$$\mathrm{Sp}\,\rho\Big\{\sum_j(\omega_j-\omega_S)S_j^z+\mathcal{H}_D\Big\}=\mathrm{Sp}\,\rho_k\Big\{\sum_j(\omega_j-\omega_S)S_j^z+\mathcal{H}_D\Big\}. \quad (6)$$

We assume that the time of the restructuring of the Zeeman ordering into dipole-dipole ordering is shorter than the cross-relaxation time. We can therefore put $P_j=\omega_j\beta_L$. For the case of a continuous distribution of the frequencies ω_j we have

$$\beta_k=\frac{\beta_L}{1+\varepsilon}\Big(1+\frac{\varepsilon\omega_I}{2D}\Big),\quad \varepsilon=\frac{D^2}{M_2},\quad D^2=\frac{\mathrm{Sp}\mathcal{H}_D^2}{\mathrm{Sp}\,S_j^2}. \quad (7)$$

Here M_2 is the second moment of the ESR line shape. Under conditions when the ESR line center is saturated[9] the coefficient of absorption of a control microwave field of frequency Ω by a quasi-homogeneous spin system is given by

$$\chi=A(\Omega-\omega_S)g(\Omega-\omega_S)\beta_L\Big(\frac{1+\varepsilon\omega_I/2D}{1+\varepsilon}\Big), \quad (8)$$

where A is a proportionality coefficient. An estimate of χ shows that the effect of the thermal contact between the NDDP and the low-frequency electron pool[8] can be easily observed because of the appreciable distortion of the ESR line shape when the NDDP is cooled under conditions of effective electron-nuclear cross relaxation. This distortion is predicted by formula (8).

Another consequence of the equations in (3) is the predicted existence of a channel for spin-lattice relaxation of the NDDP energy via the low-frequency electron pool. Let us consider the limiting case of a simple two-step relaxation. Let τ be the time required for the quantity

$$\sum_{jj_1}\Delta_{jj_1}W_{jj_1}(P_j^S-P_{j_1}^S-\Delta_{jj_1}\beta_{j_1})$$

to vanish, If the spin-lattice relaxation time T_1 of the polarizations of the electron spins is much longer than the time τ, we can assume that the following equality holds over time intervals on the order of T_1:

$$\sum_j\beta_j=\sum_{jj_1}\Delta_{jj_1}W_{jj_1}(P_j^S-P_{j_1}^S)\Big/\sum_{jj_1}\Delta_{jj_1}^2W_{jj_1}.$$

Thus, in this case the spin-lattice relaxation of the quantity $\sum_j\beta_j$ proceeds at a rate T_1^{-1}. Notice must be taken of the heuristic character of the last corollary, inasmuch as in nuclear spin-lattice relaxation via a paramagnetic impurity an important role is played by nuclear spin diffusion, a discussion of which is beyond the scope of the present note.

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Investigation of the properties of a rotating He^3-He^4 solution by the oscillating-disk method

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An experimental study was made of the increase of the radius of a vortex core as a result of the concentration of the light isotope in it. The critical velocities and their relaxation times in rotating solutions of He^3 in He^4 with different concentrations were also investigated.

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1. We report here the results of experiments that can be divided into two groups. In the first, the presence of the admixture of the light isotope plays the principal role. In the second are investigated phenomena whose physical interpretation is so far insufficiently clear, despite of the presence of a large amount of experimental material. In these investigations, any additional information (in our case, information on the in-

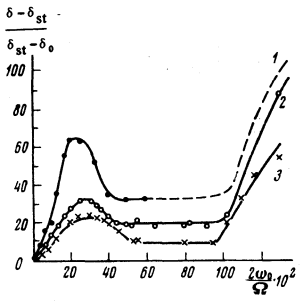

FIG. 1. Dependence of the quantity $(\delta - \delta_{st})/(\delta_{st} - \delta_0)$ on the ratio $2\omega_0/\Omega$, δ is the logarithmic decrement of the damping of the disk oscillations in the rotating liquid, δ_{st} and δ_0—the same in the stationary helium II and in vacuum, respectively. Curve 1—pure He^4, curve 2—solution with concentration $C = 3.03$ at.%, curve 3—solution with $C = 5.7$ at.% He^3.

fluence of the He^3 admixture) seems important to us.

The first group includes the experimental study of the variation of the radius of the vortex core with the concentration of the light isotope. It is known that in pure He^4 the vortex core, having a radius on the order of the interatomic distances,[1] is a concept that is more arbitrary than real. On the other hand the vortex core in a solution of the helium isotopes, owing to the concentration of the light isotope in it, increases by several orders of magnitude and becomes a macroscopic object that lends itself to a hydrodynamic treatment.

The second group includes experiments aimed at determining the critical velocities and the relaxation times.

2. We used in the experiments a "heavy" rough disk of 30.0 mm diameter and 1.0 mm thickness. To produce the roughness, the end surfaces of the disk were covered with a single layer of sand particles with linear dimensions 50 μ. The disk was suspended on an elastic phosphor-bronze filament and located in a metallic vessel of 45 mm diameter and 60 mm height. Besides executing small-amplitude oscillations, it rotated uniformly together with the vessel. A hermetic jacket insulated the vessel with the disk from the helium bath. To perform the experiments, an He^3–He^4 mixture (or only He^4 in the auxiliary experiments) was condensed in the jacket in sufficient quantity to fill the vessel, after which the amount remained unchanged. The geometrical dimensions of the system were chosen such that the volume of the liquid phase was several times the volume of the gas phase. We therefore did not take into account the negligible change of the He^3 concentration in the solution when its temperature varied in the interval 2.3–1.5 K.

The damping of the disk oscillations was measured with a fully automatic installation by a chronometric method,[2] with the information transmitted to an M-1000 computer. The "Start Printing" signal triggered a local automation block (LAB), which converted the information and fed it to a teletype (which was used as the printout unit) and to a perforator for off-line processing. The information was simultaneously fed through an interface block to an on-line computer, where the data were stored and reduced.

3. We start with consideration of the results obtained in the measurements of the dependence of the logarithmic damping decrement (henceforth called "damping" for brevity) of the oscillations of a disk immersed in a solution of He^3 in He^4 (with different concentrations) on the rate of rotation of the liquid (under conditions when the disk oscillates and simultaneously rotates uniformly together with the liquid). Figure 1 shows the corresponding results. Curve 1 was obtained in pure He^4. Curve 2 corresponds to a solution of He^3 in He^4 with concentration $C = 3.03$ at.% He^3, curve 3—to a solution with $C = 5.7$ at.% He^3. All the curves were plotted at a constant temperature $T = 1.78$ K.

Examination of this figure shows readily that when the He^3 concentration in the solution is increased the height of the maximum decreases and the maximum shifts simultaneously towards larger velocities.

Andronikashivili and Tsakadze[3] and Andronikashvili, Mesoed, and Tsakadze,[4] who investigated the velocity dependence of the damping δ of the disk oscillations in rotating liquid He^4, have shown that in helium II the damping of the disk first increases smoothly with increasing rotational velocity, goes though a maximum, remains constant up to a value $2\omega_0/\Omega \sim 1$, and then increases (Ω is the oscillation frequency and ω_0 is the rotation frequency). The damping of the disk oscillations in helium II is larger at any rotational velocity than in the stationary liquid.

The additional damping of the disk oscillations when the helium II is rotated is due to the fact that quantized Onsager–Feynman vortices[1] are produced in the superfluid rotating with transcritical velocity (corresponding in the case of our instrument to velocities on the order of 10^{-4} sec^{-1}), and are attracted to the surface of the disk, to which they become pinned. When this surface oscillates, an elastic transverse wave travels along the vortex, and carries away and dissipates in the liquid a fraction of the disk-oscillation energy.[5] With increasing rotational speed, the number of vortices increases, so that the total energy carried away by them from the vibrating disk also increases.

The energy carried away by the vortices is proportional to their tension, which is expressed by the Feynman formula[1]:

$$\varepsilon = \pi\rho_s \frac{\hbar^2}{m^2} \ln\frac{b}{a_0}\left[\frac{\text{erg}}{\text{cm}}\right], \qquad (1)$$

ρ_s is the density of the superfluid component, m is the mass of the helium atom, b is the effective radius of the vortex, and $a_0 \sim 10^{-8}$ cm is the radius of the core of the vortex.

Mamaladze[5] has shown that the presence of a maximum on the plot of $\delta = f(\omega_0)$ is due to collectivization of the vortices, which occurs under the following circumstances. First, at low rotational velocities, the vortices oscillate independently of one another. With increasing rotational velocity, the number of vortices in-

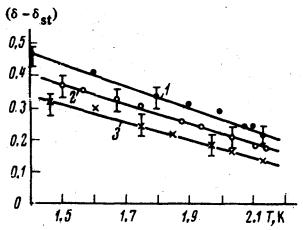

FIG. 2. Dependence of $\delta - \delta_{st}$ on the temperature (the notation is the same as in Fig. 1). Curve 1—pure He^4, curve 2—solution with $C = 3.03$ at.%, curve 3—solution with $C = 5.7$ at.% He^3.

creases and the distances between them decrease. At a fixed oscillation frequency Ω, there exists a rotational velocity $\bar{\omega}_0$ such that the distance between vortices becomes so small that the vortices begin to interact with one another (i.e., the vibrational radii of the vortices overlap at the velocity $\bar{\omega}_0$). Let us estimate the velocity at which the collectivization sets in. It is known that the effective outer radius of the oscillating vortex is of the order of $1/k$,[6] where k is the wave traveling the vortex. According to Hall[7]

$$k = \left(\frac{\Omega - 2\omega_0}{\nu_s}\right)^{1/2}, \quad \nu_s = \frac{\varepsilon}{\rho_s \Gamma_0},$$

where Γ_0 is the circulation quantum. On the other hand, the distance between vortices can be determined from the Feynman formula for the number of vortices per cm^2:

$$N = m\omega_0/\pi\hbar,$$

where m is the mass of the helium atom. Equating $1/k$ to half the distance between the vortices we obtain

$$\frac{2\bar{\omega}_0}{\Omega} = \left(\frac{2m\nu_s}{\pi\hbar} + 1\right)^{-1}. \tag{2}$$

Substituting in (2) the values of the constants corresponding to the case of rotation of liquid He^4 at $T = 1.78$ K, we find that the vibrational radii of the vortices begin to overlap at

$$2\bar{\omega}_0/\Omega \approx 0.21.$$

It is seen from (2) that when the vortex core radius is increased the position of the maximum should shift towards larger values of $2\omega_0/\Omega$.

According to Fisher and Reut[8] and also Ohmi, Tsuneto, and Usui,[9] the lighter isotope in the rotating solution of He^3 in He^4 becomes concentrated around the vortex axis, so that the radius of the vortex core increases. Since the velocity of the superfluid component outside the core decreases with the distance r like

$$v_s = \frac{h}{m}\frac{1}{r},$$

it is clear that when the radius of the core is increased the velocity of the superfluid component around the core decreases. This decreases the Bernoulli adhesion and consequently the force of the pinning of the vortex to the surface of the disk, which in turn causes a decrease in the height of the maximum.

The energy of the vortex in the mixture (at relatively high temperatures) is expressed by

$$\varepsilon' = \pi\rho_s \frac{\hbar^2}{m^2} \ln\frac{b}{a_c} + \frac{1}{2} I\omega_0^2.$$

The first term is the usual energy of a vortex with a core radius a_c that depends on the concentration C. The second term is the energy of rotation of the normal core of the vortex. An estimate shows that it is negligibly small, $\sim 10^{-14}$ erg/cm (as against $\sim 10^{-7}$ erg/cm for the vortex in pure He^4).

According to[8,9], the radius of the vortex core is a rapidly increasing function of the concentration C of the solution of He^3 in He^4. Thus, for example, according to[9] we have $a_c = 10a_0$ already at $C \approx 3$ at.%, and $a_c = 10^2 a_0$ at $C \approx 5.7$ at.%. Using formula (2) to estimate the position of the maximum in rotating mixtures of He^3 in He^4, we obtain at concentrations $C = 3$ and 5.7 at.% respectively,

$$2\omega_0/\Omega = 0.23, \quad 2\omega_0/\Omega = 0.28,$$

which is in good agreement with the experimentally observed positions of the maxima at the corresponding concentrations (see Fig. 1).

Thus, the experimentally observed decrease of the height of the damping maximum on the plot of $\delta = f(2\omega_0/\Omega)$, and the shift of the position of the maximum towards larger velocities, can be explained (the second fact—quantitatively) as being due to the swelling of the vortex core with increasing concentration of the lighter isotope.[10]

It should be noted that according to[9] isotope separation takes place near the vortex core at low temperatures and at the corresponding concentrations of the He^3 in the solution, and an interface characterized by a surface tension σ is formed. Under the conditions of our experiment, however, there is no isotope separation (owing to the high temperature).

Figure 2 shows a plot of $\delta - \delta_{st}$ against the temperature T (δ is the logarithmic damping decrement of the disk oscillations at a rotational velocity $\bar{\omega}_0$, and δ_{st} is the same in stationary helium). Curve 1 pertains to pure He^4, curve 2 to a solution with $C = 3.03$ at.% of He^3 in He^4, and curve 3 to a solution with $C = 5.7$ at.%.

It is known[11] that for pure He^4 (below the λ point) the function $\delta - \delta_{st} = f(T)$ can be calculated from the expression for δ. Using only the principal terms, we have

$$\delta - \delta_{st} \approx \frac{\pi^2 R^4 \omega_0}{I\Omega} \rho_s \nu_s^{1/2} \left[(\Omega - 2\omega_0)^{1/2} - \frac{1}{4}\frac{\rho_n}{\rho} B \frac{2\omega_0}{(\Omega - 2\omega_0)^{1/2}} \right] \tag{3}$$

(R is the disk radius, I is the moment of inertia of the suspension system, ν_s is the parameter of Hall and Vinen, and B is the mutual friction coefficient). In this expression we neglect slippage and effects of second order in the coefficients of the mutual friction.

Andronikashvili, Mesoed, and Tsakadze[4] have shown that in pure He^4, far from the λ point, the experimental points fit well the theoretical curve constructed in accordance with formula (3). It is obvious that at $T = T_\lambda$ we have $\delta - \delta_{st} = 0$. However, starting with $T \sim 1.9$ K and above, the theoretical and experimental points begin to diverge: the experimental points lie above the theoretical values. This means that near T_λ the vortex energy is larger than the value given by the theory (we note that analogous conclusions can be deduced also from direct measurements of the vortex energy[12]).

As seen from an examination of Fig. 2, similar phenomena are observed also in rotating solutions of He^3 in He^4 with concentrations 3.03 and 5.7 at.% He^3, namely, as the temperature is increased, $\delta - \delta_{st}$ likewise does not tend to zero but approaches a certain nonzero value.

4. The critical rates of vortex formation in helium II are determined by the Feynman formula

$$v_{cr} = \frac{\hbar}{md} \ln \frac{d}{a_0}, \qquad (4)$$

where m is the mass of the helium atom, a_0 is the dimension of the vortex core, and d is a geometrical characteristic of the problem. This formula agrees relatively well with results obtained in channels of width $d \gtrsim 10^{-3}$ cm (with certain variations of the coefficients at h/md and d/a_0). However, formula (4) notwithstanding, in many experiments the critical velocity was observed to depend on temperature. Thus, for example, the critical velocity determined from the vibrational experiments increases with increasing temperature.[13] We have previously shown[14] that the cause of this phenomenon may be the following circumstance (at least in part): when bodies having axial symmetry oscillate in helium II, the region of the relative motion of the n and s components extends over the viscous-wave penetration depth λ, which in turn decreases with increasing temperature. In such a case, according to formula (4), the critical velocity should increase, as is indeed observed in the experiments. It is shown in[14] that $v_{cr}\lambda$ is of the order of the constant in formula (4), and when the temperature is changed from ~1.5 to 2.13 K, it remains constant and independent of temperature, accurate to 25%.

To study the critical phenomena in the case of oscillations of a disk in a solution of He^3 in He^4, we used the well known procedure of disk oscillations with transcritical amplitudes. The critical rate of vortex production on the periphery of the disk was determined from the formula

$$v_{cr} = \varphi_{cr} R \Omega,$$

where R is the radius of the disk, $\Omega = 2\pi/\Theta$ is the cyclic frequency of the oscillations, and φ_{cr} is the critical amplitude.

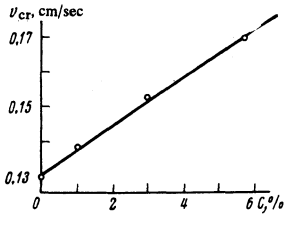

FIG. 3. Dependence of the critical rate of vortex formation on the solution concentration, $T = 1.78$ K.

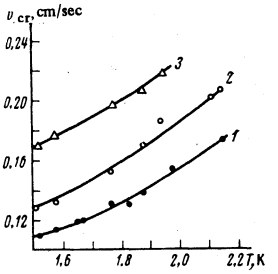

Fig. 4. Dependence of the critical rate of vortex formation on the temperature of the liquid. Curve 1—pure He^4, curve 2—solution with $C = 3.03$ at.%, curve 3—solution with $C = 5.7$ at.% He^3. In all cases $\omega_0 = \omega_0$.

As seen from Fig. 3, with increasing concentration He^3 in the solution, the critical velocity of vortex production increases linearly.

Figure 4 shows a plot of the critical rate of vortex production against temperature for a solution with He^3 concentration $C = 3.03$ at.%. The same figure shows the temperature dependence of the critical rate in pure He^4. At rotational velocities $\omega_0 \approx \tilde{\omega}_0$ (just as in pure He^4[15]), the critical rate of vortex production increases in the entire interval of investigated temperatures. Analogous curves were obtained also for a solution with He^3 concentration 5.7 at.%.

The increase of the critical rates with increasing concentration of the light isotopes in the solution, which was obtained in these experiments, agrees with the notion that a foreign particle suspended in helium II increases the amount of the normal component. As to the increase of the critical rate in a rotating solution in comparison with the stationary solution, it appears, in analogy with rotating He^4, that the reason lies in the specifics of vortex formation on the periphery of the disk oscillating with transcritical amplitude. The point is that, in contrast to the state of rest, in the rotating state there are already vortices oriented along the rotation axis. On the other hand, the vortices due to the disk vibrations are differently oriented (with components along the surface of the disk). The dragging of the immobile superfluid component into the vortical motion should therefore be easier to effect than its conversion from a vortical motion in a definite direction into a vortical motion with a different orientation of the vortex cores. In the latter case, the liquid motion is more substantially altered, and this calls naturally for a larger energy consumption.

5. We have also investigated relaxation phenomena connected with the decay of a vortex lattice in a solution following a sudden (within ~10 sec) stopping of the vessel rotation. The appropriate procedure was developed

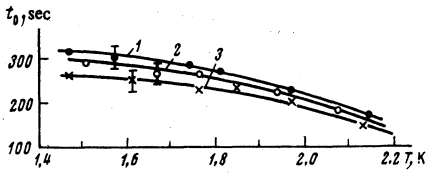

FIG. 5. Temperature dependences of the relaxation time of the vortices after the rotation is stopped. Curve 1—pure He^4, curve 2—solution with $C = 3.03$ at.%, curve 3—solution with $C = 5.7$ at. % He^3.

by Andronikashvili and Tsakadze[15] and was subsequently used many times by the Tbilisi group to investigate a great variety of relaxation phenomena in rotating helium II (due, e.g., to changes in the temperature[16] or in the rotary speed[17]).

Figure 5 shows the dependence of the relaxation time t_0 on the solution temperature. Curve 1 pertains to pure He^4, curve 2 to a solution with an He^3 concentration $C = 3.03$, and curve 3 to a solution with $C = 5.7$ at.%. In all cases, a transition was effected from a rotation at an angular velocity $\tilde{\omega}_0$ to an immobile stage.

Examination of Fig. 5 shows that as the He^3 concentration in the solution increases the relaxation times t_0 decrease in the entire temperature range from ~1.5 to 2.13 K. It must be assumed that, just as in the case of the critical velocity, this is caused by the fact that the He^3 particles dissolved in the He^4 assume the role of the normal component of the liquid.

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Nonlinear cyclotron resonance in metals

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Nonlinear reflection at the second harmonic frequency in the case of the anomalous skin effect is considered for a metal located in a magnetic field parallel to its surface. It is shown that the nonlinearity is much greater in this case than in the absence of the magnetic field. The amplitude of the reflected second harmonic undergoes cyclotron resonance oscillations and increases additionally when $\omega = 1/2l\Omega_m$, where ω is the electromagnetic field frequency, Ω_m is the extremal cyclotron frequency, and l is an integer.

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The generation of higher harmonics of an electromagnetic field in conductors has been studied experimentally and theoretically in a number of papers.[1–5] Harmonic generation in the presence of a magnetic field, however, has been previously studied only under conditions of the normal skin effect, at low frequencies $\omega\tau \ll 1$[4,5] (ω is the frequency of the electromagnetic wave, τ is the relaxation time). In the present paper we consider the nonlinear reflection, at the frequency of the second harmonic, from a metal situated in a magnetic field parallel to its surface, in the case of the anomalous skin effect, when the inequalities

$$\frac{\delta}{v_F\tau} \ll 1, \quad \frac{\delta\omega}{v_F} \ll 1, \quad \frac{\delta}{r_H} \ll 1, \tag{1}$$

are satisfied, where δ is the skin depth, v_F is the Fermi