ELECTRICAL EFFECTS IN SUPERFLUID HELIUM. I. THERMOELECTRIC EFFECT IN EINSTEIN'S CAPACITOR

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The Einstein's ideas about the thermodynamical fluctuational nature of some electrical phenomena and the difference of electrical potentials U in a capacitor at temperature T were proposed in 1906-1907. On base of these ideas we explain the experimental results, which were recently observed under the action of the second sound standing wave in the electrical capacitors which take placed in the superfluid ^{4}He and in the torsional mechanical resonator. The Einstein's approach, based on the interrelation of thermal, mechanical and electrical fluctuations, allows to obtain the quantitative results, coinciding with the experimental datas for the correlations of the alternate low temperatures difference in second sound wave and alternate electric potentials difference between the capacitor plates in superfluid helium at as well as in the rotating mechanical oscillator.

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INTRODUCTION

In 1906, Einsteinin his research paper on the Brownian motion [1], firstly showed that there is an interconnection between the thermodynamical fluctuations and the electric effects in the linear electric circuit. In the agreement with the Einstein's conclusions, the electric charge $q(t)$, which transfers through the cross section of closed circuit conductor, is defined by the temperature T, closed circuit resistance R and observation time t variables in the expression $\overline{q^2} = 2t\, k_B T / R$, where k_B is the Boltzmann constant, the upper emphasis designates the averaged value. The expression for the current is $\overline{I^2} = 2k_B T / Rt$, and the equation for the difference of electrical potentials is $\overline{U^2} = 2R\, k_B T / t$ in this electrical circuit. In 1907, Einstein [2] showed that the electric potentials difference U at plates of an electric capacitor with the capacitance C must appear because of fluctuational effects in surrounding medium at temperature T. He proposed that the electric capacitor can be considered as a Brownian particle, which has one degree of freedom, connected with its electric subsystem and in the agreement with the Einstein's calculations the fluctuations for U can be observed in an electric capacitor. According to the equipartition theorem for any degree of freedom, it appears that the electric energy stored by an electric capacitor is equal to the thermal energy as in equation $C\overline{U^2}/2 = k_B T/2$.

In [2], the corresponding calculations were completed and it was shown that the electric potentials difference U can be measured with the use of experimental measurement setup at appropriate selection of capacitance C at room temperature T. On that time, the discussed experiment [2] was not done, because the Einstein's first research paper on the thermodynamic electrophysics [2] was not appropriately noticed among his other revolutionary research ideas. A few years later, de Haas-Lorentz [5] developed these theoretical representations for other elements of linear electric circuits and showed that, in the fluctuational case, the inductance L will store the energy as in equation $L\overline{I^2}/2 = k_B T/2$. In all the considered cases, the thermodynamic fluctuations can do both to create the electrical currents as well as to scatter the electrical currents. The heating energy, which is transforming at this process during time τ, is equal to $\overline{U^2}\tau/R = 4k_B T$ (in this case $U = IR$, I is the electrical current, τ is the time, $\tau << R/L$). The difference of obtained result in the two times in the given expression in comparison with the expression in [1] is connected with the fact that the characteristic time periods for the linear magnitude U and the quadratic magnitude U^2 are different in the two times. In 1928, Nyquist [6] considered the spectrum of possible frequencies of electrical oscillations in the linear RLC circuit, and found an interconnection of the time τ with the frequencies band span $\Delta\omega = 2\pi/\tau$, in which the registration of signal is performed. Nyquist [6] also pointed to the possible quantum case, which can be realized at the following condition $\hbar\omega > k_B T$, where ω is the circular frequency of electric signal in linear circuit. In 1951, Callen and Welton [7] obtained the quantum fluctuation – dissipation formula with consideration of contribution of zero oscillations and found an important relation $\overline{U^2_\omega} = \hbar\omega\, R_\omega\, cth(\hbar\omega / 2k_B T)$ (also see [8-11]), where $\hbar = h/2\pi$, h is the Planck constant. As far as we know, the experiment for linear circuit with a capacitor, proposed by Einstein [2], was not completed in the XX century. At the same time, the fluctuational electrical noises in the resistors were researched widely. The results obtained in the fluctuation – dissipation theory for the linear circuits were confirmed in both the classic case as well as the quantum case, serving as one of the possible methods for research of the electromagnetic fluctuations and the Van der Waal's forces [12, 13].

In 2004, Rybalko [3] measured the alternating difference of electrical potentials U' between the plates of an electrical capacitor, placed in the superfluid helium (helium II) at $T < T_\lambda$ ($T_\lambda = 2.172$K is the temperature of superfluid transition). The wave of second sound with the frequency of ω_2 was propagating in helium II, and was accompanied by the oscillations of temperatures difference T'. The amplitude of oscillations of temperature was equal to $T' \approx (10^{-2} \ldots 10^{-4})$K and, as it was discovered in [3], the alternating difference of electrical potentials with the magnitude $U' \approx (10^{-7} \ldots 10^{-9})$V was generated at the same frequency of ω_2. The relation of amplitudes satisfied the condition $U'/T' \approx k_B/2e$, where e is the electrical charge of an electron.

In 2005, Rybalko and Rubets [4] placed a capacitor in the torsional mechanical oscillator with the helium II, which oscillated with the frequency of Ω. In this case, the alternating electrical signal U' with the approximately same amplitude at frequency of 2Ω was registered. Authors [3, 4] proposed that the potentials U' are due to some effects, connected with the electrical polarization of helium II, however the possible physical mechanism of polarization was not known yet.

Presently, there are more than ten well known theoretical researches [14-26], devoted to the interpretation of experimental data in [3, 4]. In these research papers, the propositions about possibility of existence some new effects, including the inertial effects [16], which, in their authors opinion, might lead to the electric activity and polarization of superfluid helium in conditions of low temperature experiments in [3, 4]. However, the critical analysis of theoretical researches in [21, 22] demonstrated that the proposed models forecast the magnitude of oscillations of potentials difference U' in $10^5 \ldots 10^6$ times less than the amplitude observed in [3, 4]. It is also not explained: why does the magnitude of oscillations of potentials difference U' not depend on the temperature T in [3], when all the properties of helium II change in the researched range of temperatures significantly.

We will show up below that, in our opinion, some of the experimental results [3, 4], related to the thermoelectric fluctuational effect, appear in a capacitor due to the effect, considered by Einstein [2], when there is an alternating difference of temperatures T' between the plates of a capacitor. Let us take to the attention the fact that the conditions $(\hbar\omega_2,\ \hbar\Omega) << k_B T$ are true for the second sound wave and rotational oscillations in [3, 4], therefore these effects belong to the classic case of fluctuational processes, hence it is enough to use the representations in [2] for their theoretical description.

FLUCTUATIONAL THERMOELECTRIC EFFECT IN A CAPACITOR

As it is known, any physical body with the temperature T, is a source of electromagnetic radiation. The spectrum of radiation depends on the body temperature only, if the body and radiation are in the state of thermal equilibrium. Following the Einstein [2], let us consider the case, when the characteristic radiation frequency ω satisfies the classic condition $\hbar\omega < k_B T$. We will believe that the quasi-statistical electric and magnetic fields are dependent on the thermal fluctuations of electrical charges. The state of physical system is characterized by some values of its physical parameters $\xi_1, \xi_2, \ldots \xi_n$, defining the thermodynamic state [2, 27]. In general case, these parameters can characterize the microscopic state as well as the macroscopic state of physical body. In the microscopic case, when the physical body can be represented by a group of microscopic particles n, the value of physical parameter ξ_i will characterize the particle i. In the macroscopic case, the value of physical parameter ξ_i will characterize all the physical body with different states of freedom with indexes i. In the equilibrium state, these parameters have some average values $\overline{\xi_1}, \overline{\xi_2}, \ldots \overline{\xi_n}$. The interconnection between the entropy of physical system $S(\xi_1, \xi_2, \ldots \xi_n)$ and the statistical weight $W(\xi_1, \xi_2, \ldots \xi_n)$ of a corresponding state of system is defined by the Boltzmann expression $S(\xi_1, \xi_2, \ldots, \xi_n) = k_B \ln W(\xi_1, \xi_2, \ldots, \xi_n)$ [27]. The probability of system's presence in a particular state, characterized by the parameter ξ_i, is equal to $P_i(\xi_i) = W_i(\xi_i) \Big/ \sum_{\xi_i} W_i(\xi_i)$. In the equilibrium state, $\xi_i = \overline{\xi_i} = \xi_{i0}$, and the entropy reaches its maximum value $S_0(\xi_{10}, \xi_{20}, \ldots, \xi_{n0}) = k_B \ln W_0(\xi_{10}, \xi_{20}, \ldots, \xi_{n0})$. The thermodynamic fluctuations lead to the deviation of given parameters from their average values. The probability P that the parameter ξ_i has its values in the range $\xi_{i0} + d\xi_i$ is defined by the completed work $dA = -TdS$, which is equal to the change of free energy in thermodynamic system. At the change from ξ_{i0} to ξ_i, the work will be equal to $A = -\int TdS$, or $A = -T(S - S_0) = k_B T \ln(P/P_0)$. The probability of system presence in this state is $P = P_0 \exp(-A/k_B T)$. Let us suppose that the deviations $\xi_i - \xi_{i0}$, appearing at the action of random fluctuations, are with the alternating signs and small values, therefore A can be decomposed in the Taylor series, which begins with the second order term. Then, we will get $A = b(\xi_i - \xi_{i0})^2 + \ldots$, where b is the constant. The probability of presence of system in the state $\xi = \xi_i$ will be

$$P(\xi_i) = P_0 \exp[-b(\xi_i - \xi_{i0})^2 / k_B T]. \qquad (1)$$

We will obtain the probability magnitude P_0 integrating $P(\xi_i)$ over $\xi_i(-\infty, +\infty)$. These limits can be set, because of the convergence of an integer, which will be equal to the one

$$\int_{-\infty}^{+\infty} P(\xi_i) d\xi_i = P_0 \int_{-\infty}^{+\infty} \exp[-b(\xi_i - \xi_{i0})^2 / k_B T] d\xi_i = \\ = P_0 \cdot (\pi k_B T / b)^{1/2} = 1. \qquad (2)$$

It follows from the above that $P_0 = (b/\pi k_B T)^{1/2}$.

Taking to the consideration that the equilibrium electric and magnetic fields are defined by the thermodynamic state of the body, which is characterized by its temperature, then, in the classic case, the intensities of the electric field E and the magnetic field H have to be among the values of parameters ξ_i [27]. The deviation of average energy from equilibrium value may be written as

$$\overline{A} = \frac{1}{2} V_E \varepsilon\varepsilon_0 \overline{(E - E_0)^2} + \frac{1}{2} V_H \mu\mu_0 \overline{(H - H_0)^2}, \qquad (3)$$

where E is the intensity of electric field, H is the intensity of the magnetic field, E_0 and H_0 are the equilibrium magnitudes of electric and magnetic field, ε is the relative electric permittivity, ε_0 is the free space permittivity, μ is the relative magnetic permeability, μ_0 is the free space magnetic permeability, V_E is the volume, in which the electric field is concentrated in the capacitor with capacitance C and V_H is the volume, in which the magnetic field is concentrated in the induction L. The expressions for the electric and magnetic energies are similar and quadratic by the fields in both cases. Let us note that there are the resonance phenomena in the LC electrical circuit. The fluctuational oscillations of the electric and magnetic fields have the maximum amplitudes near to the resonance frequency $\omega_0 = (LC)^{-1/2}$ in the LC electrical circuit, while the fluctuational oscillations of the electric and magnetic fields have a wide spectrum similar to the white noise in an electrical capacitor. We will analyze the response of the linear RC electric circuit and limit our research by the consideration of the case, directly related to the experiment [3] and only connected with the electric field in the capacitor C.

The average work $\overline{A}$, which must be done by the system in order to change the intensity of electric field from E_0 to E, can be represented as the Gaussian integral

$$\overline{A} = \frac{1}{2}V_E\varepsilon\varepsilon_0\overline{(E-E_0)^2} = \frac{1}{2}\int_{-\infty}^{+\infty} V_E\varepsilon\varepsilon_0(E-E_0)^2 P(E)dE. \quad (4)$$

Here, the probability is $P(E) = P_{E0}\exp[-b(E-E_0)^2/k_B T]$, where $P_{E0} = \left(b/\pi k_B T\right)^{1/2}$, $b>0$ and $b = V_E\varepsilon\varepsilon_0/2$. The integer, which defines the average work, can be transformed as $\overline{A} = \frac{k_B T}{\pi^{1/2}}I(\varphi)$, where $I(\varphi) = \int_{-\infty}^{+\infty}\varphi^2\exp(-\varphi^2)d\varphi = \pi^{1/2}/2$ and $\varphi = \left(V_E\varepsilon\varepsilon_0/2\right)^{1/2}\left(E-E_0\right)$ (the integer $I(\varphi)$ is shown in [28]). The final result $\overline{A} = k_B T/2$ is equal to the thermal energy, related to the one degree of freedom of macroscopic body. This is explained by the fact that the part of thermodynamic system, which is connected with electric field, can have the only one predetermined orientation of direction of vector $\boldsymbol{E}$ in every point of space in a capacitor. In a plane capacitor, the vector $\boldsymbol{E}$ is directed toward the shortest direction $\boldsymbol{n_0}$ between the two plates, and the task is effectively reduced to the one dimensional case. In particular case, it is possible to assume that there is no the external electric field, $E_0=0$. At homogenous temperature, the two orientations of vector $\boldsymbol{E}=\pm E\boldsymbol{n_0}$ have equal probabilities, hence the time dependent fluctuating electric field $E(t)$ is random with alternating plus-minus sign. The electric field average magnitude is $\overline{E(t)} = \int_{t1}^{t2}E(t)dt \Big/ \int_{t1}^{t2}dt = 0$, if the time interval $(t_2-t_1)>>RC$, where R is some equivalent resistance of circuit with an electrical capacitor in Fig. 1.

The characteristic time of correlation $\tau=RC$ corresponds to the time of attenuation of fluctuation in a circuit of a capacitor. Let us note that the resistance R has the temperature T, and the fluctuational electric current appears in it in agreement with the fluctuation-dissipation theorem. The fact that the resistance R doesn't represent a main source of the fluctuations of potentials difference, but defines the time of relaxation of the fluctuations (see below), is a main distinctive feature of such simple linear scheme. As it was shown above, the average quadratic magnitude of the electric field $\overline{E_t^2} = \int_{t1}^{t2}E(t)E(t)dt \Big/ \int_{t1}^{t2}dt$ is not equal to the nil. The full energy of electric field in a capacitor with volume V_E can be expressed by its macroscopic capacitance C as $\frac{1}{2}V_E\varepsilon\varepsilon_0\overline{E^2} = \frac{1}{2}C\overline{U^2}$, where the potentials difference is $U = \int_0^d E(x)dx$, and the capacitance of plate capacitor only depends on the geometric dimensions $C = \varepsilon\varepsilon_0 S_{pl}/d$, where d is the distance between the plates, and S_{pl} is the square of plate of a capacitor. From this, we come to the expression obtained by Einstein

$$\frac{1}{2}C\overline{U^2} = \frac{1}{2}k_B T. \quad (5)$$

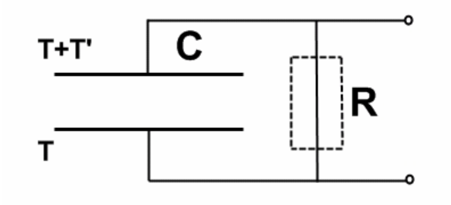

Fig. 1. Electrical circuit with capacitor C and conditional resistance R; difference of temperatures between plates is T'~T$_0$ sin(ω$_2$ t)

This expression doesn't depend on the resistance R in the electric circuit, which connects the plates of a capacitor, that is the considered case, when the frequency of thermal fluctuations is significantly more than $1/RC$. It is possible to write $\frac{1}{2}q\overline{\overline{U}} = \frac{1}{2}k_B T$, where $q = C\overline{\overline{U}}$ is the average fluctuating electric charge of a capacitor, and $\overline{\overline{U}} = \sqrt{\overline{U^2}}$ is the average quadratic value of potentials difference. The charge of capacitor in fixed time moment времени $q(t)$ consists of the discrete number of electrons, while its average quadratic value $\overline{N} = \frac{C\overline{\overline{U}}}{e}$ can be fractional as a result of time averaging (e is the charge of an electron). The stored electric energy is $\frac{1}{2}\overline{N}e\overline{\overline{U}} = \frac{1}{2}k_B T$, and it is proportional to the temperature. If T and C are constants the average quadratic difference of potentials decreases at increase of a number of fluctuating electrons

$$\overline{\overline{U}} = \left(\frac{kT}{C}\right)^{1/2} = \frac{1}{\overline{\overline{N}}}\frac{k_B T}{e} \quad (6)$$

and reaches its maximum at $N=1$. The electric energy, related to the one fluctuating electron, is $e\,\overline{\overline{U}} = \frac{k_B T}{\overline{\overline{N}}}$. The full energy, expressed by the charge and capacitance, is equal to

$$\frac{1}{2}\frac{\overline{q^2}}{C} = \frac{1}{2}\frac{\overline{N^2 e^2}}{C} = \frac{1}{2}k_B T. \quad (7)$$

The same expression between the number of fluctuating electrons and the temperature $\overline{N^2} \propto T$ is true in the metal in the degenerative electron Fermi-system at the temperature *T*, which is much less than the temperature of degeneration (see [9], §113). We didn't take to the account the Fermi statistics of conduction electrons. The matter is that the electric fields of conduction electrons in the metal are exactly compensated by the charges of metal nucleuses at the distances $r \approx a_0$, where a_0 is the distance between the nucleuses; and the condition of electro-neutrality is true in the metal. The translation invariance of metal's crystal grating allows having the free transfer of conduction electrons in the metal. In this case, the Fermi statistics has to be taken to the account in view of the big density of states and degeneration of electronic system. The electrons, which are situated near the Fermi surface in the momentum space, mainly contribute to the energy and charge transfer. The thermoelectric coefficient in metal at low temperature in a few kelvins is very small: $\alpha \propto kT/\varepsilon_F \approx 10^{-4}$ [9], ε_F is Fermi energy. In our case, the electrons, which create both the charge at plates of a capacitor and the fluctuating electric field of a capacitor, can be considered as the classic particles, because their surface density at plates of a capacitor is not big, hence their Fermi energy ε_F is very small. The characteristic de Broglie wavelength of the electrons will be significantly bigger in comparison with the distances between the nucleuses; and the distance between the energy levels is small in comparison with the temperature $\Delta\varepsilon \ll k_B T$. The electric field, created by the electrons, isn't shielded by the charges of nucleuses at distances between the atoms in the metal, and propagates at the macroscopic distance $d >> a_0$ in the space between the plates of a capacitor. In the experiment [3], a general number of the electrons wasn't big indeed (see below). The calculation of energy of this electric field was completed by the authors above.

Now, let us consider the thermoelectric effect for the fluctuational electrons, appearing in the case, when the plates of a capacitor have some different temperatures. In the experiment [3], the plates of a capacitor were in He II at certain equilibrium temperature T, and the wave of second sound generated the alternate difference of temperature $T'(t) = T'_0 exp(i\omega_2 t)$ between the plates ($T'(t) << T$). We will assume that one of plates of a capacitor is at constant temperature *T*, and the temperature of second plate is $T + T'(t)$. The change of thermal and electric energies of electrons at variation of plate temperature has to be taken to the account in view of the presence of a gradient of temperature dT'/dr between the plates of a capacitor. In the linear response theory [27], each of N electrons of electric fluctuation takes the additional energy, which is equal to $\frac{1}{2}k_B T'$. This is accompanied by an appearance of corresponding addition to the potentials difference U'. Herewith, the change of a full number of fluctuating electrons *N* at the action of small difference of temperatures T' is also small $N' << N$.

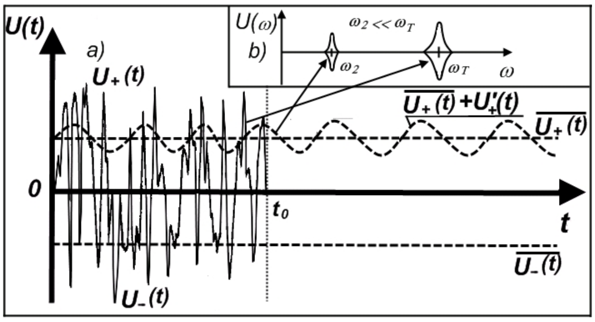

Fig. 2. Conditional chart of fluctuational dependence of potentials difference U(t) between plates of capacitor on time t at some constant temperature T (a) and on frequency (b), where ω_T is the Brownian frequency of potential difference in capacitor and ω_2 is the frequency of second sound

Let us consider some conditional dependence of potentials difference *U(t)* between the plates of a capacitor on the time in Fig. 1,a and on frequency dependence in Fig. 1,b. The following expressions to characterize the function *U(t)* can be written, if the temperature *T* on the plates of a capacitor is same:

$$\overline{U(t)} = 0, \ \overline{U^2(t)} \neq 0 , \quad (8)$$

$$\overline{U_+^2(t)} = \overline{U_-^2(t)} \neq 0 , \quad (9)$$

$$C\overline{U^2(t)} = C\left(\overline{U_+^2(t)} + \overline{U_-^2(t)}\right) = k_B T , \quad (10)$$

$$C\overline{U_+^2(t)} = C\overline{U_-^2(t)} = k_B T/2 , \quad (11)$$

$$C\overline{U_+^2(t)} = q\overline{\overline{U_+}} = k_B T/2 , \quad (12)$$

where $\overline{\overline{U}} = \left(\overline{U^2}\right)^{1/2}$ and $q = C\overline{\overline{U_+}} = Ne/2$, where *N* is the average number of fluctuating electrons at the both plates in a capacitor.

Let us assume that there are the upper and lower plates in a conditional condensator (see Fig. 1). We define the potentials difference as U_+, when the electrons, creating the charge, are at the upper plate in a capacitor. We assign the potentials difference as U_-, when the electrons, creating the charge, are at the lower plate in a capacitor. Moreover, we assume that the temperature is changing in time and is equal to $T+T'(t)$ at the upper plate of a capacitor; and the temperature is constant and is equal to *T* at the lower plate of a capacitor. The oscillating system in [3] can be divided by two parts: 1) the mechanical part, which is connected with the fluid He II, and 2) the eletrical part, which is consisted of a capacitor in the fluid He II, and its electrical circuit, including the voltmeter with the input resistance *R*. As it is shown above, the oscillations induced by the wave of second sound in the helium normal and superfluid subsystem are accompanied by the oscillations in the electrical part, which is in the thermodynamic equilibrium with the mechanical subsystem. These oscillations are accompanied by the appearance of the potentials difference and currents, flowing by the circuit and depending on its resistance R. In general case, the correlation function for the voltage U in the linear RC circuit depends on the time t as

$$<U(t_1)U(t_2)>=(k_B T/C)\exp\left[-|t_1-t_2|/RC\right].$$

Let us assume that, in the discussed experiments, the time constant of linear circuit RC satisfies the condition $|t_1-t_2|<<RC$, where $|t_1-t_2|\approx 2\pi/\omega_2$ in [3], and $|t_1-t_2|\approx 2\pi/\Omega$ in [4]. This allows us to simplify the consideration and assume that the exponential term in the correlation function is close to the one. Let us think that the heat capacity of metal walls in a capacitor and their near surface areas, where the electric charge is accumulated in a capacitor at low temperatures, is small in comparison with the heat capacity of helium fluid, and is not dependent on the thermal state of the system, which is defined by the fluid only. We don't count the possible Kapitza temperature jump on the boundary of metal, because the amplitude of oscillations of temperature T' is significantly smaller than the equilibrium temperature T.

In an agreement with the above conditions, it is possible to write an expression for the full thermal and electric energies of a capacitor with the plates at different temperatures, taking to the consideration that

$T' \ll T$

$$C\overline{\left(U_+(t)+U'_+(t)\right)^2}+C\overline{U_-^2(t)} = \frac{1}{2}k_B\left(T+T'\right)+\left(\frac{N}{2}+N'\right)k_B T'+\frac{1}{2}k_B T \quad (13)$$

and for the (+) plate of a capacitor under action of T', will be equal to

$$C\overline{\left(U_+(t)+U'_+(t)\right)^2}=\frac{1}{2}k_B\left(T+T'\right)+\left(\frac{N}{2}+N'\right)k_B T'. \quad (14)$$

The second term in the right part of equations is connected with the change of a number of electrons at an action of the temperature T'. Now, we have to take to the consideration the fact that its frequency is significantly smaller than the frequency of thermal fluctuations, hence it can be considered as an analogue of quasistationar effect. In this case, a number of fluctuating electrons changes by N' and the energy of each electron changes by $kT'/2$. Let us open the first quadratic term in the left side of equation (14), and

considering the difference of times of averaging $\tau \ll \tau'$

for U_+ and U'_+, let us leave the unaveraging $U'_+(t)$ in the second term. Thus, we will get

$$C\overline{U_+^2}+2C\overline{\overline{U_+}}U'_+(t)+C\overline{U_+'^2} = \frac{1}{2}k_B\left(T+T'(t)\right)+\frac{N}{2}k_B T'(t)+N'(t)k_B T'(t). \quad (15)$$

In the left and right parts of the equation, the second order terms, which have the dashes, are small, and they can be neglected. Then, we will obtain the expression for the first order terms with U'_+ and $N'(t)$:

$$2C\overline{\overline{U_+}}U'_+(t)=\frac{1}{2}k_B T'+\frac{N}{2}k_B T'=\left(\frac{N+1}{2}\right)k_B T'(t) \quad (16)$$

or

$$NeU'_+(t)=\left(\frac{N+1}{2}\right)k_B T'(t). \quad (17)$$

Let us note that, in the standard theory of measurements [29], the term at left part of equation (16), is assumed to be equal to the nill, that is true, if the time of averaging is significantly more than the characteristic time of change T'. However, in [3] and [4], the technique of synchronous detection was used, and theis contribution was registered at second sound frequency of ω_2, which is characteristic for T', that is why it was not averaged and is different from the nill. From this, we will obtain the final result

$$\alpha=\frac{U'_+(t)}{T'(t)}=-\frac{(N+1)}{2N}\frac{k_B}{|e|}=-\frac{k_B}{2|e|}-0\left(\frac{1}{2N}\right). \quad (18)$$

The equation (18) corresponds to the thermoelectric coefficient α for the electrons, which take part in the fluctuation process at presence of the changing temperatures difference $T'(t)$ between the plates in a capacitor.

This result quantitatively corresponds to the magnitude of α, obtained in the experiment in [3]. It also follows from the expression (18) that the negative electrons charge is accumulated at heated plate in a capacitor at increase of temperature $(T'>0)$. In the experiment [3], the plate with the high temperature was negatively charged in a capacitor.

Thus, the creation of small enough oscillations of temperatures difference $T'_{\omega 2}\propto T'_0\sin(\omega_2 t)$ by the wave of second sound in the fluid helium II has to be accompanied by an appearance of the additional in-phase potentials difference $U'_{\omega 2}=\alpha T'_0\sin(\omega_2 t)$, where $\alpha=-k_B/2|e|\approx 4.3126\cdot 10^{-5}$ V/K. The equilibrium temperature T is not included in (18), hence the results don't depend on the magnitude of equilibrium temperature T, as it was observed in [3]. In the researched case [3], the alternate electrical field reached the magnitude $E'_0\sim(10^{-4}\ldots 10^{-6})$ V/m in a capacitor. The helium atoms didn't contribute a notable change to the obtained result, because the polarizational effects for the helium II atoms are proportional to the square of intensity of electric field as in the case of all the inert gases with filled electron shells.

ELECTRICAL POTENTIALS DIFFERENCE OSCILLATIONS IN CAPACITOR IN MECHANICAL TORSIONAL RESONATOR

Let us analyze the results of experiment [4], in which the oscillations of electric potentials difference $U'(t)$ at the electrodes of cylindrical electric capacitor (Fig. 3), connected with the mechanical torsional resonator, were observed in the range of temperatures from 1.4 K to T_λ=2.172 K.

The first plate of a capacitor includes a fixed electrode (1); the second plate of a capacitor consists of the cylindrical surfaces (2) and (4) with the covers (3) and

(5), involved in the rotational movement. The maximum amplitude of electric potentials difference was $U' \approx 1.5 \cdot 10^{-7}$ V at temperature $T \approx 2$ K [4]. The helium II as the liquid or as the saturated or not saturated film, covering the inside surface of a resonator, was placed in a resonator. In an agreement with the equation (18), the oscillations of the electric potentials difference at such a scale can be originated by the oscillations of the temperatures difference $T' \sim 10^{-3}$K in a given capacitor. Considering the dependence of relative concentration of superfluid component on the temperature, we can find that, at the temperature $T=2$ K, the magnitude is $\rho_s/\rho \approx 0.3$, where ρ_s is the density of superfluid component, and ρ is the full density. In agreement with the data in [30], at the above temperature T, the change of density of superfluid component ρ'_s, appearing at the action by oscillations of given temperatures difference T', doesn't exceed the magnitude $\rho_S' / \rho \approx 4 \cdot 10^{-3}$.

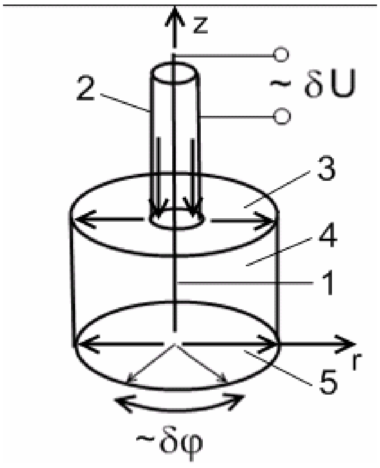

Fig. 3. Torsional resonator with fixed metal electrode (1) and oscillating cylindrical metal cavity (2, 3, 4, 5) (after [3]). Arrows show directions of superfluid helium component flow, when velocity of rotation of a resonator is at maximum

Let us consider the case, when there is a saturated film of superfluid helium inside the resonator. As it is known [30], the thickness of saturated film is $\sim 25 \dots 30$ nm, and it contains the $100 \dots 120$ layers of the helium atoms approximately, and it covers all the inside surface of a resonator. The thickness of film slightly decreases in the upper part of a resonator, but this effect has no principal influence in this case, hence we don't consider it. It is visible that the change of density ρ' is commensurable with the mass of approximately $0.4 \dots 0.5$ single layer of helium at the above described oscillations of temperature. The flow of small amount of the superfluid component from one part of a resonator to another part will result in the change of distribution of temperatures in a resonator at adiabatic conditions due to the above considered mechanism, resulting in the observed effect [4].

Let us define the physical mechanism and forces, which have the influences on the dynamics of the normal and superfluid components of the helium II, and their transfer during the rotation of a resonator in the considered research task. In [4], the resonator conducted the rotational oscillations $\varphi(t) = \varphi_0 sin(\Omega t)$, where φ_0 is the amplitude of angular oscillations, expressed in the radians, Ω is the angular frequency. The velocity of rotation of resonator's walls is $\upsilon_\varphi(r) = r d\varphi(t)/dt = r\varphi_0 \Omega cos(\Omega t)$, where r is the radius of given point of rotating surface. At the surface (4) in Fig. 3, the velocity of rotation had a maximum value [4]. It is possible to assume that, in view of the big viscosity and small thickness of the superfluid film, the normal helium component is fully drag by the rotating resonator's walls, taking part in the rotational movement with the velocity $\upsilon_{n,\varphi}(r,t)$, which is equal to the velocity of walls rotation $\upsilon_\varphi(r)$. The centrifugal force $F_c = \rho_n(\upsilon_{n,\varphi})^2/r$, acting on the normal component, can be regarded as small enough in the considered case, assuming that the radial velocity of normal component is $\upsilon_{n,r} \approx 0$. The superfluid component is not involved in the rotational movement of resonator's walls with the velocity smaller than the critical velocity of vortices generation, that is $\upsilon_{s,\varphi} = 0$. Let us note that, during the oscillations of a resonator, the superfluid component can make the oscillating movements with some radial velocity $\upsilon_{s,r} \neq 0$, and it can flow from the regions with the small radius r, that is from the surface (2) and from the central regions of covers (3) and (5) to the side surface (4), which has the biggest radius R, and then flowing backward. Let us clarify the cause of oscillating movement. In some sense, the oscillations of such a type are similar to the oscillations between the two connected vessels, when the helium II levels inside the vessels are close to the equilibrium [31], and the vessels are connected by the thin constriction or when the interflow of the helium II between the vessels is done by the means of the superfluid helium film at presence of outer pressure.

The system of hydrodynamic equations for the helium II was firstly proposed by Landau, and then developed by Khalatnikov (see [32-34]). Let us write the equation of movement for the superfluid component at coordinate r

$$\rho_s \frac{\partial \upsilon_s}{\partial t} + \rho_s \nabla_r \left(\mu + \frac{\upsilon_s^2}{2} - \frac{\rho_n (\upsilon_{n,\varphi} - \upsilon_s)^2}{2\rho} \right) = 0, \quad (19)$$

where μ is the chemical potential. Let us assume that the rotational oscillations are generated with the small angular amplitude and with the small linear velocity υ_φ, which is less then the critical velocity of vortex generation. In the initial moment, the superfluid component will be in the state of quiescence with the velocity $\upsilon_s = 0$, and by selecting the phase of oscillations, when $\nabla \mu = 0$, the equation (19) can be written

$$\rho_s \frac{\partial \upsilon_{s,r}}{\partial t} = \rho_s \nabla_r \left(\frac{\rho_n}{2\rho} \upsilon_{n,\varphi}^2 \right), \quad (20)$$

where $\upsilon_n^2 = [r\varphi_0 \Omega cos(\Omega t)]^2$.

Let us consider the above written dependence of $\upsilon_{n,\varphi}(\Omega)$ and derive the final expression for the force, acting on the superfluid component as

$$\rho_s \frac{\partial \upsilon_{s,r}}{\partial t} = \frac{\rho_s \rho_n}{\rho} r \varphi_0^2 \Omega^2 \left(1 + \cos(2\Omega t)\right) \quad (21)$$

The right part of the equations (20), (21) is the Bernoulli force which acts on the superfluid component, transferring it to the part of a resonator, where the linear velocity $\upsilon_{n,\varphi}$ has its maximum value. It is well known fact that the Bernoulli force can not originate in the experiments to research the Venturi effect in the helium II in the pipe with constriction [35-36]. In agreement with [36], in this case, the condition $rot\,\upsilon_s=0$, where the direction υ_s coincides with the direction of movement of normal component υ_n in the pipe, has to be true for the superfluid component. This results in the equality of the helium II levels, measured in the region of wide pipe and in the region of constriction of wide pipe. In the researched case, the appearing superfluid component velocity $\upsilon_{s,r}$ is directed along r and orthogonal to the normal component velocity $\upsilon_{n,\varphi}$ in the equation (16). Under these conditions, the Bernoulli effect has to originate, because the expression $rot\,\upsilon_s=0$ is true in view of the existing orthogonality between the velocity vector and the direction of circular contour bypassing. The interflow of the superfluid component, which doesn't transfer the entropy, results in an appearance of the difference of temperatures T' between the resonator's regions with the small and big coordinates r. In the turning points of a resonator, the velocity of normal component is $\upsilon_{n,\varphi}=0$, and the Bernoulli force is equal to the nil. The thermomechanical effect, which creates a contrary stream of the superfluid helium II and results in an origination of the oscillation process, plays a main role at the turning points of a resonator. The phase of oscillations of the helium II can be shifted in relation to the resonator's oscillations, because of the inertia of the flow of mass, however this effect can be disregarded in view of the small mass transfer. These forced oscillations of the temperatures difference and the flow of superfluid component at the axe r can transform to the fading oscillations, continuing for some time after the moment of resonator's rotation stopping, as observed in [4].

Going from the calculations, the contribution by a cylindrical capacitor with small radius with the electrodes (1) and (2), and the covers of a big volume resonator with the electrodes (1) and (3) and the electrodes (1) and (5) to the full value of capacitance of a sectional capacitor exceeds the capacitance of a capacitor with the electrodes (1) and (4) in more than *5* times. Therefore, namely the plates (2), (3) and (5) will create the main electric response of a sectional capacitor. In the connection with the interflow of superfluid component from these surfaces to the surface (4) during the oscillations, all the plates will experience the increases of temperatures periodically. Therefore, the plates will charge negatively in an agreement with the equation (18), but the central electrode (1) will charge positively, because it will have the lower temperature, comparing to the other plates. To account for the fluctuational contribution, let us represent the variables as $T=T_0+T'$ and $\upsilon_n=\upsilon_{n0}+\upsilon'$, where the part with the index 0 corresponds to the equilibrium value, but the second part corresponds to the value, which depends on the time and originates as a result of the oscillations of a resonator. Let us evaluate the amplitudes of temperature difference T', appearing between the central and distant regions of a resonator.

Let us substitute $d\mu=-\sigma dT+dP/\rho$, where $\sigma=S/\rho$, in the equation (19):

$$\rho_s\frac{d\boldsymbol{\upsilon}_s}{dt}+\frac{\rho_s}{\rho}\nabla P+\frac{\rho_s}{2}\nabla\boldsymbol{\upsilon}_s^2-\rho_s\sigma\nabla(T_0+T')$$
$$-\frac{\rho_s\rho_n}{2\rho}\nabla(\upsilon_{n,0}+\upsilon_{n,\varphi}-\boldsymbol{\upsilon}_s)^2=0. \qquad (22)$$

Let us assume that the gradient of external pressure $\nabla P\approx 0$ and also the relation is true $\upsilon_s/\upsilon_n<<1$ and $\nabla\upsilon_s^{\,2}\approx 0$, which are in an agreement with the conditions of experiment. In the extremum points $d\boldsymbol{\upsilon}_s/dt=0$, and we can derive the intercoupling expression between the temperature and the velocity of normal component of the helium II by integrating the two last terms in the equation (22) over the r (see the similar solution for the thin capillary in [32] §140). From the equation (22) we will obtain

$$\frac{\rho_s\rho_n}{2\rho}\overline{\overline{(\upsilon_{n0}+\upsilon_{n,\varphi})^2}}=-\rho_s(T_0+T')\sigma\,. \qquad (23)$$

In this case $\upsilon_{n,\varphi}<<\overline{\overline{\upsilon_{n0}}}$ where $\overline{\overline{\upsilon_{n0}}}$ is the average thermal velocity of the helium atoms, $\upsilon_{n,\varphi}$ is the velocity of the normal component on the surface of rotation. For the numerical evaluation of the effect's magnitude, let us write the expression (23) for a capacitor with small diameter (the surface number (2), see Fig. 3) and a capacitor with big diameter (the surface number (4), see Fig. 3), taking to the consideration the volumes V_1 and V_2 of films of fluid helium II, situated in every capacitor. Let us assume that, in the adiabatic case in the corresponding phase of wave process, the superfluid component of helium II, which flows from the small capacitor, results in an increase of temperature at the surface (2) and in a small change in a kinetic term at left part of equation (23), because of the small magnitude of surface radius and small velocity of its rotation. This superfluid helium, inflowing into a big capacitor at the surface (4), leads to the small decrease of temperature in view of its small volume in comparison with the volume V_2, situated inside it, but the term, connected with the kinetic energy, is significantly increased, because of big velocity of rotation of the surface. Let us assume that the linear velocity of rotation doesn't increase above the critical value, hence the superfluid component is not trapped by the oscillating resonator and $\upsilon_{s,\varphi}=0$. Let us sum up the equations (23) for the both considered capacitors, leaving the main terms, which have an influence on the change of temperature only.

Then, as in the case of the equation (16), we will obtain

$$V_2\frac{\rho_s\rho_n}{2\rho}(\overline{\upsilon_{n0}^2}+2\overline{\overline{\upsilon_{n0}}}\upsilon_{n,\varphi}+\upsilon_{n,\varphi}^2)=-V_1\rho_s(T_0+T')\sigma\,, \qquad (24)$$

where $\upsilon_{n,\varphi}$ is the velocity of the normal component of helium on the rotation surface (4) (see Fig. 3).

Let us believe that the value $\upsilon_{n\varphi}^{\,2}$ is quadratically small, and it can be disregarded. Equalizing the linear T' and $\upsilon_{n\varphi}$ terms, we will find the dependence of amplitude of oscillations of the temperature T' in a small capacitor on the velocity of rotation of surface $\upsilon_{n\varphi}$ in a big capacitor (4) as

$$T' = -V_2 \rho_n \overline{\overline{\upsilon_{n0}}} \upsilon_{n,\varphi} \Big/ V_1 \rho \sigma . \quad (25)$$

Let us conduct the qualitative evaluation of amplitude of oscillations of temperature, for example, at the temperature $T = 2$ K. In [4], the maximum linear velocity of rotation was $\upsilon_{n,\varphi} = 7 \cdot 10^{-4}$ m/s. At the given temperature the thermal velocity for the helium atoms is $\overline{\overline{\upsilon_{n0}}} \approx 100$ m/s, the specific entropy of helium II is $\sigma \approx 940$ J/kg·K, $\rho_n/\rho = 0.7$, and the relation between the volumes of the helium II films on the surfaces (2) and (4) is $V_2/V_1 \approx 16.7$. Then, going from the equation (25), we will obtain $T' \approx 1.3 \cdot 10^{-3}$K. The oscillations of difference of electric potentials will be mainly defined by the change of temperature in a capacitor with small radius (electrodes (1) and (2)), and in an agreement with the equations (18) and (25), we will obtain

$$U'_{2\Omega} = \frac{k_B}{2|e|} V_2 \rho_n \overline{\overline{\upsilon_{n0}}} \upsilon_{n,\varphi} \Big/ V_1 \rho \sigma . \quad (26)$$

This result is in a good qualitative agreement with the data, obtained in [4]. From the equation (21), it follows that $\upsilon_{n,\varphi} \sim r \varphi_0 \Omega cos(\Omega t)(1 - sin^2(\Omega t))$, and the maximum value of the electric potentials difference must be observed at the maximum deflection angle of a resonator, but not at the moment, when the maximum value of acceleration is reached, as confirmed in [4].

Thus, the rotation of an oscillator in [4] results in both an increase of the normal component with subsequent interflow of superfluid component of the helium II at the Bernoulli force action on the resonator's wall (4) with the biggest radius of rotation as well as an appearance of the biggest difference of temperatures between the plates of a capacitor with the small radius of rotation (1-2). In the experiments [3] and [4], the physical foundations of observed processes are based on the thermoelectric effect, appearing for the Einstein's fluctuating electrons at presence of the temperatures difference between the plates of a capacitor.

DISCUSSION

Going from the research by Einstein [1], the authors developed the theory of thermoelectric effect for the fluctuating electrons, allowing to explain the results of experiments in [3] and [4], which are connected with the thermal effects, accompanied by an appearance of the small electric fields in a capacitor in the helium II. The thermoelectric coefficient α seems to be equal to the value, which corresponds to the value in the known classic theory by Drude [37], and approximately in 10^4 times bigger, than it can be in the metals at such low temperatures, where it is reduced on $k_B T/\varepsilon_F$. Using the expression (7), it is possible to evaluate a total number of fluctuating electrons in the experiment [3], where the capacitance of a capacitor was $C \approx 5 \cdot 10^{-13}$F [39]. We obtain that the total number of fluctuating electrons is $\overline{\overline{N}} \approx 23$ at temperature $T = 2$ K. At $T = 1{,}4$ K, the total number of fluctuating electrons is $\overline{\overline{N}} \approx 19$. In the researched case, the average number of fluctuating electrons is small, and they can be considered as an ensemble of classic particles, without taking to the account the Fermi statistics. The change of temperature fields in the He II is directly connected with the transfer of the superfluid and normal components of the He II, and observed at the propagation of waves of second and third sounds or at the interflow of superfluid films [31, 33].

The dielectric constant ε of the fluid helium II depends on the temperature, and it can have an influence on the capacitance magnitude of a capacitor. At the change of temperature from T_λ to 1 K, the relative value of change of density is approximately $\Delta\rho/\rho \approx 10^{-3}$, therefore the change of $\Delta\varepsilon/\varepsilon$ has the same value. The correction of coefficient α in this mechanism is near 10^{-8} V/K, that is why it was not taken to the consideration in this case. Undoubtedly, it is necessary to take to the account this correction in the case of experiments with the big magnitudes of electric fields.

In our opinion, the maximum U' at temperature of around 2 K (see Fig. 3) in [4] is connected with the maximum of amplitude of oscillations of heat flux $W' = \rho C T' u_2$ in the case of second sound propagation, where C is the heat-capacity of the helium II. During the propagation of superfluid film, the maximum W' is in the same temperatures range, though the velocity of superfluid film propagation is approximately one order of magnitude less than the velocity of second sound propagation.

We don't provide the exact numerical analysis of frequency spectrum in [3], because it significantly depends on a number of conditions of experiment, which are not provided in [3].

Let us draw attention to the fact that the clear difference of amplitudes U' at the rotation of a resonator in different directions is visible on the dependence of the amplitude of oscillations U' on the time, described by the equation (21) (see Fig. 2) in [4]. This difference of amplitudes U' can be explained by the varying velocity of normal component of helium $\upsilon_{n,\varphi}$, appearing in view of the non-symmetric polishing of resonator's plates, but not because of the presence of some circulating superfluid He II stream, as it was assumed by the researchers [4]. In the case of circulation, the time semi-periods of oscillations, connected with the rotation of a resonator in different directions, must not be equal, however they are equal precisely in [4].

Let us pay attention to the fact that the generation of vortices at the velocities above the critical velocity results in a suppression of the electric effect [4], because the magnitude of flowing superfluid helium stream, the oscillations of concentrations difference of Helium II components, the thermal and electric effects are significantly limited, because both the superfluid component of Helium as well as the normal component take part in the rotational movement during the process of vortices generation, which is characterized by the average value expression: $\langle \mathrm{rot}\, \upsilon_{s,\varphi} \rangle \neq 0$.

In this research, the we don't consider the effect [3], connected with the generation of oscillations of second sound, when the alternate difference of electric potentials U' with the magnitude in $10^8 \ldots 10^{10}$ times bigger, than the magnitude in this research, was applied to the additional capacitor inside the second sound resonator, reaching the electric field magnitude $E \approx 1.67 \cdot 10^4 \mathrm{V/m}$. In this case, the electric field can not be considered as small enough, and its influence on the properties of superfluid Helium II have to be taken to the account. The different research approach has to be used to interpret this effect, which can be discussed in our next research paper.

CONCLUSION

The theory of thermoelectric effect with the fluctuational electrons at the plates of a capacitor in the superfluid Helium II with the oscillations of second sound wave is created. The results of theoretical calculations are in good agreement with the experimental data, obtained at the research of electric signals in a second sound resonator and in a rotational resonator in [3, 4]. The similar described thermoelectric effect can be realized in the capacitors at the creation of temperatures difference between the plates at various temperatures. The thermoelectric effect can be used in numerous measurement systems in view of a big value of thermoelectric coefficient. In the authors opinion, the capacitor can represent an effective thermoelectric transducer of a new type.

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ЭЛЕКТРИЧЕСКИЕ ЭФФЕКТЫ В СВЕРХТЕКУЧЕМ ГЕЛИИ. 1. ТЕРМОЭЛЕКТРИЧЕСКИЙ ЭФФЕКТ В ЭЛЕКТРИЧЕСКОМ КОНДЕНСАТОРЕ

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Идеи Эйнштейна о термодинамической флуктуационной природе некоторых электрических явлений и разнице электрических потенциалов U на обкладках электрического конденсатора при температуре T были изложены еще в 1906-1907 годах. На основании этих представлений мы объясняем экспериментальные результаты, которые недавно были получены под действием волны второго звука в электрических конденсаторах, находившихся при низких температурах в сверхтекучем гелии и в торсионном механическом резонаторе. Подход, базирующийся на взаимосвязи термических, механических и электрических флуктуаций, позволяет получить количественные результаты, совпадающие с экспериментальными данными по корреляции малой переменной температурной разности в волне второго звука и переменной разности электрических потенциалов между обкладками конденсатора как в сверхтекучем гелии, так и в торсионном механическом резонаторе.

ЕЛЕКТРИЧНІ ЕФЕКТИ В НАДПЛИННОМУ ГЕЛІЇ. 1. ТЕРМОЕЛЕКТРИЧНИЙ ЕФЕКТ В ЕЛЕКТРИЧНОМУ КОНДЕНСАТОРІ

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Ідеї Ейнштейна про термодинамічну флуктуаційну природу деяких електричних явищ і різницю електричних потенціалів U на обкладках електричного конденсатора при температурі T було ще в 1906-1907 роках. На основі цих пропозицій ми пояснюємо експериментальні результати, які недавно було отримано під дією хвилі другого звуку в електричних конденсаторах, що знаходились при низьких температурах у надплинному гелії та в торсіонному механічному резонаторі. Підхід, що базується на взаємодії термічних, механічних та електричних флуктуацій, дозволяє отримати чисельні результати, співпадаючі з експериментальними даними за кореляцією малої змінної температурної різниці в хвилі другого звуку і змінної різниці між обкладками конденсатора як у надплинному гелії, так і в торсіонному механічному резонаторі.