$$\omega=\pm 2\frac{s_{l,d}}{c}\omega_0\sin\frac{\vartheta}{2}. \qquad (46)$$

To estimate the extinction coefficient and the frequency shift of the scattered light we note first of all that all the formulas obtained by us are valid in a region of temperatures that are much lower than the quasiparticle Fermi energies. At low temperatures the presence in the crystal of delocalized fermions should lead, besides the high-frequency effects considered above, to a contribution linear in temperature to the heat capacity. On the basis of the experimental data for liquid He^3 (see, e.g.,[7]), one can expect the heat capacity to become linear at a temperature lower by one order than the quasiparticle Fermi energy. At $T>0.1\epsilon_F\sim 0.1$ K the Fermi excitations in liquid He^3, in view of the strong interaction with one another, are not well-defined quasiparticles and the temperature dependence of the heat capacity is determined principally by the phonon contribution.

For solid He^3, the Fermi energy of the quasiparticles is apparently low in comparison with the Fermi energy in the liquid phase. Accordingly, the linear temperature dependence shifts into the region of much lower temperatures. The presently available measurements of the heat capacity can therefore not yield data on the number of quasiparticles in solid He^3.

An appreciable delocalization of the defects is possible only in an ideal quantum crystal in which there is magnetic order besides the spatial ordering of the atom. Recently Andreev, Marchenko, and Meĭerovich[8] have advanced a hypothesis, based on magnetic measurements,[9] that zero-point vacancies at a concentration 6×10^{-3} exist in magnetic fields exceeding 0.2 T. Assuming that the quasiparticle effective mass is of the order of the mass of the He^3 atom, Andreev *et al.*[8] obtained for the Fermi energy the value $\epsilon_F\sim 0.1$ K.

The coefficient of light extinction on the zero-point oscillations of the vacancy density in solid He^3, at $M^*\sim M$ and $N_d\sim 6\times 10^{-3}N_\lambda$, amounts according to (45) to 0.1% of the coefficient of light extinction on ordinary sound waves. The relative change of the light frequency is here lower by one order of magnitude than the corresponding value for scattering by phonons, and is within the present experimental capabilities.

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[1)]This assumption can be justified only for the bcc phase of He^3.

[1]A. F. Andreev and I. M. Lifshitz, Zh. Eksp. Teor. Fiz. **56**, 2057 (1969) [Sov. Phys. JETP **29**, 1107 (1969)].
[2]A. F. Andreev, Usp. Fiz. Nauk **118**, 251 (1976) [Sov. Phys. Usp. **19**, 137 (1976)].
[3]I. E. Dzyaloshinskiĭ, P. M. Kondratenko, and V. S. Levchenkov, Zh. Eksp. Teor. Fiz. **62**, 1574 (1972) [Sov. Phys. JETP **35**, 823 (1972)].
[4]A. A. Abrikosov and I. M. Khalatnikov, Zh. Eksp. Teor. Fiz. **34**, 198 (1958) [Sov. Phys. JETP **7**, 286 (1958)]; I. M. Khalatnikov, Teoriya sverkhtekuchesti (Theory of Superfluidity), Nauka, 1971.
[5]A. I. Akhiezer, I. A. Akhiezer, and I. Ya. Pomeranchuk, Nucl. Phys. **40**, 139 (1963); I. Ya. Pomeranchuk, Sobranie trudov (Collected Works), vol. 1, Nauka, 1972.
[6]C. Kittel, Quantum Theory of Solids, Wiley, 1963 [Russ. transl., Nauka, 1967].
[7]V. P. Peshkov, Usp. Fiz. Nauk **94**, 607 (1968) [Sov. Phys. Usp. **11**, 209 (1968)].
[8]A. F. Andreev, V. I. Marchenko, and A. É. Meĭerovich, Pis'ma Zh. Eksp. Teor. Fiz. **26**, 40 (1977) [JETP Lett. **26**, 36 (1977)].
[9]R. B. Kumer, E. D. Adams, W. P. Kirk, A. S. Breenberg, R. M. Mueller, C. V. Britton, and D. M. Lee, Phys. Rev. Lett. **34**, 517 (1975).

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Measurement of internal friction in solid He^4

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The internal friction in crystalline He^4 (molar volumes 19.2–20.95 cm^3/mol) was investigated at ~15 kHz. The temperature dependence of the logarithmic damping decrement down to 0.55 K and the dependence of the damping on the oscillation amplitude were measured. It is concluded on the basis of the results that the principal internal-friction mechanism is due to dislocations. The temperature dependences of the damping were reduced by the theory of Granato and Lucke; a number of dislocation parameters are obtained.

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Measurement of internal friction is an effective means of studying defects in solids. As shown in[1,2] in crystalline helium the quantum character of the point defects (vacancies) leads to a peculiar dependence of the internal friction on the temperature and frequency. The logarithmic damping decrement Δ_{vac} when the crystal is inhomogeneously deformed is described according to Meĭerovich[1] by the relation

$$\Delta_{vac}\sim N(T)\frac{\tau/\omega}{1+\tau^2\omega^2},$$

where $N(T)$ is the equilibrium vacancy concentration and varies exponentially with temperature, $N(T)\propto\exp(-\epsilon_0/T)$, $\tau\propto T^{-9}$ is the relaxation time, and ω is the cyclic fre-

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quency of the oscillation. The temperature dependence of the damping is determined mainly by the vacancy concentration, and according to studies of ion mobility[3] and of the diffusion of He^3 in He^4[4] the energy is of the order of $\epsilon_0 \sim 15$ K for a molar volume $V_m = 20.5$ cm^3/mol. Unlike the behavior of damping in ordinary bodies, where $\Delta \sim \omega\tau/(1+\omega^2\tau^2)$, the decrement Δ_{vac} increases monotonically with decreasing frequency.

Until recently defects in crystalline helium were investigated mainly by ultrasonic methods. An anomalous behavior of the speed of sound as a function of temperature and frequency was observed in[5,6]. It was suggested in[5] ($V_m = 20.3$ cm^3/mol, $f = 8-12$ MHz) that these anomalies are due to the presence of dislocations in the crystal, and the Granato-Lucke theory was used to determine a number of dislocation parameters, such as the dislocation density, the loop length, the damping constant, and the temperature dependence.

The damping of sound was measured directly[7] in crystals with molar volume $V_m = 20.5$ cm^3/mol in the temperature interval 1.63–1.77 K. It was concluded there that the observed damping is due to the presence of dislocations in the crystal. The frequencies used in the cited papers were in the 5–50 MHz range. One investigation[8] at a lower frequency, ~500 Hz, was made on samples grown by the blocked-capillary method. Two damping maxima were observed on the temperature dependence.

The purpose of the present paper was to study the internal friction in single-crystal samples at a frequency on the order of 15 kHz.

EXPERIMENTAL PROCEDURE

The crystals were grown at constant pressure and a low temperature gradient in the container shown in Fig. 1. Measurements of the thermal conductivity of crystals grown under such conditions[9] point to high monocrystallinity of the samples.

A quartz resonator 3 with dimensions 2.8×2.8×48

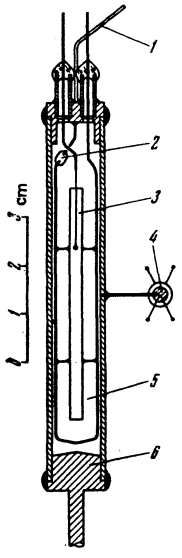

FIG. 1. Construction of container: 1—filling capillary, 2—glass isolator, 3—quartz resonator, 5—internal volume filled with the crystal, 6—copper cold finger.

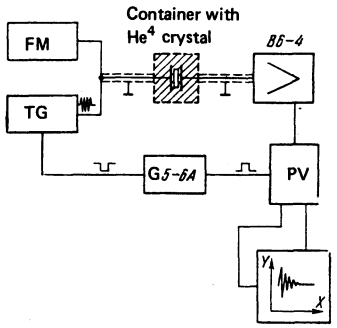

FIG. 2. Schematic diagram of the damping measurement: FM—frequency meter, TG—train generator, PV—peak voltmeter.

mm was placed along the axis of an ampul inside diameter 10 mm. The volume 5 was filled through capillary 1 with liquid helium at the required pressure (up to 61 atm) and then, as the temperature decreased, a crystal started growing from the copper cold finger. After a time on the order of 2 hours the crystal filled the entire internal volume 5. The sample was then annealed at a temperature 0.05–0.1 deg lower than the melting temperature. The annealing was assumed complete if the damping did not change by more than 10% in a time 0.5 –1 hr. The annealing time was thus 1–6 hours. The temperature was measured with a carbon resistance thermometer and was maintained constant accurate to ~0.01 K during the measurement time.

The internal friction in the quartz + solid helium system was determined from the damping of the free oscillations of the quartz. The measurement setup is shown in Fig. 2. A generator (G5-6A) produced negative and positive rectangular pulses at a repetition period 20 msec. The negative pulse, of 1.2 msec duration, triggered a generator producing a train of sinusoidal waves

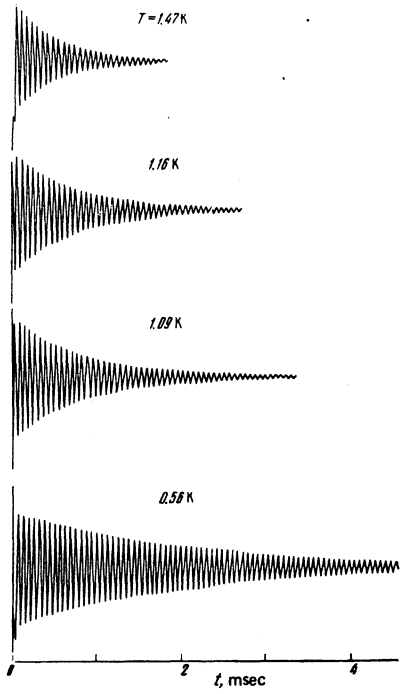

FIG. 3. Typical plot of the voltage produced on the quartz in the case of free vibrations of the quartz + solid helium system. The He^4 crystal was grown at $p = 32$ atm ($V_m = 20.5$ cm^3/mol).

with fundamental frequency 14–17 kHz as measured by a Ch3-24 frequency meter. The amplitude of the generated train could be varied from 5 mV to 5 V. After the end of the train, the amplitude of the signal voltage on the quartz decreased exponentially. The signal was amplified with a low-frequency V6-4 amplifier and registered with a peak voltmeter with time gates, operating in a stroboscopic-integrator regime.[10] The peak voltmeter was synchronized by the positive pulse of the G5-6A generator. This made it possible to record the signal on an x-y recorder and, furthermore, to improve significantly the signal/noise ratio. A typical record is shown in Fig. 3.

The successive values of the amplitudes of the recorded signal were approximated with a computer by least squares by the relation $\ln A_n = \text{const} - n\Delta$. The mean squared error in the measurement of the damping decrement was calculated from the scatter of the points and reached ~5%.

The temperature dependence of the damping was measured on the same sample both in the course of the cooling and during the heating. This made it possible to verify that the internal state of the sample remained essentially unchanged during the time of the experiment, usually ~20 hours. The rate of change of the temperature did not exceed 5×10^{-5}deg/sec.

The parameters of the fundamental flexural mode of the oscillations of the quartz resonator in vacuum at $T = 4.2$ K were $f_{res} = 9.886$ kHz and $Q = 1.91\times10^5$.

RESULTS

The investigated samples were grown at four pressures: 25.8, 32, 43, and 61 atm. The resonant frequency of the quartz + liquid helium system, depending on the elastic constants of the helium crystal, ranged from 17 kHz at $V_m = 19.2$ cm^3/mol to 14.3 kHz at $V_m = 20.95$ cm^3/mol, and was constant in the entire temperature interval accurate to ~3%. Figures 4–7 show the measured values of the damping Δ.

The amplitude dependence of the damping decrement is of considerable interest. Figure 4 shows this dependence for three temperatures at $V_m = 20.5$ cm^3/mol. The amplitude $A = 1$ corresponds to a maximum applied-voltage amplitude ~5 V and to a relative strain $\epsilon \sim 10^{-5}$. It is seen from the figure that our measurements were

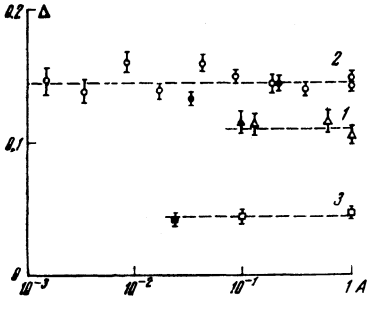

FIG. 4. Amplitude dependence of the damping decrement. Crystal with molar volume $V_m = 20.5$ cm^3/mol. Light symbols—sequence of measurements from the smallest to the largest amplitudes, dark symbols—reverse sequence. Curve 1 – $T = 1.62$K, 2–$T = 1.37$K, 3–$T = 0.56$K.

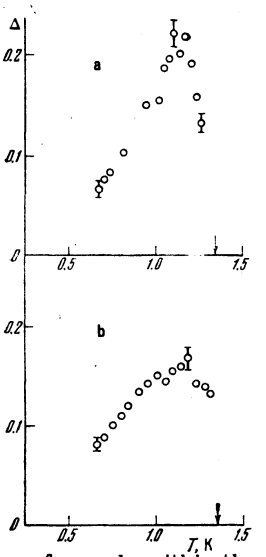

FIG. 5. Temperature dependence of the damping for samples grown at $p = 25.8$ atm.

performed, within the limits of errors, in the amplitude-independent region.

Application of a higher voltage at the resonant frequency led already to a noticeable heating of the crystal. Thus, at an amplitude ~100 V ($\epsilon \sim 10^{-4}$) the overheat reached 0.02 K.

Typical temperature dependences of the damping Δ, for samples grown at three pressures (25.8, 32, and 61 atm), are shown in Figs. 5–7. The plots obtained for the same sample in the course of cooling and heating were in agreement (see, e.g., Fig. 7); in other words, no significant change in the internal state of the samples occurred in ~20 hours. From sample to sample, however, the shape of the curve, for the same molar volume, differed substantially. It is possible nevertheless to point to a number of common features: a) the decrements for all samples lie in the interval $0.01 < \Delta < 0.5$; b) the damping of all samples decreases monotonically as $T \to 0$; c) a maximum of the damping is observed for a number of samples (see, e.g., Figs. 5a, 6a, and 7b) at temperatures ~$0.8\,T_m$.

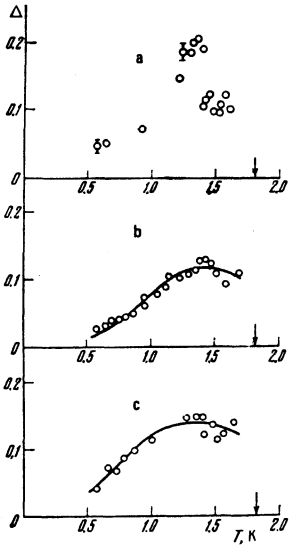

FIG. 6. Dependence of damping on the temperature for samples grown at $p = 32$ atm. Solid curves—approximation of points by relation (8), b—at $\Delta_{0D} = 0.23$, $T_{max} = 1.41$K, $k = 2.84$; c—at $\Delta_{0D} = 0.27$, $T_{max} = 1.30$K, $k = 2.15$.

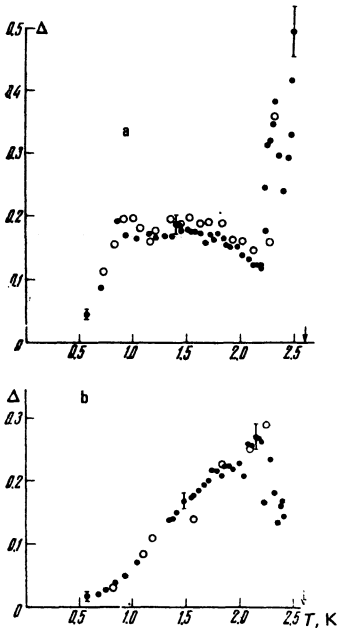

FIG. 7. Dependence of damping on the temperature for samples grown at $p = 61$ atm: •—measurements with decreasing temperature, ○—with increasing temperature.

DISCUSSION OF RESULTS

The energy loss in the oscillations of the quartz + solid helium system consists of the loss in the He^4 crystal (W_1), in the quartz crystal (W_2), and in the container walls and to sound radiation to the outside (W_3). The loss W_3 is independent of temperature, and the corresponding decrement Δ_3 can be estimated from the minimal values of the damping obtained in the experiment: $\Delta_3 \lesssim 10^{-2}$. The damping decrement connected with the sound radiation can be estimated from the formula $\Delta_s \sim \rho_1 c_1/\rho_2 c_2$ (where ρ_1 and ρ_2 are respectively the densities of the solid helium and of stainless steel, and c_1 and c_2 are the sound velocities in them). In our case we obtain $\Delta_s \sim 5\times 10^{-3}$. To determine the loss decrement Δ_1 in the helium it is necessary to consider the coupled oscillating quartz + solid helium system. The measurement decrement is

$$\Delta = (W_1+W_2)/(E_1+E_2), \tag{1}$$

where W_2 and W_1 are the energy losses in one-half of the period in the quartz and helium crystals, and E_2 and E_1 are the average energies of the mechanical vibrations of the quartz and helium crystals. The damping decrement in the helium crystal is $\Delta_1 = W_1/E_1$ and we obtain from (1), recognizing that $\Delta_2 \ll \Delta_1$,

$$\Delta_1 \approx \Delta(1+E_2/E_1). \tag{2}$$

The ratio of the vibration energies E_1 and E_2 can be estimated from the resonant frequencies of the vibrations of free quartz and the quartz + helium crystal system. This ratio is $E_2/E_1 \sim 0.3$, and it follows therefore from (1) that $\Delta_1 \approx 1.3\Delta$.

In view of the high purity of the samples, the internal friction in the helium is caused by crystal-lattice defects, i.e., by dislocations and vacancies, and has been estimated for vacancies in[1] as $\Delta_{vac} = 10^{-3}-10^{-4}$ for a temperature close to the melting point. The temperature dependences obtained by us for the damping allow us to assume that the observed internal friction is due to dislocations rather than vacancies. Favoring this assumption is also the fact that in practice it was possible to grow two samples with identical $\Delta(T)$ dependences. A similar phenomenon is observed also in ordinary materials (see, e.g., [11]). This non-reproducibility is attributed to the non-reproducibility of the dislocation network.

There is at present no theory that described the behavior of dislocations in a quantum crystal and capable of calculating the dislocation-induced internal friction. It was noted in [12,13] that the large amplitude of the zero-point vibrations of the atoms in the He^4 crystals can lead to specific properties of the dislocations. Thus, according to Petukhov and Pokrovskii[13], the formation of kinks on the dislocation can take place not only as a result of thermal activation but also on account of tunneling. Andreev[14] discusses the possibility of delocalization of the kink and its conversion into a quasiparticle. No quantitative estimate was made of the contribution of these phenomena to internal friction.

Besides quantum effects, contributions to the internal frictions should be made by processes occurring also in ordinary bodies. We consider three loss mechanisms:

1) loss due to thermal conductivity;

2) loss due to relaxation processes (e.g., thermally activated kink motion);

3) loss due to oscillation of a dislocation segment between pinning point (the theory of Granato and Lucke[14]).

For the first case we estimate the damping decrement by using the formula from the book of Landau and Lifshitz[15]:

$$\Delta_T \propto \varkappa T\omega\alpha^2/\rho C_p^2, \tag{3}$$

where $\varkappa$ is the thermal conductivity, α is the coefficient of volume expansion, ρ is the density, and C_p is the specific heat of the helium. For our experiment the upper bound is $\Delta_T \lesssim 10^{-4}$.

In the second case the internal friction is given by

$$\Delta_r = \Delta_{0r}\frac{\omega\tau_r}{1+\omega^2\tau_r^2}, \tag{4}$$

where τ_r is the relaxation time and depends on the temperature: $\tau_r \sim \exp(q/k_B T)$. The $\Delta_r(T)$ dependence is determined mainly by the temperature dependence of the relaxation time. One cannot exclude the presence in the crystal of several relaxation processes having activation energies q about which we have no information at present. The presence of a large number of unknown parameter prevents us from reducing our experimental data with the aid of formula (4).

In the third case, Granato and Lucke[15] obtained for the amplitude-independent internal friction the expression

$$\Delta_D=\Delta_{0D}\omega\tau_D/(1+\omega^2\tau_D^2), \tag{5}$$

$$\Delta_{0D}\approx 4.4\Omega G b^2\Lambda L^2/\pi^3 C, \tag{6}$$

$$\tau_D=11.9BL^2/\pi^2 C, \tag{7}$$

where Ω is the orientation factor, G the shear modulus, b the Burgers vector, Λ the dislocation density, L the length of the loop, $C=2Gb^2/\pi(1-\nu)$ the effective tension of the dislocation, ν the Poisson ratio, and B the damping constant.

The temperature dependence of the internal friction is due to the temperature dependence of τ_D. The change of τ_D is determined by the change of the damping constant, which has a power-law dependence on temperature, $B=gT^k$, where k is a proportionality constant. Substituting this relation in (7) we obtain the explicit dependence of τ_D on the temperature and next, substituting $\tau_D(T)$ in (5), we obtain the temperature dependence of the damping decrement

$$\Delta_D(T)=\Delta_{0D}\frac{(T/T_{max})^k}{1+(T/T_{max})^{2k}}, \tag{8}$$

where we have introduced, to simplify the notation, the parameter T_{max} defined by

$$T_{max}\approx\left[\frac{0.53Gb^2}{(1-\nu)\omega gL^2}\right]^{1/k}. \tag{9}$$

We have approximated with the aid of (8) the experimental data obtained for six crystals grown at $p=32$ atm. In four cases the points fit the relation (8) well (see, e.g., Figs. 6b and 6c), but in two cases there is no agreement (Fig. 6a). From the obtained values Δ_{0D}, T_{max}, and k we calculated the values of gL^2 and $\Omega\Lambda L^2$, found to be in the intervals

$$gL^2=(5\text{–}8)\cdot 10^{-13}\ \text{cgs units},\quad \Omega\Lambda L^2=1.4\text{–}2.3,\quad k=2.15\text{–}2.85.$$

The maximum value of Ω is 0.5. In our experiment its value was not determined, since the deformation has a very complex character and the crystal orientation is unknown.

We present for comparison the same parameters determined by Wanner, Iwasa, and Wales[5] from the sound velocities:

$$gL^2=(1\text{–}3)\cdot 10^{-13}\ \text{cgs units},\quad \Lambda L^2=0.04\text{–}0.18,\quad k=1.5\text{–}2.3.$$

The quantities gL^2 and k are close, and this confirms indirectly the correctness of the chosen model, but the cause of the large discrepancy in the values of ΛL^2 is not clear.

To identify the mechanism responsible for the internal friction in solid helium the damping must be measured on the same single-crystal sample at different frequencies. If the dampling is due to relaxation (case 2), then the damping maximum shifts with increasing frequency towards lower temperatures. Measurements of the positions of the damping maximum on the temperature dependence at various frequencies make it possible to determine the activation energy q of the relaxation process. If, however, the damping is determined by the dislocation vibrations (case 3), then the maximum will shift towards higher temperatures with decreasing frequency. Thus, measurements at different frequencies enable us to distinguish between these mechanisms. In addition, by choosing the frequency we can decrease the dislocation damping near the melting temperature. This will permit a measurement of the internal friction due to vacancies, a friction fully masked in our experiments by the dislocation damping.

Measurements, by Hiki at Tsuruoka[7], of ultrasound damping at frequencies 5–50 MHz yield dislocation parameters that differ substantially from ours. Thus, at $t=1.7$ K they obtained[7] $BL^2=1.4\times10^{-15}$ cgsu and $\Lambda L^2=0.36$. Our data extrapolated to 15 MHz, however, yield at $T=1.7$ K a damping $\Delta\sim5\times10^{-4}$, which agrees with the data of[7].

When our results are compared with those of Andronikashvili, Gachechiladze, and Melik-Shakhnazarov[8], it must be taken into account that the samples in[8] were prepared by the blocked-capillary method. Such a procedure should lead to appreciable residual internal stresses. Therefore the internal states of our samples and those of[8] differ greatly. Since our results were poorly reproducible, no detailed comparison with the results of [8] is possible, with the exception of the maximum damping values. To compare the latter we must convert the data obtained in [8] for the capillary + solid helium system to the damping in the sample itself with the aid of relation (2). The ratio of the vibration energies of the capillary and of the helium sample in the geometry used in [8] is given by the formula

$$E_2/E_1\sim\rho_2 S_2/\rho_1 S_1, \tag{10}$$

where ρ_2 and ρ_1 are the densities of the capillary material and of the solid helium, S_2 is the capillary cross section area, and S_1 is the helium sample cross section area. Assuming $\rho_2/\rho_1\sim40$ and $S_2/S_1\sim2$, we get the ratio $E_2/E_1\sim100$. The maximum damping is then $\Delta_1\sim0.1$, which agrees in order of magnitude with our data for a crystal with $V_m=19.2$ cm^3/mol.

It follows from our results that to explain the energy-dissipation mechanisms in oscillations of solid helium the internal friction must be measured in single-crystal samples in a wide range of frequencies. Such measurements, with controlled variation of the internal state of the sample, for example under plastic deformation, can yield information on the dislocation-induced loss mechanism.

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[1]A. E. Meĭerovich, Zh. Eksp. Teor. Fiz. 67, 744 (1974) [Sov. Phys. JETP 40, 368 (1975)].
[2]A. E. Meĭerovich, Zh. Eksp. Teor. Fiz. 71, 1180 (1976) [Sov. Phys. JETP 44, 617 (1976)].
[3]K. O. Keshishev, Zh. Eksp. Teor. Fiz. 72, 521 (1977) [Sov. Phys. JETP 45, 273 (1977)].
[4]V. N. Grigor'ev, B. N. Esel'son, and V. A. Mikheev, Zh. Eksp. Teor. Fiz. 66, 321 (1974) [Sov. Phys. JETP 39, 153 (1974)].
[5]R. Wanner, I. Iwasa, and S. Wales, Solid State Commun. 18, 853 (1976).
[6]I. D. Calder and J. P. Franck, Phys. Rev. B 15, 5262 (1977).
[7]Y. Hiki and F. Tsuruoka, Phys. Lett. A 56, 484 (1976); A 62, 50 (1977).
[8]E. L. Andronikashvili, I. A. Gachechiladze, and V. A. Melik-Shakhnazarov, Fiz. Nizk. Temp. 1, 635 (1975) [Sov. J. Low Temp. Phys. 1, 305 (1975).
[9]L. P. Mezhov-Deglin, Zh. Eksp. Teor. Fiz. 49, 66 (1965) [Sov. Phys. JETP 22, 47 (1966)].
[10]V. I. Voronin, Prib. Tekh. Eksp. No. 4, 118 (1976).
[11]D. O. Thompson and D. K. Holmes, J. Appl. Phys. 27, 713 (1956).
[12]B. V. Petukhov and V. L. Pokrovskiĭ, Pis'ma Zh. Eksp. Teor. Fiz. 15, 63 (1972) [JETP Lett. 15, 44 (1972)].
[13]A. F. Andreev, Zh. Eksp. Teor. Fiz. 68, 2341 (1975) [Sov. Phys. JETP 41, 1170 (1975)].
[14]A. Granato and E. Lucke, in: Physical Acoustics, W. Mason, ed., Vol. 4 A, Academic, 1968 [Russian transl., Mir, 1969, p. 261].
[15]L. D. Landau and E. M. Lifshitz, Teoriya uprugosti (Theory of Elasticity), Nauka, 1965, p. 192 [Pergamon, 1971].

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Spatial amplification of helical waves in the course of uniaxial deformation of Ge crystals

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Measurements were made of the spatial gain of helical waves in Ge crystals compressed and stretched along the ⟨111⟩ direction. At frequencies corresponding to the maximum amplification, the value of the gain increased (decreased) in n-type samples and decreased (increased) in p-type samples as a result of elongation (compression). The results are attributed to a change in the velocity of the ambipolar drift of helical waves in the course of intervalley redistribution of electrons caused by the deformation. The calculated values of the gain are in qualitative agreement with the experimental data. Analogies with gaseous plasma are pointed out.

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1. The absolute instability of helical waves (oscillation regime) was first observed in the experiments of Ivanov and Ryvkin,[1] who discovered an instability of the current in Ge samples subjected to a sufficiently strong longitudinal magnetic field. The results of these experiments were explained by Glicksman[2] on the basis of the theory of helical instabilities developed by Kadomtsev and Nedospasov[3] for gaseous plasmas. The regime of spatial amplification of helical waves (convective instability) was first investigated by Hurwitz and McWhorter.[4] This regime appears in the case of ambipolar drift of helical perturbations in the direction of an electric field and is characteristic of semiconductor plasmas when the drift velocity can be controlled by varying the ratio of the electron and hole densities through suitable doping of a sample. The phase velocity of helical waves is equal to the velocity of ambipolar drift. An increase in this phase velocity is accompanied by a reduction in the maximum value of the gain k_{im} and an increase in the frequency corresponding to the gain maximum ($f=f_m$).[4] A considerable change in the ambipolar drift velocity results from an intervalley redistribution of electrons when the anisotropy of the electron mobility becomes important.[5] In this case, the drift occurs even when the densities of electrons and holes are equal ($n=p$). The influences of this anisotropic drift resulting from such an intervalley redistribution on the absolute instability of helical waves was studied in detail by Bondar *et al.*[5] in Ge and Si crystals. We shall show that this effect greatly alters the nature of the spatial amplification of helical waves.

A considerable intervalley redistribution of electrons in Ge occurs when a crystal is deformed along a ⟨111⟩ axis. The constant-energy surfaces of Ge near the bottom of the conduction band are four ellipsoids of revolution elongated along such ⟨111⟩ axes. Compression transfers electrons to a valley parallel to the direction of deformation and elongation removes electrons from this valley.[6] In the former case, the transverse mobility averages over all the valleys is greater than the longitudinal value ($\bar{\mu}_{e\perp} > \bar{\mu}_{e\parallel}$), because the electrons are transferred to a valley with a higher transverse mobility, whereas, in the latter case, we have $\bar{\mu}_{e\parallel} > \mu_{e\perp}$. An expression for the ambipolar mobility, which governs the drift velocity ($v_a = \mu_0 E$), has the following form in the anisotropic case[5]

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