various types of crystals over a broad range of temperatures and frequencies. It was found that the attenuation of elastic waves is well described by the Akhiezer mechanism in all crystals. Among other things, it was shown that injection of impurities into the crystal lowers the attenuation.

One of the possible mechanisms of elastic-wave attenuation in crystals is their interaction with the free carriers. It is shown that the experimental results are in good agreement with the theory of V. L. Gurevich.

The interaction of elastic and spin waves in magnetically ordered crystals has been studied in detail. A new phenomenon—natural magnetoelastic resonance, a resonant interaction between elastic and spin waves in the absence of an external field—was detected in the internal fields of the magnetocrystallographic anisotropy. The acoustic Faraday and birefringence effects in magnetic crystals were investigated.

The generation of acoustic harmonics was studied, yielding information on the anharmonicity of the interaction forces in the crystals and its third-order elastic moduli. The appearance and development of this trend is associated with the name of V. A. Krasil'nikov (Moscow State University).

The phenomenon of diffraction of light on hypersonic waves is useful in the study of various crystal properties. The case in which scattering of light on elastic waves is attended by rotation of the polarization plane of the light proved highly interesting. There are two possible scattering geometries in an optically anisotropic crystal at a given elastic-wave frequency: two angles of incidence and two angles of diffraction.

Study of the velocity and attenuation of sound waves in crystals can yield useful information on the nature of phase transformations and on the so-called "soft" modes[4].

[1] G. A. Smolenskiĭ, R. V. Pisarev, N. N. Kraĭnik, and I. G. Siniĭ, Vestn. Akad. Nauk SSSR No. 8, 62 (1969).
[2] G. A. Smolenskiĭ, R. V. Pisarev, and I. G. Siniĭ, Usp. Fiz. Nauk **99**, 151 (1969) [Sov. Phys.-Uspekhi **12**, 695 (1970)].
[3] G. A. Smolenskiĭ, R. V. Pisarev, I. G. Siniĭ, and N. N. Kolpakova, J. de phys. **32**, 1048 (1971).
[4] G. A. Smolenskiĭ and V. V. Lemanov, Vestn. Akad. Nauk SSSR **12**, 15 (1970).

U. Kh. Kopvillem, V. N. Osipov, B. P. Smolyakov, and R. Z. Sharipov. Analogs of Electron Spin Echo in Ferroelectrics and Glasses.

E. K. Zavoĭskiĭ's discovery of electron paramagnetic resonance[1] resulted in the rapid development of resonance methods for the study of condensed media. Nuclear spin echo, which was detected by E. Hahn[2] by the nuclear spin induction method developed theoretically and experimentally by F. Bloch[3], occupies a special position among these methods of studying matter. The high promise of the use of spin-echo technique in electronic systems was defended theoretically in[4,5] and confirmed experimentally in[6,7]. The possibility of using sound to excite the spin echo was investigated in[8,9]. Then the proposition that all of the observed resonances in matter can be studied in greater detail by observing the spin-echo-type signals corresponding to them was demonstrated theoretically[10]. A method of selecting the appropriate external coherent fields for excitation of these signals was also indicated. Signals of the spin-echo type were indeed observed in ferromagnetics[11,12], on Landau levels[13,14], and in optical systems[15,16].

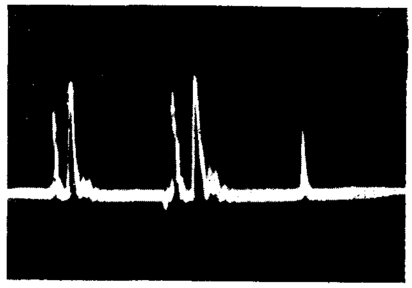

FIG. 1. Oscillogram of echo signal in KH_2PO_4 single crystal at 4.2°K. After each exciting pulse (narrow spikes), we observe a sequence of hypersonic pulses reflected from domain walls. The echo signal follows the second hypersonic signal at an interval $\tau \sim 10^{-6}$ sec. The abscissa is signal amplitude.

Observation of a signal of the spin-echo type on fluxoids in class two superconductors was reported in[17]. A theoretical analysis indicated[18] that observation of the fluxoid echo also augurs well for the detection of spin-echo-type signals in other systems that have quasi-continuous spectra and in which resonances do not occur on a change in the static magnetic, electric, and elastic fields, e.g., on the vibrations of domains and their boundaries in ordered states of matter (ferro- and antiferromagnetics, ferro- and antiferroelectrics, ferroelastic systems[19]), on vortex filaments in superfluid helium, and on dislocations in crystals and tubes of channeled optical and acoustic radiation (filaments)[20]. All of the systems enumerated above have definite natural frequencies and can produce spin-echo-type signals. The theory indicates that these signals will exhibit a number of distinctive properties inherent to the cyclotron echo[14]. An investigation of ferroelectric single crystals at 4.2°K using electronic spin-echo apparatus[21] led to the detection of electrical analogs of signals of the ferromagnetic-echo and stimulated-ferromagnetic-echo types at a frequency of 10^{10} sec^{-1} and an exciting-pulse duration of 3×10^{-8} sec[12].

Figure 1 shows an oscillogram of the echo signals in KH_2PO_4. The longitudinal and reversible and irreversible transverse relaxation times were found to be of the order of $T_1 \sim 10^{-5}$ sec, $T_2^* \sim 10^{-8}$ sec, and $T_2 \sim 1.6 \times 10^{-6}$ sec, respectively. Similar signals were observed in single crystals of KD_2PO_4, CsD_2AsO_4, CsH_2AsO_4, RbH_2PO_4, and RbH_2AsO_4, but the signals were absent in $LiNbO_3$ and Rochelle salt.

Basic properties of the signals: 1) When a sample is ground to a powder, the signals from the hypersonic pulses excited in it vanish, but the echo signals persist. 2) The signals are one order higher in strength than electron spin-echo signals from radicals. 3) Signal strength does not change in the range (8.9—9.6) $\times 10^9$ sec^{-1}. 4) The echo is excited by the electric component of the alternating electromagnetic field. 5) In the range from 0—1.2 $\times 10^4$ G, the signals are independent of the static magnetic field. 6) In the 0—10 kV/cm range, there is no dependence on the static electric field.

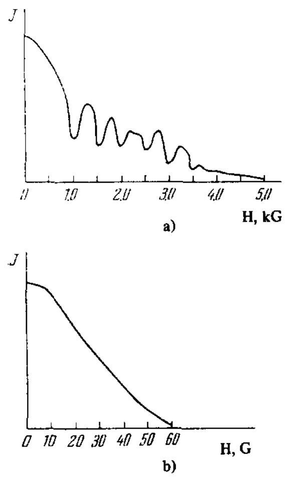

FIG. 2. Amplitude of electron spin echo in glasses as a function of static magnetic field intensity H at temperature of 4.2°K: a) in quartz glass without injected impurities; b) in glass with the impurities (CeO_2 + TiO_2).

7) The strength of the echo does not depend on the angle between the crystal axes and the alternating electric field vector. 8) An echo appears only in the ordered phase of a ferroelectric. 9) When the temperature is raised to T > 4.2°K, the time T_1 rapidly becomes shorter and the echo signals vanish. 10) The phase-memory mechanism is governed by the scatter of the internal electric fields. It can be assumed that the echo is due to collective vibrations of electric dipoles (dipole plasmons) or to electric spin waves whose frequency is a complex combination of the frequencies of tunneling, exchange, multipole-multipole interactions, and elastic vibrations of the atomic groups in the ferroelectrics[23]. It appears that the new physical phenomenon discerned here might be used for identification of the ordered state in ferroelectrics and for study of their properties, as well as in quantum-electronics devices.

The electron spin-echo technique has also been found highly promising for the investigation of glasses, in which the ordinary electron paramagnetic resonance signals[24] are very broad and practically preclude separate measurements of the parameters T_1, T_2, and T_2^*. Figure 2 shows the intensity J of the electron spin echo at 4.2°K in quartz glass (without special injection of impurities) (a) and in glass with impurities (CeO_2 and TiO_2) (b) as functions of the static magnetic field H. Interestingly, the signals are observed at H = 0 and are independent of frequency over a range of one gigahertz. The times are $T_2 \sim 10^{-6}$ sec, $T_2^* \sim 10^{-9}$ sec, and $T_1 \lesssim 10^{-3}$ sec; signals were observed at $H \perp H_1$ and $H \parallel H_1$ (H_1 is the alternating-field vector). This is apparently the first report on observation of an electronic analog of the nuclear quadrupole echo discovered in 1951[25]. Electron spin echo signals were also detected at 4.2°K on Fe^{3+} ions (I center) in a synthetic single crystal of tiger's-eye quartz ($T_2 \sim 6 \times 10^{-6}$ sec) on all five transitions[26].

Methods of the spin-echo type permit temporal separation of the excitation acts and observation of the signals and measurement of the dynamic characteristics of the systems in the range ($10^6 - 10^{15}$) sec^{-1}, and are therefore highly promising for the investigation of substances.

[1] E. K. Zavoĭskiĭ, Doctorate thesis (Physics Institute, USSR Academy of Sciences, 1944).
[2] E. Hahn, Phys. Rev. 80, 580 (1950).
[3] F. Bloch, Phys. Rev. 70, 460 (1946).
[4] N. G. Koloskova and U. Kh. Kopvillem, Fiz. Tverd. Tela 2, 1368 (1960) [Sov. Phys.-Solid State 2, 1243 (1961)].
[5] U. Kh. Kopvillem, ibid. 3, 754 (1961) [3, 549 (1961)].
[6] J. R. Klauder and P. W. Anderson, Phys. Rev. 125, 912 (1962).
[7] W. B. Mims, Phys. Rev. 141, 499 (1966).
[8] N. G. Koloskova and U. Kh. Kopvillem, Fiz. Met. Metalloved. 10, 818 (1960).
[9] A. V. Alekseev, U. Kh. Kopvillem, V. R. Nagibarov, and M. I. Pirozhkov, Zh. Eksp. Teor. Fiz. 55, 1852 (1968) [Sov. Phys.-JETP 28, 980 (1969)].
[10] U. Kh. Kopvillem, ibid. 42, 1333 (1962) [15, 924 (1962)].
[11] D. E. Kaplan, Phys. Rev. Lett. 14, 514 (1965).
[12] U. Kh. Kopvillem, Fiz. Tverd. Tela 9, 1038 (1967) [Sov. Phys.-Solid State 9, 813 (1967)].
[13] R. M. Hill and D. E. Kaplan, Phys. Rev. Lett. 14, 1062 (1965).
[14] Ya. Ya. Asadullin and U. Kh. Kopvillem, Fiz. Tverd. Tela 9, 2737 (1967) [Sov. Phys.-Solid State 9, 2150 (1968)].
[15] U. Kh. Kopvillem and V. R. Nagibarov, Fiz. Met. Metalloved. 15, 313 (1963).
[16] N. A. Kurnit, I. D. Abella and S. R. Hartmann, Phys. Rev. Lett. 13, 567 (1964).
[17] I. B. Goldberg, E. Ehrenfreund and M. Weger, Phys. Rev. Lett. 20, 539 (1968).
[18] U. Kh. Kopvillem, Fiz. Tverd. Tela 11, 129 (1969) [Sov. Phys.-Solid State 11, 93 (1969)].
[19] K. Aizu, Phys. Rev. B2, 754 (1970).
[20] C. A. Sacchi and C. H. Townes, Phys. Rev. 174, 439 (1968).
[21] A. G. Semenov and V. E. Khmelinskiĭ, Pribory i Tekh. Eksperim. No. 5, 197 (1967).
[22] R. Lobo, S. Rodriguez and J. E. Robinson, Phys. Rev. 161, 513 (1967).
[23] W. Cochran, Adv. Phys. 18, 72, 157 (1969).
[24] T. S. Al'tshuler, Fiz. Tverd. Tela 9, 2070 (1967) [Sov. Phys.-Solid State 9, 1623 (1968)].
[25] H. I. Dehmelt and H. Kruger, Zs. Phys. 129, 401 (1951).
[26] L. M. Matarrese, J. S. Wells and R. L. Petuson, J. Chem. Phys. 50, 2350 (1969).

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