sufficiently large number of nuclear spins, so that it can be treated macroscopically. On the other hand, the frequency interval Δf of the precession of the nuclear spins, which enter in an individual isochromate regardless of their location in the crystal, must be small enough to be able to neglect the inhomogeneity of the precession frequency within the limits of the isochromate.

[2)]We define as a Hahn system a system of spins whose precession frequencies do not depend on the amplitude of the excitation of the spin system. The two-pulse echo in such spin systems is formed by the Hahn mechanism.[1]

[3)]In the comparison of the intensities, the duration τ of the pulse that exites the single-pulse echo has been chosen equal to the delay τ_{12} between two pulses in the two-pulse measurement procedure, so as to exclude the influence of relaxation effects.

[4)]We assume that the vector $\mathbf{H}_1$ in a rotating coordinate system is directed along the **y** axis. The relaxation processes in (2) are disregarded for simplicity.

[5)]Expression (7) shows that in the case when the first exciting pulse satisfies the nonresonant excitation condition and the second pulse is resonant, then three additional echo signals at the instants of time τ_{12} and $\tau_{12} \pm \tau_{12}\Delta\omega_0/(\Delta\omega_0^2+\omega_1^2)^{1/2}$, phased by the Hahn mechanism, can appear following the action of the pulses, on top of the stimulated echo due to the single-pulse mechanism.

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Electron emission from condensed noble gases

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A pulsed ionization chamber was used to measure the dependences of the emission coefficient (departure probability) of conduction electrons from liquid Ar and from solid and liquid Xe in their own gas at equilibrium, as functions of the external electric field intensity. It is shown that the emission coefficient reaches unity in fields exceeding 1 kV/cm for Ar and exceeding 5 kV/cm for Xe. The emission curve calculated under the assumption of scattering by only acoustic phonons yields for solid Xe a mean free path and an average electron energy 10^{-5} cm and 0.5 eV respectively at $E = 2$ kV/cm.

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INTRODUCTION

At the present time, condensed noble gases are attracting increasing attention in research, first as simple objects for the study of electronic processes, and second as promising working media for elementary-particle detectors. Little attention has been paid so far, however, to one of the most interesting properties of condensed noble gases—the emission of conduction electrons from the condensed phase into gas or vacuum under the influence of an external electric field.[1,2] Yet studies of the dependence of the emission coefficient (of the electron escape probability) on the electric field intensity at various temperatures can yield important information on the electronic processes in condensed noble gases, and also make it possible to formulate the principles of construction of two-phase emission instruments. We have measured in this connection the coefficients of emission of electrons from liquid argon and from liquid and solid xenon. The results and their discussion are the subject of this article.

EXPERIMENTAL SETUP

To investigate the emission properties of condensed noble gases we used the setup described in detail in Ref. 3. The initial gas was cleaned for two hours to rid it of impurities, using a titanium getter heated to 1000 °C, and was condensed in the two-electrode ionization chamber shown in Fig. 1. Prior to admission of the gas, the chamber was kept in a vacuum cryostat and evacuated for 10 hours to a pressure ~10^{-5} Torr.

The source of the ionizing radiation was a pulsed

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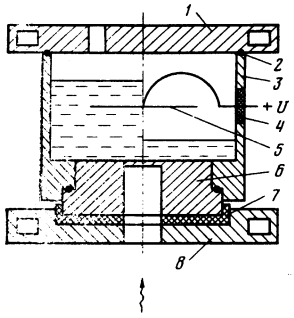

FIG. 1. Chamber for the measurement of the coefficient of electron emission from condensed noble gases. 1—Cover, 2—indium or teflon gasket, 3—housing, 4—high-voltage lead, 5—anode, 5—aluminum cathode liner, 7—insulating teflon insert, 8—bottom.

BSV-7 x-ray tube with pulse durations from 0.1 to 10 μsec, maximum x-ray photon energy 25 keV, and pulse energy 100 MeV/μsec. The electronic component of the current pulse produced in the chamber was amplified and observed on an oscilloscope screen.

MEASUREMENT PROCEDURE

The most important condition in investigations involving electron drift is that no electrons be captured by electronegative impurities. The significant factor here is not the absolute concentration of the impurities, determined, for example, by chromatography, but the relative number $\Delta q/q$ of the electrons captured during the drift. We have used a simple and reliable method of directly measuring this quantity, consisting in the following.

If the x-ray pulse duration $\tau \ll T = L/V_c$ (L is the gap between the electrodes and V_c is the electron drift velocity) and the thickness of the condensed layer $l \geq L$, the current pulse in a homogeneous electric field takes the form shown in Fig. 2a, with

$$i_1 \sim q_0 f(E) V_c E/U,\ i_1' \sim q_0 f(E) e^{-L/D} V_c E/U,$$

where $q_0 = e\mathscr{E}/\omega, E = U/L, f(E)$ is the coefficient of electron departure from the track of the x-ray photoelectron, U is the potential difference, $\mathscr{E}$ is the integrated energy of the x-ray pulse, ω is the energy of electron-ion pair production, and D is the average displacement and depends on the impurity concentration and on the electron capture cross section.

Then

$$\frac{\Delta q}{q} = \frac{i_1 - i_1'}{i_1} = 1 - e^{-L/D}.$$

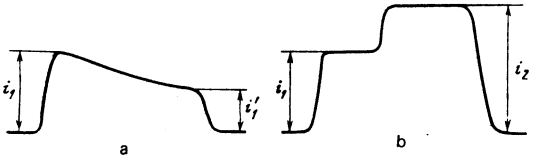

FIG. 2. Current pulse at $\tau \ll T$ in single-phase (a) and two-phase (b) systems.

The initial gas was cleansed to an impurity concentration such that the current pulse assumed a rectangular form, meaning satisfaction of the condition $\Delta q/q \ll 1$.

The emission coefficient $K(E)$ could then be determined from the ratio of the values of i_2 and i_1 in the current pulse at $l < L$ (two-phase system, Fig. 2b):

$$K(E) = \frac{i_2(E) V_c(E)}{\alpha_c i_1(E) V_g(E)},$$

where α_c is the dielectric constant of the condensed phase, V_g is the drift velocity of the electrons in the gas. However, the presence in this expression of the drift velocities V_c and V_g makes it difficult to use this expression for quantitative measurements of the emission coefficient. It can be shown at the same time that if $\tau > T$ we have

$$K(E) = \frac{I_2(E)}{I_1(E)}\left[\frac{l}{\alpha_c(L-l)} + 1\right] - \frac{l}{\alpha_c(L-l)},$$

where I_2 and I_1 are the amplitudes of the current pulse at $l < L$ and $l \geq L$, respectively. Since the quantities I_2 and I_1 are measured at different thicknesses of the condensed phase, the need for satisfying the condition $\Delta q/q \ll 1$ on a path L is obvious. Therefore the absence of electron capture was constantly monitored in the $\tau \ll T$ regime by the method described above.

MEASUREMENT RESULTS

Argon. It was shown in earlier experiments that in a homogeneous electric field exceeding 3 kV/cm practically all the free electrons leave the liquid Ar and go into the gas phase.[1] Figure 3 shows the emission coefficient measured by us as a function of the intensity of the electric field E inside the liquid. Even though the initial section was not investigated, it is seen that saturation is reached already at $E > 1$ kV/cm.

Exact measurements could not be made with solid argon because of the strong polarization, which manifested itself in an irreversible decrease of the current pulse with increasing irradiation. The causes of this phenomenon have not been examined within the framework of the present study. It was established at the same time that the saturation of the emission curve in the solid Ar takes place at lower electric field intensities than in liquid argon.

Xenon. Electron emission from solid Xe was investigated in Ref. 2. However, the results of that study are contradictory, a fact attributed by the authors to differences in the crystallization regimes. Electron emis-

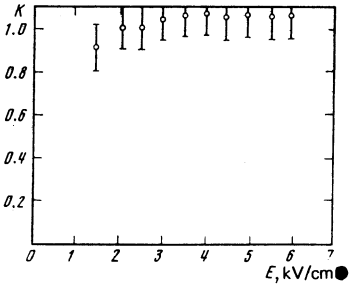

FIG. 3. Coefficient of electron emission from liquid Ar as a function of the electric field intensity inside the liquid.

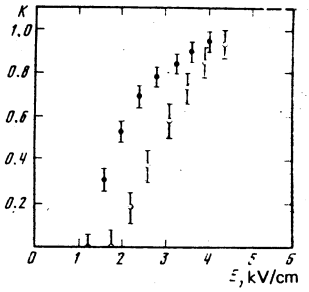

FIG. 4. Coefficient of electron emission from liquid (○) and solid (●) Xe vs. the electric field intensity inside the liquid (crystal).

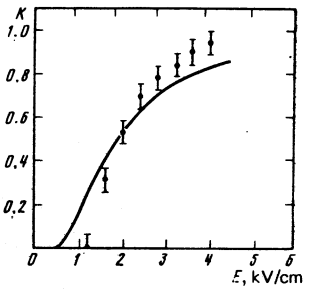

FIG. 5. Calculated (solid curve) and experimental (●) dependences of the coefficient of electron emission from solid Xe on the electric field intensity.

sion from liquid Xe had not been observed at all to date. Figure 4 shows the emission curves measured by us for solid and liquid Xe. Attention is called to the abrupt thresholds on the curve, the threshold field intensity being lower for the crystal than for the liquid (1.25 and 1.75 kV/cm, respectively). It is seen that saturation is reached at $E > 5$ kV/cm.

Measurements of the coefficient of electron emission from the crystal into the liquid were not made, but it was established that the qualitative behavior of the emission curve is the same in this case as in a condensed medium +gas system, and saturation is reached already in fields ~100 V/cm. It was also established that when the temperature is lowered the threshold value of the electric field intensity for solid Xe does not at any rate increase.

DISCUSSION OF RESULTS

It is natural to assume that emission in such relatively weak fields is due to "hot" electrons with energy ε exceeding tje potential barrier (the electron affinity ε_0) on the surface. Since $\varepsilon_0 = 0.5$ eV for solid Xe,[4] the contribution of the tunnel effect in such fields can be neglected, just as the lowering of the barrier as a result of the Shottky effect:

$$\Delta\varepsilon = \left[\frac{(\alpha_c - 1)e^3E}{\alpha_c + 1}\right]^{1/2} \sim 0{,}01\,\text{eV}.$$

The electron-emission coefficient can then be determined by using the electron-energy distribution function $F(\varepsilon, E)$, which is not Maxwellian, as follows from the measurements of the electron drift velocities in condensed noble gases,[5] where deviation from linearity is observed already at $E \sim 100$ V/cm:

$$K(E) = \int_{\varepsilon_0}^{\infty} e^{1/2} F(\varepsilon, E)\, d\varepsilon. \tag{1}$$

The form of the function $F(\varepsilon, E)$ in condensed noble gases is not known, but it has been shown[6,7] that if the electrons are scattered only by acoustic phonons then the electron energy distribution in the solid is quite similar to the distribution in the gas in the case of only elastic collisions with the gas molecules. Then the absence of an optical lattice-vibration mode[8] and the low concentration of the impurities and of the free electrons allow us to use the Davydov distribution[6]

$$F(\varepsilon, E) = A_1[\varepsilon/kT + (E/E_0)^2]^{(E/E_0)^2} \exp(-\varepsilon/kT), \tag{2}$$
$$E_0 = [6mu^2kT/e^2\lambda^2]^{1/2}$$

or the Druyvesteyn distribution[9]

$$F(\varepsilon, E) = A_2 \exp[-(E_0/E)^2\varepsilon^2/2(kT)^2], \tag{3}$$

where A_1 and A_2 are normalization factors, k is Boltzmann's constant, T is the absolute temperature, u is the speed of sound, m is the effective mass of the electron, and λ is the mean free path of the electron.

The exact value of m in condensed noble gases is not known, but it is assumed that it differs little from the free-electron mass m_e. In particular, $m = 0.43m_e$ for liquid argon.[5] Assuming $m = 0.5m_e$, we have calculated the emission curves for solid xenon, given by Eqs. (1) and (2). The value of λ was varied in the range from 10^{-4} to 10^{-7} cm. The closest to experiment is the curve calculated for $\lambda = 1 \cdot 10^{-5}$ cm (Fig. 5). The average energy in the distribution (3), which is a particular case of the distribution (2), is given by the expression $\bar{\varepsilon} = 0.427eE\lambda(kT/mu^2)^{1/2}$, whence at $\lambda = 1 \cdot 10^{-5}$ cm and $E = 2$ kV/cm we have $\bar{\varepsilon} = 0.5$ eV.

However, as seen from Fig. 5, it is impossible to obtain full agreement between the calculated and experimental curves. The apparent reason is that the mean free path depends on ε, whereas the Druyvesteyn and Davydov distributions were obtained assuming that λ is constant. It is possible that better agreement can be obtained by using the Lekner distribution function.[10,11]

In conclusion, we note an interesting phenomenon, viz., the polarization of both the crystal and of the liquid at $K(E) < 1$. This "emission" polarization is due to accumulation of negative charge on the phase separation boundary because of incomplete departure of the electrons. This is confirmed both by the absence of a similar polarization at $K = 1$, and by the fact that removal of the electric field for a short time restores completely the emissivity of the material.

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Influence of plastic deformation and of impurities on internal friction in solid He^4

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Internal friction at frequencies 15 and 78 kHz were measured in samples of solid He^4 with molar volume 20.55 cm^3. The samples were grown at constant pressure, and also by the blocked-capillary method. The construction of the container made it possible to carry out measurements of the damping in plastic deformation of solid helium. The internal friction in samples of solid helium with He^3 admixture (0.01–0.1 at. %) was also investigated. The reduction of the temperature and amplitude dependences of the damping by the theory of Granato and Lucke has made it possible to determine a number of dislocation parameters.

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Measurements of the internal friction in crystalline helium make it possible to investigate defects in the crystal structure. Because of the high purity of crystal (impurity concentration less than 10^{-6} at. %), such defects are vacancies and dislocations. The study of these defects is of great fundamental interest, since the large amplitude of the zero-point oscillations of the helium atoms can lead to specific effects not observed in ordinary substances. Meĭerovich[1] has discussed the contribution of vacancies to the internal friction; it was shown that delocalization of the vacancies leads, for example, to absorption of the energy of the mechanical oscillations even under spatially homogeneous deformation. This effect was not observed in ordinary materials.

The measurements of the internal friction in crystalline He^4 were carried out up to now on pure single-crystal samples grown at constant pressure, at megahertz[2,3] and kilohertz[4,5] frequencies. On the basis of these results it was suggested that the main mechanism of the damping is due to dislocations. A reduction of the measurement results[2,5,6] by a Granato-Lucke theory[7] has made it possible to determine a number of dislocation parameters. However, the values of the parameters determined at various frequencies are in poor agreement. Thus, at the present time there is no model that describes well all the experimental results.

The internal friction due to dislocations depends on the internal state of the sample. By changing this state, for example by changing the crystal-growth conditions or by plastic deformation, it is possible to attempt to separate the contribution of the dislocations to the internal friction. The presence of a small amount of impurities also influences the value of the dislocation internal friction.

The present study was devoted to the influence of these actions on the internal friction in He^4 crystal with molar volume $V_{mol} = 20.55$ cm^3.

EXPERIMENTAL PROCEDURE

To excite and register the oscillations of solid helium we used quartz resonators of two types. The container in which the resonator of the first type was mounted, with the fundamental flexural oscillation mode (in vacu-

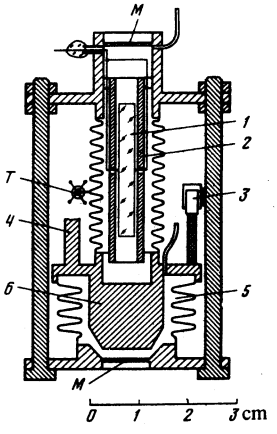

FIG. 1. Construction of container: 1—quartz resonator, 2—stainless tube, 3—capacitive displacement pickup, 4—copper cold finger, 5—pressure chamber, 6—movable bottom, *T*—resistance thermometer, *M*—membrane of capacitive pickup.

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