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ATTENUATION OF SECOND SOUND IN ROTATING HELIUM ON GOING THROUGH THE PHASE TRANSITION TEMPERATURE

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The formation of quantized Onsager-Feynman vortices in rotating helium on going through the phase transition point is investigated by means of second-sound attenuation. It is shown that an isotropic mass of vortex nuclei is initially produced, which then gradually lines up in a vortex system along the axis of rotation. The relaxation times are measured for various angular velocities and different degrees of cooling.

THE problem of the formation of Onsager-Feynman vortices has to date been insufficiently studied, in particular in those cases in which they are formed in rotating liquid helium going through the phase transition temperature.

It was shown experimentally by Hall and Vinen[1] in 1956 that second sound propagated radially in a resonator is damped much more rapidly in the presence of quantized vortices of the Onsager-Feynman type than in their absence. It was therefore natural to use this phenomenon in the investigation of the process of vortex formation in the transition from rotating helium I to rotating helium II.

The phase transition helium I–helium II is a transition of second order, at any rate in the absence of the superposed vortex field.[1)] It is well known that in a second order transition supercooling of the system is not possible. And since the Onsager-Feynman vortices are a steady type of motion for rotating helium II, then it would seem obligatory that in a state of rotation the vortices should arise directly at the moment of going through the phase transition temperature, provided it remains a second order transition.

It should be noted that experiments have also been undertaken by us to establish the shift in the phase transition point in rotating helium.[2] However, the shift of this point (if it exists) was shown to be beyond the limits of sensitivity of the experiment carried out with accuracy up to 0.0005°K for angular velocities $\omega = 0.057-0.560\ \text{sec}^{-1}$.

[1)]At the present time there are sufficiently weighty preliminary experiments which indicate that in a state of rotation, the transition helium I – helium II is of first order.

With the aim of investigating the kinetics of vortex formation, we constructed a resonator in which second sound could propagate in a radial direction. The immobile resonator was tuned at a given temperature (below the λ point) to a certain wavelength. Then the liquid helium was heated to a temperature 2.25°K, set into uniform rotation, and again cooled to the temperature of the tuning, while continuing to rotate with unchanged velocity.

As seen in Fig. 1, which pertains to an angular

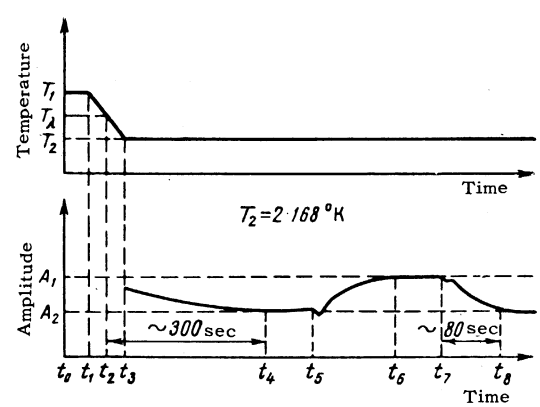

FIG. 1. Experiment with a radial resonator. At the instant t_0, the helium I is set in rotation; at t_1, cooling begins; at t_2, cooling of the helium II ceases and recording of the resonance amplitude of the second sound begins (lower graph) at the constant temperature T_2 (upper curve); at t_4, the amplitude of second sound reaches the value A_2, corresponding to the presence of a stable system of the Onsager-Feynman vortices; at t_5, rotation ceases; at t_6 the amplitude of second sound reaches a value which exceeds A_2 by the quantity corresponding to the absence of additional damping, brought about by scattering of the wave from the vortices; at t_7, rotation is again started; at t_8, the amplitude again reaches the value A_2.

velocity $\omega_0 = 1.76\ \text{sec}^{-1}$, the amplitude of second sound in the resonator cooled to 2.168°K falls continually for many hundreds of seconds and finally reaches some constant value A_2, corresponding to the presence of a formed system of quantized Onsager-Feynman vortices. Upon sudden cessation of the rotation, the amplitude of second sound increases to a value A_1, corresponding to the complete absence of quantum vortices. The decay of this system of vortices takes place in a time of the order of 100 seconds.

It should be noted that the time τ of formation of the stable system of vortices for a given angular velocity depends on the rate of cooling (see Fig. 2). It was however not possible for us to observe the formation of vortices at temperatures below 2.12°K in any of the experiments because of the relatively slow rate of cooling of helium II.

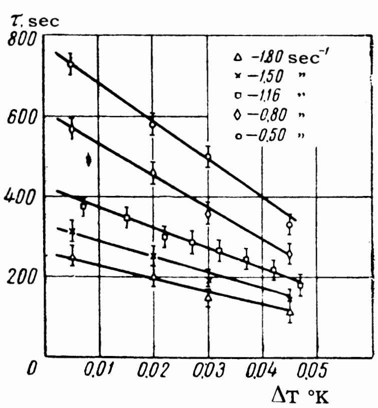

FIG. 2. Curves of the dependence of τ on $\Delta T = T_\lambda - T_2$ for different angular velocities.

The tendency of the material toward cooling quickly calls to mind a phase transition of first but not of second order; however, the rate of cooling is so large that this forces us to assume the following: some sort of intermediate motion can arise before the system of vortex lines is formed.

With the purpose of finding these, we constructed a second, axial resonator in which second sound is propagated along the axis of rotation. From the already mentioned researches of Hall and Vinen,[1] it is known that the propagation of second sound along the vortices does not lead to an additional attenuation of its amplitude. Therefore, if the system of oriented vortices were the only reason for additional scattering of the second sound, then, even in their presence, the rotating helium II should turn out to be transparent for heat waves propagating along the axis of rotation.

Experiments carried out with the axial resonator have shown that in the immediate vicinity of the phase transition point, the rotating helium II turns out to be "turbid" when second sound is axially "projected" through it. The fog which arises evidently consists of a uniform distribution of vortex nuclei and forms subsequently a regular set of vortices, because of which, with the increase in time or in proportion to the deviation from the phase transition temperature, the helium II becomes more and more transparent. Finally, after ~200 sec, for the same angular velocity $\omega_0 = 1.76\ \text{sec}^{-1}$ the amplitude of the second sound reaches its resonance value (Fig. 3).

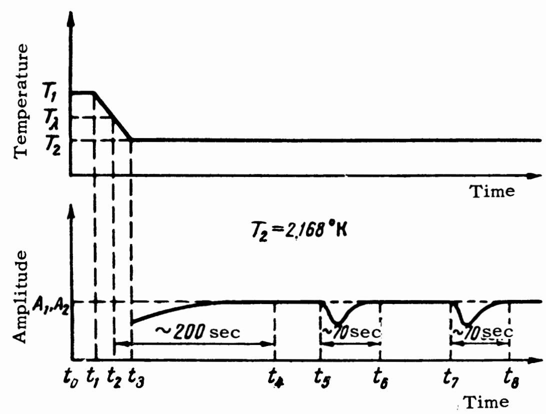

FIG. 3. Experiment with axial resonator. All the notation is the same as in Fig. 1.

Controlled experiments in motionless helium have shown that this fog has nothing in common with the convection flow arising in the process of pumping.

The dependence of the time of formation of vortices on the angular velocity is of interest. It is seen from Fig. 4 that the formation time is the larger the smaller the angular velocity. In other words, the smaller the vortices, the more difficult is it to form them. Taking it into account that in the first period a fog is formed in helium II, one can assume that the diffusion path which should be

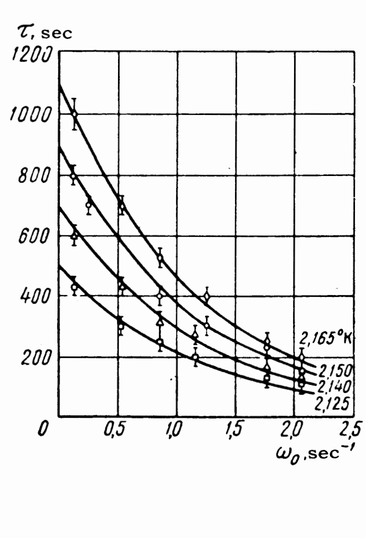

FIG. 4. Dependence of the time of establishment of the stable set of vortices in the transition from rotating helium I to rotating helium II on the angular velocity of the resonator for different temperatures.

followed by each particle of this fog in order that it be joined to the vortex core, on the average is larger for small velocities of rotation than for large.

The family of curves of Fig. 4 represents exponents for which the empirical relation

$$\tau = \tau_0 \exp\left(-\frac{\omega_0 - \omega_{0c}}{\alpha}\right)$$

is found. Here ω_{0c} is the critical angular velocity for a resonator of given characteristic dimensions, τ_0 is the time required for the formation of vortices at $\omega = \omega_0$, and α is some parameter with the dimensions of angular velocity. As seen from Fig. 4, τ_0 changes in wide limits depending on the temperature for which the vortex formation takes place.

So far as the parameter α is concerned, for all temperatures it remains at the same value within the range of experimental error. For all curves shown in Fig. 4, it is equal to $\alpha = 1.18\ \text{sec}^{-1}$. Evidently such an independence of the temperature of the coefficient α, which has the dimensions of angular velocity, is associated with Feynman's postulate that the total number of vortices which should be formed in rotation with a given ω is independent of the temperature.

The application of resonators of different geometrical dimensions shows that the size of the inner surface of the rotating glass does not show any effect on the formation of the system of vortex lines.

It remains to say a few words about the relaxation times of classical types of motion which can be "frozen" for a short time in the quantum liquid. Such a classical type of motion is the central macroscopic vortex, which is formed in helium I rotating with high velocity under conditions of its rapid cooling by pumping off the vapor of the boiling liquid. This vortex, which was originally discovered by Andronikashvili,[3] was later investigated in detail by Tsakadze,[4] who also established its completely classical nature.

It turned out that on going through the phase transition point, this vortex can exist in helium II for about 70 sec, and at a sufficiently high rate of cooling can be observed down to temperatures of 2.09°K. With the passage of time (or with cooling) the central macroscopic vortex begins to contract, tightening from below and soon after ceases to exist.

Thus the relaxation times of the classical type of motion in a rapidly rotating quantum liquid are of the same order as the time of formation of the quantized Onsager-Feynman vortices for large angular velocities.

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[4] Dzh. S. Tsakadze, JETP **14**, 105 (1964), Soviet Phys. JETP **17**, 72 (1963).

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6