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CONDENSED MATTER

Generation of Quantum Vortices by Waves on the Surface of Superfluid Helium

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The formation of quantum vortices by two mutually perpendicular waves excited on the surface of superfluid helium has been observed. The interaction of negative charges injected under the surface of He-II with the vortex flow of the liquid, which is formed by surface waves at frequencies from 20 to 49.9 Hz, in the temperature range of 1.5–2.17 K has been studied experimentally by analyzing the current distribution detected by vertically oriented segments of a receiving collector. The efficient capture of injected charges by quantum vortices has been observed at a temperature of $T = 1.5$ K, which leads to a significant redistribution of currents between segments of the receiving collector. Charges leave traps on quantum vortices at temperatures near $T = 1.7$ K. With a further increase in the temperature, injected charges are scattered on vortex flows of the normal component, which are generated by surface waves.

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1. INTRODUCTION

In this work, we study the interaction of injected negative charges (negatively charged electron bubbles in liquid ^{4}He) with vortex flows, which are generated by nonlinear waves propagating on the surface of liquid helium. A vortex flow generated by waves in normal liquid He-I at $T > 2.17$ K is classical and is described by the Navier–Stokes equation. Vortex motion at temperatures $T < 2.17$ K involves the normal and superfluid components. The feature of the superfluid component is the quantization of the circulation of the velocity of the liquid [1]. A quantum vortex is a topological defect, which ends on the surface of liquid helium or on the walls of a vessel; i.e., quantum vortices usually extend from a wall to a wall of the experimental vessel or from the wall to the free surface of the superfluid liquid [2]. Quantum vortices in the form of rings can also be formed, e.g., at the fast motion of injected charges in helium [3]. The reconnection of intersecting quantum vortices results in the formation of complex structures such as vortex bundles [4].

The properties of quantum vortices were experimentally studied mainly in the restricted geometry where the liquid did not have a free surface [5, 6]. However, the interaction of quantum vortices with the free surface of the superfluid liquid has been recently considered in [7], where the dynamics of charged nanoparticles interacting with quantum vortices ending on the free surface of the liquid was studied. Two types of particle trajectories and the related vortex structures were revealed: vertical linear vortices whose one end attached to the bottom of the vessel and half-ring vortices moving along the free surface of the liquid.

In the experiments reported in [8], it was shown that two mutually perpendicular standing waves on the surface of a classical liquid form a periodic structure—checkerboard—of vortices with opposite vorticities. The period of this lattice is equal to the length of the surface wave λ. Vortices penetrate into the bulk of the liquid, and the vorticity Ω decreases with the depth z according to the exponential law $\Omega \sim \exp(-z/\zeta_0)$, where ζ_0 is the penetration depth of the wave. In the case of the excitation of standing capillary or gravitational waves on the surface of superfluid He-II, it could be expected that the interaction of waves leads to the formation of loops of quantum vortices, which begin and end on the free surface of the superfluid liquid, in addition to usual classical vortices, which are excited in the normal component of the liquid [7].

To study features of vortex structures formed by waves on the surface of superfluid He-II, we chose a method used in [9]. An electron injected in liquid helium forms a spherical vacuum cavity ("bubble") with a radius of about 20 Å at saturated vapor pressures [10]. The negative charge at low temperatures $T <$ 1.5 K is localized on a quantum vortex in a potential well with the depth ΔU estimated from 50 to 130 K according to [11–14]. However, with increasing temperature, the lifetime of the charge in the trap should decreases exponentially as $\tau \sim \exp(-\Delta U/T)$. Information on the structure of the vortex system and on the interaction of charges with quantum vortices can be obtained by varying the directions of motion of charges in the liquid [15].

Thus, negative charges injected in superfluid helium interact with quantum vortices and can be used as probe particles to detect quantum vortices and to study their properties [5].

Our first experiments were carried out at temperatures of $T = 1.8$ and 2.3 K [9]. It was shown that the formation of vortex structures by standing waves on the free surface of liquid helium results in the deviation of particles from the initial trajectory in an applied electric field due to scattering on vortex flows appearing in the bulk of the normal component. The interaction between waves on the surface of liquid helium leads to the generation of mainly classical vortices.

One of the aims of reported experiments is to detect the generation of quantum vortices by nonlinear waves propagating on the surface of superfluid helium by studying the interaction of injected negative charges (electron bubbles) with vortex structures generated by capillary or gravitational waves in the He-II layer in a wide temperature range down to 1.5 K.

2. METHOD

Studies were carried out in a helium optical cryostat, where a chamber with an experimental cell was placed in the vacuum cavity. The chamber was connected to the helium cavity of the cryostat through a copper rod. The working cell was a 50 × 50 × 30-mm rectangular parallelepiped with six electrically isolated faces (Fig. 1). Liquid helium was condensed into the chamber from an external transport Dewar vessel through a capillary. To remove impurities, helium was passed through a finely porous copper filter cooled to 4.2 K. The working temperature of the experimental cell could be varied from 4.2 to 1.5 K by pumping the helium vapor from the helium cavity of the cryostat.

The sketch of the experimental cell is presented in Fig. 1. The upper face of the cell was made from a 2-mm transparent quartz plate whose bottom was coated with a semitransparent metal film. A point source of charges 3 mm in diameter (*1* in Fig. 1) was placed on one of the vertical metal fased above its center. The source of charges was electrically connected to the face on which it located. A composite recording collector consisted of five 9 × 30 mm segments (*3* in Fig. 1) was placed on the face adjacent to the face with the source. Each segment was connected to an independent current amplifier, an electrical signal from which was guided through an analog-to-digital converter to a computer.

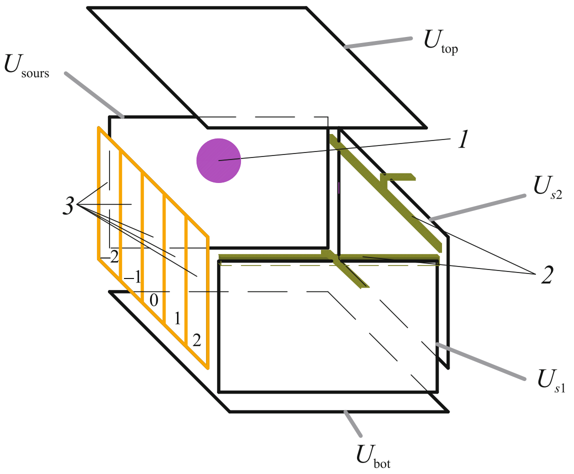

Fig. 1. (Color online) Sketch of the experimental cell: (*1*) source of charges, (*2*) plungers, and (*3*) composite receiving collector.

As in [9], to excite waves on the surface of helium, we used two plane wave generators (plungers *2* in Fig. 1), which were parallel to free adjacent vertical faces at a distance of 3 mm from the wall. The plungers were driven by electromagnetic actuators to which an ac voltage was supplied from a two-channel functional generator. They oscillated in the horizontal plane at a frequency specified by the external generator.

The voltage to the faces of the cell was supplied from five independent dc voltage sources with a common ground electrode. This allowed us to induce driven electric fields with a given configuration in the bulk of the liquid in order to control the motion of injected charges from the source of charges *1* to the composite receiving collector *3*. The time dependence of the current on various segments of the collector was measured before the application of the pump, in the presence of the wave pump, and after the removal of the pump. To suppress the effect of random and electrical noise and to separate a constant component of the current in each sector of the collector segment I_i, we performed the Fourier filtering of the recorded dependences at low frequencies.

3. EXPERIMENTAL RESULTS

Figure 2 presents temperature dependences of the currents $I_i(T)$ recorded in the sectors of the collector in the absence of the wave pump. The voltages $U_{source} = U_{s2} = -100$ V, $U_{top} = -50$ V, $U_{bot} = -100$ V, and $U_{s1} = 0$ V were applied to the faces of the cell. It is seen that the current mainly flows in the central 0 and –1 segments of the collector. A smooth decrease in the currents $I_i(T)$ with increasing temperature is due to a change in the viscosity of He-II. Low-frequency noise on the $I_i(T)$ curves is caused mainly by uncontrollable vibration of the charged He-II surface in the experimental cell.

Figure 3 shows the distribution of currents over the segments of the receiving collector in He-II at a constant temperature of $T = 1.5$ K at the application of the wave pump with the frequency $f_g = 49.88$ Hz at the 140th s and its removal at the 290th s. The distribution of dc voltages on the faces of the cell is the same as that in Fig. 2. The vertical dashed straight lines mark the times of switch-on and switch-off of the ac voltage on the actuators of the plungers. At the pump frequency $f_g = 49.88$ Hz, the length of the standing capillary wave excited on the surface is $\lambda = 0.2$ cm (wavenumber $k \approx 31.4\ \text{cm}^{-1}$). According to estimates presented in [9], when the ac voltage with an amplitude of $A = 7000$ mV was supplied to the actuators of the plungers, the amplitude and steepness of capillary waves were $H \approx 0.003$ cm and $kH \approx 0.05$, respectively.

When the pump was switched on, the collector current was redistributed mainly between three segments. The current $I_0(t)$ in segment 0 decreased from 390 to ≈50 fA, the current $I_{-1}(t)$ in segment −1 increased to ≈400 fA, and the current $I_{-2}(t)$ in segment −2 also increased slightly. The total collector current $I_{\text{sum}} \approx 640$ fA remains almost the same. After the pump was switched off, the currents detected in segments returned to almost the initial values.

Figure 4 presents the temperature dependences of the currents $I_i(T)$ in the segments of the collector that were recorded upon a smooth increase in the temperature of the liquid from 1.5 to 2.17 K at a rate of ≈16 mK/min for 1850 s under the continuous wave pump with the frequency $f_g = 49.88$ Hz. It is noteworthy that the distribution of currents over the segments in Fig. 4 in the temperature range of $T = 1.5$–1.7 K qualitatively coincides with the distribution shown in Fig. 3. With a further increase in the temperature in the narrow range of $T = 1.68$–1.75 K, the current I_0 increases sharply, whereas the current I_{-1} decreases abruptly.

The inset of Fig. 4 presents the semi-log plot of currents of negative charges I_0 and I_{-1} versus the inverse temperature $1/T$ in the temperature range of $T = 1.68$–1.75 K. The straight lines are the dependences $I \sim \exp(\pm\Delta/T)$, where $\Delta = 121$ K.

As seen in Fig. 4, the distribution of currents over segments in the presence of the pump at temperatures above 2.0 K again noticeably changes compared to the distribution of currents in the absence of pump in Fig. 2. The current in the central segment of the collector $I_0(T)$ decreases to 80 fA at $T = 2.17$ K, whereas the current $I_{-1}(T)$ in segment −1 increases to 330 fA. The smooth decrease in the total current $I_{\text{sum}}(T)$ and

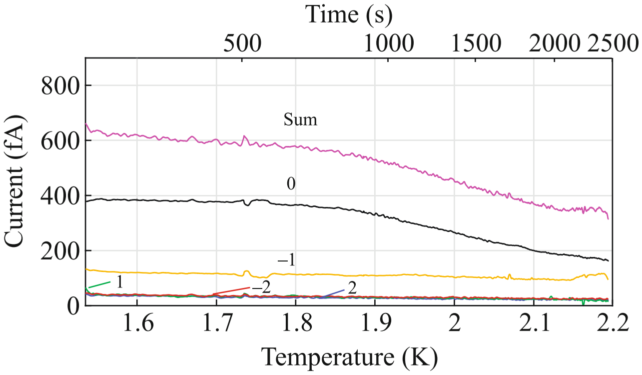

Fig. 2. (Color online) Temperature dependences of currents of negative charges $I_i(T)$ reaching segments of the collector upon a smooth increase in the temperature of He-II in the temperature range of $T = 1.5$–2.17 K in the absence of pump.

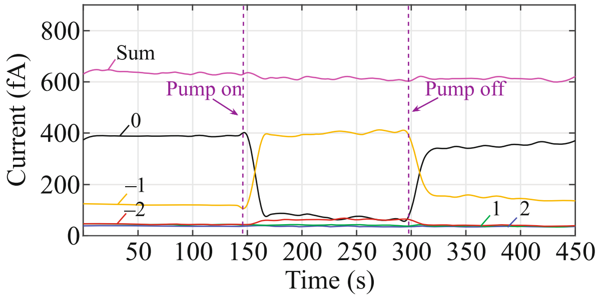

Fig. 3. (Color online) Effect of the wave pump with the frequency $f_g = 49.88$ Hz on the distribution of currents over segments of the receiving collector in He-II at a constant temperature of $T = 1.5$ K. The vertical dashed straight lines mark the switch-on and switch-off times of the pump.

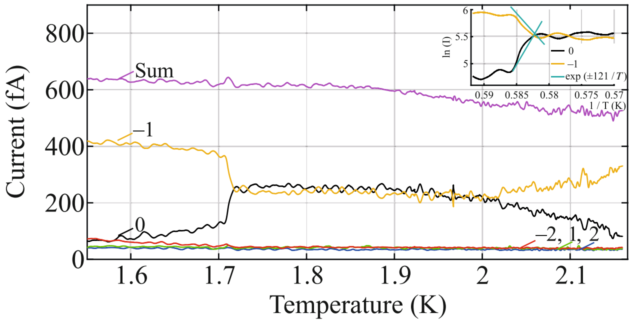

Fig. 4. (Color online) Temperature dependences of currents of negative charges detected by segments of the collector under the wave pump with a smooth increase in the temperature of He-II from 1.5 to 2.17 K. The inset shows the semi-log plot of currents of negative charges $I_0(T)$ and $I_{-1}(T)$ versus the inverse temperature $1/T$ in the temperature range of $T = 1.68$–1.75 K. The straight lines are the dependences $I \sim \exp(\pm\Delta/T)$, where $\Delta = 121$ K.

the currents $I_0(T)$ and $I_{-1}(T)$ with increasing temperature above 1.9 K can be due to an increase in the density of the normal component and the kinematic viscosity coefficient of liquid helium near T_λ [9, 16].

We note that currents in other segments of the collector in the temperature range of 1.7–2.17 K hardly changed in the presence of the pump.

4. DISCUSSION

As shown in [17], the distribution of the steady vertical vorticity on the surface and in the bulk of the liquid $\Omega(x, y, z)$, which is formed by two mutually perpendicular standing waves on the surface of the liquid, can be described by the sum of two terms differing only in multipliers:

$$\Omega(z) = (2e^{-2kz} + \sqrt{2}e^{-\sqrt{2}kz})H_x H_y \omega k^2 \times \sin(\varphi)\sin(kx)\sin(ky). \quad (1)$$

The first term is the vorticity caused by the Stokes drag and the second term is the Euler vorticity due to the nonlinear interaction between waves.

The Stokes drag-induced vorticity is formed on the surface and in the bulk of liquid helium in the time of establishment of the standing wave. This time in our experiment is equal to the double time of traveling of the wave from the wall to the wall of the cell ≈1 s [18].

The generation of vortex motions in the bulk of the superfluid liquid due to the nonlinear interaction between waves occurs in the surface viscous sublayer, which is a source of turbulence. Under the wave pump with the frequency $f_g = 49.88$ Hz, the depth of the viscous sublayer on the surface of He-II at $T = 1.5$ K is about $\delta = \sqrt{\nu/\omega} \approx 5\times10^{-4}$ cm [19], which is much smaller than the length of the capillary wave $\lambda = 0.2$ cm and the amplitude of excited waves $H \approx 0.003$ cm. Turbulence penetrates into the bulk of the viscous liquid in the characteristic viscous time $\tau_{\rm vis} = (2\nu k^2)^{-1} \approx 5.5$ s. The vorticity at times $t \gg \tau_{\rm vis}$ after the wave pump is switched on and off varies by the exponential law $\Omega_E \sim \exp(-t/\tau_{\rm vis})$ [20].

Figure 5 presents the dependence of the characteristic time τ_0 on the wavenumber k (the pump frequency f_g), which is obtained by the approximation of the exponential function $\exp(-t/\tau_0)$ of the experimental dependences $I_i(t)$ upon the switch-on and switch-off of the pump at five resonance frequencies. The times τ_0 presented by red circles in Fig. 5 are obtained by averaging over four measurements at each of the frequencies. The solid line is the calculated dependence of the viscous time $\tau_{\rm vis}$ on the wavenumber $\tau_{\rm vis} = (2\nu k^2)^{-1}$.

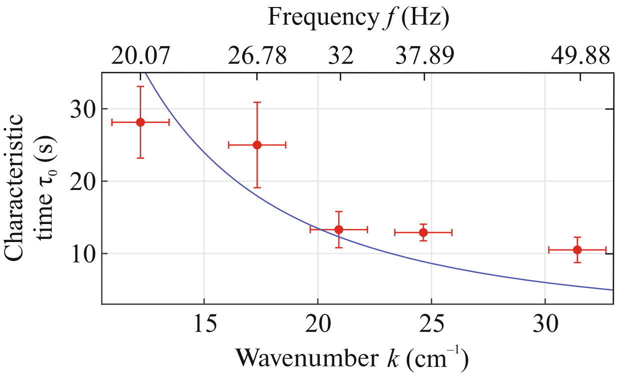

Fig. 5. (Color online) Characteristic time of current variation τ_0 versus the wavenumber k of the pump wave at $T = 1.5$ K: experimental points and the dependence $\tau_{\rm vis} = (2\nu k^2)^{-1}$ shown by the line.

It is seen that the characteristic time τ_0 decreases with increasing frequency and is close to the viscous time $\tau_{\rm vis}$. Errors in the calculated τ_0 values are due to high bias currents caused by the vibrations of the surface of the liquid.

As mentioned above, after the pump is switched on, the lattice of vortices in the form of a checkerboard (1) consisting of vortices having pairwise opposite vorticities appears on the surface of liquid helium. The density of the normal component at a temperature of $T = 1.5$ K is about 11% of the total density of liquid helium; consequently, the vorticity excited in the superfluid component should play dominant role in the excitation of vortex flows in He-II. It can be assumed that quantum vortices begin on one vortex of the checkerboard on the surface and end on the neighboring vortex with the opposite vorticity; i.e., loops of quantum vortices are formed under the surface. In this case, according to the principle of minimum energy, the length of the charged vortex should be close to $\lambda/2$, which can lead to the formation of separated directions under the surface along which loops of quantum vortices are primarily located and the density distribution of quantum vortices under the surface becomes anisotropic.

To estimate the density of quantum vortices that are formed under the surface, we write the circulation of the velocity of the vortex motion of the quantum liquid in the form

$$\Gamma = \int_S {\rm curl} V\, dS = n\frac{h}{m}, \quad (2)$$

where integration is performed over the area S, ${\rm curl} V = \Omega$ is the vorticity, h is the Planck constant, m is the mass of the He-4 atom, and n is the number of vortices on the area S. Therefore, the density of quantum vortices in the order of magnitude is $N \sim \Omega/\left(\frac{h}{m}\right)$. The vorticity of the vortex of the lattice on the surface of the liquid under the pump with a frequency of

49.88 Hz estimated by Eq. (1) is $\Omega \approx 3\ \mathrm{s}^{-1}$. Then, the average density of quantum vortices under the surface of superfluid helium is in the order of magnitude $N \sim \Omega / \frac{h}{m} = 10^3\ \mathrm{cm}^{-2}$.

The electric field E presses negative charges moving in liquid helium to the free surface of the liquid. The upward vertical component of the force eE at the distance z_0 under the surface becomes equal to the repulsive force of the image of charges [21]:

$$eE = e^2/16z_0^2\pi\varepsilon_0(\varepsilon_i - \varepsilon_g)/\varepsilon_i(\varepsilon_i + \varepsilon_g). \qquad (3)$$

As a result, a quasi-two-dimensional charged layer of negative charges with the density $\sigma \approx 10^7$ charges/cm^2 (the dielectric constants of liquid ^{4}He and of saturated vapor are $\varepsilon_i = 1.057$ and $\varepsilon_g = 1.00$, respectively) appears in liquid He-II in the vertical electric field with the strength $E \approx 10$ V/cm at the distance $z_0 \approx 100$ nm from the surface. This estimate does not include the possibility of the quantum tunneling of electrons from vacuum bubbles to vapor; i.e., it is assumed that the quasi-two-dimensional charged layer of negative charges with the density $\sigma \sim 10^7$ charges/cm^2 formed under the surface screens the vertical component of the applied electric field, and the average distance between electron bubbles in the layer is ≈ 3 μm. We note that the quasi-two-dimensional charged layer is located in the viscous sublayer where the vorticity appears [8].

Further, we assume that moving charges can be trapped by quantum vortices because the temperature of He-II in the working cell is below 1.7 K. One quantum vortex with the length $\lambda/2 = 0.1$ cm, which is located at the distance z_0 from the surface, can trap up to 300 electron bubbles. If the average density of quantum vortices generated by the wave pump is $N \approx 10^3\ \mathrm{cm}^{-2}$, the density of charges trapped by vortices can reach $\sigma_{\mathrm{tr}} \approx 3 \times 10^5\ \mathrm{cm}^{-2}$, which is almost a factor of 30 smaller than the density of free untrapped charges $\sigma \sim 10^7\ \mathrm{cm}^{-2}$ in the quasi-two-dimensional layer. As a result, electron bubbles moving from the source of charges to the collector in He-II cooled below 1.7 K can be scattered on charged quantum vortices. In other words, when the wave pump is switched on, in addition to the excitation of ordinary classical vortices in the bulk of the normal component of superfluid He-II, quantum vortices are also formed in the superfluid component of He-II and can be trapped by negatively charged electron bubbles at temperatures below 1.7 K, as previously shown in experiments [9]. The formation of complex bubble–quantum vortex structures in a Bose–Einstein condensate was studied in detail in [22].

The inset of Fig. 4 presents semi-log plots of the currents I_0 and I_{-1} as functions of the inverse temperature $1/T$ in the temperature range of $T = 1.68$–1.75 K. This temperature range was passed in a time of more than 200 s. Since the rate of increasing temperature is low and the time of capture of the charge in the trap at $T \approx 1.68$ K and at a comparable density of quantum vortices is ~10 s [14], it can be assumed that the distribution of charges in traps is quasi-equilibrium. The density of trapped charges σ_{tr} is proportional to the lifetime of charges in a trap on the quantum vortex τ_{tr} and can be described by the exponential function $\sigma_{\mathrm{tr}} \sim \exp(-\Delta/T)$. A sharp change in the currents $I_i(T)$ at temperatures near 1.7 K is due to the processes of escape of negative charges from traps on quantum vortices. It can be assumed that deviations ΔI_i of the currents I_0 and I_{-1} from the initial values under the variation of the temperature near 1.7 K are proportional to the density of charges on quantum vortices σ_{tr}; i.e., $\Delta I_i \sim \exp(-\Delta/T)$. Straight lines in the inset are exponential dependences with $\Delta = 121$ K. This estimate of the depth of the trap is quite close to the estimate of the depth of the potential well $\Delta = 132$ K obtained in experiments [12], where the average capture time of negative charges in traps on quantum vortices in He-II were measured at temperatures near 1.7 K. The closeness of two estimates of activation energies and the coincidence of temperature ranges confirm our assumption. Since the probability of capture of the charge by the trap at temperatures above $T = 1.7$ K is small [11–14], quantum vortices in He-II are electrically neutral. Consequently, the scattering of negative charges on vortex flows in He-II at temperatures above 1.7 K is primarily due to the drag of mobile charges by vortex flows in the normal component, which is a mechanism considered in [9].

5. CONCLUSIONS

To summarize, it has been experimentally established for the first time that the interaction of two mutually orthogonal standing waves on the surface of superfluid He-II at temperatures below 1.7 K results in the formation of quantum vortices near the surface; these quantum vortices can trap injected negative charges (electron bubbles with a radius of about 20 Å), which were pressed to the surface of the liquid by the external electric field. The scattering of free charges on charged vortices leads to change in the direction of their motion under the surface of the liquid in a static electric field. The capture of negative charges by quantum vortices becomes insignificant at temperatures $T = 1.7$–2.17 K, and after the application of the wave pump on the surface, charges moving in the electric field are scattered mainly on vortex flows generated by surface waves in the normal component of superfluid He-II.

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CONFLICT OF INTEREST

The authors declare that they have no conflicts of interest.

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REFERENCES

1. W. F. Vinen, Proc. R. Soc. London, Ser. A **260**, 218 (1961).
2. W. F. Vinen and R. J. Donnelly, Phys. Today **60** (4), 43 (2007).
3. P. M. Walmsley, A. A. Levchenko, and A. I. Golov, J. Low Temp. Phys. **145**, 143 (2006).
4. S. K. Nemirovskii, Phys. Rev. B **102**, 064511 (2020).
5. P. M. Walmsley, A. I. Golov, H. E. Hall, A. A. Levchenko, and W. F. Vinenet, Phys. Rev. Lett. **99**, 265302 (2007).
6. W. F. Vinen, J. Low Temp. Phys. **145**, 7 (2006).
7. P. Moroshkin, P. Leiderer, K. Kono, S. Inui, and M. Tsubota, Phys. Rev. Lett. **122**, 174502 (2019).
8. S. V. Filatov, V. M. Parfenyev, S. S. Vergeles, M. Yu. Brazhnikov, A. A. Levchenko, and V. V. Lebedevand, Phys. Rev. Lett. **116**, 054501 (2016).
9. I. A. Remizov, M. R. Sultanova, A. A. Levchenko, and L. P. Mezhov-Deglin, Low Temp. Phys. **47**, 378 (2021).
10. R. J. Donnelly, *Quantized Vortices in Helium II* (Cambridge Univ. Press, Cambridge, 1991), Vol. 233, p. 690.
11. R. J. Donnelly, Phys. Rev. Lett. **14**, 39 (1965).
12. R. L. Douglass, Phys. Rev. Lett. **13**, 791, (1964).
13. D. Mateo, J. Eloranta, and G. A. Williams, J. Chem. Phys. **142**, 064510 (2015).
14. J. W. P. Pratt and J. W. Zimmermann, Phys. Rev. **177**, 412 (1969).
15. P. M. Walmsley, A. A. Levchenko, S. E. May, and A. I. Golov, J. Low Temp. Phys. **146**, 511 (2007).
16. R. Donnelly and C. F. Barenghi, J. Phys. Chem. Ref. Data **27**, 1217 (1998).
17. S. V. Filatov and A. A. Levchenko, J. Surf. Invest.: X-ray, Synchrotr. Neutron Tech. **14**, 751 (2020).
18. S. V. Filatov, A. V. Poplevin, A. A. Levchenko, and V. M. Parfenyev, Phys. D (Amsterdam, Neth.) **434**, 133218 (2022).
19. L. D. Landau and E. M. Lifshitz, *Course of Theoretical Physics,* Vol. 6: *Fluid Mechanics* (Pergamon, New York, 1989).
20. V. M. Parfenyev and S. S. Vergeles, Phys. Rev. Fluids **5**, 094702 (2020).
21. V. B. Shikin and Yu. P. Monarkha, *Two-Dimensional Charged Systems in Helium* (Nauka, Moscow, 1989) [in Russian].
22. V. P. Ruban, J. Exp. Theor. Phys. **133**, 779 (2020).

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