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Creation of bulk elementary excitations in superfluid helium-II by helium atomic beams at low temperatures

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The experimental results of creating bulk elementary excitations (BEEs) in isotopically pure liquid helium-II by helium atomic beams at low temperatures ∼60 mK are presented. In the present experiment, BEE signals generated by ^{4}He-atomic beams incident on the liquid free surface were detected by a bolometer positioned in the liquid helium-II. Some detected signals were very weak and depended on the heater power. Some examples of BEE detected signals are shown. Also, group velocities of the detected BEEs are evaluated and the threshold velocities of the helium atoms are discussed. The present experimental results demonstrate BEE creation, such as the third non-dispersive Zakharenko waves (supra-thermal phonons), with energies ∼17 K (the Cooper pairing phenomenon doubles the supra-thermal phonon energy $E_k \sim 2 \times 17$ K∼34 K in order to fulfil the energy conservation law) in the positive roton branch of the BEE energy spectra by helium atomic beams with suitable energies ∼35 K, which perturb the liquid surface at incidence points similar to heaters.

1. Introduction

The so-called 'quantum evaporation' of ^{4}He-atoms by bulk elementary excitations (BEEs) of the liquid helium-II with energies greater than the binding energy E_B ∼7.15 K [1] is now well known owing to, for example, the experimental and theoretical works of A. F. G. Wyatt *et al.* [2, 3]. The quantum evaporation effect occurs in the liquid helium at low temperatures below the λ_0-point, $T_{\lambda 0} = 2.17$ K, at which the bulk liquid possesses three different types of BEEs in the phonon, negative and positive roton branches of the BEE energy spectra. The BEEs phonon branch represents a mesoscopic scale branch because the wavelengths $\lambda = 2\pi/k$ (k is the wavenumber) are much greater than the line size a_4 of a ^{4}He-atom, $a_4 \sim$ 1Å, at the first boundary of the phonon branch and there is $k \sim 1/a_4$ and $\lambda \sim a_4$ at the second boundary of the branch. Indeed, corresponding surface elementary excitations (SEEs) of the liquid helium-II can participate in the quantum evaporation process in addition to the corresponding BEEs, for example, interacting with incoming BEEs at the liquid–vacuum interface.

This report presents experimental evidence confirming the existence of the 'quantum condensation' process, in which the helium atoms can condense on the ^{4}He-liquid surface and

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can create some bulk elementary excitations. A helium atomic beam propagating in vacuum can consist of many ^{4}He-atoms with a distribution of kinetic energies. When a ^{4}He-atom condenses on the liquid surface, there are several events that may be possible:

(a) a fraction of its kinetic energy is given to a ripplon and/or the helium atom is reflected from the liquid surface;
(b) a bulk elementary excitation, for example a phonon, may be created at the surface and further propagate in the bulk liquid helium.

It is thought in [4] that the phonon creation probability by a ^{4}He-atom is very small, but not equal to zero. D. O. Edwards *et al.* [5] studied phonons and rotons, which were produced at the surface of the liquid helium-II by ^{4}He-atomic beams, where each ^{4}He-atom was converted into a single bulk elementary excitation at the surface. It is also noted that helium atomic beams can create surface elementary excitations (ripplons) at the surface, energy of which can be detected at the liquid surface.

2. Experiment and results

The experiments described in this paper show that it is possible for a ^{4}He-atom to create a phonon in the ‘quantum condensation’ process, when the helium atoms give their energies in order to create phonons. In this experiment, the heater $\boldsymbol{H}$ is situated above the liquid helium surface in vacuum as shown in figure 1. Signals of BEEs were detected by the bolometer $\boldsymbol{B}$ positioned in the bulk liquid helium. The point $\boldsymbol{O}$ in figure 1 represents the incidence point of the helium atoms to the liquid surface. The time between a heater pulse and detection of a BEE by the bolometer $\boldsymbol{B}$ is written as follows, using [6]:

$$t = \frac{x_1}{C_g^{ex}} + \frac{x_2}{V_{at}} \tag{1}$$

where the distances x_1 and x_2 are shown in figure 1; C_g^{ex} and V_{at} are the velocities of bulk elementary excitations and helium atoms, respectively. It is assumed that condensation time is equal to zero or is too negligible in comparison with the propagation times of corresponding BEEs in the liquid ($t_1 = x_1/C_g^{ex}$) and free quasi-particles in vacuum ($t_2 = x_2/V_{at}$). Therefore, velocities of propagating BEEs can be readily obtained from the equation (1) as follows:

$$C_g^{ex} = \frac{x_1}{t - x_2/V_{at}} \tag{2}$$

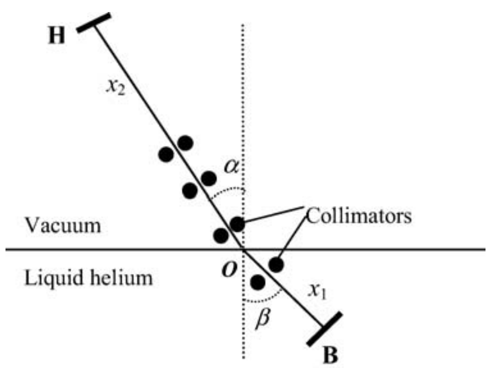

Figure 1. The experimental arrangement, where the angle α between the heater $\boldsymbol{H}$ and the liquid surface normal is 30° and the distance x_2 is ~25 mm. The angle β between the bolometer $\boldsymbol{B}$ and the surface normal is 40° and the distance x_1 is ~7 mm.

where the total time $t = t_1 + t_2$ is measured; the velocity V_{at} is evaluated in additional experiments using the same experimental cell with a small amount of the superfluid helium in order to have a vacuum between the heater $\boldsymbol{H}$ and bolometer $\boldsymbol{B}$ (the atoms in vacuum propagate the total distance $x_1 + x_2$, see figure 1) and the distances x_1 and x_2 are unchanged.

Since a helium atomic beam has a kinetic energy distribution of the helium atoms, it is useful to know about atom energies that can participate in the 'quantum condensation' process. By straightforward comparison of equation (2) with the experimental data, it is apparent that only the fast atoms contribute to the detected signals. Therefore, for helium atom velocities, as well as for atom energies, there is a threshold atom velocity, solving equation $t - x_2/V_{at} = 0$

$$V_{at}^{th} = \frac{X_2}{t_0} \tag{3}$$

which shows that atom velocities should be greater than the threshold atom velocity (3), because the value for V_{at}^{th} given above requires an infinite velocity of a bulk elementary excitation (see equation (2)).

The criterion (3) assumes that at the threshold atom velocity, a corresponding BEE velocity should be equal to infinity. This fact requires making such a correction that practically it is possible in the liquid helium at low temperature to create BEEs with velocities not greater than the maximum group velocity of the phonons that is equal to ~250/ms [7–10, private communication (W.G. Stirling, 1983)]. Taking that into account, the criterion can be now introduced in the following view, denoting experimentally measured total time as t_0:

$$V^{th} = \frac{x_2}{t_0 - x_1/C_0} \tag{4}$$

where C_0 can be equal to ~238 /ms for the wavenumber $k \to 0$. The given distances x_1 and x_2 are shown in figure 1. It is thought that a ^{4}He-atom can create a BEE only if it has energy which correlates with the corresponding specific energy.

The signals detected by the bolometer $\boldsymbol{B}$ in the liquid are shown in figures 2 and 3 for different heater powers. The two peaks in figure 2 could correspond to two different types of BEEs that were created by helium atomic beams in the present experiment. In this case the heater power attenuation of −13 dB was used. There was a slight warming in the experimental cell owing to this level in the heater power. The first arrival time for the first large peak is ~ 150 to 160 μs, but even ~110 to 125 μs, because very weak signals are observed slightly

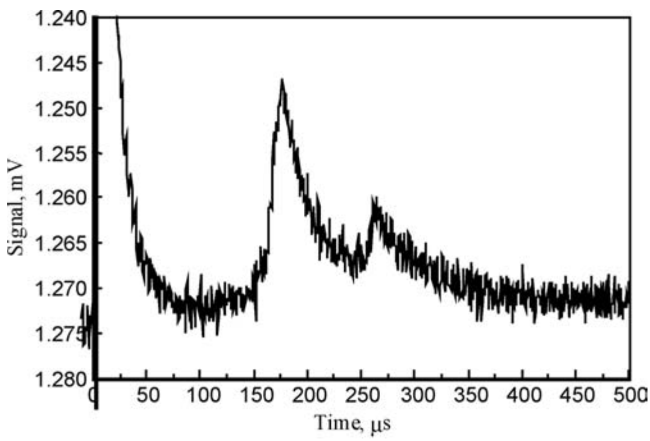

Figure 2. The experimentally detected signals of the bulk elementary excitations for the heater power attenuation −13 dB.

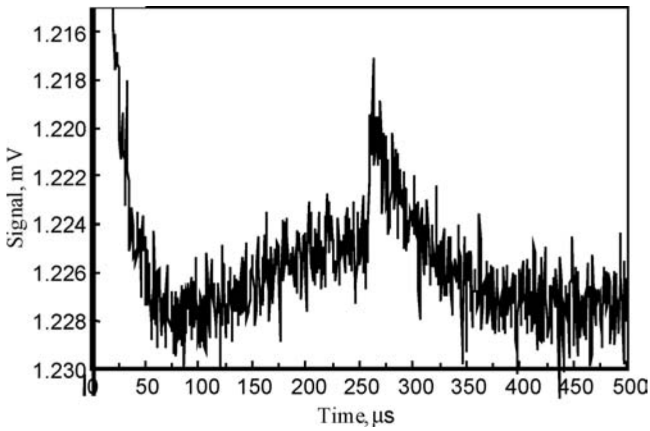

Figure 3. The experimentally detected signal of the bulk elementary excitations for the heater power attenuation −23 dB.

above the noisy level in figures 2 and 3. In the present experiment, the distance x_1 is ~7 mm and the distance x_2 is ~25 mm. The threshold atom velocity using criterion (3) is ~180/ms, but according to the corrected criterion (4) it would be ~213/ms.

The important features from the measured signals are summarized in table 1. The second smaller peak in figure 2 has a first arrival time of ~256 μs. The corresponding threshold atom velocity and the corrected threshold atom velocity in this case are ~117/ms and ~130/ms, respectively. Note that the second peak is also present when a smaller heater power is used (see figure 3), while the first peak in figure 2 disappears. However, there is a very weak signal slightly above the noise level in figure 2. This may be explained by the fact that the maximum in the energy distribution of an atomic beam is shifted up to greater atom energies with increasing heater power. The dependence of atom energy in an atomic beam on the time of flight to the surface is shown in figure 4 for the heater power attenuation −23 dB. It is obvious that the helium atom energy at the point of first arrival is approximately equal to $E_k^{at} \sim 12$ K that is already enough for the helium atoms with such an energy level to create the second non-dispersive Zakharenko wave (corresponding BEEs in the negative roton energy branch) and to excite the third non-dispersive Zakharenko wave (corresponding positive rotons with energy ~35 K) satisfying the energy conservation law, according to the theory recently introduced in Ref. [11]. It is obvious that propagating BEEs, which can travel for a macroscopic distances used in this experiments in a condensed matter such as a solid or a liquid, must represent non-dispersive or weakly-dispersive waves. Because all BEEs possessing velocities from zero up to ~250 m/s in the phonon and rotons energy spectra can be treated as weakly dispersive waves, it is possible to account only non-dispersive waves suggesting that the dispersive waves can propagate for longer distances than (weakly) dispersive waves in the same energy branch. The existence of one corresponding non-dispersive Zakharenko wave ($C_g = C_{ph} <> 0$) in

Table 1. Measured amplitudes and peak times of the detected signals shown in figure 2.

Power, dB	Signal, μV		Time, μs	
−13	13	28	264.5	176
−20	10	–	263.0	–
−23	8	–	262.5	–
−26	3	–	263.0	–

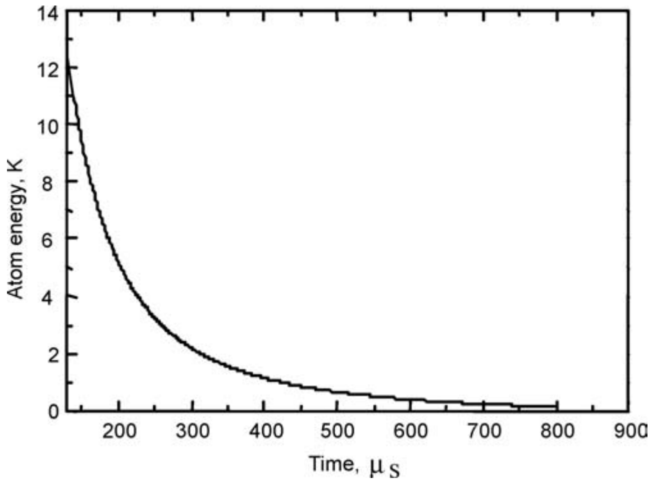

Figure 4. The ^{4}He-atoms' energies for the atoms incoming to the liquid surface from the first arrival point ∼140 μs (hottest atoms).

each BEEs energy branch was discussed in [11], because in each branch there are dispersive BEEs with $C_g > C_{ph}$ and $C_g < C_{ph}$.

There is a wide range of allowed atom velocities in figure 5 between the first arrival time and the threshold velocity time. The threshold velocity is smaller than the atom velocity corresponding to the peak. But because there is such a weak signal, it is thought that it is better to take the fastest atom velocity in order to calculate the bulk excitation velocity. For example, in figure 3 the time of first arrival is $t_0 = 256\ \mu$s. The atom velocity at the point of first arrival is 213/ms in figure 5. Therefore, substituting t_0 and V_0 in equation (2) the corresponding BEE velocity is ∼52/ms. This velocity is in the maxon region of the phonon branch of the bulk elementary excitation spectra [private communication (W. G. Stirling 1983), 10]. It is believed that this small signal corresponds to the phonons, because the signal is weak and there is no dependence on the heater power. That could mean that in helium atomic beams only atoms with specific energies can excite the phonons with corresponding specific energies. It is thought

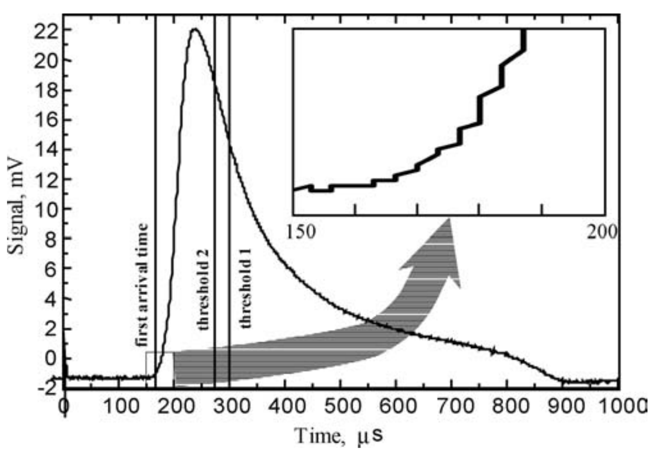

Figure 5. The atom signal for heater parameters −23 dB and 2 μs with the thresholds 1 and 2 calculated using the criteria (3) and (4), respectively. The insertion shows the time of first arrival.

that if the heater power increases, more atoms with suitable energies will appear to excite the phonons, because there is no dependence of the first arrival time of the detected phonon signals on the heater power. There are other possible ways to evaluate the group velocity. For example, one can measure the point of 'maximum gradient' (inflexion point in figure 5) or point of 'maximum temperature' (maximum in figure 5). In the first case the velocity is equal to ~81/ms and in the second case there is ~116/ms. Both the criteria (3) and (4) in figure 5 clearly show that created BEE signal can be caused by the helium atoms possessing kinetic energies in the energy range near the first arrival time. Two points of the criteria (3) and (4) are enough to see what we are dealing with. Note that there is a small amount of fastest helium atoms that is seen near the first arrival time shown in the figure 5 insertion.

By careful analysis of helium atom reflection spectra, it may be possible to observe a clear minimum corresponding to the energy of condensed helium atoms. This would make it possible experimentally to obtain atoms with specific energies able to excite bulk elementary excitations in the liquid helium and maybe to confirm the assumption of 'zero condensation time'. The previous experimental works [12, 13], concerning the specular reflection of ^{4}He-atomic beams from the liquid surface, were not intended to investigate ^{4}He-atom-to-BEE interactions at the liquid surface. However, this may be possible but very difficult owing to the very weak interaction. Reference [14] concluded that ripplon creation owing to the condensing helium atoms was experimentally observed. Also, it is necessary to discuss the binding energy E_b^a in a helium atomic beam which is less than 2 mK, according to [15]. The binding energy E_b^a is small compared with the atomic energies in figure 4, and therefore, it is possible to omit it. A second possible way to find out more about the condensation process would be to set different screens between a heater and the liquid surface in order to cut out atoms with specific energies.

According to the criteria (3) and (4), as well as to figure 5, it is necessary to take only the first arrival point for calculations of the excitations velocity, but not the other points discussed in this paper, because the signals at the bolometer are very long ~850 μs, but an initial heater pulse is only 2 μs. This could be attributed to the fact that the bolometer surfaces in such low temperature experiments are covered with thin liquid-helium film and, therefore, SEEs in the liquid film produced by incident helium atomic beams are incoming to the bolometer work area from many places to where broad ^{4}He-atomic beams strike. In addition, it is thought that some ^{4}He-atoms closing to the liquid helium surface can reflect from the surface within each collimator aperture that can also cause a significant broadening of the helium atomic beams outgoing from such a collimator, surfaces of which are covered with a thin film of the liquid helium that is schematically shown in figure 6. It is also thought that trajectory of some slow ^{4}He-atoms travelling along the liquid surface can be significantly changed, because any surface is active possessing a potential. According to figures 4 and 5 as well as table 1, already for the heater power attenuation −23 dB the quickest helium atoms have their kinetic energies ~12 K, i.e. enough to create the negative rotons (the second non-dispersive Zakharenko waves [11]), but their energies are still not enough to create the positive rotons, for which a ^{4}He-atom needs to reach its kinetic energy ~35 K. Indeed, it is expected that the time of first arrival of the helium atomic beams will decrease with changes in the heater power attenuation as shown in figure 7, where faster atoms can be created with greater heater power under smaller attenuation. Note that the heater power attenuation −23 dB corresponds to attenuation of an original heater pulse of 200 times. In figure 7, the helium atoms must go in vacuum the distance $d_a = x_1 + x_2 \sim 32$ mm between the bolometer and heater (see figure 1). Hence, group velocities V_g and energies E_a of the created helium atoms by the heater can be readily calculated with the following well-known formulae such as $V_g = d_a/t_a$ and $E_a = m_4 V_g^2/2$, using the first arrival time t_a of the atoms for the heater power attenuations shown in figure 7 and the constant distance $d_a \sim 32$ mm. The calculated velocities V_g of the helium atoms are

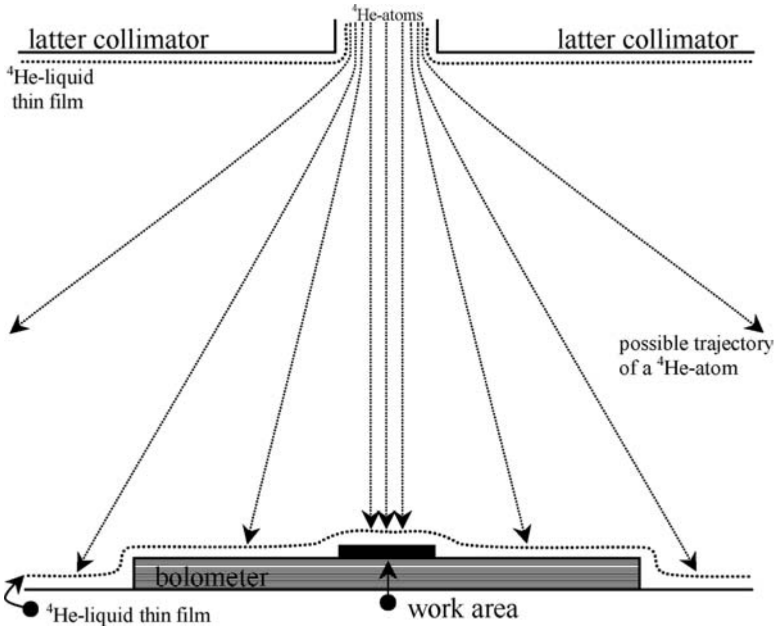

Figure 6. The schematic representation of incoming ^{4}He-atoms down to the bolometer in the area between the latter collimator and the bolometer in the experimental cell at low temperatures with small amount of the liquid helium enough to cover the bolometer with a thin film of the superfluid liquid.

used in formula (1) for the main experiment shown in figure 1, in order to verify the creation of non-dispersive waves (propagating BEEs) in the liquid. The theory of Ref. [11] suggests that the helium atoms, which can create non-dispersive BEEs with $C_g = C_{ph} <> 0$ propagating in the liquid helium with the velocities C_g in the both roton branches, must have the velocities $V_g = 2C_g$ due to $V_g = 2V_{ph}$ and $C_g = C_{ph} = V_{ph}$, assuming that atom-to-BEE conversion should be in the same k-ω-domain. For the creation of the second and third non-dispersive

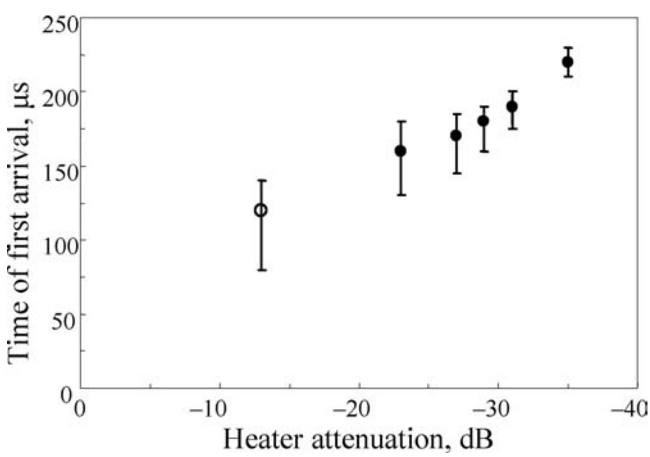

Figure 7. The measured first arrival time with error bars of incoming ^{4}He-atomic beams at the bolometer. The empty cycle for the heater power attenuation −13 dB shows possible time of first arrival, using the experimental results with the greater attenuations in the heater power (see the filled cycles).

Zakharenko waves, the helium atoms must have the group velocities $V_g \sim 200$–220 m/s and $\sim$380–400 m/s, respectively. The creation evidence of the second non-dispersive Zakharenko waves with energies $\sim$12 K by ^{4}He-atoms with the suitable kinetic energies $\sim$12 K in the helium atomic beams can be reported in the future.

It is noted that non-dispersive Zakharenko waves exist only in systems that possess dispersion, namely a dependence of the phase velocity C_{ph} on both the angular frequency ω and wavenumber k. Therefore, independence of the phase velocity C_{ph} on both the frequency ω and wavenumber k can be mathematically shown by the following formula:

$$\frac{\mathrm{d}C_{ph}}{\mathrm{d}k} = \frac{\mathrm{d}C_{ph}}{\mathrm{d}\omega} = 0 \tag{5}$$

because there is the following well-known relationship:

$$\frac{\mathrm{d}C_{ph}}{\mathrm{d}k} = C_g \frac{\mathrm{d}C_{ph}}{\mathrm{d}\omega} \tag{6}$$

where $C_g = \mathrm{d}\omega/\mathrm{d}k$ is the group velocity. This manifests that one deals here with the same k- and ω-domain. It is thought that it is already well-known that the first derivatives of the phase velocity, $\mathrm{d}C_{ph}/\mathrm{d}k$ and $\mathrm{d}C_{ph}/\mathrm{d}\omega$, depend on both the phase and group velocities as follows:

$$\frac{\mathrm{d}C_{ph}}{\mathrm{d}k} = \frac{1}{k}(C_g - C_{ph}) \tag{7}$$

$$\frac{\mathrm{d}C_{ph}}{\mathrm{d}\omega} = \frac{C_{ph}}{\omega}\left(1 - \frac{C_{ph}}{C_g}\right) \tag{8}$$

The formulae (5) and (6) are right for any point in dispersion relations $C_{ph}(k)$ and $C_{ph}(\omega)$. However, for extreme points there is equality of the phase velocity C_{ph} with the group velocity C_g in both formulas.

It was discussed in [11] that the BEE energy spectra around both the maxon maximum and the roton minimum can be described as free quasi-particles with negative and positive kinetic energies for the De Broglie waves, respectively. They are quasi-particles of two different types. For example, a free electron possesses positive energy, but a free positron possesses negative energy. Quasi-particles of both types can show two possible dispersion types, $C_{ph} < C_g$ and $C_{ph} > C_g$, depending on positive and negative wavenumbers. However, their dispersions for the same wavenumber sign are different. For example, free quasi-particles with positive energies possess the dispersion $C_{ph} < C_g$ for positive wavenumber, while free quasi-particles with negative energies possess the dispersion $C_{ph} > C_g$ for the same positive wavenumber. According to this fact that was discussed in [11], there are bulk elementary excitations with both dispersion types in each energy zone of the BEE energy spectra for the liquid helium-II. Therefore, there are two sub-modes (modes) of BEE dispersive waves with different dispersion types in each energy zone (in the phonon, negative and positive energy branches) resulting in the presence of one corresponding non-dispersive Zakharenko wave in each branch.

It is thought that a propagating wave velocity corresponding to the non-dispersive Zakharenko wave for a taken elementary-excitations energy branch obtained experimentally can be readily evaluated by an experimentalist, using the well-known Landau's 'paper-and-pencil' technique applied to the BEEs energy spectra of the superfluid helium-4, which is described in the famous classic books [16, 17]. According to [16, 17], $\mathrm{d}E_p/\mathrm{d}p$ represents the BEE velocity where the function $E_p(p)$ and $p = k\hbar$ are the BEE energy and quasi-impulse, respectively, working with the Planck's constant $\hbar$. It is possible to apply some modifications such as separate treatment of each BEEs energy branch for finding the points $\mathrm{d}E_p/\mathrm{d}p = E_p/p$ ($C_g = C_{ph} <> 0$) of the function $E_p(p)$, using the corresponding minimum energies for each energy branch (i.e. $E_p = 0$ for the phonon branch and $E_p = E_R = 8.6$ K for the roton branches with $E_R \sim 8.6$ K being the roton minimum energy), but not the Landau's *et al*. treatment of these three branches as single branch for calculations, using only the zero minimum energy at the wavenumber $k = 0$, that allows only right evaluation of the velocity ~250 m/s corresponding to the first non-dispersive Zakharenko wave in the BEEs phonon branch and gives the incorrect value of ~60 m/s for the third non-dispersive Zakharenko wave in the positive roton branch, as well as nothing for the negative roton branch. Indeed, the same technique can be applied to evaluate propagation velocity in a superconducting-electron energy branch experimentally measured, as well as to any energy branch (mode of dispersive waves) in (complex) solids.

It is thought that use of purified materials can significantly improve experimental verifications of elementary-excitations propagating waves. For example, usage of pure liquid helium is practically important in such the experiments at low temperatures below 100 mK carried out in this work, because ^{3}He-impurities go to the liquid surface and can thus contribute to detection signals. Isotopically pure liquid helium [18] is therefore used which possesses a residual ^{3}He content of 6 ± 4 parts in 10^{10}, according to measurements by the US Bureau of Mines (Department of the Interior), Amarillo, Texas, USA. It is noted that ^{3}He atoms preferentially go to the free surface of liquid helium when the number of ^{3}He atoms is low enough that less than a monolayer is formed [18]. From the surface area of the free liquid cooled down to <100 mK with a dilution refrigerator, the estimation of [6] gave the concentration of ^{3}He on the liquid surface being ~0.1% of a monolayer.

Theoretical modeling wave processes in an energy branch (mode of dispersive waves) are naturally based on experimental data. Additional conditions on branch boundaries are also very important. Concerning the negative roton energy branch, boundary conditions for dispersive waves such as $\mathrm{d}^2C_g/\mathrm{d}p^2 = \mathrm{d}^2C_{ph}/\mathrm{d}p^2 = 0$ can be used on both boundaries of the branch in addition to $C_g = C_{ph} = 0$ for the Bose–Einstein condensation (BEC) representing inflection points for both velocities C_g and C_{ph} of dispersive waves. It is noted that dispersion relations are similar to the ones of a free quasi-particle about both the maxon maximum and roton minimum of the BEEs energy spectra. Dispersion relations for a free quasi-particle such as a free ^{4}He atom will be discussed in the next section. Indeed, presence of the non-dispersive Zakharenko wave in each energy branch must be accounted. For example, in the BEEs phonon branch there is the first non-dispersive Zakharenko wave due to the so-called phonon backflow effect measured in [personal communication (W. G. Stirling, 1983), 10] by Stirling and the effect significantly complicates study of quantum systems that is true for the roton branches with possible possession of roton backflow effects. One of possible modeling method is to choose a suitable function $E_p(p)$, for example, a polynomial. It is thought that nowadays the most popular mathematical method of the quantum field theory is finding suitable Green's functions. A Green's function is an integral kernel and can be used to solve an inhomogeneous differential equation with boundary conditions. It can roughly serve an analogous role in partial differential equations as does Fourier analysis in the solution of ordinary differential equations. It was noted in [16] that 'Green's functions' in the quantum field theory (QFT), satisfying a non-linear equation with well-known δ-function, has a different sense in QFT from that exists for the theory of linear equations. However, Green's functions for free quasi-particles actually are Green's functions of linear equations for Heisenberg's field operators. The phrase 'Green's functions' originally applied only to the linear case was also applied to any interacting system.

3. Discussions

It is possible to discuss the three energy branches of the BEEs energy spectra of the superfluid helium-II at low temperatures concerning the so-called quantum condensation process, when

^{4}He-atoms can be condensed creating BEEs which have non-zero propagating velocity. The so-called BEEs phonon energy branch has two natural boundaries in the k-space and begins with the long-wavelengths λ regime for the wavenumber $k \to 0$, $k = 2\pi/\lambda$, where it is possible to assume that macroscopic phenomena play a role. On the other hand, the phonon energy branch has the second natural limit (maxon maximum) coupled with the line size a_4 of a ^{4}He-atom such as $a_4 \sim 1$ Å^{-1} that corresponds to wavenumber $k \sim 1$ Å^{-1}. Hence, the liquid helium-II is treated as a quantum liquid because the maxon maximum position at the wavenumber $k \sim 1.13$ Å^{-1} gives wavelengths close to the ^{4}He-atom line size a_4. Therefore, the phonon energy branch is situated on the mesoscopic scale from $k \to 0$ to $k \sim 1.13$ Å^{-1}. The evaluated maxon mass at the wavenumber $k \sim 1.13$ Å^{-1} approaches the mass of a free ^{4}He-atom, according to the recent theory [11]. It is well known that mesoscopic is used in order to indicate the scale between microscopic and true macroscopic phenomena. Experimental investigations of [19] (see also in [2]) were oriented towards studying the phonon-maxon part of the BEEs energy spectra representing a region of the transition between of the collective zero sound mode to the single particle mode. The presence of the first non-dispersive Zakharenko wave [11] in the phonon branch can be explained as a natural hybridization of these two modes. The recent theory [11] shows the ^{4}He-atom condensation possibility in each BEEs energy branch, in the phonon and two roton branches, at the points representing so-called binding energies when the BEEs phase velocity crosses the ^{4}He-atom phase velocity giving the same k-ω-domains for both oscillation types such as BEEs and ^{4}He-atoms. However, it is thought that the condensation mechanism is different in each branch. In the mesoscopic-scale phonon branch, the crossing point exists at some wavenumber between the wavenumbers for the first non-dispersive Zakharenko wave and the maxon maximum, where it is thought that there is the relationship for the BEEs phase and group velocities such as $C_{ph} > C_g$. It is also thought that in the phonon branch, the created BEEs dispersive waves cannot propagate in the bulk liquid for long distances and will very quickly disperse their energy in the bulk liquid near the liquid surface within a liquid slab of several microns (1μm $>> 10$ Å). Note that the surface elementary excitations (SEEs or ripplons) exist within the slab of $\sim$10 Å according to an X-ray study of the liquid-vapor density profile of the liquid helium carried out in [21]. Such the phase velocity dispersion with $C_{ph} > C_g$ is called normal dispersion using reference-books, for example, see in [22].

In addition to the normal dispersion with $C_{ph} > C_g$ there is so-called anormal dispersion for $C_{ph} < C_g$. However, all free quasi-particles propagating in vacuum can possess such the anormal dispersion when the phase velocity is less than the group velocity that is also true for a free ^{4}He-atom. Therefore, it is thought that to say ‘anormal dispersion’ is somewhat incorrect because it is met not less that the so-called ‘normal dispersion’. It is better to state that there are two possible types of the phase velocity dispersions such as $C_{ph} > C_g$ and $C_{ph} < C_g$. The kinetic energy, phase and group velocities for a free ^{4}He-atom are written as follows:

$$E_k = \hbar\omega = \hbar^2 k^2/2m_4 \tag{9}$$

$$V_{ph} = \hbar k/2m_4 \tag{10}$$

$$V_g = \hbar k/m_4 \tag{11}$$

where $\hbar$ and m_4 are the Planck’s constant, $\hbar = 1.054571596 \times 10^{-34}$ Js, and the ^{4}He-atom mass, $m_4 = 6.667 \times 10^{-27}$ kg. It is clearly seen in equations (10) and (11) that a free quasi-particle (a free ^{4}He-atom) possesses the dispersion $V_g > V_{ph}$ with the constant relationship:

$$V_g = 2V_{ph} \tag{12}$$

It is thought that negative and positive wavenumbers are identical because they give the same positive energy in equation (9). However, a positive wavenumber gives positive phase and group velocities in equation (12) and a negative wavenumber gives negative phase and group velocities:

$$-V_g = -2V_{ph}. \tag{13}$$

Equation (13) represents the second possible case of the dispersion $V_g < V_{ph}$, because negative values of the phase and group velocities are compared. Hence, it is possible to state that dispersion of a system can be different for positive energies. This statement gives a possibility for a free ^{4}He-atom to participate in the condensation process in each BEEs energy branch (including the BEEs negative roton branch), because it is expected that a free ^{4}He-atom can be simultaneously in both positive and negative k-spaces giving positive energies.

Similar to the mesoscopic-scale phonon branch, the negative roton branch can be treated as the energy branch with an atomic-nucleus intermediate scale, because the branch boundaries on the k-scale are the wavenumbers for the maxon maximum and the roton minimum. The roton minimum is situated at the wavenumber $k \sim 1.925$ Å^{-1} that corresponds to $\lambda \sim a_4/2$. It is well-known that a ^{4}He-atom consists of two neutrons and two proton-electron pairs (four-particle system or 4PS) and the proton mass is $m_p = 1.6726215813 \times 10^{-27}$ kg. Note that the maxon and roton effective masses are close to the masses of free quasi-particles such as the masses of a free ^{4}He-atom and a free neutron, respectively. Using the energy conservation law, the quantum condensation process in the negative-roton energy branch is possible when a single ^{4}He-atom with the kinetic energy $\sim$12 K is converted into one corresponding BEE such as the negative roton with the same energy about 12 K. The created BEEs of the energy branch at the liquid surface can propagate for long distances and, hence, detected in the bulk liquid far from the liquid surface. They represent the second non-dispersive Zakharenko waves existing at shorter wavelengths in the negative roton energy branch. It is noted that in this energy branch, the quantum condensation process must be reverse to the quantum evaporation process, because the corresponding wavelengths of fast ^{4}He-atoms and created BEEs are significantly smaller than the line size a_4. Therefore, these quantum processes occur when smaller quasi-particles, for instance neutrons, can be excited that can result in complex motions of an excited 4PS (a condensed ^{4}He-atom) in the liquid such as oscillations and rotations. It is expected that coherent helium atomic beams as well as coherent corresponding BEEs can be created in such the reverse quantum processes, because they must possess the same angular frequency ω.

The positive roton energy branch starts at the wavenumber k corresponding to the roton minimum. According to the recent theory [11], ^{4}He-atoms are very energetic and should have their own kinetic energy about 35 K corresponding to the velocity $V_g = 2V_{ph} \sim 380-400$ m/s in order to create corresponding BEEs in the positive roton branch. The very fast helium atoms can readily create at the liquid surface the third non-dispersive Zakharenko waves possessing energies about 17K and the velocity $C_g = C_{ph} \sim$ 190–200 m/s, which can propagate far from the surface of the isotopically pure liquid helium-II and detected there by a bolometer situated in the bulk liquid, and such the experiments were reported in this paper. The created BEEs in the positive roton branch manifest that they are coupled into pairs giving an evidence of the Cooper pairing phenomenon occurred in superconductors at low temperatures as well as in many other complex systems. Indeed, the Cooper pairing phenomenon doubles the BEEs energy about 17 K giving doubled energy of 34 K to 35 K for the reverse quantum processes such as condensation and evaporation. The wavelengths of the created BEEs (the third non-dispersive Zakharenko waves) as well as of the helium atoms are already about 2.5 times less than the atomic line size a_4. Therefore, it is expected that there is no a dependence of such reverse quantum processes on a curvature of the liquid surface. It is noted that the atomic energy in equation (9) increases very quickly for wavenumbers $k > 2$ Å^{-1} that complicates the problem. Also, there is an assumption that there must be a second roton-like minimum for wavenumbers $k \gg 3$ Å as well as a second maxon-like maximum before the second roton minimum.

The corresponding BEEs (the third non-dispersive Zakharenko waves) in the positive roton branch can be readily created by heaters situated in the bulk liquid (for instance, see in [7–9] by Wyatt *et al*.). However, Wyatt *et al*. have incorrectly explained their experimental results on observation of two BEEs signals stating that they have observed low-energy phonons with energies ~1 K to 2 K and high-energy phonons with energies ~10 K to 11 K belonging to the same phonon branch. Nevertheless, it is right to state that the created BEEs belong to different BEEs branches such as the phonon and positive roton branches, according to the recent theory [11]. It is noted that two signals are observed in many quantum systems, where the Cooper pairing phenomenon can be identified. For example, two polaritons were observed in [23] studying GaAlAs samples excited in the absorption continuum with a weak cw-laser. It was rightly distinguished that these two polaritons, the so-called lower and upper polaritons, belong to two different energy branches, and the upper polaritons are at thermal equilibrium. Experiments were demonstrated in [23] on the polariton parametric amplification surviving almost up to room temperatures (~220 K). Hybridization with photons is sufficient to make condensation of polaritons, even if the electronic transition associated with polaritons generates fermionic excitations like electrons and holes. It has been proposed in some theoretical models [24] that polariton condensation can occur in microcavities embedding quantum dots, even if the optical excitation of quantum dots creates perfect fermions. A scenario originally proposed in [25] by Keldysh could be possible, where electrons and holes are free particles, but above a certain threshold density undergo a 'BCS-like' phase transition, as the Cooper pairing of one electron and one hole is energetically favoured by the appearance of an energy gap whose amplitude is much lower than the exciton binding energy [26]. Here the exciton binding energy plays a fundamental role in the high-temperature polariton amplification indicating that the phenomenon takes place only if excitons exist as bound particles. That makes possible the 'BCS-like' scenario confirming that the interaction between electron and hole dominates for the excitons as bosonic quasi-particles.

4. Conclusions

It was shown that it is possible to generate the bulk elementary excitations with different energies by helium atomic beams, which are incident on the free liquid helium surface. The created bulk elementary excitations can be readily detected by a bolometer situated in the bulk liquid at quite long distances ~5–10 mm from the liquid surface. More intensive study of the condensation process at the liquid surface assuming zero condensation time could open some interesting behaviour of helium atoms on the surface. Also, some researchers believe that the second weak signal could be noisy from somewhere, but not the phonon signal that it is necessary to check in next experimental works. The first large signal, which appears for the heater power attenuation −13 dB, corresponds to the third non-dispersive Zakharenko waves [11, 27], namely to positive rotons [11]. In addition, Brawn and Wyatt in their experimental work [28] have reported that they have created some propagating BEEs in the positive roton branch of the BEE energy spectra (it is noted that they must be the third non-dispersive Zakharenko wave according to [11]). However, using the recent theory [11], it is possible to conclude that the created BEEs by Brawn and Wyatt [28] must represent BEEs of the negative roton branch (namely, the second non-dispersive Zakharenko wave [11]). Thus, their explanations of their experimental results in [28] are incorrect. Therefore, the creation evidence of the corresponding negative rotons (the second non-dispersive Zakharenko wave) by helium atomic beams will be presented by the current author elsewhere, using some additional results of [29].

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