J Low Temp Phys (2007) 148: 527–534
DOI 10.1007/s10909-007-9448-0

Electric Induction in He II

**A. Rybalko · E. Rudavskii · S. Rubets · V. Tikhiy ·
V. Derkach · S. Tarapov**

Abstract The correlation between the relative mechanical motion of normal and superfluid components of He II and its electrical characteristics has been observed for the first time. Three types of experiments in which the relative velocity of the components $\mathbf{V}_n - \mathbf{V}_s$ was excited by different methods (second sound, torsion oscillator, and heat flux) are discussed. An electrical response of the system was registered in superfluid liquid in all the cases.

PACS 05.70Ln · 05.70Jk · 64

1 Introduction

Until now the problem of a possible interrelation between the macroscopic mechanic motion of He II and its electrical properties remained practically unclear. For the first time the macroscopic motion in superfluid helium with definite direction of the relative velocity of the normal and superfluid component $\mathbf{V}_n - \mathbf{V}_s$ was demonstrated by Kapitza [1]. He observed a deflection of the light feather by the normal component flow. It was shown that the heat flux in He II was actually a clearly directed jet nonexpanding with distance, i.e., the jet possessed the property of persistence ("inertia"). It is then natural to clear up the origin of this "inertia", i.e. to identify the force generating the superfluid flows. This study is the first step in this direction focused on a search for a possible connection between the mechanical motion in He II

A. Rybalko (✉) · E. Rudavskii · S. Rubets · V. Tikhiy
B. Verkin Institute for Low Temperature Physics and Engineering, National Academy of Sciences of Ukraine, 47 Lenin ave., 61103 Kharkov, Ukraine
e-mail: rybalko@ilt.kharkov.ua

V. Derkach · S. Tarapov
Institute for Radiophysics and Electronics, National Academy of Sciences of Ukraine, 12 Proskury str., 61085 Kharkov, Ukraine

and an electric induction. Several types of experiments have been performed for this purpose.

Experiment I was made using the second sound method [2] in which the normal and superfluid components move in an antiphase [3]. The electric response of the system was measured by the electric capacitor technique [4].

In experiment II relative motion of the components $\mathbf{V}_n - \mathbf{V}_s$ was created with a torsion oscillator similar to that described in [5] in which only the normal component was entrained into motion by the wall.

In experiment III the investigation of the electric properties of He II was continued by the electromagnetic wave (30–198 GHz) method.

2 Observation of Electric Induction in the Second Sound Wave

The experiments with first and second sounds were performed using the resonance method in the temperatures range $1.3 \div 4.2$ K in two cavities with working lengths 1.05 and 28 mm. Piezoceramic sensors served as a first sound generator and a detector. A gold or copper thin-film heater was used to generate a second sound. A thin-film thermometer (bolometer) served as a second sound detector.

A specific feature of the experimental devices was that the cavity and capacitor used to measure the polarizability of He II were combined in one apparatus; the first- and second-sound cavities also functioned as capacitors for detecting possible electric induction (displacement) in the He II. An electrode placed at the location of the bolometer and the inner wall of resonator body formed the plates of the capacitor. We measured the potential difference ΔU of the capacitor and the value of the charge Δq (induction) was determined as $\Delta q = \Delta U \cdot C_{\text{in}}$, where C_{in} is the input capacitance. Current was passed periodically through the heater and a second sound wave was excited in the cavity. The wave was registered either from the temperature variations shown by the thermometer or with the capacitor plate from the appearing electric induction.

The typical resonance curves of the temperature oscillations ΔT which ordinarily appear when the second sound in He II is excited are shown in Fig. 1a. The results obtained for the second sound velocity and absorption (determined from the resonance widths) agree very well with the published data [3, 6].

An unusual result was obtained when the bolometer was replaced with an electrode sensitive to an electric induction (displacement): sharp resonances of electric induction ΔU (Fig. 1b) appeared at the same frequencies as for ΔT. It means that the relative motion $\mathbf{V}_n - \mathbf{V}_s \neq 0$ in the second sound wave is accompanied by electric induction of the liquid. Note that our measurements above the λ-point did not show a signal ΔU. It appeared only in the He II region and its amplitude increased as the temperature decreased. The typical temperature oscillations were <1 mK, and the induced potential was <1 μV at the power from the heater <1 mW/cm^2. Since we used the AC technique in the experiment, it is natural to suppose that the electrical induction is caused by the acceleration of the two fluid components. The role of the acceleration in this effect is studied also using torsion experiments (Sect. 3) and this question was considered theoretically in [7].

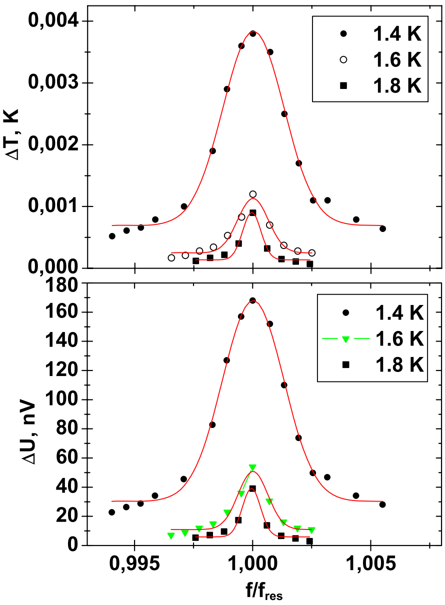

Fig. 1 (Color on-line) Amplitude–frequency curves of the second-sound cavity: **a** amplitude of the oscillations of temperature of the thin-film thermometer (bolometer); **b** amplitude of the oscillations of the electric induction potential. *Dots*—experimental results, *solid line*—a fit of the Gaussian distribution to the experimental points

To eliminate the possibility of thermo-emf, due to Kapitza's thermal resistance, on the receiving electrode, the film electrode was replaced with a solid brass electrode. Because of its higher thermal heat capacity, the time thermal relaxation was several orders of magnitude greater than f_{res}^{-1}, but the amplitudes ΔU did not change much. This was unequivocal evidence that there was no thermo-emf.

It was natural to search for the reverse effect of the second sound wave that might appear due to artificial polarization of superfluid helium. For this purpose the heater at one edge of the second sound resonator was replaced with a capacitor (see details in [4]). The second sound wave was excited by periodical electrical polarization of a small portion of liquid. For the first time the experiment showed that the second sound can be excited by electrical method in addition to the thermal and mechanical techniques. The ΔT is natural to be considered as the characteristic of thermal energy of system, and ΔU as electrostatic energy. The analysis showed that the ratio between ΔT and ΔU measured under identical conditions does not depend on temperature and is a constant 2.3×10^4 K/V with accuracy of $\pm 25\%$ (see Fig. 2).

The experiments with first sound in which wave $\mathbf{V}_n = \mathbf{V}_s$ within a similar scheme show that no electrical induction occurs in this case, even with high powers applied to the emitter. Thus, He II with counterflowing normal and superfluid components behaves like a ferroelectric to which mechanical stresses are applied, i.e., it is polarized.

3 Observation of Mechanoelectric Effect

The second experiment was performed using the torsion generator technique [5]. Its basic feature is that the motion of a solid in He II at a subcritical velocity entrains only a normal component. It is thus possible to create the relative motion of the superfluid

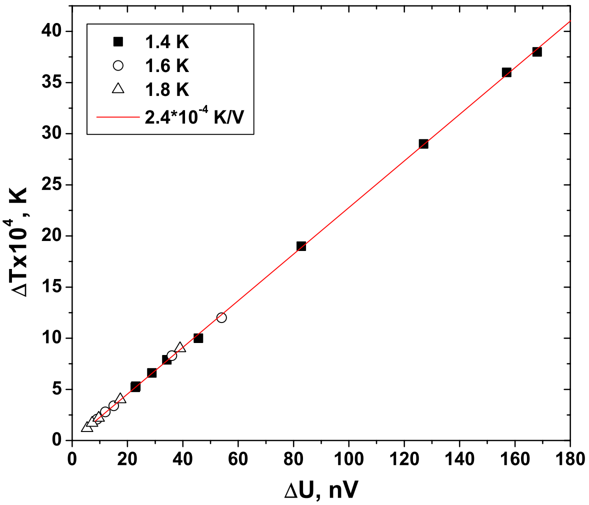

Fig. 2 (Color on-line) Relation between the bolometer signal ΔT and the potential signal ΔU of the electric displacement which is induced with the same power fed to the sound generator for different temperatures. The *solid line* is drawn through the experimental points; $\tan\alpha = \Delta T/\Delta U = 2.3 \times 10^4$ K/V

and normal components without changing either temperatures or normal and superfluid densities ρ_n and ρ_s. The measuring device was a torsion oscillator developed by Reppy [5] for operation with helium. Our unit however differs from device of [5] in that an electrode was passed the center of the chamber via the filling capillary. The electrode (a wire 0.2 mm in diameter) was mounted at the bottom of the suspension without touching the wall of the capillary and was not involved in the motion when the oscillator was in operation. The inner wall of oscillator and an electrode formed a capacitor for measuring the electric response. In the experiment, force was applied to excite oscillations of the oscillator, and the frequency and amplitude of mechanical torsion oscillations of the chamber and the electric induction were measured.

The most interesting result of experiment was that the motion of the normal component of He II entrained by the wall of the filled torsion oscillator caused polarization of liquid at velocities that are below a certain critical value, 30 μm/s. The induction was observed at much higher velocities of the motion of the chamber wall in saturated and unsaturated He films covering the oscillator walls. A positive potential of doubled frequency was always induced on electrode located inside the chamber at temperature below T_λ. The potential was observed to modulate with time (in several minutes), which turned out to be due to the appearing circulating flow (see Fig. 3). The observed hysteretic phenomena are also connected with the dynamics of changes in circulation. It has been found that the induction is proportional to (i) the mass of superfluid component, (ii) the square of the oscillation velocity $\mathbf{V}$ (inertial force). The latter fact confirms that the value of the electrical induction is proportional to the acceleration of the components. An analysis of the experimental results showed that the amplitude of the induction signal near the λ-point is proportional to $\mathbf{V}^2$, but the agreement with theoretical calculation [7] is qualitatively only so far. There is a correlation between the mechanical energy losses in the torsion oscillator and the induction magnitude, which points to a close interrelation of mechanical and electric phenomena in He II (see Fig. 4). Above T_λ the induction signal was not observed within the accuracy of 3×10^{-9} V/Hz$^{-1/2}$.

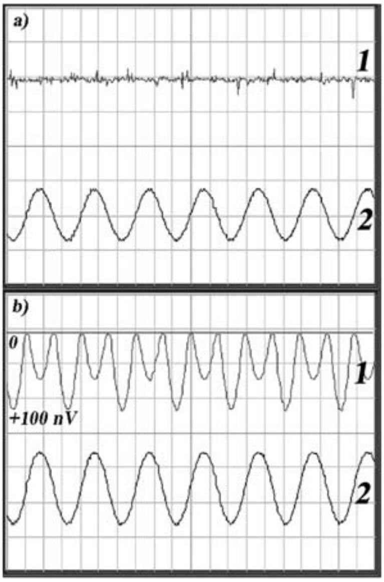

Fig. 3 Traces of the signal shape on the oscilloscope screen at temperatures of 2.3 K (**a**) and 2.0 K (**b**) versus time: *curves* (*1*) are the amplitudes of the electrical induction; *curves* (*2*) are the amplitudes of the mechanical oscillations of the oscillator ($f \approx 136$ Hz)

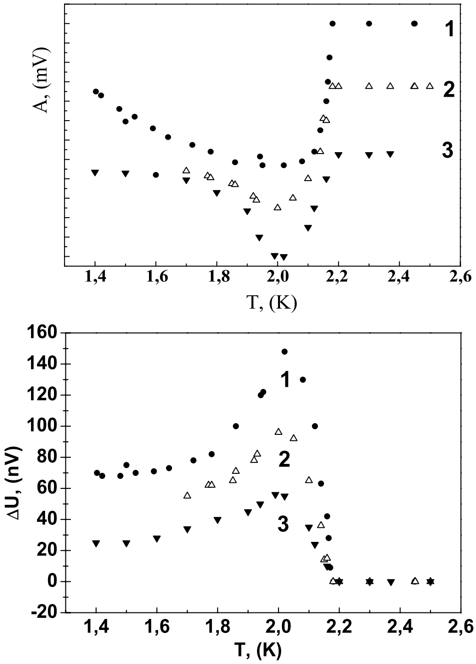

Fig. 4 Primary experimental data: **a** temperature dependence of the amplitude of the torsion generator oscillations; **b** the electric induction (electric displacement) for three values of the wall velocity **V**. (*1*) 700 µm/s; (*2*) 600 µm/s; (*3*) 500 µm/s

4 Investigation of Electromagnetic Absorption Under Condition of Relative Motion of the Components

In the experiment described above the occurrence of the electric induction in liquid helium under presence of superfluid flow is observed. It can be expected that the

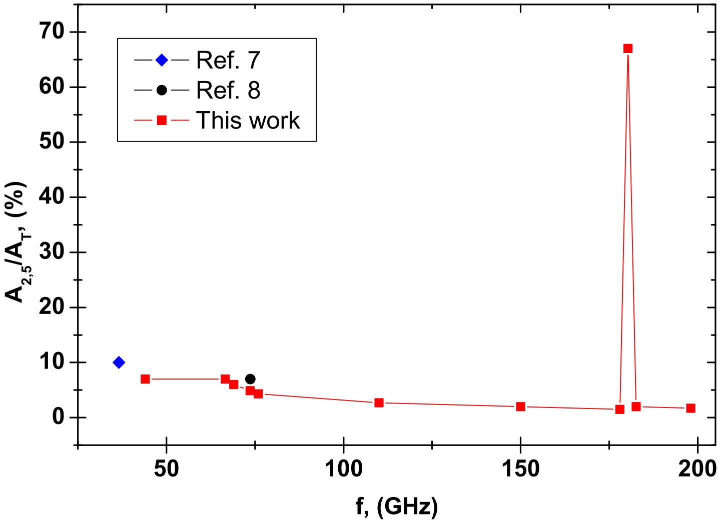

Fig. 5 (Color on-line) Frequency dependence of relative absorption of electromagnetic wave at $T = 1.9$ K

electrical polarization of He II in the presence of the flow of normal (superfluid) component should lead to specific peculiarities of electromagnetic waves propagation. To check this fact, the absorption of the electromagnetic wave by liquid helium was investigated in the frequency range $30 \div 198$ GHz and at temperatures $1.3 \div 4.2$ K.

The relative motion of the superfluid and normal components was initiated using the DC heat flux technique. A thermally insulated flask with a thermometer and a heater inside (similar [1]) was placed in the cell and connected, via a nozzle with a 1000×10 μm^2 throat, to a helium bath. As current was switched on through the heater, the normal component gushed from the nozzle at a tangent to the sidewall of the disc resonator [8, 9] of electromagnetic waves, which located horizontally in liquid helium. The exciting elements were dielectric rectangular wave guides placed in the plane of disc at its diametrically opposite sides. The antennas thus arranged excited quasi-travelling "whispering gallery" $TE_{mn\delta}$ waves in the dielectric disc resonator that had a high azimuthal index ($m = 24$–110) and a preferential direction of propagation along the cylindrical surface of the resonator. The electromagnetic field of the "whispering gallery" mode was concentrated near the cylindrical surface of the resonator and attenuated rapidly on the outside and inside of the disc with distance from the cylinder. As a result, the oscillations suffer ultimately small radiation losses [8, 9]. The unit made it possible to measure the absorption of electromagnetic wave power near the wall of the resonator under different conditions with spontaneous or artificial circular flows of superfluid component evolved around the cylinder. Using this unit, it was easy to generate and vary the flow circulation velocity around the sidewall of the resonator. A similar flask was mounted at the diametrically opposite side of the resonator to excite a counterflow.

The idea of experiment was as follows. The resonator was continuously excited by an electromagnetic wave in one of the selected mode and the absorption of electromagnetic energy was measured. The frequency dependence of the electromagnetic

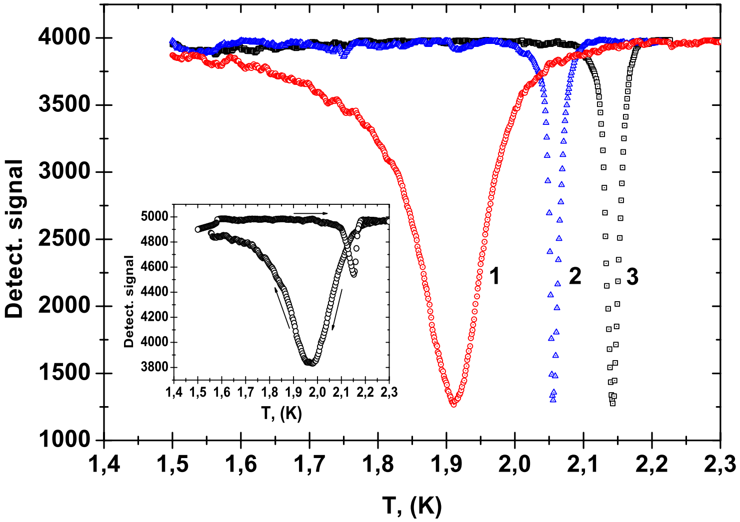

Fig. 6 (Color on-line) Temperature dependence of the signal amplitude at $f = 180.3$ GHz: (*1*) $I^2R = 0$; (*2*) $I^2R = 3 \times 10^{-5}$ W; (*3*) $I^2R = 6 \times 10^{-5}$ W

wave absorption coefficient exhibits a sharp maximum at 180.3 GHz (Fig. 5), which is close to the minimum roton energy 8.65 K.

A typical temperature dependence of the electromagnetic wave amplitude is presented at Fig. 6 for various velocities of the superfluid flow around the sidewall of the resonator (various heater power $\dot{Q}$). The curve 1 was obtained under cooling of the system with the cooling velocity of 0.05 K/min for the case $\dot{Q} = 0$. The observed position of the minimum is very sensitive to the heat flow running from the flask (curves 2–3). As it seen from Fig. 6, the minimum of the signal amplitude becomes more sharp and shifts to the higher temperatures with the heater power. The curves 1–3 were measured under cooling with the same velocity. At the inset the temperature dependence of the signal amplitude is presented for the temperature drift up and down for the case $\dot{Q} = 0$. The marked hysteresis is observed in this case. The mechanism of the superfluid flow influence on the electromagnetic waves absorption has not been calculated so far.

5 Conclusions

The results obtained show that the relative motion of the normal and superfluid components leads to appearance of electrical induction. It was observed directly using both second sound and torsion techniques. Experiments with UHF electromagnetic waves showed resonance absorption of electromagnetic wave. The amplitude of wave is very sensitive to the velocity of the superfluid flow. The correlation between mechanical and electric properties of superfluid helium calls for further experimental and theoretical investigation.

Acknowledgements This study was supported in part by the Ukrainian Government Foundation for Basic Research (Project 02.07.00391, agreement F7.286-2001).

References

1. P.L. Kapitza, Sov. Phys. JETP **11**, 1 (1941)
2. V.P. Peshkov, Sov. Phys. JETP **18**, 857 (1948)
3. E.M. Lifshits, Sov. Phys. JETP **14**, 116 (1944)
4. A.S. Rybalko, Low Temp. Phys. **30**, 994 (2004)
5. J.E. Berthold, D.J. Bishop, J.D. Reppy, Phys. Rev. Lett. **39**, 348 (1977)
6. K.N. Zinoveva, Sov. Phys. JETP **25**, 2(8), 235 (1953)
7. L.A. Melnikovsky, arXiv:cond-mat0505102v115, 2006. J. Low Temp. Phys., in press
8. E.M. Ganapolsky, A.V. Golik, A.P. Korolyuk, Phys. Rev. B **51**, 11962 (1995)
9. V.N. Derkach, R.V. Golovashchenko, S.V. Nedukh, O.S. Plevako, S.I. Tarapov, in *Proceedings of 15th International Conference CriMiCo'2005* (Weber, Sevastopol, 2005), p. 836
10. A.S. Rybalko, S.P. Rubets, Low Temp. Phys. **31**, 623 (2005)