Institute of Solid State Physics Russian Academy of Sciences

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DISCRETE WAVE TURBULENCE ON THE SURFACE OF A QUANTUM LIQUID

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DISSERTATION TOPIC

The present dissertation has studied experimentally phenomena in turbulent wave systems on the liquid surface, which arise due to the discreteness of the k-space. Discrete wave turbulence is the turbulent state of a nonlinear wave system in which the discreteness of the k-space results in additional resonant constraints on the possible processes of wave interaction [1, 2]. Interest in the problem of discrete turbulence has the following reasons. Additional resonant constraints may lead to the emergence of local peculiarities in a direct turbulent cascade. The formation of an inverse energy flow is also possible in a discrete turbulence regime since the processes of energy transfer in a direct turbulent cascade are suppressed due to discreteness. Moreover, wave systems are somehow confined in the real world. Therefore, clear understanding of the peculiarities of discrete turbulence is necessary to compare theoretical predictions with experimental results. Despite the development of the theory of discrete turbulence, very few experimental studies have been performed in this area. Therefore, the acquisition of experimental information on discrete wave turbulence is a fundamental scientific problem in modern physics. A system of nonlinearly interacting waves on the ideal liquid surface is a convenient model object to study discrete wave turbulence. However, all real liquids have finite viscosity which leads to the broadening of surface oscillations. If the viscosity is high, broadened resonances overlap each other, and the system stops being discrete. Consequently, a liquid with very low viscosity is necessary to study experimentally discrete turbulence. Therefore, the most suitable liquids for these studies are liquid hydrogen and superfluid helium-4 the kinematic viscosity of which is very low compared with other liquids, such as water. In the experimental works on wave turbulence on the liquid hydrogen surface which were performed earlier in our laboratory, M.Yu. Brazhnikov used the unique experimental technique of the excitation and recording of waves on the charged surface of liquid hydrogen [3]. L.V. Abdurakhimov [4] adopted this technique to study wave turbulence on the surface of superfluid helium-4. This technique was used also in the experiments discussed below on the investigation of discrete wave turbulence in quantum liquids.

The **goal** of the present dissertation has been to study discrete wave turbulence in a wave system on the surface of superfluid helium and liquid hydrogen in a finite size resonator. To achieve the stated goal it has been necessary to solve the following **tasks:**

1. To determine optimal experimental conditions under which a discrete turbulence regime is realized on the liquid surface by selecting the shape and sizes of experimental cells.
2. To produce experimental cells for the study of nonlinear waves on the surface of liquid helium and hydrogen.

3. To study peculiarities in the turbulent spectra of surface waves in the discrete turbulence regime at high pump levels and to compare the measurement results with the theoretical predictions.

The scientific novelty has been as follows:

1. It has been shown for the first time that by selecting the spectral characteristic of the exciting force and the discreteness in the spectrum of liquid eigenmodes in the resonator (experimental cell), it is possible to create optimal conditions for the formation of an energy flow to both high-frequency (Kolmogorov–Zakharov direct turbulent cascade) [5, 6] and low-frequency regions of a turbulent spectrum by changing the sizes and shape of the experimental cell.
2. The coefficient of three-wave interaction in the system of gravity-capillary waves on the liquid hydrogen surface in a rectangular cell has been estimated for the first time.
3. The formation of a dynamic local maximum near the high-frequency end of the inertial interval of a turbulent spectrum on the liquid hydrogen surface in a cylindrical cell has been observed for the first time.
4. The Kelvin–Helmholtz instability on the free He-II surface, induced by constant heat flow in the liquid bulk, has been studied in detail for the first time.

The **theoretical and practical significance** of the results obtained is in widening modern theoretical concepts of the mechanisms of energy transfer in nonlinear wave systems. Quantum liquids are widely used in modern space engineering (cryogenic fuels, cooling systems of the sensitive elements of different types of detectors and telescopes) and in cooling systems of high-power superconducting solenoids. Thus, the understanding of turbulent wave processes on the free surface of a quantum liquid in a finite size container may have practical value when working with cryogenic liquids.

Veracity of the obtained results The results of our measurements agree with other authors' experimental data and theoretical predictions in the part where their applicability fields overlap.

MAIN RESULTS AND CONCLUSIONS

1. The formation of an inverse energy flow in the discrete turbulence regime has been observed experimentally under monochromatic pumping in the system of capillary-gravity waves on the surface of liquid hydrogen and superfluid helium.
2. The formation of subharmonics in the discrete wave turbulence regime on the liquid hydrogen surface in the capillary-gravity region of the spectrum of cell eigenmodes has been studied and the coefficient of three-wave interaction has been estimated.

3. The formation of a dynamic local maximum has been discovered which arises in a turbulent spectrum near the high-frequency end of the inertial interval as a result of the emergence of the bottleneck caused by the finite viscous decay in the inertial interval and discreteness of the spectrum of cell eigenmodes.
4. The Kelvin–Helmholtz instability of the free surface of superfluid He-II, induced by steady heat flow in the bulk at the flow density higher than some threshold density, has been observed.

Personal contribution. The author has participated directly in the statement and solution of experimental problems, as well as in the discussion of the results obtained and writing of articles. The dissertation has been prepared in the Laboratory of Quantum Crystals, Institute of Solid State Physics of the Russian Academy of Sciences, from 2010 to 2018.

PUBLICATIONS AND APPROBATION OF THE RESEARCH

First-tier publications

1. L. V. Abdurakhimov, M. Arefin, G. V. Kolmakov, A. A. Levchenko, Yu. V.Lvov, and I. A. Remizov, «Bidirectional energy cascade in surface capillary waves», Physical Review E. – 2015. – V. 91. – I. 2. – P. 23021.

Second-tier publications

1. M. Yu. Brazhnikov, A.A. Levchenko, L.P. Mezhov-Deglin, I.A. Remizov, «Low-frequency subharmonics in the turbulent spectrum on the surface of liquid hydrogen», JETP Letters - 2014. - V. 100. - I 10. - P. 754-759.
2. L.V. Abdurakhimov, M.Yu. Brazhnikov, A.A. Levchenko, A.M. Likhter, I.A. Remizov, «Formation of low-frequency harmonics on the surface of liquid hydrogen and helium in a turbulent regime», Low Temperature Physics. - 2015. - I 41. - P. 215-222.
3. M. Yu. Brazhnikov, A. A. Levchenko, L. P. Mezhov-Deglin, I. A.Remizov, «Wave turbulence on the surface of liquid hydrogen in restricted geometry: the influence of the boundary conditions», Low Temperature Physics. – 2015. – V. 41. – № 6. – P. 484–487.
4. I. A. Remizov, M. Yu. Brazhnikov, A. A. Levchenko, «Observation of dynamic maximum in a turbulent cascade on the surface of liquid hydrogen», Low Temperature Physics. – 2016. – V. 42. – I. 12. – P. 1067–1070.
5. I. A. Remizov, A. A. Levchenko, L. P. Mezhov-Deglin, «Instability on the Free Surface of Superfluid He-II Induced by a Steady Heat Flow in Bulk», Journal of Low Temperature Physics. – 2016. – V. 185. – I. 3. – P. 324–338.

Reports at conferences and seminars

The main results of the dissertation have been reported at the following conferences:

1. 9-th International Conference on Cryocrystals and Quantum Crystals CC-2012 (Odessa, Ukraine, September 2012)
2. Conference on Low-Temperature Physics HT-36 (Russia, St. Petersburg, July 2012).
3. Conference “Turbulence and Wave Processes” (Russia, Moscow, November 2013).
4. XXII-nd Scientific Session of the Council of Nonlinear Dynamics of the Russian Academy of Sciences (Russia, Moscow, December 2013).
5. VII-th International Conference «SOLITONS COLLAPSES AND TURBULENCE: Achievements, Developments and Perspectives» (SCT-14) in honor of Vladimir Zakharov’s 75th birthday (Chernogolovka, Russia, August 2014.).
6. 10th International Conference on Cryocrystals and Quantum Crystals (Almaty, Kazakhstan, August 2014).
7. XXIII-rd Scientific Session of the Council of Nonlinear Dynamics of the Russian Academy of Sciences (Russia, Moscow, December 2014).
8. XXIV-th Scientific Session of the Council of Nonlinear Dynamics of the Russian Academy of Sciences (Russia, Moscow, December 2015).
9. 11th International Conference on Cryocrystals and Quantum Crystals (Turku, Finland, August 2016).
10. XXV -th Scientific Session of the Council of Nonlinear Dynamics of the Russian Academy of Sciences (Russia, Moscow, December 2016).

CONTENTS AND STRUCTURE OF THE DISSERTATION

The **dissertation consists** of introduction, six chapters, conclusion, and main results. The total volume of the dissertation is 101 pages including 39 figures, one table, and a list of references.

The introduction provides the proofs of the relevance of the dissertation topic, states the goals of the dissertation and ideas to be defended, and describes the structure of the dissertation.

Chapter 1 contains an introduction to the research subject, provides a brief overview of modern theoretical concepts and experimental results of the study of discrete turbulence which have been accumulated by the time of the statement of the present dissertation.

Chapter 2 describes the experimental setup and technique of the excitation and recording of capillary-gravity waves on the surface of liquid hydrogen and superfluid helium.

Chapter 3 is devoted to the observation of subharmonics in a stationary turbulent spectrum on the surface of liquid hydrogen and superfluid helium.

Chapter 4 provides the results of the study of the dynamics of subharmonics formation and decay on the liquid hydrogen surface.

Chapter 5 provides the results of the experimental observation of a dynamic maximum in a turbulent spectrum near the high-frequency boundary of the inertial interval as a result of energy accumulation in the system of capillary waves on the surface of liquid hydrogen excited by an external harmonic force.

Chapter 6 is devoted to the study of the Kelvin–Helmholtz instability of the surface of superfluid He-II which arises as a result of heat flow passing in the bulk, with the density higher than some threshold density.

The **Conclusion** enumerates the main results of the dissertation and provides the conclusions.

Bibliography

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