POSSIBLE EXISTENCE OF ONSAGER-FEYNMAN VORTICES AT TEMPERATURES ABOVE THE λ POINT

É. L. ANDRONIKASHVILI, K. B. MESOED, and Dzh. S. TSAKADZE

Physics Institute, Academy of Sciences, Georgian S.S.R.; Tbilisi State University

Submitted to JETP editor August 6, 1963

J. Exptl. Theoret. Phys. (U.S.S.R.) **46**, 157-161 (January, 1964)

It is shown that effects connected with the existence of Onsager-Feynman vortices continue to exist in rotating liquid helium above the λ point, provided that this state is attained by superheating the rotating He II.

In 1958 we reported[1] that rotating helium has vortex properties in the temperature region directly above the λ point. However, the temperature measurement procedure used in the first experiments was not accurate enough to fully corroborate this point of view. We recently repeated the experiment under much better conditions, and all the previously observed facts received new and reliable confirmation.

We measured the damping of a rough disc that executed axial-torsional oscillations in its own plane and participated in the uniform rotation of a cylindrical dish filled with liquid helium, over and above the damping which would be produced in stationary helium. The difference $\delta - \delta_{st}$ between the logarithmic damping decrements in rotating and stationary helium was measured as a function of the angular velocity ω_0 of the dish at a constant disc oscillation frequency.

DESCRIPTION OF SETUP

The measurements were made with the aid of a setup analogous to that used in the earlier work [2]. The setup rotated the dish with helium uniformly together with the immersed disc, which at the same time executed axial-torsional vibrations. The logarithmic damping decrement of these vibrations was measured by a method described in [3]. We describe here only that part of the setup which ensured the necessary uniformity of rotation and the necessary accuracy of temperature measurement.

A kinematic diagram of the setup is shown in Fig. 1. The motion of the internal part was rotated by strong electromagnets driven at a strictly uniform speed by a special unit. The electric motor was coupled through a reduction gear to a system of sheaves, which in turn was coupled to

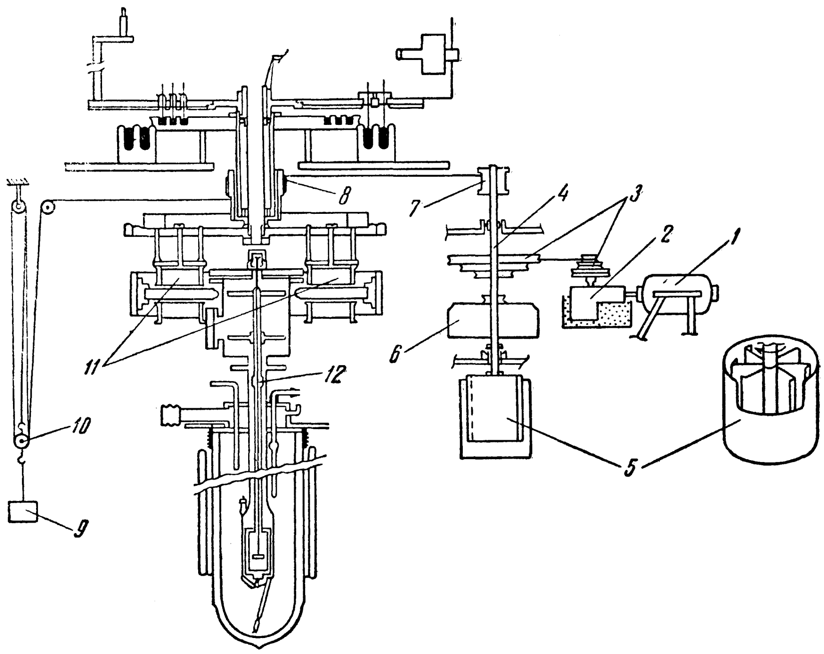

FIG. 1. Kinematic diagram of the setup: 1–electric motor, 2–reduction gear, 3–sheaves, 4–intermediate shaft, 5–oil damper, 6–flywheel, 7–driving drum, 8–driven drum, 9–weight, 10–pulley block, 11–electromagnets, 12–internal rotating part of the setup.

another system of sheaves secured to an intermediate shaft carrying a heavy flywheel and an oil damper. By combining sheaves of different diameters, it was possible to vary the period of rotation of the system between 30 and 500 seconds. On the intermediate shaft was placed a drive drum, on which a steel wire was wound (turn by turn) from a driven drum. Even all these measures were insufficient, and really uniform motion was obtained only after a constant mechanical load was added to the system, in the form of a weight hanging from the lower part of a pulley block. The block wire was also wound turn by turn, on the driven drum.

The helium temperature was measured with a carbon resistance thermometer placed on the bottom of the rotating dish (see Fig. 2), in which a rough brass disc executed the axial-torsional oscillations. The current and potential terminals of the resistance thermometer were connected through slip-ring mercury contacts to a dc potentiometer. The temperature was calibrated against the pressure of saturated helium vapor, measured with a mercury manometer and a cathetometer accurate to 0.05 mm Hg.

The experimental results at temperatures below the λ point were obtained with the helium cooled by pumping the vapor down to the investigated temperature, at which the helium was set to rotate (curve a of Fig. 3 was obtained in this manner). Two methods were used to investigate the properties of the liquid above the λ point. In one the helium temperature was lowered to 2.14°K, after which the liquid was set to rotate and the pumping-on interrupted simultaneously. The measurements began immediately after passage through the λ point (curve b of Fig. 3 was obtained in this manner). In the second method the temperature of the

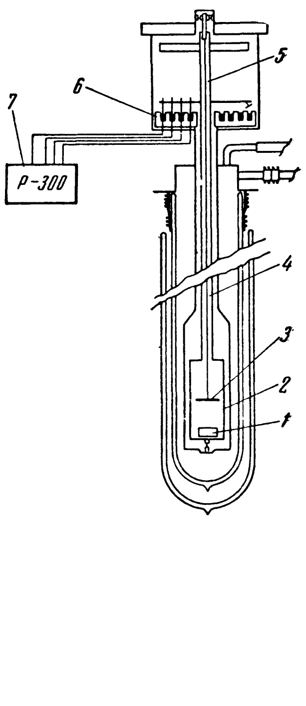

FIG. 2. Diagram of instrument: 1–carbon resistance thermometer, 2–rotating dish, 3–oscillating disk, 4–straightened glass rod, 5–phosphor bronze suspension filament, 6–mercury slip ring contacts, 7–dc potentiometer.

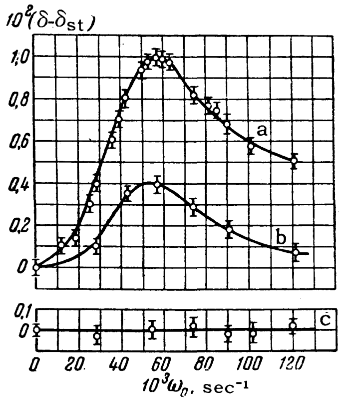

FIG. 3. Dependence of $\delta - \delta_{st}$ on the speed of rotation. Curve a–He II, T = 1.78° K, curve b–He I, T = 2.21° K (curve b has been obtained under conditions when the rotating He II was converted into a state above the λ point by "squeezing"), curve c–plot illustrating the fact that $\delta - \delta_{st}$ does not depend on the speed of rotation under conditions when He I is untwisted; T = 2.21° K. The oscillation frequency in all cases when $\Omega = 0.581\ \text{sec}^{-1}$.

He I was lowered to practically the λ point, and then the liquid was set to rotate, the pumping-on was stopped, and the measurements of the disc damping initiated under uniformly rising temperature conditions (the experimental points of curve c of Fig. 3 were obtained in this manner).

RESULTS AND DISCUSSION

In He I set to rotate at temperatures above the λ point in the rotational-velocity interval $2\omega_0/\Omega = 0$–0.4 (Ω — oscillation frequency), the damping was practically independent of the rotation speed (see Fig. 3, curve c), as expected on the basis of earlier investigations with a classical liquid[4,5] 1). However, if the pumping-on over the rotating He II is turned off and the liquid is heated to temperatures above the λ point, thus producing an excess pressure above the liquid, then $\delta - \delta_{st}$ not only differs from zero, but the plot curve $\delta - \delta_{st} = f(\omega_0)$ (see Fig. 3, curve b) exhibits a characteristic maximum at just the angular velocities where the maximum is observed at all temperatures below the λ point (Fig. 3, curve a). As is well known, this maximum is directly connected with the elastic properties of the Onsager-Feynman vortices produced in the rotating He II.

The described phenomenon was observed to T = 2.23°K. As in the preceding case, the rotation was produced here, too, at a uniformly rising tem-

1) According to [4,5], in the interval of rotation frequencies $2\omega_0/\Omega = 0 - 0.4$ the logarithmic damping decrement in a classical liquid should decrease by only 2%.

perature, the increase of which is shown in Fig. 4. The 2.23°K temperature corresponds to the center of the time interval during which damping was measured.

We also investigated the temperature dependence of the quantity $\delta - \delta_{st}$ at the maximum of the curve $\delta - \delta_{st} = f(\omega_0)$. This dependence can be established theoretically for He II from the expression obtained by Mamaladze and by Matinyan[6] for the logarithmic damping decrement. If we use only the principal terms of the formula, we get

$$\delta - \delta_{st} \approx \frac{\pi^2 R^4 \omega_0}{I\Omega} \rho_s \sqrt{\nu_s} \left(\sqrt{\Omega - 2\omega_0} - \frac{1}{4} \frac{\rho_n}{\rho} B \frac{2\omega_0}{\sqrt{\Omega - 2\omega_0}} \right), \quad (1)$$

where R — radius of the disc (1.5 cm), I — moment of intertia of the suspension system (5.2 g-cm^2), ν_s — parameter of Hall and Vinen (8.5 $\times 10^{-4}$ cm^2/sec), B — coefficient of mutual friction, and ρ, ρ_n, and ρ_s — the densities of the liquid and of the normal and superfluid components, respectively. This expression was obtained from (4.6) and (4.21) of [6] neglecting slip and second-order effects of second order in the mutual-friction coefficient. The difference between δ_{st} and the damping due to the viscosity of the rotating normal component, which is insignificant when $2\omega_0/\Omega \sim 0.4$ [6], was likewise neglected. In the calculations we used the known temperature dependences of B and of ρ_n/ρ[7,8].

Figure 5 shows the results of these investigations. The continuous curve a is experimental and curve b is theoretical, calculated in accordance with (1). The points are the experimental results normalized to the theoretical value at T = 1.38°K. The normalization factor, equal to 0.72, compensates for the neglect of the slipping of the vortex cores relative to the surface of the disc, and also the neglect of the edge correction.

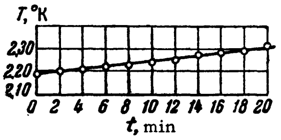

FIG. 4

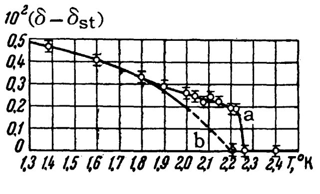

FIG. 5

FIG. 4. Dependence of the temperature of the liquid helium on the time in a dish with pumping shut off, measured with a carbon resistance thermometer.

FIG. 5. Dependence of $\delta - \delta_{st}$ on the temperature of the liquid helium. Curve a is drawn through the experimental points (disc oscillation frequency $\Omega = 0.360$ sec^{-1}), curve b is theoretical and plotted, in accordance with formula (1). Cross-damping in He I rotated at temperatures above the λ point.

Away from the λ point, as can be readily verified from examination of Fig. 5, the experimental points agree well with the theoretical curve. Starting with T = 1.9°K and above, the measurements diverge from the theoretical values. This clearly indicates the presence of stronger vortex effects, characterizing He II near the λ point, than would be expected from the theory. These vortex effects remain even at temperatures exceeding 2.17°K, up to T = 2.23°K, if the liquid helium was untwisted in the He II state.

One could advance the hypothesis that this phenomenon is connected either with a shift of the λ point in the rotating He II or with relaxation effects, as a result of which the vortices remain for some time even in the He I. The experiments described in [9], which indicate clearly that when rotating He I is cooled below the λ point a noticeable delay is observed in the formation of the Feynman vortices, favor the second assumption.

The authors are grateful to Yu. G. Mamaladze for a discussion of the results and to G. V. Gudzhabidze for help with the measurements.

[1] Andronikashvili, Tsakadze, Mamaladze, and Matinyan, Paper at Fifth All-Union Conference on Low Temperature Physics, Tbilisi, 1958.

[2] É. A. Andronikashvili and Dzh. S. Tsakadze, JETP **37**, 322 and 562 (1959), Soviet Phys. JETP **10**, 227 and 397 (1960).

[3] Andronikashvili, Mamaladze, and Tsakadze, Trudy, Institute of Physics, Georgian Academy of Sciences **7**, 59 (1961).

[4] Yu. G. Mamaladze and S. G. Matinyan, PMM (Applied Mathematics and Mechanics) **24**, 4749 (1960).

[5] K. B. Mesoed and Dzh. S. Tsakadze, Soobshcheniya (Communications), Georgian Academy of Sciences **2**, 145 (1961).

[6] Andronikashvili, Mamaladze, Matinyan, and Tsakadze, UFN **73**, 3 (1961), Soviet Phys. Uspekhi **4**, 1 (1961).

[7] H. E. Hall and W. F. Vinen, Proc. Roy. Soc. **A238**, 204 and 215 (1956).

[8] É. A. Andronikashvili, Supplement to the Translation of "Helium" by Keeson, IIL, 1949, Chapter IX.

[9] Andronikashvili, Tsakadze, and Bablidze, JETP **43**, 1562 (1962), Soviet Phys. JETP **16**, 1103 (1963).

Translated by J. G. Adashko
22