the peak in Fig. 4.

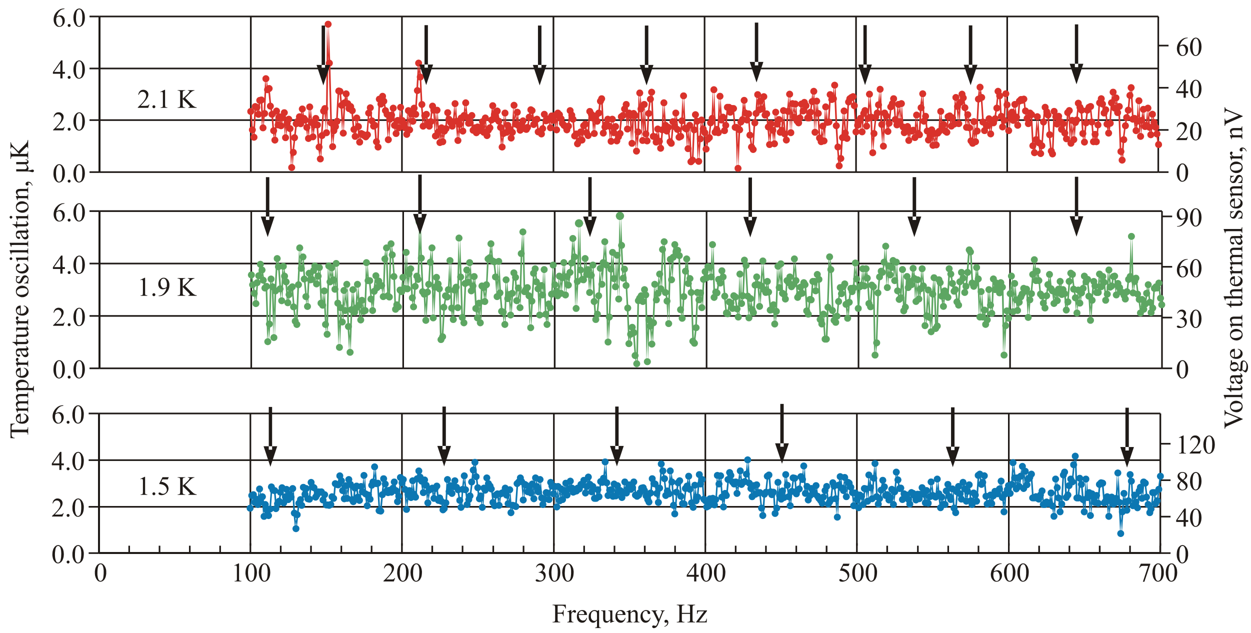

Fig. 6. (Color online) Results of the reverse effect measurements in cavity B. The temperature oscillation was measured by the thermal sensor for different temperatures while sweeping the frequency of the voltage applied to the Corbino-type electrodes (see Fig. 2). The arrows show the resonance frequencies calculated from Eq. (2).

for the cavity A and 80 nV for the cavity B, which corresponds to the average temperature oscillations of 0.3 μK for the cavity A and 3 μK for the cavity B.

Of note in Fig. 6 are two peaks around the expected resonance peaks at 2.1 K of 145 and 218 Hz. These peaks are not caused by the intrinsic phenomenon in the cavity because of the following two reasons. Firstly, these peaks did not appear in other runs with the same experimental conditions as the one at 2.1 K in Fig. 6. Secondly, they do not occur at lower temperatures. According to the two-fluid model, a larger fraction of helium will be in the helium II state at lower temperatures. While it is unknown how the ratio of superfluid and normal fluid helium affects second sound, previous experiments [5] have shown the normal effect to be of similar magnitude regardless of temperature in the regime of 1.76 to 1.92 K. As such, the reverse effect is not expected to vanish for lower temperatures, as is the case here.

3.3. Difference between cavities

For cavity A, the noise levels were lower due to shielding being more effective, as the copper mesh itself also acts as an electric shield. This is not the case for cavity B, where a stray capacitance between the electrodes and the thermal sensor occurs as the inner electrode is exposed to the interior of the cavity. Combined with the successful reproduction of electrical activation by second sound (Fig. 4), it can be said that the reverse effect either does not occur or is smaller than the observed noise levels. Also of note is the difference in signal strength. Figure 6, using cavity B, shows a decidedly larger noise than Fig. 5 (cavity A). The origin of this noise is thought to lie in a stray capacitance. This capacitance is not present to the same degree in cavity A because the copper mesh covers the entire cross-section of the cavity.

4. Conclusion

The reverse effect of electric response induced by second sound in helium II was searched for by detecting the second sound resonance in two types of cavities with different electrode structures. The results showed that the reverse effect was absent or undetectable for the given noise levels. These findings can help aid the understanding of the relationship between the electrical and thermal properties in helium II.

1. A.S. Rybalko, *Fiz. Nizk. Temp.* **30**, 1321 (2004) [*Low Temp. Phys.* **30**, 994, 2004].
2. A. Rybalko, E. Rudavskii, S. Rubets, V. Tikhiy, V. Derkach, and S. Tarapov, *J. Low Temp. Phys.* **148**, 527 (2007).
3. A. Rybalko, S. Rubets, E. Rudavskii, V. Tikhiy, S. Tarapov, R. Golovashchenko, and V. Derkach, *Phys. Rev. B* **76**, 140503-1 (2007).
4. T.V. Chagovets, *Fiz. Nizk. Temp.* **42**, 230 (2016) [*Low Temp. Phys.* **42**, 176 (2016)].
5. H. Yayama, Y. Nishimura, H. Uchiyama, H. Kawai, J.-P. van Woensel, and A.G. Hafez, *Fiz. Nizk. Temp.* **44**, 1386 (2018) [*Low Temp. Phys.* **44**, 1090 (2018)].
6. T.V. Chagovets, *Physica B: Condens. Matter* **488**, 62 (2016).

Дослідження оборотності електричного відгуку, викликаного другим звуком в надплинному гелії

Jean-Paul van Woensel and Hideki Yayama

Вивчено оборотність електричного відгуку, індукованого другим звуком в гелії II, так званий «зворотний ефект». Щоб забезпечити різний напрямок електричного поля та перевірити роль уривчастості поздовжньої течії від мідного сітчастого електрода використано дві різні циліндричні порожнини. Перевірено та зіставлено з даними попереднього експерименту відтворюваність нормального електричного відгуку, індукованого другим звуком. Ознак зворотного ефекту не виявлено. Результати показують, що незалежно від температури зворотний ефект відсутній або його величина нижче за межу чутливості вимірювань в нановольтовому діапазоні.

Ключові слова: надплинний гелій, другий звук, електрична активність, електричний відгук, зворотний ефект.

Исследование обратимости электрического отклика, вызванного вторым звуком в сверхтекучем гелии

Jean-Paul van Woensel and Hideki Yayama

Изучена обратимость электрического отклика, индуцированного вторым звуком в гелии II, так называемый «обратный эффект». Чтобы обеспечить разное направление электрического поля и проверить роль прерывистости продольного течения от медного сетчатого электрода использованы две различные цилиндрические полости. Проверена и сопоставлена с данными предыдущего эксперимента воспроизводимость нормального электрического отклика, индуцированного вторым звуком. Признаков обратного эффекта не обнаружено. Результаты показывают, что независимо от температуры обратный эффект отсутствует или его величина ниже предела чувствительности измерений в нановольтовом диапазоне.

Ключевые слова: сверхтекучий гелий, второй звук, электрическая активность, электрический отклик, обратный эффект.