Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

# Studying creation of bulk elementary excitation by heaters in superfluid helium-II at low temperatures

ZAKHARENKO A. A.

(*International Institute of Zakharenko Waves, Krasnoyarsk 660037, Russia*)

E-mail: aazaaz@inbox.ru

Received Jan. 20, 2007; revision accepted Mar. 1, 2007

**Abstract:** In this paper, the obtained experimental results concerning creation of bulk elementary excitations (BEEs) in isotopically pure liquid $^4$He at low temperatures ~60 mK are discussed. Positive rotons' ($R^+$-rotons) creation by a pulsed heater was studied. Signals were recorded for the following quantum processes: quantum evaporation of $^4$He-atoms from the free liquid-helium surface by the BEEs of the liquid helium-II, and BEEs reflection from the free surface back into the bulk liquid. Typical signals are shown, and ratios of signal amplitudes are evaluated. For long heater pulses from 5 to 10 μs, appearance of the second atomic cloud consisting of evaporated $^4$He-atoms was observed in addition to the first atomic cloud. It is thought that the first atomic cloud of the evaporated helium atoms consists of very fast $^4$He-atoms with energies ~35 K evaporated by positive rotons with the special energies ~17 K (~$2E_R$~2×8.6 K with $E_R$ representing the roton minimum energy) corresponding to the third non-dispersive Zakharenko wave. The second cloud of slower $^4$He-atoms was created by surface elementary excitations (SEEs or ripplons) possessing the special energies ~7.15 K representing the binding energy. It was assumed that such SEEs can be created by phonons incoming to the liquid surface with special energies ~6.2 K corresponding to the first non-dispersive Zakharenko wave, which can interact at the liquid surface with the same phonons already reflected from the surface for long heater pulses. Also, some pulsed-heater characteristics were studied in order to better understand the features of such heaters in low temperature experiments.

**Key words:** Superfluid helium-II, Bulk elementary excitations (BEEs), Low temperatures, Cooper pairing phenomenon, Non-dispersive Zakharenko waves

**doi:**10.1631/jzus.2007.A1065 **Document code:** A **CLC number:** O59

## INTRODUCTION

It would be extremely useful to completely understand how the heaters used in low temperature experiments behave, in order to improve their features or to make other heaters with properties optimised for the creation of phonon or roton excitations (in particular, $R^+$-rotons). For example, it should be possible to answer the question: are the rotons created directly by a heater in liquid helium or are they created by phonons that are initially injected by a heater (Brown, 1990). The question is very interesting, because it asks about physical processes that occur at the solid-liquid helium boundary, and one can try to answer it by studying and analysing the properties of a heater pulse in the liquid helium at low temperatures far from those of the heater. In addition, it is useful to have a boundary far from the heater, at which the excitations can reflect, or cause evaporation, in order to gain additional information about properties of the generated excitations. The interface between vacuum and the liquid helium is the simplest possible boundary that is apparent. At this interface, the bulk elementary excitations (BEEs) can be reflected back to a bolometer in the liquid or liberate $^4$He-atoms in the so-called quantum evaporation process (Wyatt and Brown, 1990; Tucker and Wyatt, 1990; Forbes and Wyatt, 1990).

Probably, isotopically pure liquid helium is the most popular condensed state matter, which can be readily liquefied and purified on the Earth compared with the other condensed matter such as solids, growth of which still requires microgravity conditions in order to have very pure materials. It is preferable to study liquid regarding the superfluidity phenomenon, which is in many ways akin to the superconductivity phenomenon (Landau, 1941) in some suitable solids. It is obvious that the liquid helium-II is an isotropic material, because the propagating velocity does not depend on propagation direction in contrast to crystals, which are interesting for their superconductivity including high temperature superconductivity. However, BEEs in the liquid travel ballistically that could show difference in propagating velocity for BEEs travelling for a very long distance. This can be avoided in microgravity experiments. It is noted that there is no sure experimental evidence of significant change in the propagating velocity of the BEEs in liquid helium in experiments done under Earth conditions. It is well-known that the propagating velocity in liquid helium-II cannot be higher than ~250 m/s. However, liquid helium-II represents a complex liquid, for which several theories already exist. The next section briefly reviews existing theories.

## SHORT REVIEW OF EXISTING THEORIES

There is much theoretical study of the quantum effects in liquid helium-II, such as quantum evaporation and quantum condensation. It is thought that the most successful theoretical description of the phonon-roton energy branches of liquid helium-II was represented by Dalfovo *et al*.(1995b) based on the density-functional theory (DFT). However, even this theory (Dalfovo *et al*., 1995b) representing an improvement of the other theories discussed by Dalfovo *et al*.(1995b) does not take into account the backflow effects, and there is significant discrepancy between theory and experiments in the positive roton branch of the BEEs energy spectra. Also, it was generally noted by Dalfovo *et al*.(1995b) that theories and experiments have no satisfactory overlap yet. Dalfovo *et al*.(1995a) represents also one attempt to better understand roton participation in the quantum evaporation. Also, discussions concerning the role of quantum effects, as well as about the theory of classical orbits, can be found in (Dalfovo *et al*., 1995a) together with additional references for the subject. It is interesting that the theory of classical orbits predicts no evaporation from rotons with energies smaller than the maxon energy (~13.85 K), because a barrier occurs at the vacuum-liquid interface. On the other hand, it is thought accounting for the role of the quantum effects that only phonons and rotons with energies greater than the maxon energy can give rise to evaporation. Both are contradictory to each other and represent forbidding theories, which forbid some BEEs to propagate or to evaporate. Dalfovo *et al*.(1995a) give the first calculation of the evaporation rates using a many body approach accounting for several effects, such as both a description of the structure of the liquid surface (as well as the BEEs of the system) and a quantum description of the scattering processes involving elementary excitations at the surface, but excluding inelastic channels (multi-phonons and multi-ripplons). Dalfovo *et al*.(1995a) chose a slab greater than $100\times10^{-10}$ m for their calculations, and the binding energy $E_b$~7.15 K was chosen by Wilks (1967) as the chemical potential. They treated liquid as a condensed matter consisting of free $^4$He-atoms and also used holes and particles in their theory. Probably, such thick slab is suitable for investigations of any dispersive wave BEEs. However, it is already a well-known fact that some BEEs with special energies can propagate for very long macroscopic distances. In addition, neutron scattering experimental data showed that liquid helium-II consists of maxons and rotons as free quasi-particles existing near the maxon maximum and roton minimum, respectively, but not of free $^4$He-atoms. Moreover, it is thought that the binding energy $E_b$~7.15 K relates to the evaporation by surface elementary excitations (SEEs) of liquid helium-II representing the single possibility, but not the evaporation by the BEEs, for which there are three binding energies (one in each energy branch, according to recent theory (Zakharenko, 2005a)). Indeed, the binding energy $E_b$~7.15 K is close to the ripplon-maxon energy (the SEEs chemical potential), but they represent different phenomena. Therefore, it is necessary to take both the maxon (~13.85 K) and roton (~8.6 K) energies as some hybridized chemico-nuclear potentials for such complex liquid. It is noted that liquid helium-II is also treated as a neutron liquid, because the roton mass at the roton minimum approaches the mass of a free neutron, and the mass of a proton-electron pair and hence, the mass of a free hydrogen atom.

Recent phenomenological theory (Zakharenko, 2005a) is based on the phenomenon called the non-dispersive Zakharenko waves (Zakharenko, 2005b), as well as on the experimentally discovered phenomenon mentioned in (Lardat *et al*., 1971) in that there is an energy leak from one oscillation type into another at crossing points of two phase velocities corresponding to two different types of oscillations. The existence of the non-dispersive Zakharenko waves in the BEEs energy branches represents a solid argument for the problem of some BEEs propagation for very long macroscopic distances in the liquid helium-II at low temperatures. Indeed, it is a well-known fact in Acoustics that non-dispersive waves can propagate for longer distances than dispersive waves in the same mode (energy branch). Therefore, the recent theory (Zakharenko, 2005a) does not forbid both dispersive and non-dispersive waves to exist in the liquid. The two possible types of dispersive waves, $C_g>C_{ph}$ and $C_g<C_{ph}$, exist in each energy branch of the BEEs energy spectra, where $C_g$ and $C_{ph}$ are the BEEs group and phase velocities, respectively. Both dispersions occur in the BEEs phonon branch due to the measured "backflow effect" by Stirling (1983; 1985), in the BEEs negative roton branch due to existence of maxon with negative kinetic energy and roton with positive kinetic energy at the corresponding boundary of the branch and the possible roton backflow effect as a product of a complex hybridization of two quasi-particles, as well as in the BEEs positive roton branch due to the unique BEEs dispersion and the possible roton backflow effect. It is noted that the backflow effects are small ones giving significant rise in the system non-linearity. It is also noted that there is the dispersion $V_g=2V_{ph}$ for a free $^4$He-atom, where $V_g$ and $V_{ph}$ are the atom group and phase velocities, respectively. It is obvious that any free quasi-particle can be in both real and imaginary $k$-spaces ($k=2\pi/\lambda$ is the wavenumber with $\lambda$ being the wavelength) that was also discussed by Zakharenko (2005a), because their kinetic energy depends on the wavenumber $k$ as $E_k=\pm\hbar^2(\pm \mathrm{i}k)^2/(2m)$, where $\hbar$ and $m$ are the Planck's constant and the quasi-particle mass, respectively, and $\mathrm{i}=(-1)^{1/2}$ is the imaginary unity. It is mentioned that the existence of the non-dispersive Zakharenko waves in both quantum and layered systems was lost that resulted in difficulties to correctly explain experimental data of both quantum evaporation and condensation effects. Zakharenko (2005a) discusses that the phenomenon of energy leak between different oscillations mentioned by Lardat *et al*.(1971) is associated with the binding energy that occurs in each BEEs energy branch, where $V_{ph}=C_{ph}$.

It was reported that quantum and layered systems have dispersion, namely dependence of the phase velocity $C_{ph}$ on both the wavenumber and the angular frequency. However, there is a possibility when dispersion relations show presence of non-dispersive Zakharenko waves, according to (Zakharenko, 2005a). For instance, this can occur for surface waves in layered systems consisting of a layer on a substrate, where parameters of both media can result in appearance of the non-dispersive Zakharenko waves in dispersion relations. It is well-known that in the superfluidity theory by Landau (1941), superfluid helium-II at low temperature below the critical temperature $T_\lambda$~2.17 K is described as liquid with normal and superfluid parts. It is possible to assume that liquid helium-II as a complex system is somewhat the same as solid layered systems. Therefore, it is possible to say that dispersion relations for such complex system as liquid helium-II can have non-dispersive Zakharenko waves. Indeed, independence of the phase velocity $C_{ph}$ of the BEEs on the wavenumber $k$ in the liquid energy spectra can be naturally shown by Eq.(1) for the dispersion $C_{ph}(k)$:

$$\frac{\mathrm{d}C_{ph}}{\mathrm{d}k}=0, \tag{1}$$

In addition to Eq.(1), Eq.(2) should be also fulfilled for non-dispersive waves showing independence of the angular frequency $\omega$:

$$\frac{\mathrm{d}C_{ph}}{\mathrm{d}\omega}=0, \tag{2}$$

It is obvious that Eqs.(1) and (2) are fulfilled as soon as one of them is true:

$$\frac{\mathrm{d}C_{ph}}{\mathrm{d}k}=C_g\frac{\mathrm{d}C_{ph}}{\mathrm{d}\omega}=0, \tag{3}$$

It is noted that for layered systems $C_g \neq 0$ and $C_{ph} \neq 0$. However, for quantum systems such as liquid helium-II there can be $C_g=C_{ph}=0$ ($C_g=C_{ph}\rightarrow 0$), for example, for the Bose-Einstein condensation giving dispersive waves, because $dC_{ph}/dk \neq 0$. The non-dispersive Zakharenko waves are readily recognized in any dispersion relation representing the dependence $C_{ph}(k)$:

$$\frac{dC_{ph}}{dk}=\frac{1}{k}(C_g-C_{ph}). \quad (4)$$

Eq.(4) shows that the non-dispersive Zakharenko waves correspond to extreme points of the dependence $C_{ph}(k)$ with $C_g=C_{ph}$. The same is true for the second dependence $C_{ph}(\omega)$ with $C_g=C_{ph}$:

$$\frac{dC_{ph}}{d\omega}=\frac{C_{ph}}{\omega}\left(1-\frac{C_{ph}}{C_g}\right), \quad (5)$$

Zakharenko (2005a) shows that in each energy zone of the BEE energy spectra, namely in the phonon, positive and negative roton branches, one corresponding non-dispersive Zakharenko wave should exist, because in each energy branch there are two possible dispersions: $C_g<C_{ph}$ and $C_g>C_{ph}$. It is noted that for a free quasi-particle, for example, for a free $^4$He-atom propagating in vacuum, there is a constant relationship between the phase and group velocities: $C_g=2C_{ph}$.

The work by Wyatt and Brown (1990) concerns the quantum evaporation effect illuminating $^4$He-atoms evaporation from the liquid surface by incoming BEEs created in the bulk liquid far from the surface. However, their explanations of the quantum evaporation effect, as well as of created incoming BEEs, are incorrect. In their works (Tucker and Wyatt, 1994a; 1994b; 1994c; 1994d; 1994e; Wyatt *et al*., 1989), they studied BEEs created by pulsed heaters in low temperature experiments. However, they did not state that the created propagating BEEs represent non-dispersive waves that can be found in recent alternative theory (Zakharenko, 2005a). Moreover, they concluded that the created propagating BEEs are so-called low-energy (1~2 K) and high-energy (~10 K) phonons in the BEEs phonon branch. However, it is impossible to have two non-dispersive Zakharenko waves in the phonon branch, because the phonon backflow effect increases the phonon velocity, which becomes zero at the maxon maximum. Wyatt *et al*.'s explanations (including those of Dalfovo, Pitaevskii, Edwards, Inkson, *et al*.'s research groups that is collective error in low temperature Physics relating to the human factor) preclude existence of the first non-dispersive Zakharenko waves ($C_g=C_{ph}\neq 0$) in the phonon branch due to the phonon backflow effect. The other thing is that they still use the Landau's critical velocity $C_g=C_{ph}$~60 m/s in the positive roton branch. However, the third non-dispersive Zakharenko wave exists in the positive roton branch with $C_g=C_{ph}$~190~200 m/s and energy (~17 K) that was shown and discussed by Zakharenko (2005a), where huge difference in explanations of such experiments was highlighted. It is noted that Landau's theory precludes BEEs existence with velocities less than the velocity ~60 m/s so the Landau's theory also relates to forbidding theories.

Wyatt and Brown (1990) noted that negative rotons cannot be created by such heater used in the experiments. In order to explain their experimental results on atom evaporation by BEEs, they also used the binding energy $E_b$~7.15 K by Wilks which is for SEEs, but not for BEEs. For BEEs there are three binding energies, one in each BEEs energy branch, that was discussed above. However, Brown and Wyatt applied $E_b$ (~7.15 K) for both BEEs phonon and roton branches to explain their experimental results concerning the quantum evaporations by BEEs. As the result, they have assumed the quantum evaporation process as one BEE phonon to one $^4$He-atom process and that positive rotons with energy (~$2E_b$~14 K) can evaporate two helium atoms, which is incorrect. The alternative theory (Zakharenko, 2005a) states that two positive rotons (the Cooper pairing phenomenon) with $C_g=C_{ph}$~190~200 m/s and energy ~17 K corresponding to the third non-dispersive Zakharenko wave can evaporate one $^4$He-atom fulfilling the energy conservation law. That is natural because positive rotons possess wavelengths which are several times less than the line size ~$1\times10^{-10}$ m of a $^4$He-atom. It is obvious that the one BEE to one $^4$He-atom quantum evaporation process exists only in the negative roton branch, because the second non-dispersive Zakharenko wave, as well as an evaporated $^4$He-atom has energy ~12 K.

Liquid helium-II is also treated as a neutron liquid due to the presence of the roton minimum, because the roton mass is close to the mass of a free neutron, as well as to the mass of a proton-electron pair. It is noted that the Landau's superfluidity theory is a macroscopic theory, with which Landau has shown difference between the first sound (density oscillations) and the second sound (pure temperature waves) using many simplification in his macroscopic theory. Therefore, the evaluated velocities for the first, second and fourth sounds are $u_1=(dP/d\rho)^{1/2}$~250 m/s with $P$ and $\rho$ being pressure and density at constant entropy, respectively, $u_2=u_1/3^{1/3}$ and $u_4=u_1(\rho_s/\rho)^{1/2}$ with $\rho_s$ being the superfluid component of the density $\rho$. It is noted that this gives $u_4=u_1$ at low temperature with $\rho_s=\rho$. However, it is thought that there is hybridization in each BEEs energy branch on a microscopic level. This is so because neutrons and proton-electron pairs of condensed $^4$He-atoms in the liquid can be coupled with the ones of neighbour atoms. It is thought that coupling among particles within each four-particle system (two neutrons and two proton-electron pairs, which show a free $^4$He-atom dispersion law as soon as they propagate in vacuum) is much stronger than that between (among) neutrons or/and proton-electron pairs of adjacent four-particle systems (FPS). Therefore, such condensed state can result in complex motions, such as wave motion of an FPS as a whole, as well as wave motion of each particle of the FPS. Indeed, such complex motions are very small and can result in rotations and/or oscillations of FPSs showing their own hybridized motions in each BEEs energy branch. It is thought that as soon as a quasi-particle (neutron or/and proton-electron pair) in an FPS receives an additional impulse from a quasi-particle of a neighbour FPS, whose local temperature, as well as local density, will be changed until it is passed further. This manifests existence of thermal excitations. It is well-known in high-energy Physics that very large energy (therefore, temperature) is required in order to find out about oscillation types in smaller quasi-particles consisting of larger quasi-particle (for example, atom→neutron→quark). Such representation of the BEEs nature is close to the Glyde and Griffin (1990)'s treatment of the BEEs energy spectra with hybridizations occurring in each BEEs branch. Also, huge difference in explanation of experimental data concerning the quantum condensation process between the work by Brown and Wyatt (2003) and recent alternative theory (Zakharenko, 2005a) will be reported in the future. It is noted that Brown and Wyatt (2003) found that positive rotons are created by helium atomic beams but negative rotons cannot be created by the beams, while negative rotons (the second non-dispersive Zakharenko waves) should be first created.

From this viewpoint, it is possible to state that the high-energy phonons are phonons with energy $E$ greater than the energy $E_{Z1}$ of the first non-dispersive Zakharenko wave (Zakharenko, 2005a) ($E>E_{Z1}$=6.17 K, according to (Stirling, 1983; 1985), and even $E_{Z1}$~7 K according to (Brown and Wyatt, 2003) that can depend on the liquid temperature). Now it is possible to classify the BEEs in liquid helium-II, according to the recent theory (Zakharenko, 2005a):

The phonon branch (the so-called first sound) consists of (1) the low-energy phonons with energies $E<E_{Z1}$~6.17 K, which possess dispersion $C_g>C_{ph}$; (2) the high-energy phonons with energies $E>E_{Z1}$~6.17 K, which possess dispersion $C_g<C_{ph}$; (3) the first non-dispersive Zakharenko wave ($C_g=C_{ph}\neq 0$) with energy $E_{Z1}$~6.17 K.

The negative roton branch (the so-called second sound) consists of (1) the low-energy R$^-$-rotons with energies $E<E_{Z2}$~12 K, which possess dispersion $C_g>C_{ph}$; (2) the high-energy R$^-$-rotons with energies $E>E_{Z2}$~12 K, which possess dispersion $C_g<C_{ph}$; (3) the second non-dispersive Zakharenko wave ($C_g=C_{ph}\neq 0$) with energy $E_{Z2}$~12 K.

The positive roton branch (the so-called fourth sound) consists of (1) the low-energy R$^+$-rotons with energies $E<E_{Z3}$~17 K, which possess dispersion $C_g>C_{ph}$; (2) the high-energy R$^+$-rotons with energies $E>E_{Z3}$~17 K, which possess dispersion $C_g<C_{ph}$; (3) the third non-dispersive Zakharenko wave ($C_g=C_{ph}\neq 0$) with energy $E_{Z3}$~17 K.

Therefore, this experimental paper uses the recent alternative theory (Zakharenko, 2005a) for explanation of obtained experimental data, but not any forbidding theories discussed above. It is thought that Nature forbids nothing in this case, and there is the so-called human factor to explain observed experimental results. The recent theory (Zakharenko, 2005a) is based on propagation of the corresponding non-dispersive Zakharenko waves in each energy branch, which can bring energy of the BEEs created in the bulk liquid far from the liquid surface up to the vacuum-liquid interface, while the other dispersive waves spread their energy in the bulk liquid.

## EXPERIMENTAL CONFIGURATION

In this low-temperature experiment done at temperatures below 100 mK of isotopically pure liquid helium-II, the Au-thin-film heater, which can excite the BEEs, is located in the liquid as shown in Fig.1. A small experimental cell (line sizes ~100 mm) with liquid helium was successively cooled down to the temperatures below 100 mK by well-known dilution refrigerator techniques (Betts, 1989; Lounasmaa, 1974). There are three detectors representing thin films of superconducting zinc on a glass substrate, two of which (the bolometers $B_1$ and $B_2$) are situated above the liquid-vacuum interface. The bolometers $B_1$ and $B_2$ are thus situated in order to detect $^4$He-atoms evaporated by the BEEs, which can reach the liquid surface. The third bolometer $B_3$ is positioned in the liquid and detects the BEEs reflected from the surface back into the bulk liquid. The bolometers $B_1$ and $B_3$, as well as the heater $H$, are situated at the same angle 10° to the liquid surface normal (Fig.1), while the bolometer $B_2$ is positioned at angle ~35° to the surface normal. It is necessary to note that both the bolometers $B_1$ and $B_2$ in vacuum, as well as the bolometer $B_3$ in the liquid, are situated at the same distance ~7 mm from the point $O$ of the incoming BEEs created by the heater $H$ in the liquid as shown in Fig.1. The distance between the heater $H$ and the point $O$ at the vacuum-liquid interface is about 15 mm. Both the bolometers and the heater used in this experiment have the same work area ~1 mm$^2$ for BEEs detection and excitation, respectively. Details on collimators in Fig.1 used in this work in order to improve such low temperature experiments, can be found in (Williams *et al.*, 2002). The collimators represent apertures with diameter ~1 mm and are for bolometer protection from additional signals which can reflect from many places due to the small experimental cell used in such experiments, in which suitable liquid helium-II energies below 100 mK can be reached. Created BEEs are travelling in the liquid for distance ~5 mm up to the first collimator and ~4 mm between the first and second collimators as shown in Fig.3c in (Williams *et al.*, 2002).

The BEEs created by the heater $H$ are travelling in the liquid up to the point $O$ at the interface, where some BEEs can evaporate $^4$He-atoms travelling already in vacuum up to the bolometers $B_1$ and $B_2$, and some BEEs can reflect from the interface back into the liquid towards the bolometer $B_3$. A fraction of the BEEs can also take part in interactions between the BEEs and SEEs (ripplons) at the interface that will be discussed below. The ripplon detection evidence (probably, indirectly) created by a pulsed heater in the bulk liquid helium-II and detected by a bolometer situated at the vacuum-liquid interface will be reported elsewhere later.

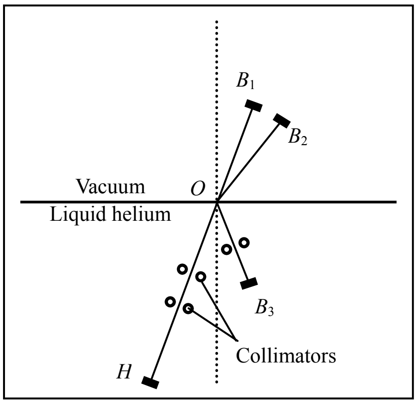


**Fig.1 The experimental arrangement for both the heater *H* and the bolometers $B_1$, $B_2$, and $B_3$**

## QUANTUM EVAPORATION AND REFLECTION OF THE BEES

Some typical detected signals from long heater pulse widths (5 μs, 10 μs) are shown in Figs.2, 3, and 4 from the bolometers $B_1$, $B_2$, and $B_3$, respectively. The typical signal of $^4$He-atom evaporation in Fig.2 has its peak at time ~140 μs with the time of first arrival being ~120 μs. It is noted that the BEEs time of first arrival is ~110 μs, and the BEEs have gone the same distance ~22 mm (Williams *et al.*, 2002) which corresponds to the distances ~15 mm travelled by BEEs in the liquid plus ~7 mm distance gone by $^4$He-atomic beams in vacuum shown in Fig.1. The evaporation signal shown in Fig.2 has quite a long decay tail extending up to 250 μs. It is very interesting that the beginning fraction of the signal between the first arrival time and the peak has an inflexion point of about –0.9 mV (shown by symbol 2). This suggests that there are two different clouds of $^4$He-atoms overlapping each other and that they are travelling with each other in vacuum from the liquid surface up to the bolometer $B_1$. Therefore, the inflexion point shows the first arrival time of the second cloud of the helium atoms. It can mean that the cloud of the slower helium atoms with the first arrival time at the inflexion point could correspond to the atom evaporation by BEEs participating in some complex processes at the interface that results in appearance of suitable energies, which are equal to the binding energy $E_b$~7.15 K (Wilks, 1967).

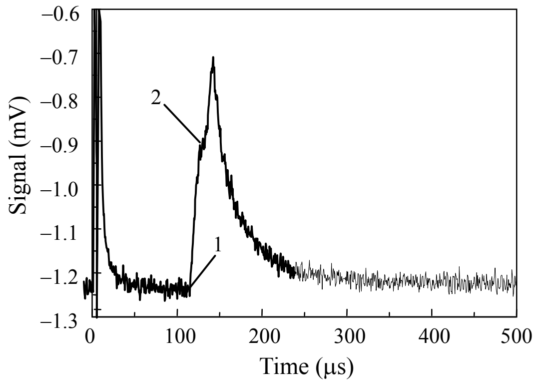


**Fig.2 The typical signal detected by the bolometer $B_1$ with the heater power attenuation –23 dB and the heater pulse width 5 μs**

The first $^4$He-atomic cloud with quicker $^4$He-atoms could correspond to the atom evaporation by the R$^+$-rotons with suitable energy $E$~17 K, according to (Zakharenko, 2005a). The first arrival time from the bolometer $B_2$ is ~110 μs, because the helium atoms can travel a shorter distance through vacuum from the liquid surface up to the bolometer $B_2$. A typical signal from the bolometer $B_2$ is shown in Fig.3. The distance between the point $O$ and the bolometer $B_2$ is ~7 mm. It is thought in this work that the signal in Fig.3 is due to the atoms evaporated by the R$^+$-rotons with energies $E$~17 K corresponding to the energy of the third non-dispersive Zakharenko wave. In addition, the "heterodyne signal" in Fig.2 is due to the evaporation by both the R$^+$-rotons and the phonons because there are two clouds of the helium atoms. On the other hand, the evaporated signal shown in Fig.3 corresponds to the atom evaporation only by the suitable positive rotons ($E$~17 K). It is thought that it is necessary to improve quantum evaporation experiments by increasing the distance gone in both the liquid and vacuum.

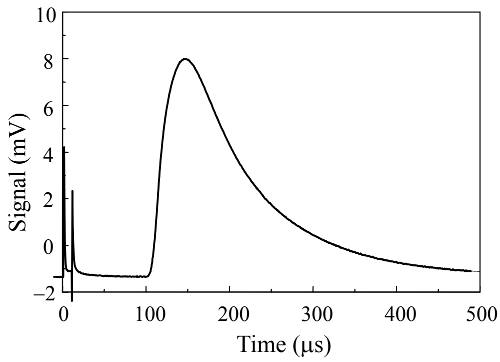


**Fig.3 The atomic signal detected by the bolometer $B_2$ with the heater power attenuation –20 dB and the heater pulse width 10 μs**

There are two reflected signals from the liquid surface shown in Fig.4. To observe two reflected signals was very surprising. The BEEs injected by the heater in the liquid with pulse length 10 μs and power attenuation −23 dB reach the liquid-vacuum interface and reflect back into the bulk liquid. The reflected signals are detected by the bolometer $B_3$ situated in the liquid. Both the heater and the bolometer $B_3$ are situated at the same angle 10° to the surface normal. The distance between the point $O$ and the bolometer $B_3$ is ~7 mm. The first large sharp peak of the reflected signal shown by symbol 1 in Fig.4 can correspond to the first type of the BEEs (phonons, namely the first non-dispersive Zakharenko wave) with the velocity $C_{ph}$=$C_g$~250 m/s (Zakharenko, 2005a), but not low-energy phonons with energies $E$~(1~2) K (Tucker and Wyatt, 1994a; 1994b; 1994c; 1994d; 1994e; Wyatt *et al*., 1989). The low-energy phonons with dispersion $C_g$>$C_{ph}$ and energies $E$<$E_{Z1}$ do not evaporate helium atoms from the liquid surface, because their energy is unequal to the binding energy $E_b$~7.15 K (Wilks, 1967). It is assumed that the binding energy $E_b$ corresponds to the crossing point between the SEEs phase velocity and the straight-line dependence of the phase velocity of a free $^4$He-atom. It is thought that the binding energy $E_b$ represents the minimum energy for the quantum evaporation process by SEEs, while there are also three binding energies, one in each BEEs energy branch for the evaporation by BEEs. Hence, it is assumed that only phonons with energy $E$~$E_b$, and possessing dispersion $C_g$<$C_{ph}$, can evaporate the helium atoms. This is possible due to the fact that the non-dispersive Zakharenko waves (phonons) with energy $E_{Z1}$~6.17 K (which is close to the binding energy $E_b$~7.15 K (Wilks, 1967)), can bring their energy to the liquid surface, where phonons can interact with ripplons, as well as with already reflected BEEs for long heater pulses resulting in possible energy increase. Indeed, the BEEs can interact with the ripplon gas that is localised at the liquid surface and can be experimentally observed. Therefore, the original incoming BEE signal can be changed at the liquid surface due to the interactions. This means, that at the liquid surface, there are several events with an initial phonon signal: a large fraction of the phonons with $E\neq E_b$ is reflected back to the bulk liquid; a fraction of the phonons reaching $E=E_b$ at the surface due to interactions with both reflected BEEs and SEEs can evaporate the helium atoms up to the vacuum.

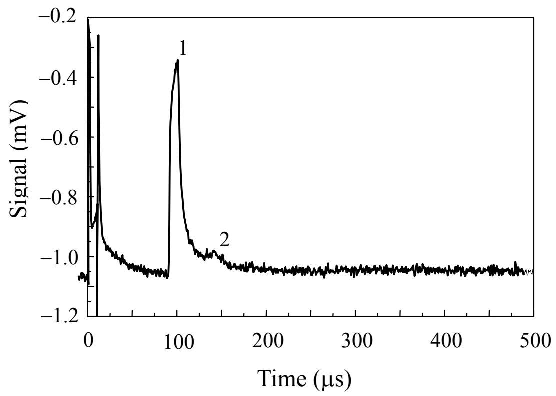


**Fig.4 The generated by the heater *H* and detected by the bolometer $B_3$ reflected signals from the liquid surface for the heater pulse width 10 μs and the heater power attenuation –23 dB. Here the sharp mean phonon peak is labeled by symbol 1. Symbol 2 shows the second weak signal**

The second peak in Fig.4 indicated by the symbol 2 could also correspond to the other type of the BEEs (positive rotons), a small fraction of which could be reflected from the liquid surface back into the bulk liquid (that must be verified in the next experiments). Note that the presence of this peak gives an additional surprise. That can mean that a very small fraction of this BEEs type can be reflected from the liquid surface. However, it is also possible to suggest that it corresponds to some noisy reflected signal. The other suggestion is that the reflected fraction of the second weak signal will be increased relative to the first big signal, when the BEEs will travel for greater/smaller distances from the heater up to the liquid surface and back into the bulk liquid. It could be so because the reflection of the BEEs from the liquid surface was not widely studied in this direction. It is also noted that Wyatt *et al*. have never shown reflected BEEs signals together with atomic signals evaporated by the BEEs. Furthermore, there are no detailed experimental data for studying reflections from different solid surfaces.

## EXPERIMENTAL RESULTS AND DISCUSSIONS

The signal amplitude depends approximately linearly on the heater pulse width that is shown in Fig.5. This is true over a wide range of heater pulse widths, from 0.1 μs to 10 μs. The gradient for increasing the amplitudes is dependent on increasing the heater pulses to about $10^3$ μV/s$^{3/4}$. For heater pulse lengths below 0.1 μs, there is a deviation of the measured signal amplitudes from the linear approximation. Further shortening of the heater pulses caused the measured signals to drop rapidly to zero amplitude (in the case of heater power –23 dB).

Fig.6 represents the dependence of both the reflected signals measured at the bolometer $B_3$ and the measured signals at the bolometer $B_1$ for helium atom evaporation on the heater pulse width in the range 0.05 μs to 10 μs. The heater power attenuation of –23 dB was constant corresponding to 200 times attenuation of an original heater pulse. Linear behaviour occurs for the measurements of signal amplitudes at the bolometer $B_3$, which detects reflection from the free liquid surface. The gradient of the amplitude decreases with the heater pulse length at a rate of ~230 μV/s$^{3/4}$. It is clearly seen that the dependence is approximately linear over a wide range of heater pulses from 0.02 μs up to 2 μs. For longer heater pulses of between 2 μs and 10 μs, the dependence has a lower gradient. This may be already a long cloud of bulk elementary excitations injected by a heater in the liquid, in which can be angular dependence of interactions, namely decay. On the other hand, it is possible that for long pulses the tail of a long pulse incident on the free surface may interact with the earlier part that has already been reflected from the free surface. Figs.2 and 4 support this assumption of reflected signal scattering at the vacuum-liquid interface, because there are two atomic clouds travelling in vacuum (shown in Fig.2) and cut-like reflected signal (shown in Fig.4). This may be the determination of “long pulse width” for a pulsed heater. If it is true, there should be a significant dependence of heater long pulses on the angle of incidence of a long pulse to the surface normal. In this case the angle of incidence is 10°.

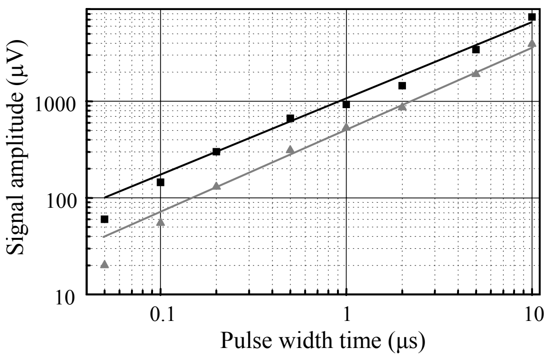


**Fig.5 The $\log_{10}/\log_{10}$ scale linear dependence of signals detected by the bolometer $B_2$ on heater pulse length time for two different power attenuation –20 dB (rectangles) and –23 dB (triangles)**

The dependence of the bolometer $B_1$ measured signal amplitudes on the bulk elementary excitations to evaporation of the helium atoms on the heater pulse width is more complicated than the case of reflected signals detected by the bolometer $B_3$ shown in Fig.6. However, there is similar behaviour in both cases of long heater pulses in the range 0.2 μs to 10 μs. The heater pulse width time 2 μs is the threshold one for the onset of non-linearity for the signals from the bolometer $B_1$ and bolometer $B_3$. Below 2 μs signals from the bolometers $B_1$ and $B_3$ are proportional to pulse width. However, the linear region of the measured signals from the bolometer $B_1$ is due to the inflexion point about heater pulse 0.7 μs. For shorter pulses less than 0.2 μs, a dramatic drop occurs. The straight-line region of the measured signals from the bolometer $B_1$ shown in Fig.6 represents the best working range of the heater, in order to obtain a dependence of BEE creation on the heater pulses.

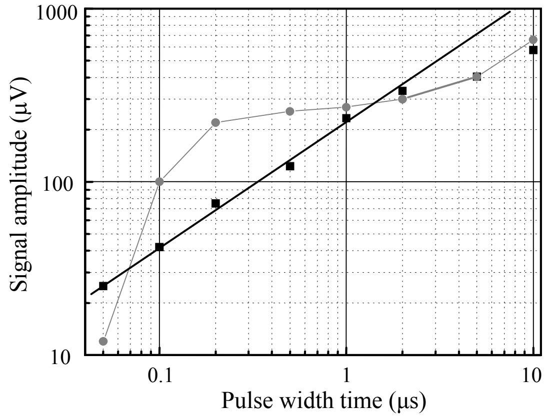


**Fig.6 The $\log_{10}/\log_{10}$ scale dependence of signals detected by the bolometer $B_1$ (circles) and by the bolometer $B_3$ (rectangles) on the heater pulse width time**

The power-law dependence of measured signals on the heater power is shown in Fig.7. The decreasing signal amplitude corresponds to attenuation of the heater pulses from –23 dB down to –41 dB. This rapid change of the signal amplitude occurs for the signals from both the bolometers $B_1$ and $B_2$ that is shown by two parallel black lines. Note that both the bolometers $B_1$ and $B_2$ are situated above the free liquid surface, in order to detect evaporated helium atoms, but the bolometer $B_3$ was positioned in the liquid, in order to detect reflected bulk elementary excitations. Also, shown in Fig.7 is the result for the measured signal amplitude from the bolometer $B_3$ showing smaller power-law dependence. Indeed, the slope of this linear dependence for the reflected signal amplitude is essentially less than that for the signals of atom evaporation that are shown in Fig.7 by the grey

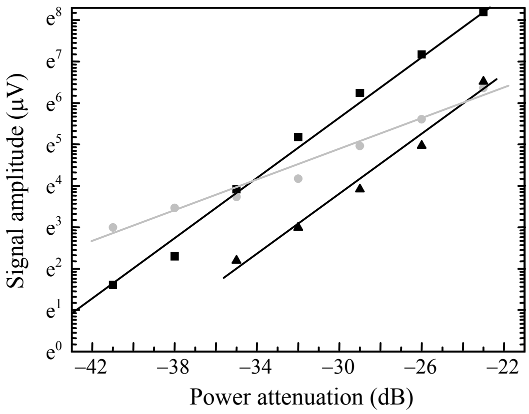


**Fig.7 The power-law dependence of signal amplitude detected by the bolometers $B_1$ (rectangles), $B_2$ (circles), and $B_3$ (triangles) on the power attenuation**

straight line.

Comparing with previous dependencies of the measured signals on the heater pulse width and the heater power, there is a more complicated dependence of the measured signals when the pulse energy of the heater was kept constant by simultaneously changing both the heater power and the heater pulse width time. The results of these measurements are shown in Table 1. The first two columns list variation data of the heater pulse width from 10 μs down to 0.02 μs and the heater power attenuation from –30 dB to –3 dB, respectively. The measured signals at the bolometer $B_3$ (signals were reflected from the free liquid surface back to the bulk liquid helium) have a clear single maximum at the heater pulse width 0.5 μs and the heater power attenuation of –16 dB. However, for the measured signals from the bolometer $B_2$ (evaporation of the helium atoms) there are both maximum at 1 μs & –20 dB and minimum at 0.2 μs & –13 dB with rapid increasing in signal amplitude down to pulses of 0.2 μs & –13 dB, while for the measured signals from the bolometer $B_1$ (helium atom evaporation, too) there are two equivalent maximal values both at 0.5 μs & –16 dB and at 0.2 μs & –13 dB with a slight decrease of the maximal value down to pulses of 0.02 μs & –3 dB. The maximum signal from the bolometer $B_3$ is less then half of the one from the bolometer $B_1$. The behaviour of the measured signals from the bolometer $B_2$ is more complicated than the one from the bolometers $B_1$ and $B_3$. There is a general increase of the signal amplitude from the bolometer $B_2$ (Table 1), from its lowest value at 10 μs & –30 dB to the highest value at 0.02 μs & –3 dB. However, there is a local maximum at 1 μs & –20 dB and a local minimum at 0.2 μs & –13 dB. This is well-correlated with the data from the bolometer $B_1$, from which there is the maximal value at the heater pulse power 0.2 μs & –13 dB (Table 1).

**Table 1 The signal features measured by the bolometers $B_1$, $B_2$, and $B_3$ for the constant heater pulse-energy (μs and dB)**

| Pulse width (μs) | Power attenuation (dB) | $B_1$-signals (μV) | $B_2$-signals (μV) | $B_3$-signals (μV) | Ratio $A(B_2)/A(B_1)$ |
|---|---|---|---|---|---|
| 10 | –30 | 30 | 360 | 126 | 12.00 |
| 5 | –26 | 80 | 708 | 235 | 8.85 |
| 2 | –23 | 322 | 800 | 400 | 2.48 |
| 1 | –20 | 970 | 970 | 659 | 1.00 |
| 0.5 | –16 | 1800 | 665 | 842 | 0.37 |
| 0.2 | –13 | 1810 | 598 | 553 | 0.33 |
| 0.1 | –10 | 1770 | 740 | 500 | 0.42 |
| 0.05 | –6 | 1750 | 1330 | 400 | 0.76 |
| 0.02 | –3 | 1650 | 2000 | 320 | 1.21 |

Fig.8 compares signals obtained from the bolometers $B_1$ and $B_2$ for heater pulses 0.05 μs to 10 μs at heater power –23 dB. The ratio of signals has a clear minimum at the heater pulse power 0.13 μs & –23 dB. The value of the minimum ratio of the measured amplitudes is $A(B_2)/A(B_1)$~0.3. This value agrees with the minimum value of ratios found during the constant heater power runs. Thus, at the constant energy pulse 0.1 μs & –13 dB there is a minimum value of ratios $A(B_2)/A(B_1)$ in the last column of Table 1 that increases for both the shorter and the longer heater pulses, when pulse energy is kept constant. That gives the boundary between short and long heater pulses, which indicates the start of additional energy incoming to the bolometer $B_1$ for the long heater pulses.

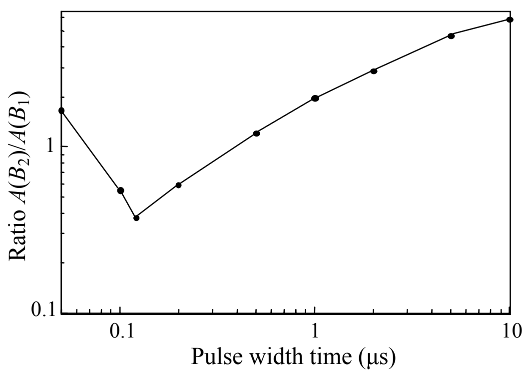


**Fig.8 The dependence of the signal amplitudes' ratio on the heater pulse width time at the constant attenuation –23 dB in the heater power**

## CONCLUSION

For long heater pulses, two clouds of the helium atoms evaporating from the liquid surface were observed in the quantum evaporation process shown in Fig.2. The reflected signal in Fig.4 leads to the conclusion that the first atomic cloud, consisting of very quick helium atoms shown in Fig.2 by symbol 1, was evaporated by the positive rotons with suitable energies ~17 K, while the second atomic cloud of slower helium atoms, shown in Fig.2 by symbol 2, was evaporated through a complex process in which there are interactions of incoming phonons of energy ~6.17 K with reflected phonons and ripplons resulting in energy apparently related to the binding energy $E_b$~7.15 K. In addition, it is possible that amplitudes of the heater long pulses for excited BEEs are greater than those excited by heater short pulses. Therefore, dispersive BEEs of the heater long pulses can travel for longer distances, because BEEs damping time could depend on initial amplitude of excited dispersive BEEs. Additional experimental results concerning BEEs creation and propagation in the bulk liquid helium-II at low temperatures can be found in (Zakharenko, 2007), in which the Cooper pairing phenomenon is also shown.

The experimental results discussed in this work, concerning investigations of heater long pulses, must be more widely studied in the future, using wide verifications in both distances gone by excited BEEs in the liquid (as well as by helium atoms in vacuum) and heater long pulses. Moreover, for the future the distances should be as long as possible in order to improve experimental results, because created helium atoms are very quick (~380 to 400 m/s), according to (Zakharenko, 2005a). The presence of the second cloud of the helium atoms, that was detected only at the bolometer $B_1$, but not at the bolometer $B_2$ in Fig.1, showed the possibility to detect the atoms at angles of the bolometer $B_1$ less than 10° to the surface normal. Also, in this report of the experimental results, many factors have been shown to affect the BEEs created by pulsed heaters. It has been shown that it is possible to optimise the operating conditions of the heaters to suit various circumstances. The possibility to know in advance where the heaters have linear regimes of work is useful. Indeed, there are threshold heater pulse width times and inflexion points originating a linear fraction of the dependence and linear behaviour around, respectively. It can be useful to carry out the investigations widely for particular cases, in order to completely understand the features of heaters in low temperature experiments, and to try to obtain a heater parameter of possible influence on generated BEEs.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge support for this work from EPSRC, with which it was possible for the author during 2000~2001 academic year to study low temperature Physics at Exeter University, England. Also, it is a pleasure to thank Dr. S. Roshko and Dr. M.A.H. Tucker for their help in preparing the experiment. I also thank Dr. C.D.H. Williams and Prof. A.F.G. Wyatt for their care and Prof. I.N. Adamenko and Dr. A. Usher for useful notes.

## References

Betts, D.S., 1989. An Introduction to Millikelvin Technology. Cambridge University Press, England.

Brown, M.G., 1990. The Boundary Conditions for Quantum Evaporation in Liquid $^4$He. Ph.D Thesis, University of Exeter, England, UK.

Brown, M., Wyatt, A.F.G., 2003. Quantum condensation of liquid $^4$He. *Journal of Physics: Condensed Matter*, **15**(27):4717-4738. [doi:10.1088/0953-8984/15/27/306]

Dalfovo, F., Fracchetti, A., Lastri, A., Pitaevskii, L., Stringari, S., 1995a. Rotons and quantum evaporation from superfluid $^4$He. *Physical Review Letters*, **75**(13):2510-2513. [doi:10.1103/PhysRevLett.75.2510]

Dalfovo, F., Lastri, A., Pricaupenko, L., Stringari, S., Treiner, J., 1995b. Structural and dynamic properties of superfluid helium: A density-functional approach. *Physical Review B*, **52**(2):1193-1209. [doi:10.1103/PhysRevB.52.1193]

Forbes, A.C., Wyatt, A.F.G., 1990. A direct comparison of the scattering of phonons and rotons from rotons in superfluid $^4$He. *Physica B: Condensed Matter*, **165-166**(1):497-498. [doi:10.1016/S0921-4526(90)81098-9]

Glyde, H.R., Griffin, A., 1990. Zero sound and atomic-like excitations: The nature of phonons and rotons in liquid $^4$He. *Physical Review Letters*, **65**(12):1454-1457. [doi:10.1103/PhysRevLett.65.1454]

Lardat, C., Maerfeld, C., Tournois, P., 1971. Theory and performance of acoustical dispersive surface wave delay lines. *Proceedings of the IEEE*, **59**(3):355-368.

Landau, L.D., 1941. The theory of superfluidity of helium-II. *Journal of Physics (Moscow)*, **5**(1):71-90.

Lounasmaa, O.V., 1974. Experimental Principles and Methods Below 1 K. Academic Press, England.

Stirling, W.G., 1983. Precision measurement of the phonon dispersion relation in superfluid $^4$He. Proceedings of the 75th Jubilee Conference on $^4$He, World Scientific, Singapore, p.109 and private communication.

Stirling, W.G., 1985. New High-resolution Neutron Scattering Investigations of Excitations in Liquid Helium-4. Proceedings of the 2nd International Conference on Phonon Physics, Budapest, Hungary, p.829-832.

Tucker, M.A.H., Wyatt, A.F.G., 1990. Time of flight of phonon-atom quantum evaporation signals. *Physica B: Condensed Matter*, **165-166**(1):493-494. [doi:10.1016/0921-4526(90)90638-B]

Tucker, M.A.H., Wyatt, A.F.G., 1994a. Phonons in liquid $^4$He from a heated metal film. I. The creation of high-frequency phonons. *Journal of Physics: Condensed Matter*, **6**(15):2813-2824. [doi:10.1088/0953-8984/6/15/004]

Tucker, M.A.H., Wyatt, A.F.G., 1994b. Phonons in liquid $^4$He from a heated metal film. II. The angular distribution. *Journal of Physics: Condensed Matter*, **6**(15):2825-2834. [doi:10.1088/0953-8984/6/15/005]

Tucker, M.A.H., Wyatt, A.F.G., 1994c. Double pulse phonon injection into liquid $^4$He. *Physica B: Condensed Matter*, **194-196**:547-548. [doi:10.1016/0921-4526(94)90603-3]

Tucker, M.A.H., Wyatt, A.F.G., 1994d. The spectrum of high-energy phonons injected into liquid $^4$He. *Physica B: Condensed Matter*, **194-196**:549-550. [doi:10.1016/0921-4526(94)90604-1]

Tucker, M.A.H., Wyatt, A.F.G., 1994e. Phonon beams with a narrow angular width created by gold film heater. *Physica B: Condensed Matter*, **194-196**:551-552. [doi:10.1016/0921-4526(94)90605-X]

Wilks, J., 1967. The Properties of Liquid and Solid Helium. The International Series of Monographs on Physics, Oxford University Press.

Williams, C.D.H., Zakharenko, A.A., Wyatt, A.F.G., 2002. Narrow-angle beams of strongly interacting phonons. *Journal of Low Temperature Physics*, **126**(1/2):591-596. [doi:10.1023/A:1013727403790]

Wyatt, A.F.G., Brown, M., 1990. Generating beams of high energy phonons and rotons in liquid $^4$He. *Physica B: Condensed Matter*, **165-166**(1):495-496. [doi:10.1016/S0921-4526(90)81097-8]

Wyatt, A.F.G., Lockerbie, N.A., Sherlock, R.A., 1989. Propagating phonons in liquid $^4$He. *Journal of Physics: Condensed Matter*, **1**(22):3507-3522. [doi:10.1088/0953-8984/1/22/010]

Zakharenko, A.A., 2005a. Different Dispersive Waves of Bulk Elementary Excitations in Surperfluid Helium-II at Low Temperatures. The CD-ROM Proceedings of the Forum Acusticum, Budapest, Hungary, p.L79-L89.

Zakharenko, A.A., 2005b. Dispersive Rayleigh type waves in layered systems consisting of piezoelectric crystals bismuth silicate and bismuth germinate. *Acta Acustica united with Acustica*, **91**(4):708-715.

Zakharenko, A.A., 2007. Creation of bulk elementary excitations in superfluid helium-II by helium atomic beams at low temperatures. *Waves in Random and Complex Media*, **17**(3):1-14. [doi:10.1080/17455030601178164]