ENTROPY OF THE GROUND STATE AND THE ELECTRIC ACTIVITY OF SUPERFLUID HELIUM ON THE EXCITATION OF SECOND-SOUND WAVES

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UDC 539

We propose a possible explanation of the nature of the temperature-independent component of the entropy of He II, whose existence was assumed by E.A. Pashitskii and S.M. Ryabchenko [Fiz. Nizk. Temp. **33**, 12 (2006)] on the consideration of the polarization of superfluid helium during the propagation of a second-sound wave. The ground state of He II is considered in the random phase approximation (RPA), and it is shown that the energy of this state can be rewritten in terms of the distribution function of virtual quasiparticles (phonons or rotons), rather than that of particles, as it is made in the impulse approximation limit, because the proposed representation seems to be more general. With this distribution function, the temperature-independent contribution to the entropy of superfluid helium is calculated. This part has sense of the Shannon entropy as a measure of a quantum mechanical uncertainty, because the given quasiparticles are quantum mechanical fluctuations against the background of the ground state of superfluid helium.

1. Introduction

The investigation of the relationship of a microstructure of He II to its macroscopic properties is one of the central problems of low-temperature physics. Recently, a previously unknown phenomenon has been observed: the appearance of electric polarization in superfluid ^{4}He upon the excitation of a periodic relative motion of the normal and superfluid components in it [1,2]. In particular, on the radiation of the second sound, the appearance of the electric polarization directed in parallel to the vector of velocity of the superfluid component $\mathbf{v}_s$ has been observed [1]. It was established that the amplitude of oscillations of the temperature ΔT in a second-sound wave and the variation of the electric potential ΔU have the same frequency and are connected to within $\pm 25\%$ by the relation

$$\frac{\Delta T}{\Delta U} \approx \frac{2e}{k_{\rm B}} = 2,32 \times 10^4 \text{K}\cdot\text{B}^{-1}, \tag{1}$$

where e is the electron charge, and $k_{\rm B}$ is the Boltzmann constant. In the interval of temperatures $T \leq 2$ K, relation (1) is independent of the temperature in the limits of the indicated accuracy.

In some theoretical works, the attempts were undertaken to explain the causes of the appearance of electric polarization in He II, but the results obtained poorly fit the experimental data. However, one of the possible mechanisms of this phenomenon was proposed in work [3]. Relation (1) was explained by the inertia mechanism of the appearance of electric polarization on the excitation of second-sound waves in the assumption that the superfluid component has the contribution in entropy which is independent of the temperature. The authors of the mentioned paper considered the superfluid component as a superposition of contrarily charged coherent condensates: the nuclear condensate (sN) and the pair electron one (se). These systems are connected with each other by forces of Coulomb attraction under conditions of electroneutrality of the environment $\langle \mathbf{v}_{\rm sN}\rangle = \langle \mathbf{v}_{\rm se}\rangle = \mathbf{v}_s$ (the brackets mean the space and time averages). In the frame of two-liquid hydrodynamics, taking the big difference of electron's and nucleus's masses $m_e \ll m_N \approx m_4$ into account, the authors obtained the equation which determines the electric potential gradient $\nabla\varphi$ in terms of changes of the pressure $\triangle P$ (first sound) and the temperature

$\triangle T$(second sound):

$$\left(\frac{1}{\rho}\triangle P-\frac{\sigma}{m_4}\triangle T\right)=-\frac{4e}{m_4}\nabla\varphi, \quad (2)$$

where $\rho=\rho_s+\rho_n$ is the helium density (the sum of densities of the normal and superfluid components), and σ is the entropy per one atom with the dimension of $k_{\rm B}$.

In the case of the second-sound waves, one can neglect by variations in the pressure, $\triangle P=0$, and obtain the analog of expression (1):

$$\frac{\Delta T}{\Delta U}\approx\frac{4e}{\sigma}. \quad (3)$$

This means that the amplitude of small oscillations of the electric potential in the second sound is determined by the entropy per one atom, and the condition of conformity to each other of Eqs. (1) and (3) is $\sigma=2k_{\rm B}$. That is, the nonzero contribution $\sigma_0=2k_{\rm B}$ to the entropy exists at low temperatures and dominates in the interval of temperatures $T\leq 2$ K.

Proceeding from the aforesaid, the problem of our paper is reduced to the elucidation of the physical nature of the constant contribution σ_0 to the entropy of the superfluid state of helium. It is obvious that the von Neumann entropy is equal zero in the ground state. However, as was mentioned above, the superfluid component of ^{4}He can be represented as a superposition of contrarily charged coherent condensates due to the quantum-mechanical spreading (uncertainty). This means that this case must be characterized by the entropy which plays the role of the degree of such an uncertainty and is present in the equations of generalized hydrodynamics of the superfluid liquid [3].

2. The Ground State of He II and Its Entropy

Let's consider the boson system with average density $n=1/\upsilon=N/V$ which consists of particles interacting via the pairwise repulsive potential $\Phi\left(|\mathbf{r}_i-\mathbf{r}_j|\right)\equiv\Phi\left(r\right)$, because a Bose-gas with attraction is unstable [4]. The quantum equation for the operator which corresponds to the collective variable of fluctuations of the local density of particles $\rho_{\mathbf{k}}=\frac{1}{\sqrt{N}}\sum\limits_{j=1}^{N}e^{-i\mathbf{k}\mathbf{r}_j}$ in RPA has the form

$$\ddot{\hat{\rho}}_{\mathbf{k}}+\omega_k^2\hat{\rho}_{\mathbf{k}}=0, \quad (4)$$

where $\nu_k=\int e^{-i\mathbf{kr}}\Phi\left(r\right)d\mathbf{r}$ is the Fourier transform of the interaction potential of particles, the operator of fluctuations of the density $\hat{\rho}_k$ satisfies the commutation relations

$$\hat{\rho}_{-\mathbf{k}}\dot{\hat{\rho}}_{\mathbf{k}}-\dot{\hat{\rho}}_{\mathbf{k}}\hat{\rho}_{-\mathbf{k}}=i\hbar\frac{k^2}{m} \quad (5)$$

and ω_k is the frequency of the k-th oscillator with the energy quantum

$$\varepsilon_k=\hbar\omega_k=\sqrt{\left(\frac{\hbar^2k^2}{2m}\right)^2+\frac{\nu_k}{m}\frac{N}{V}\hbar^2k^2}. \quad (6)$$

It is seen that, in RPA, a degenerate system of interacting Bose-particles, e.g. liquid helium below the λ-point, is equivalent to the collection of harmonic oscillators with frequencies ω_k and independent random phases for different values of the wave vectors $\mathbf{k}$. Then the possible values of the energy of a quantum liquid can be defined as

$$E=\sum_{\mathbf{k}}\hbar\omega_k\left(n_{\mathbf{k}}+\frac{1}{2}\right),\quad n_{\mathbf{k}}=0,1,2,... \quad (7)$$

We consider the ground state of such a system as that, in which the quantum numbers of all aforesaid oscillators are zero: $n_{\mathbf{k}}=0$ for $\forall\mathbf{k}$. It is obvious that this state corresponds to the absolute zero temperature. Then, the energy of the ground state of a weakly unideal Bose-gas is

$$E_0=\sum_{\mathbf{k}}\frac{1}{2}\hbar\omega_k=\int\limits_0^{1/d}\frac{1}{2}\hbar\omega\left(k\right)\frac{4\pi k^2dk}{\left(2\pi\right)^3}\approx\frac{2\pi\hbar^2aN^2}{mV}, \quad (8)$$

where $d\sim\sqrt[3]{V/N}$ is the average distance between liquid's particles, and a is the scattering length. If, for some $\mathbf{k}\neq0$, the occupation numbers $n_{\mathbf{k}}\neq0$, then n elementary excitations with the energy spectrum $\varepsilon\left(k\right)=\hbar\omega\left(k\right)$, which consists of the phonon and roton parts in the case of He II, exist in the system.

For the subsequent calculations, we need an expression for the free energy at zero temperature $T=0$. For a system of interacting bosons in RPA, it has the form [5]

$$F_0=F_{id}+\frac{N^2}{2V}\nu_0-\sum_{\mathbf{k}\neq0}\frac{\hbar^2k^2}{8m}\left(\alpha_k-1\right)^2, \quad (9)$$

where

$$\alpha_k=\sqrt{1+\frac{2N}{V}\nu_k\Big/\frac{\hbar^2k^2}{2m}}\equiv\varepsilon_k\Big/\frac{\hbar^2k^2}{2m}\equiv\frac{1}{S_k}, \quad (10)$$

and S_k is the structure factor of the quantum Bose-liquid at $T=0$. The average value of kinetic energy K_0 can be calculated by differentiating the free energy (9) with respect to the particle's mass m as a parameter [5]:

$$K_0 = -m\frac{\partial F}{\partial m} = \sum_{\mathbf{k}\neq 0} \frac{\hbar^2 k^2}{2m}\frac{(\alpha_k - 1)^2}{4\alpha_k}. \tag{11}$$

Thus, the kinetic energy in the ground state of a nonideal Bose-gas is different from zero, which allows the following interpretation: unlike the ideal gas of Bose-particles, the above-condensate particles exist in superfluid ^{4}He at $T = 0$ with the dispersion $\varepsilon_k = \frac{\hbar^2 k^2}{2m}$ and the occupation numbers

$$N_{\mathbf{k}} = \frac{(\alpha_k - 1)^2}{4\alpha_k} + N_0\delta(0). \tag{12}$$

This dispersion law is typical of free particles. However, the obtained distribution function is sufficiently close to zero already at $k \approx 2$ Å^{-1} [6,7], which is situated in the area of the wavevectors of elementary excitations $k < 2.4$ Å^{-1} with dispersion $\varepsilon(k)$. Moreover, at $k > 2.4$ Å^{-1}, the wave functions of quasiparticles are damped, i.e. quasiparticles are decaying. Thus, in the general case, we cannot speak about the above-condensate particles as about free particles like those in the ideal gas, but we must built a more adequate representation.

The experiments [6–8] on deep-inelastic neutron scattering in He II allowed one to determine both the distribution function which corresponds to the occupation numbers (12) with a typical condensate peak and the condensate density. The estimates showed that the condensate comprises 6–12% of the total mass at absolute zero temperature. However, the energy of neutrons (or the transferred momentum) is much greater than the energy of elementary excitations. That's why the neutrons are scattered by liquid helium as by a system of noninteracting particles: each atom plays the role of s density fluctuation, and, what's more, it has no time to interact with its environment. Thus, we can imagine the picture, as if the scattering of neutrons takes place in the ideal Bose-gas at a certain effective temperature. Such a picture is named "impulse approximation". The above-mentioned condensate peak disappears on the passage to lower energies.

In view of the aforesaid, in order to obtain the entropy of the ground state, it is necessary to have expression for the distribution function of a more general view than (12) corresponding to the impulse approximation. To this end, we rewrite the expression for the kinetic energy of the ground state through the dispersion law for quasiparticles (6). Then, after simple transformations with the help of (6) and (10), expression (12) becomes

$$K_0 = \sum_{\mathbf{k}\neq 0} \varepsilon_k \frac{(\alpha_k - 1)^2}{4\alpha_k^2} \equiv \sum_{\mathbf{k}\neq 0} \varepsilon_k n_{\mathbf{k}}^0, \tag{13}$$

where

$$n_{\mathbf{k}}^0 = \frac{1}{4}\left(1 - \frac{1}{\alpha_k}\right)^2 = \frac{1}{4}\left(1 - \frac{\hbar^2 k^2}{2m}\frac{1}{\varepsilon_k}\right)^2 \tag{14}$$

are already the occupation numbers of quasiparticles, and $\hbar\mathbf{k}$ plays the role of quasimomentum. Such a transformation gives a basically new picture of the ground state of He II. As was mentioned above, the system is in the ground state, if all oscillators are at the zero level. This state is pure, since the system is described by the wave function Ψ which is a solution of the Gross–Pitaevskii equation in the model of weakly nonideal gas [9]. In the first approximation for He II, it has the form [14, 15]

$$\ln\Psi_0(r_1, ...r_N) = \sum_{\mathbf{k}} \frac{1}{2}(1 - \alpha_k)\rho_{\mathbf{k}}\rho_{-\mathbf{k}}. \tag{15}$$

Due to the principle of uncertainty, the quantum fluctuations, which are displayed as elementary excitations distributed by law (14) with the spectrum ε_k, exist in the system. However, we know that the quasiparticles are not in the ground state. That's why the given quasiparticles are virtual phonons and rotons, rather than real ones. In order to transform them into real quasiparticles, the system must be heated or driven to the critical speed. In the virtual state, such excitations do not cause friction. However, they can bring to a number of effects, one of which is electrical activity, as it will show below. We want to emphasize once more that the existence of the given quasiparticles is due to the principle of quantum mechanical uncertainty, rather than to thermal or mechanical excitations.

It is not difficult to notice that the occupation numbers of virtual quasiparticles (14) are related to the wave function of the ground state (15). If $\ln\Psi_0 = \sum\limits_{\mathbf{k}} a(k)$, then $n_{\mathbf{k}}^0 = \langle a(k)\rangle_0^2$, where

$$\langle a(k)\rangle_0 = \frac{1}{2}(1 - \alpha_k)\langle\rho_{\mathbf{k}}\rho_{-\mathbf{k}}\rangle_0. \tag{16}$$

Using the definition of the structure factor $S_k^{T=0} = \langle\rho_{\mathbf{k}}\rho_{-\mathbf{k}}\rangle_0$ and formula (10), we can write

$$\langle a(k)\rangle_0 = \frac{1}{2}(1 - \alpha_k)S_k = \frac{1}{2}(1 - \alpha_k)\frac{1}{\alpha_k}. \tag{17}$$

Squaring this expression, we can obtain the distribution of virtual quasiparticles in the form (14).

The given description of the ground state of the system is more general than that with the help of the conception of Bose–Einstein condensation, because the latter has a clear physical sense only in the case of the ideal Bose-gas. For systems with interaction, the Bose–Einstein condensation is valid only in the impulse approximation, which is not always convenient.

We now pass to the calculation of the temperature-independent contribution σ_0 to the entropy. At the absolute zero temperature, all processes are running so that an entropy is constant. It is believed that this value is equal to zero. However, in our representation of the superfluid component ^{4}He as a superposition of contrarily charged boson condensates, this constant contribution can be nonzero and will play a decisive role in the explanation of electric activity. As was mentioned above, the quantum mechanical fluctuations caused by the principle of uncertainty give the nonzero kinetic energy of the ground state and the distribution function of virtual quasiparticles. In work [13], various quantum mechanical states were described with the use of the Shannon entropy [12] which has sense of the degree of quantum mechanical uncertainty and is calculated on the modulus square of a wave function as on the distribution function. Moreover, the Heisenberg principle of uncertainty can be reformulated in terms of the entropy of a given state.

Let's present an example. Let an oscillator be in the ground state which is described by the known wave function. It is obvious that the von Neumann entropy is equal to zero. However, there exist the coordinate distribution $|\psi_x|^2 \sim e^{-x^2 m\omega/\hbar}$ and the momentum distribution $|\psi_p|^2 \sim e^{-p^2/m\omega\hbar}$, with which the nonzero Shannon entropy can be calculated as

$$\sigma_x = -\int |\psi_x|^2 \ln|\psi_x|^2 dx, \tag{18}$$

$$\sigma_p = -\int |\psi_p|^2 \ln|\psi_p|^2 dp. \tag{19}$$

The uncertainty relation for the ground state of an oscillator in the terms of the Shannon entropy can be written as

$$\sigma_x + \sigma_p = \ln(\pi e). \tag{20}$$

The given entropy has a simple physical sense, because it is expressed through the dispersion $D\xi$ of the oscillator dimensionless coordinate ξ as follows: $\sigma_\xi = D\xi + \ln\sqrt{\pi}$. That's why the Shannon entropy is the degree of quantum mechanical uncertainty.

The quantity $|\psi_p|^2$ plays the role of the distribution function of virtual quasiparticles corresponding to the occupation numbers $n^0_{\mathbf{k}}$. On the other hand, the superfluid component can be represented as a superposition of contrarily charged coherent condensates, the nuclear condensate (sN) and the pair electron one (se) due to the quantum mechanical spreading, whose degree is the Shannon entropy. Then we can calculate it as

$$\sigma_0 = -k_B \frac{1}{N} \sum_{\mathbf{k}} \frac{n^0_{\mathbf{k}}}{\Xi} \ln \frac{n^0_{\mathbf{k}}}{\Xi}, \tag{21}$$

where σ_0 is the entropy per atom, and Ξ is such normalization multiplier that $\sum\limits_{\mathbf{k}} \frac{n_{\mathbf{k}}}{\Xi} = 1$. Since the spectrum of quasiparticles is continual and no special states of the Bose-condensate type, as in the distribution function of particles (12), exist, we can pass from the summation to the integration, $\sum\limits_{\mathbf{k}} \to V \int\limits_0^{+\infty} \frac{d^3k}{(2\pi)^3}$, and get

$$\sigma_0 = -k_{\mathrm{B}} \frac{V}{N} \int\limits_0^{+\infty} \frac{n_0(k)}{\Xi} \ln \frac{n_0(k)}{\Xi} \frac{4\pi k^2 dk}{(2\pi)^3}, \tag{22}$$

where the normalization multiplier is

$$\Xi = \frac{V}{N} \int\limits_0^{+\infty} n_0(k) \frac{d^3k}{(2\pi)^3}. \tag{23}$$

The value of σ_0 on the distribution $n_0(k)$ is nonzero and corresponds to the pure state. The overlapping of the wave functions of atoms (as that for de Broglie waves) disappears above the λ-point. Hence, the superposition of contrarily charged coherent states of the system stops to exist. This manifests itself mathematically in that the Shannon entropy (22) tends to zero. As a result, the effect is not present above the λ-point.

We now pass to specific calculations with the use of different model potentials with the corresponding collections of parameters. In the first approximation, we use the pseudopotential of hard cores

$$\nu_k \approx \nu_0 = \frac{4\pi\hbar^2 a}{m}, \tag{24}$$

where ν_k is the Fourier transform of the interaction potential expressed via the scattering length $a > 0$. Substituting (24) in the expression for the spectrum ε_k

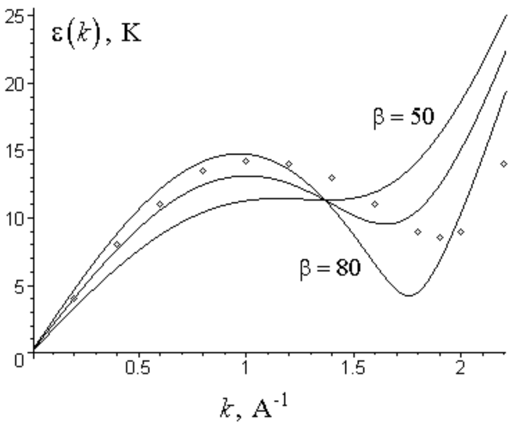

Fig. 1. Theoretical spectrum of He II for the Brueckner–Sawada model potential with the parameters a = 2.3 Å and β = 50, 60, 80. The experimental curve is shown by points

(6) and then in (14), we obtain the distribution function of virtual qusiparticles in the form (see Fig. 2)

$$n_0\left(k\right)=\frac{1}{4}\left(1-\left(1+\frac{16\pi Na}{V}\frac{1}{k^2}\right)^{-1/2}\right)^2. \tag{25}$$

It is worth noting that the distribution function $k^2 n_0\left(k\right)$ has maximum at the point

$$k_{\max}^2\sim\frac{N}{V}a \tag{26}$$

that coincides with the maximum of the distribution function of above-condensate particles in the field-theoretic method of Bogolyubov. The relevant value of the energy gap in the first approximation corresponds to that of the ordinary perturbation theory in the same approximation (in the second approximation, the gap is filled by the phonon spectrum) for the Bose-gas of hard cores [10].

Now we can calculate entropy (22) knowing the average equilibrium density N/V = 0.02185 Å^{-3} and the typical scattering lengths for a He atom (Table 1).

We consider our result as quite satisfactory in view of both the fact that liquid helium is strongly nonideal and the roughness of our approximation

The spectrum ε_k calculated on pseudopotential (24) doesn't correspond to the well-known spectrum of superfluid helium. Therefore, our next step will be the further consideration of peculiarities of the interaction potential for helium atoms (the presence of attraction). With this purpose, we use the Brueckner–Sawada potential [16], whose Fourier transform is

T a b l e 1. Values of the Shannon entropy of superfluid helium corresponding to the scattering lengths a of atoms in the model with pseudopotential

a (Å)	2.30	2.40	2.50	2.60	2.70
$\sigma_0 k_{\rm B}^{-1}$	6.50	6.58	6.65	6.72	6.80

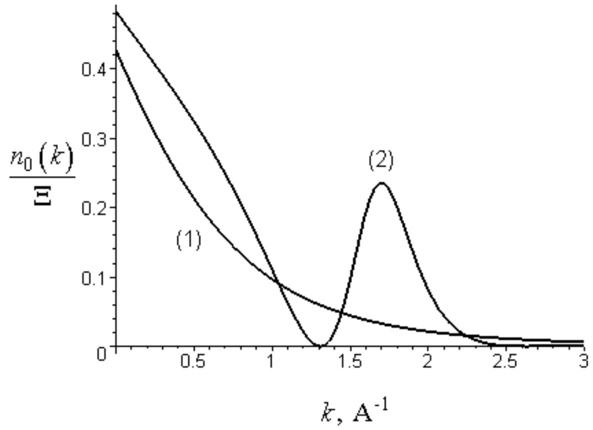

Fig. 2. Distribution function of virtual quasiparticles in superfluid helium. Curve (*1*) corresponds to the approximation by the pseudopotential with a = 2.3 Å. Curve (*2*) corresponds to the Brueckner–Sawada model potential with a = 2.3 Å and β = 55

$$\nu_k=V_0\frac{\sin(ka)}{ka}, \tag{27}$$

where V_0 is the potential amplitude, and a is its characteristic length. Then the spectrum is determined by the expression

$$\varepsilon_k=\frac{\hbar^2}{2m}\sqrt{k^4+\frac{\beta\sin\left(ka\right)}{a^3}k}, \tag{28}$$

where the dimensionless parameter $\beta = 4nma^2V_0/\hbar^2$. The approximation of helium's spectrum by function (28) is presented in Fig. 1.

Within this model, we can construct the distribution function of virtual quasiparticles:

$$n_0\left(k\right)=\frac{1}{4}\left(1-\left(1+\beta\frac{\sin ka}{\left(ka\right)^3}\right)^{-1/2}\right)^2. \tag{29}$$

The plot of the given function has a characteristic maximum corresponding to elementary excitations of the roton type (Fig. 2), unlike the earlier considered function in the model with a pseudopotential. The left part of the plot corresponds to phonons.

Now we can calculate entropy (22) on the distribution function (29), by taking such parameters which ensure a satisfactory agreement of the theoretical spectrum of quasiparticles and the experimental data (Table 2).

On this stage of approximations, the dispersion of obtained values of the Shannon entropy for the ground state is situated in the limits of experiment's errors on the variation of the parameters of the spectrum of elementary excitations.

3. Conclusion

We have shown that the Shannon entropy as the degree of quantum mechanical uncertainty gives the temperature-independent contribution to the entropy, which induces quantum fluctuations of the superfluid state's density. For this reason, the kinetic energy of He II (as a part of the internal energy) isn't equal to zero in the ground state. This energy can be written in terms of the energy of virtual quasiparticles with the Bogolyubov spectrum, rather than in terms of the energy of particles, as it is made in many papers in the impulse approximation limit. The quantum fluctuations, which have a form of virtual phonons and rotons, make a background of the ground state and give the above-mentioned temperature-independent contribution to the entropy. The entropy can be calculated in the random phase approximation with the help the model potentials such as the pseudopotential and the Brueckner potential. The obtained result $\langle\sigma_0\rangle = 2.3k_{\rm B}$ is in good agreement with experimental data $(2 \pm 0.5)\,k_{\rm B}$. This representation corresponds to the ideas of quantum field theory, where there exist the vacuum fluctuations which cause such phenomena as the Lamb shift, Casimir effect, etc. The electric activity in helium (the appearance of polarization in the second-sound field and, conversely. the generation of the second sound by the induced polarization) is an analogous effect. We may assume that the mechanism of polarization in He II is the ordering of virtual dipole moments in the coherent medium (the medium with strong quantum correlations) by a second-sound wave.

T a b l e 2. Values of the Shannon entropy $\sigma_0 \cdot k_{\rm B}^{-1}$ of superfluid helium in the model with the Brueckner–Sawada potential as a function of the interaction length a and the intensity $\beta = \frac{4nma^2V_0}{\hbar^2}$. The values of the parameters which give the best agreement with experiment are distinguished with a frame

a (Å) / β	2.10	2.20	2.30	2.40	2.50
50	2.60	2.46	2.32	2.19	2.10
55	2.58	2.44	2.31	2.18	2.06
60	2.53	2.39	2.26	2.13	2.00
65	–	2.30	2.17	2.04	1.91

The authors thank A.O. Semenov and E.A. Pashitskii for the valuable remarks and the useful discussions in the process of preparation of this work.

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Received 23.10.07

ЕНТРОПІЯ ОСНОВНОГО СТАНУ І ЕЛЕКТРИЧНА АКТИВНІСТЬ НАДПЛИННОГО ГЕЛІЮ ПРИ ЗБУДЖЕННІ ХВИЛЬ ДРУГОГО ЗВУКУ

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Р е з ю м е

Запропоновано можливе пояснення походження температурно-незалежної частини ентропії He II, існування якої припускається у роботі Е.А. Пашицького та С.М. Рябченка (ФНТ **33**, 12 (2006)) для пояснення ефекту поляризації надплинного гелію під час проходження хвилі другого звуку. З даною метою розглянуто основний стан He II у наближенні випадкових фаз. Показано, що енергія цього стану може бути переписана через функцію розподілу віртуальних квазічастинок (фононів та ротонів), а не частинок, як це роблять у наближенні імпульсної апроксімації. Запропоноване представлення уявляється більш загальним. З функції розподілу обчислюється температурно-незалежний внесок в ентропію надплинного гелію, який має зміст ентропії Шеннона як міри квантово-механічної невизначеності, оскільки дані квазічастинки являють собою квантово-механічні флуктуації на фоні основного стану надплинного гелію.