Superfluid film on the surface of a solid immersed in a nonsuperfluid solution of He^4 in He^3

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It is established that a film of the superfluid lower phase is produced on the wall in the upper phase of laminating He^3–He^4.

Even in the first experiments[1] on the lamination of liquid solutions of He^3 in He^4 there were observed phenomena indicating that superfluid motion sets in through the upper, rich in He^3, phase of the liquid helium. Further experiments on the propagation of sound, however, as well as other experiments, have shown that the liquid-helium phase rich in He^3 is not superfluid.

The experiments described below have explained this contradiction and have established that a superfluid film consisting of the lower, rich in He^4 phase, is produced on the surface of a solid immersed in the upper phase, which is rich in He^3.

In the first series of experiments, the motion of the phase-separation level was examined visually in a test

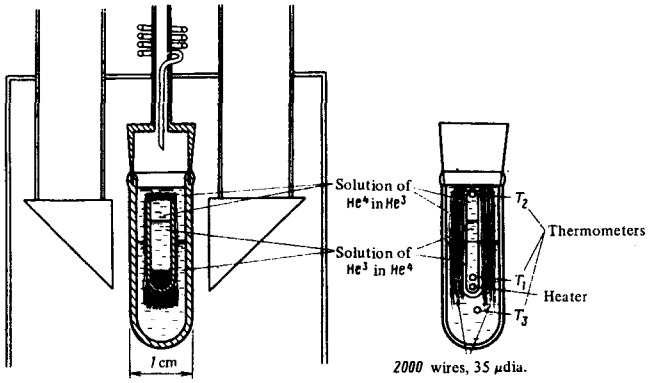

FIG. 1.

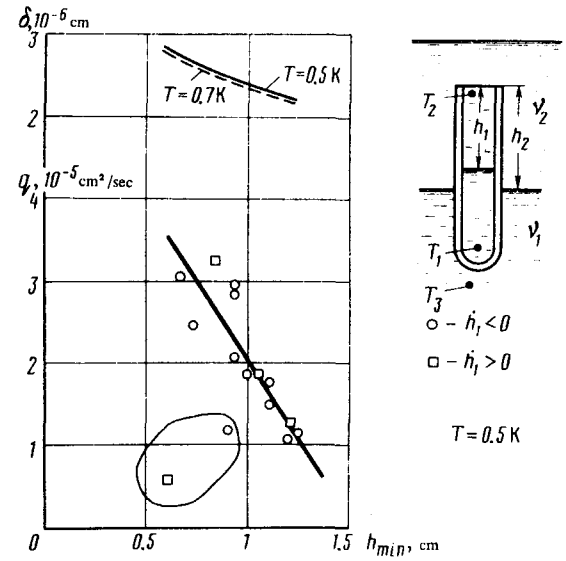

FIG. 2.

tube immersed in the laminating solution of He^3 in He^4, as shown in Fig. 1. For more rapid flow along the film, and also to gain more assurance that superfluid motion along the films is produced rather than diffusion through the upper phase, 2000 or 1074 copper wires of 35 μ diameter, or 390 constantan wires of 100 μ diameter, were placed in the test tube. The superfluid was set in motion by increasing and decreasing of the intensity of light aimed on the instrument, or by turning on a heater in the test tube. The experiments were performed close to 0.5 °K. Both filling of the test tube with the lower phase following intense illumination, and the outflow of He^4 and equalization of the levels in the case of weak illumination, were observed. The experimental results are shown in Fig. 2, where the ordinates represent the bulk outflow velocity ($\dot{h}_1 > 0$) or of the inflow ($\dot{h}_1 < 0$) of the lower phase into the test tube, divided by the sum of the perimeters of all the wires and the internal perimeter of the test tubes. The abscissas represent the distance from the edge of the test tube to the nearest level. In spite of the appreciable change in the perimeter and in the type of material—copper, constantan, glass—the results of the measurements, albeit with a certain scatter, still fit one curve. As is the case with ordinary superfluid films, several cases were observed with noticeably different velocities, and these are circled in the figure. Since the motion along the film is superfluid, one could expect in vessels with small volumes, besides the observed limit of flow velocity, weakly damped oscillations of the phase-separation level at amplitudes not exceeding the critical velocity. To observe this phenomenon a capacitor was placed in the dissolution chamber of He^3 cryostat. The capacitor consisted of two coaxial copper-foil cylinders, closed at the bottom, with a third cylinder inserted between them and constituting one of the capacitor electrodes. The gap between the electrodes was 0.13 mm, and their height was 3.7 cm. The capacitor was connected in an oscillator circuit, and the change of the oscillator frequency as a result of the change of the interface level inside the capacitor was recorded with an automatic plotter. The experiments indeed revealed weakly damped oscillations of the level. Moreover, under certain conditions the level executed undamped oscillations, i.e., the phenomenon of the "singing film" was observed, analogous to the onset of sound oscillations in dewars with liquid helium.

To interpret the results, we assume that the chemical potential for each of the He isotopes is

$$\mu(x, z) = \mu(P) + mgz + Ax^{-3},$$

where P is the pressure, m is the mass of the atom, g is the acceleration due to gravity, and A is a constant. From the equality of the chemical potentials at $x=\infty$, $z=0$ and $x=\delta$, $z=z$ (see upper Fig. 3), we obtain for the dependence of the thickness of the lower-phase film on the height the formula $\delta = A^{1/3}[m_4 g(1-\nu_2/4)z]^{-1/3}$. Since the He^3 concentration ν_2 in the upper phase is close to unity, the thickness of the film in the solution will be approximately 10% larger than for He^4 in the

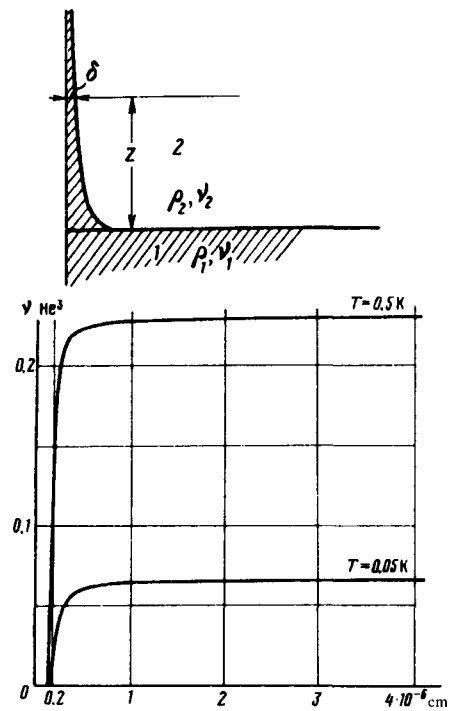

FIG. 3.

vapor phase (at $\nu_2 = 0$). Knowing $\delta(z)$, we can calculate, from the amplitude y_0 of the level oscillations in the capacitor and from the period τ of the oscillations, the value of the critical velocity v_c and the thickness of the film on the upper edge of the capacitor, namely $v_c \approx g\Delta\rho y_0/3\pi\rho_1 z$ and $\delta = 2\pi a\rho y_0/\tau\rho_s v_c$. At $T = 0.05$ °K we have $\rho_1 = 0.142$ g/cm^3, $\Delta\rho = \rho_1 - \rho_2 = 0.06$ g/cm^3 and $\rho_s/\rho_1 = 0.88$, and at $a = 0.013$ cm and $z = 3$ cm we observed $y_0 = 0.028$ cm and $\tau = 40$ sec, i.e., $v_c = 16$ cm/sec and $\delta = 4\times10^{-6}$ cm.

Unfortunately, from the visual observation of the flow we can only conclude that at $T = 0.5$ °K and $h = 1$ cm the rate of flow along the superfluid film is $q = 1.9\times10^{-5}$ cm^2/sec. If we assume $\delta = 2.4\times10^{-6}$ cm and $\rho_s/\rho = 0.57$, then $v_c = 14$ cm/sec, which coincides in order of magnitude with the preceding value.

Using for the He^3 in the film a chemical potential in the form

$$\mu(x, \nu) = \epsilon_0 + kT_{ph}[1 - \pi^2 T^2/12T_{ph}^2] + Ax^{-3}(n_4 - n_3)/n_4,$$

where $T_{ph} = \hbar^2(3\pi^2 n\nu)^{2/3}/2m^*k$, ϵ_0 is the zero-point energy, $m^* = 2.4m_3$ is the effective mass, n is the atomic density of the solution, and n_3 and n_4 are the atomic densities of the liquid He^3 and He^4, we obtain for the $\nu(x)$ dependence in the film the curve shown in the lower part of Fig. 3.

The concentration at large x was assumed to be the same as in the lower phase. It is seen from the figure that the He^3 concentration is constant in the film and only at $x < 20$ Å does it drop abruptly to zero. This means that the He^3 atoms do not interact with the smooth wall. This phenomenon was indeed observed[2] in a study of shear oscillations of quartz in the upper phase. The effective viscosity turns out to be smaller by a factor of several hundred than for pure He^3, although the He^4 concentration in the upper phase was of the order of 10^{-5}—10^{-10}.

Thus, on the basis of the data presented here, and also of the results of[2], it follows that the presence of the superfluid film leads to the appearance of a number of new effects.

One should review the question of the limiting temperatures in the cryostat for the dissolution of He^3 and the designs of the heat exchanges; the statements that He^3 assumes the tangential velocity of the solid walls in He^3-He^4 solutions, and some other concepts should be revised.

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[1] V. P. Peshkov and K. N. Zinov'eva, Zh. Eksp. Teor. Fiz. **32**, 1256 (1957) [Sov. Phys.-JETP **5**, 1023 (1957)].
[2] A. P. Borovikov and V. P. Peshkov, Tezisy dokladov (Abstracts of Papers) NT-18, Kiev (1974), p. 27; V. P. Peshkov, NT-18, p. 25.