SOVIET PHYSICS JETP VOLUME 24, NUMBER 5 MAY, 1967

CONDENSATION OF ROTATING HELIUM II AND THE DENSITY JUMP AT THE PHASE TRANSFORMATION

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Submitted to JETP editor June 14, 1966

J. Exptl. Theoret. Phys. (U.S.S.R.) 51, 1344–1347 (November, 1966)

It is demonstrated that a density jump (discontinuity of first derivative of the Gibbs free energy function) occurs at the helium II–helium I phase-transition point under conditions of rotation.

THE question of the change of density in rotating helium II, relative to its stationary state, is of appreciable interest in view of the presence in it of a system of quantized Onsager-Feynman vortices.[1, 2]

To elucidate the velocity dependence of the density of helium II, we undertook an experiment in which sensitive pycnometers were set to rotate. These pycnometers were copper bulbs (see Fig. 1) to which glass capillaries were fastened. The capillaries expanded on the top into small spheres. During the time of the experiment, the upper end of the capillary was inserted into the collar of the valve used to regulate the amount of liquid helium in the pycnometer. During the measurements, the valve was tightly shut. The pycnometer was inserted into a vessel machined from organic glass and immersed in a bath with liquid helium. This glass was rotated by the usual means, with the drive passing through a stuffing gland coaxial with the pycnometer.

We present the parameters of the employed pycnometers:

	Pycnometer I	Pycnometer II
Volume, cm^3:	52.6	37.1
Inside diameter, cm:	3.9	3.9
Height of cylindrical part, cm:	4.4	3.1
Wall thickness, cm:	0.15	0.15
Length of working part of the capillary, cm:	6	7
Inside diameter of the capillary, cm:	0.175	0.160

Inasmuch as the mass of the helium contained in the pycnometer was not determined, the apparatus was suitable only for the determination of the change in the density, and not its absolute value. In this connection, we employed the following procedure to determine the temperature dependence of the density of stationary helium II: we fixed the level of helium in the pycnometer at a certain temperature T_1, after which we measured the change of the level as the helium was heated to a temperature T_2, and then determined the density by means of the formula

$$\rho_2 = \rho_1 + \rho_1 \frac{\pi r^2}{V_0} (\Delta_1 h + \Delta_2 h). \qquad (1)$$

Here ρ_1 is the density of the helium II at a temperature T_1, as given by Kerr,[3] r the radius of the capillary, V_0 the volume of the pycnometer, $\Delta_1 h$ the change of the level in it on heating from T_1 to T_2, and $\Delta_2 h$ the correction describing the change in the level as a result of a similar heating of the liquid helium in the capillary with the copper vessel disconnected (in this case the lower opening of the capillary was welded shut). Thus, as a result of introducing the quantity $\Delta_2 h$, formula (1) takes into account both the evaporation and the change in the density of the liquid and the vapor.

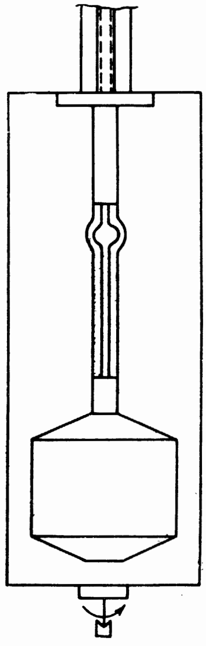

FIG. 1. Schematic diagram of rotating pycnometer.

To measure the condensation of the liquid helium as a result of rotation, we used the formula

$$\Delta\rho = \rho_{\omega_0} - \rho = \pi r^2 V_0^{-1}\rho\Delta_3 h,$$

where $\Delta_3 h$ is the level difference due to the rotation.

Since the capillary of the pycnometer, which was illuminated with a daylight lamp, was viewed in a KM-6 catetometer, the accuracy of the individual reading could be improved to ± 0.05 mm. But owing to the rotation of the apparatus, the scatter of the experimental values of the level difference reached ± 0.2 mm. Nonetheless, this made it possible to measure the relative change in the density $\Delta\rho/\rho$ with sufficiently small error $\delta(\Delta\rho/\rho) \sim \pm 10^{-5}$, and the absolute value of its change with an error $\delta(\Delta\rho) \sim 1.5 \times 10^{-6}$ g/cm³.

However, since the density at the "reference" temperature is given with a degree of accuracy inherent in the measurements of Kerr,[3] the absolute values of the densities measured by us are also determined "to Kerr's accuracy," whereas the error in the difference between the two densities is determined by the sensitivity of our pycnomenters.

Our first step was to study the dependence of the density of helium II on the angle of velocity of rotation at constant temperature. The results of this experiment are shown in Fig. 2. What is striking is that when helium II is twisted it becomes much denser, and this effect is the larger the lower the temperature. As to the velocity dependence of the relative condensation, it is close to $\Delta\rho/\rho \sim \omega_0^{3/2}$.

Attempts to attribute this phenomenon to the action of centrifugal pressure were not successful. Indeed, the centrifugal pressure $0.5\rho\omega_0^2 r^2$ (ω_0—angular velocity, r—distance to the axis of rotation), the maximum value of which at $\omega_0 = 30$ sec^{-1} is 2.5×10^{-4} atm, can ensure a compression $\Delta\rho/\rho \sim 2 \times 10^{-6}$ ($\Delta\rho/\rho = 0.25\rho\omega_0^2 r^0 \chi$). It is assumed here that the compressibility coefficient $\chi = \rho^{-1}(\partial\rho/\partial P)_T$ for rotating helium is the same as for stationary helium; at low pressures it amounts to approximately 1.3×10^{-2} atm^{-1}. Actually, however, the measured quantity is of the order of 4×10^{-4}, which is approximately 200 times the calculated value.

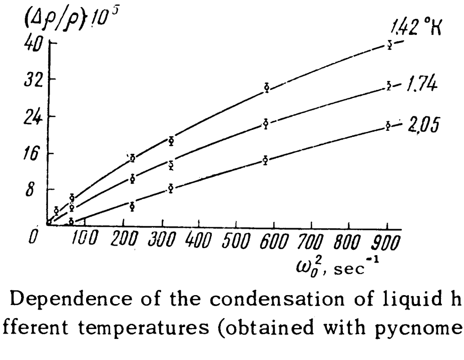

FIG. 2. Dependence of the condensation of liquid helium on ω_0 at different temperatures (obtained with pycnometer 1).

Starting from the fact that the compressibility coefficient increases with increasing temperature, we would expect $\Delta\rho/\rho$ to increase with rising temperature. However, as already noted (Fig. 2), this quantity drops noticeably as the helium II is heated.

The solid curve of Fig. 3 illustrates the dependence of the density in the stationary helium, after Kerr,[3] whereas the points on the curve represent the data of our measurements, referred to T = 2.14° K. The dashed curve, drawn through the circles, shows how the density of helium II rotating at an angular velocity 30 sec^{-1} changes. Above the λ-point, the data for the rotating and stationary helium coincide.

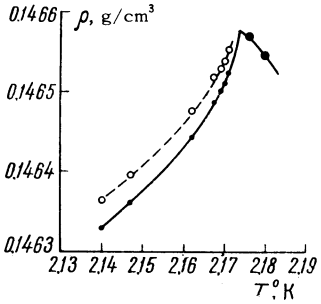

FIG. 3. Dependence of the density of liquid helium on the temperature. The solid curve was obtained by Kerr; points—our results; ●—at ω_0 = 0, ○—at ω_0 = 30 sec^{-1} (obtained with pycnometer 2).

However, we still cannot draw from this curve the unambiguous conclusions that a jump in density occurs in the rotating helium on going from the nonsuperfluid state into the superfluid state. In order to answer this question, we have made a special investigation in the temperature interval to 2.14 to 2.18° K at a fixed amount of liquid in the pycnometer and with special attention to all precautions. The results of the measurements are illustrated in Fig. 4, from which it is seen that the density of the rotating liquid helium changes abruptly in the temperature interval 2.171–2.176 °K, as if a density jump characteristic of first-order phase transitions were to take place at the phase transformation point (T = 2.172° K). At $\omega_0 = 30$ sec^{-1}, this jump amounts to 0.02% of the density of the liquid.

Estimates show that under the conditions of this experiment we can freely neglect the change in the

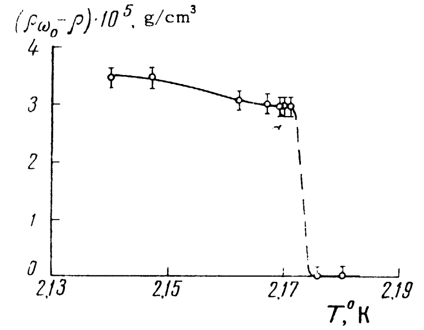

FIG. 4. Density jump of liquid helium at the phase transformation point. ρ_{ω_0}—density of rotating liquid helium (ω_0 = 30 sec^{-1}), ρ—the same at rest (pycnometer 2).

liquid level in the capillary as it goes over into film and back during the time of the phase transformation, as well as the change in the depth of the meniscus in the capillary, which occurs as a result of the rotation. Indeed, for capillary 2 the volume of the film, which covers its wall, is in any case smaller than 2×10^{-5} cm³. Vanishing of such a volume at the point of the phase transition would raise the liquid level in the capillary by 10^{-3} cm, which is much smaller than the error in the measurement of the level difference. The deepening of the meniscus, due to the rotation of the liquid, is likewise small compared with the error. At a maximum rotation speed of 30 sec^{-1}, it amounts to an order of 0.03 mm in both capillaries.

An unexpectedly large effect was the decrease in the hydrostatic pressure as a result of the dropping of the helium-II level in the capillary which registered the condensation of the liquid. For example, at the maximum condensation, which was observed in the case of capillary 1 (Fig. 2), the level dropped by approximately 0.94 cm. The hydrostatic pressure decreased with this by 1.4×10^{-4} atm, which balanced in practice the increased pressure resulting from the rotation (the average centrifugal pressure, which is equal to half the maximum, is in this case 1.25×10^{-4} atm). At the same rotation speeds, but at higher temperatures, the decrease in the hydrostatic pressure is already smaller than the average centrifugal pressure.

Comparing the observed phenomena with the previously established prolonged relaxation times for the formation and decay of the vortices, the supercooling and superheating of the metastable types of motion,[4] on the one hand, and the fact that the λ-point is invariant, as was established by the heat-transfer jump method,[5] on the other, we can conclude that in rotating helium a phase transition of second order is accompanied by a first-order phase transition, connected with the formation (vanishing) of the vortices. By the same token, this suggests the deduction that the very occurrence of vortices at $T < T_\lambda$ on going through the critical velocity is also a first-order phase transition.

The authors thank Yu. G. Mamaladze and L. P. Pitaevskiĭ for fruitful discussions.

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Translated by J. G. Adashko
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