
**ON THE POSSIBILITY OF “DRY” FRICTION
IN SUPERFLUID He⁴****M.D. TOMCHENKO**PACS 67.10.Hk; 67.30.hp;
68.08.-p
©2011**Bogolyubov Institute for Theoretical Physics, Nat. Acad. of Sci. of Ukraine**
(14b, Metrolohichna Str., Kyiv 03680, Ukraine; e-mail: *mtomchenko@bitp.kiev.ua*)

A possible microscopic explanation for the exhaustion of ρ_s in helium-II at the wall at $T > T_c \simeq 0.5 \div 1$ K has been proposed, and a possibility for the “dry” friction to exist in He-II at $T \leq T_c$ has been predicted. Both effects are related to the fact that the energy of 2D-rotons is lower by 2 K than that of 3D-rotons, so that the wall is a potential well for the latter.

At wetting, helium atoms stick to a wall. However, taking into account that $\text{rot } \mathbf{v}_s = 0$, the velocity \mathbf{v}_s cannot grow permanently, when moving away from the wall. From this reason, V.L. Ginzburg drew conclusion [1] that \mathbf{v}_s has a jump near the wall and, therefore, there must be “dry” friction in He II. However, such friction was not found experimentally [2], whence it follows [3] that $\rho_s = 0$ at the wall. Later, this hypothesis was confirmed experimentally [4]. To our knowledge, the microscopic reason of such an “exhaustion” of ρ_s has not been elucidated yet. In addition, the helium temperature was not specified in work [2]. However, if ultralow temperatures are not required, experiments with helium-II are usually carried out at $T > 1.2$ K, which is associated with a cooling procedure. Below in this work, simple microscopic reasonings are proposed, which can explain the exhaustion of ρ_s at the wall and allow us to predict “dry” friction at $T \lesssim 1$ K.

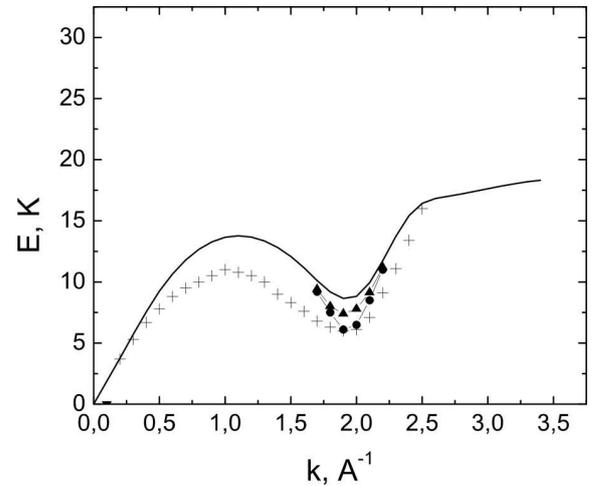
By definition, $\rho_s = \rho - \rho_n$. Therefore, the exhaustion of ρ_s at the wall can originate from the behavior of either ρ or ρ_n . It is known that the ρ corresponds to the atomic density, and ρ_n does to the quasiparticle one. The properties of ρ can ensure the equality $\rho_s = 0$ in two cases. First, it can be, if $\rho = 0$. However, the exact zero is impossible, because the wall is not an in-

initely high energy barrier, so that the wave function of He II, together with ρ , must be different from zero. Second, it can take place as a result of the exact equality $\rho = \rho_n$. However, nothing forces atoms to arrange in such a manner that the equality $\rho = \rho_n$ be satisfied just at the wall. The following variant is also possible: the ρ -value is very low near the wall, so that ρ_s is also small; in this case, dry friction does exist, but it is too low to be detected. However, in this case, ρ_s must be close to zero only in a close vicinity to the wall, at distances not farther than the average interatomic one (because nothing prevents atoms from approaching so closely). However, in accordance with the experiment [4, 5], ρ_s is close to zero at larger distances from the wall (approximately 2 atomic layers). Whence it follows that it is more likely the properties of ρ_n rather than ρ that are responsible for the equality $\rho_s = 0$ at the wall. In other words, $\rho_s \rightarrow 0$ near the wall as a result of the quasiparticle behavior rather than the atomic one: owing to a certain reason, the highest possible concentration of quasiparticles is attained at the wall, and the condition for λ -transition, $\rho_s = 0$, is realized. Let us examine this variant. The fact that the thickness of a helium layer, for which $\rho_s \approx 0$ (about 2 atomic layers), approximately coincides with the effective radius of a roton [6] (about 1.5 atomic layers) testifies in favor of this hypothesis.

The following simple mechanism is possible. From the results of microscopic calculations [7, 8] and the experiment [9], it follows that the energy Δ_{2D} of a surface (2D) roton is lower by approximately 2 K than the energy of a bulk (3D) roton. From the dispersion curves for 2D- and 3D-rotons (see Figure), it is evident that two processes may run near the wall: (a) a direct one, i.e. a 3D-roton creates a 2D-roton and a 3D-phonon, and (b) an inverse one: a 2D-roton and a 3D-phonon merge to create a

3D-roton. One may choose an arbitrary point in the 3D-curve in a vicinity of the roton minimum and draw two straight lines from it downwards to the right and to the left at a definite angle with respect to the vertical, which is equal to the slope angle of the phonon branch. The intersection points of those straight lines with the 2D-roton curve determine possible states of a 2D-roton, whereas the vector connecting those points determines a required 3D-phonon. In this case, the conservation laws for energy and momentum can be satisfied. The only restriction is that the z -component of the 3D-roton momentum has to be small. The binary process 2D-roton \rightarrow 3D-roton and the inverse one, as well as the ternary process 2D-roton \rightarrow 3D-roton + 3D-phonon and the inverse one, are forbidden by the conservation laws. There may also be quaternary and higher-order processes, but their probabilities are low.

Therefore, two processes, (a) and (b), dominate among the roton-assisted ones running near the wall. Every 3D-roton that approaches the wall can decay into a 2D-roton and a 3D-phonon with a certain probability. Accordingly, every 2D-roton can merge, with a certain probability, with a 3D-phonon to create a 3D-roton. However, those probabilities are evidently different: the former is governed by the process itself, whereas the latter is also proportional to the concentration of 3D-phonons with a momentum that corresponds to the transition. While a 3D-roton can decay immediately, a 2D-roton has to wait until a required 3D-phonon appears around it. Therefore, the characteristic time of the latter process has to be larger. As a result, the creation of a 2D-roton must occur more frequently than its decay. At $T \gtrsim 1$ K, the number of rotons is large, and those 3D-rotons which come to the wall will decay into 3D-phonons and 2D-rotons, until the highest possible concentration of 2D-rotons is attained, so that ρ_n becomes equal to ρ at the surface and ρ_s vanishes here. It is what is observed in the experiment. At very low $T \lesssim 0.1$ K, the number of rotons is several orders of magnitude smaller than the number of phonons. In this case, the equality $T = T_\lambda$ at the wall is impossible. To prove it, let us suppose the contrary, i.e. let the concentration of 2D-rotons at the wall be maximum, and let $T = T_\lambda$. It is evident that, in this case, process (b) prevails for 2D-rotons, because its probability is proportional to the considerable concentrations of 2D-rotons and 3D-phonons, whereas the probability of process (a) is proportional to the concentration of 3D-rotons, which is very low at $T \lesssim 0.1$ K. Process (b) continues until the concentration of 2D-rotons reduces to a certain equilibrium value which is to be calculated. However, even



Experimental dispersion curve for bulk quasiparticles in He II (solid curve), theoretical dispersion dependence for surface quasiparticles [7, 8] (crosses), and experimental dispersion dependences for surface rotons [9] (circles and triangles)

without calculations, it is clear that the temperature T of the walls is much lower than T_λ . One may expect that the equilibrium concentration of 2D-rotons would be of the same order of magnitude as the concentration of 3D-rotons, i.e. very low. In addition, if one takes into account that, at low temperatures, phonons with low energies, for which the dispersion curves for 3D- and 2D-phonons (the theoretical one) [7, 8] coincide, play a crucial role, we come to a conclusion that, if the bulk temperature $T_{3D} \lesssim 0.1$ K, the helium temperature at the wall has to be close to the former; accordingly, $\rho_s \approx \rho$ near the wall.

The critical temperature T_c , at which the exhaustion of ρ_s at the wall disappears, is probably a little lower than the temperature of transition from the roton domination to the phonon one and equals to $T_c \simeq 0.5 \div 1$ K.

Note that our conclusions do not demand any calculations. It is enough to know that processes (a) and (b) run with different rates; therefore, the number of 2D-rotons will either decrease until the wall temperature falls to the phonon one (of about 1 K) or grow until the concentration of 2D-rotons at the wall reaches the maximum with $T = T_\lambda$ and $\rho_s = 0$. The experiment ($\rho_s = 0$ at the wall) testifies that the latter scenario is realized. Since the energy of 2D-rotons is lower by 2 K than that of 3D-rotons, the wall is a potential well for the latter.

From those reasons, it follows that, in the first helium layers near the wall, there exists a temperature gradient. From the symmetry viewpoint, it can emerge as a result of the system isotropy violation near the wall. This violation is also responsible for the pressure gradi-

ent near the wall [4]. Note that, as early as in 1941, P.L. Kapitsa [10] observed a temperature jump in a helium layer $\lesssim 0.01$ mm in thickness located near the heater, when the latter was heated up. This jump was explained in work [11] as a result of the high thermal conductivity in helium-II. However, in the calculations of work [11], the surface excitations of helium were not taken into account. In accordance with the arguments presented above, those excitations give rise to a temperature jump in a much thinner helium layer near the wall, namely, of a few atomic sizes. This jump has a different nature. It does not require for the heat to be pumped from outside, and, despite the presence of a temperature gradient, the state is equilibrium, of course, and the heat flow is absent. Owing to a high thermal conductivity of helium, the equilibrium is established, first of all, in the bulk and near-surface helium, whereas the heat exchange with the wall is much slower. Nevertheless, a weak heat exchange between surface helium excitations and the wall must evidently take place. Therefore, there must exist a small jump of the temperature between the wall and the helium bulk, even in the absence of a thermal pumping to the wall or helium. It can be verified in the experiment. In so doing, one has to take into consideration that such a jump of T must exist both between a heater and helium, and between a thermometer and helium.

It is of importance that, at $T \leq T_c$, $\rho_s \neq 0$ at the wall. Therefore, there must exist “dry” friction [1] which can be tested in a direct experiment of the type proposed in work [2] or by measuring the dependence of the width of the surface roton peak on the temperature [9] (at $T = T_c$, the width should jump). In experiments with the third sound [5], it was obtained that the restoration length of ρ_s grows with the temperature at $T \gtrsim 1$ K and is constant at $T \lesssim 1$ K. As far as we know, those dependences have not been explained yet, and the temperature $T \approx 1$ K, at which the dependence changes its character, may probably be T_c .

The properties of the free helium surface are somewhat different from those of helium near the wall. However, the energy difference between the surface and bulk rotons is associated, first of all, with the geometric factor. Therefore, for the free surface, the equality $\Delta_{2D} \simeq \Delta_{3D} - 2$ K should probably be valid as well. In this case, the arguments presented above are valid, and, at $T_{3D} \geq T_c$, rotons must condensate on the surface, so that $\rho_s = 0$ and $T = T_\lambda$ there. In view of a probable high temperature ($\simeq T_\lambda$) of the surface helium layer, an issue arises concerning the temperature of free He atoms

above the He II surface. For He II, “temperature” means “quasiparticles”. From the conservation laws, it is evident that, in the case of atoms above the He II surface, the probability of the energy exchange with He II quasiparticles is high for quasiparticles in the bulk and low (however, nonzero) for near-surface ones. Therefore, the helium vapor temperature has to be higher than that in the bulk of He II by a small value, which is to be calculated.

Only the qualitative arguments were presented above. It seems that the processes in helium-II near the wall and near the free surface are of interest, being not quite trivial. They remain to be not clear enough and deserve a more attention from theorists and experimenters.

1. V.L. Ginzburg, Zh. Èksp. Teor. Fiz. **29**, 254 (1955).
2. G.A. Gamtsemlidze, Zh. Èksp. Teor. Fiz. **34**, 1434 (1958).
3. V.L. Ginzburg and L.P. Pitaevsky, Zh. Èksp. Teor. Fiz. **34**, 1240 (1958).
4. S.J. Putterman, *Superfluidity Hydrodynamics* (North-Holland, Amsterdam, 1974).
5. J.H. Scholtz, E.O. McLean, and I. Rudnick, Phys. Rev. Lett. **32**, 147 (1974).
6. G.W. Rayfield and F. Reif, Phys. Rev. **136**, A1194 (1964).
7. V. Apaja and E. Krotscheck, Phys. Rev. B **67**, 184304 (2003).
8. V. Apaja and E. Krotscheck, J. Low Temp. Phys. **134**, 793 (2004).
9. O. Plantevin, B. Fak, H.R. Glyde *et al.*, Phys. Rev. B **63**, 224508 (2001).
10. P.L. Kapitsa, Zh. Èksp. Teor. Fiz. **11**, 1 (1941).
11. I.M. Khalatnikov, Zh. Èksp. Teor. Fiz. **22**, 687 (1952).

Received 28.06.10.

Translated from Ukrainian by O.I. Voitenko

ПРО МОЖЛИВІСТЬ “СУХОГО” ТЕРТЯ У НАДПЛИННОМУ He⁴

М.Д. Томченко

Р е з ю м е

Запропоновано можливе мікроскопічне пояснення “виснаження” ρ_s гелію-II біля стінки при $T > T_c \simeq 0,5-1$ K та передбачено можливість існування у He II “сухого” тертя при $T \leq T_c$. Обидва ефекти пов'язані з тим, що енергія 2D-ротонів на 2 K менша за енергію 3D-ротонів, тому стінка є потенційною ямою для останніх.