Parametric echo and magnetoelastic excitation of NMR in $FeBO_3$

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Nuclear spin echo of ^{57}Fe in $FeBO_3$ parametrically pumped at double the NMR frequency is investigated. An influence is observed of the preliminary pump on the ordinary echo signal and on the parametric echo produced if a pump pulse is applied to the sample in place of the second resonance pulse. It is shown that magnetoelastic oscillations are parametrically excited, excite in turn the nuclear spin system, via the hyperfine interaction, and ensure formation of the parametric echo. A theoretical analysis is carried out of the mechanism of parametric excitation of the magnetoelastic oscillations. A model of echo formation under inhomogeneous excitation is proposed. The calculations presented are in satisfactory agreement with experiment.

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Parametric action on a nuclear spin system has been observed up to now in ferromagnets with appreciable dynamic shift of the NMR frequency. In particular, parametric excitation of the pair made up of an electron spin wave and a nuclear spin wave were investigated.[1,3] Studies were made of direct energy absorption by the sample on account of excitation of nuclear spin waves only.[2,3] The parametric echo induced by action of a radio pulse of frequency $2\omega_n$ on a nuclear spin system excited beforehand by a resonant radio pulse of frequency ω_n, where ω_n is the NMR frequency, was investigated.[4] The pump field in these experiments was parallel to the constant magnetic field.

In an earlier brief communication[5] we have reported observation of parametric pumping and of parametric echo in the easy-plane antiferromagnet $FeBO_3$, where the dynamic frequency shift at 77 K is practically nonexistent. In the present paper we present the data of a more detailed experimental investigation of parametric phenomena in $FeBO_3$. It is shown that an alternating magnetic field of frequency $\omega_H = 2\omega_n$ excites parametrically in the sample magnetoelastic oscillations (a quasielastic mode) of frequency ω_n. There oscillations excite resonantly in turn the nuclear spin system, i.e., this is a two-step process. Both a change in the z component of the nuclear magnetization and echo excitation are then possible.

SAMPLES AND EXPERIMENTAL PROCEDURE

$FeBO_3$ has a space group $D_{3d}^6(R\bar{3}C)$ and at a temperature lower than 348 K it is an antiferromagnet with weak ferromagnetism. Data on the magnetic properties of $FeBO_3$ were reported earlier.[6] The magnetic moments of the sublattices, as well as the weak resultant moment, lie in an "easy" plane perpendicular to the a threefold axis.

The $FeBO_3$ single crystals were obtained by the chemical transport method from previously synthesized polycrystalline iron borate. The polycrystalline material was made of Fe_2O_3 and B_2O_3 of OSCh (special high purity) grade, mixed in a molar ratio 1:1.5. To improve the conditions of the reaction between the initial components, the mixture was pressed into pellets. The synthesis was in a sealed quartz ampoule kept at 600°C for 50 hours. After the synthesis the ground material was washed in hot water to remove the B_2O_3 that did not enter in the reaction. The polycrystalline material prepared in this manner was subjected to chemical transport in the sealed quartz ampoule. The transport temperature was in the range 760–650°C. A chemical analysis by Ya. S. Kamentsev has shown that the iron oxide and the boron excite are contained in the $FeBO_3$ in a molar ratio 1:1.0016.

The crystals were oriented by their faceting and in a magnetic field, after which they were mechanically shaped into disks. The plane of the disk coincided with the easy plane. The sample diameter was 1–3 mm, and the thickness about 1 mm.

Besides the samples with natural ^{57}Fe content at (2.2 at.%), samples enriched with ^{57}Fe to 85 at.% were also prepared.

The nuclear spin echo on the ^{57}Fe nuclei in $FeBO_3$ at a frequencies 45–76 MHz were observed with a commercial ISSh-1-2 pulsed radiospectrometer adapted for the observation of spin echo at low exciting-pulse levels. A low-noise preamplifier was used to increase the sensitivity of the receiver. An 130–170 MHz parameteric-pumping pulse-shaping system was added, with circuitry similar to that of the corresponding channel of the spectrometer. It was possible to vary the delay time τ of the pump pulse relative to the first pulse of the spectrometer within an interval ±1 sec. The oscillating systems of the spectrometer and of the pump block were either quarter-wave or half-wave coaxial resonators in parallel with inductance coils inside of which the sample was placed. The constant magnetic field was produced by Helmholtz coils and was applied in the easy plane. The resonant RF field and the pump field were also applied in the easy plane.

The absolute value of the alternating magnetic field in the pump-resonator coil was calculated from the known geometric dimensions of the coil and from its dimensions, as well as from the volatge on the coil. The absolute calibration accuracy for the field amplitude was about 50%.

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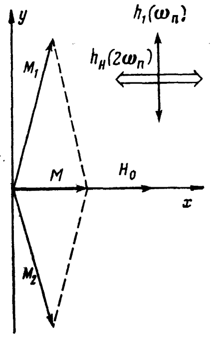

FIG. 1. Magnetic structure and polarization of the applied alternating fields (h_H—pump field, h_1—resonant field). The z axis is directed along the difficult axis.

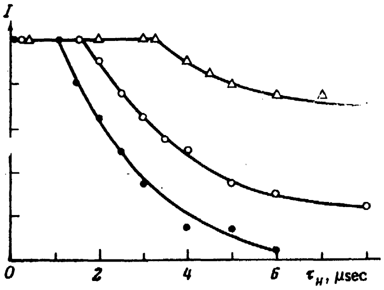

FIG. 3. Dependence of the intensity of ordinary echo on the duration of the pump pulse in an unenriched sample at $H_0 = 100$ Oe for different values of the pump field h_HΔ– 3.7 Oe, ○– 6.2 Oe, ●– 7.7 Oe.

EXPERIMENTAL RESULTS

We examine first the influence of parallel parametric pump on the nuclear echo signal. The measurements were made mainly at $T = 77$ K, in which case the NMR frequency was $\omega_n/2\pi = 75$ MHz. The pump field at the frequency $2\omega_n$ was applied parallel to the constant field H_0, and the alternating field at the NMR frequency was polarized perpendicular to H_0 (Fig. 1). The pump pulse was turned on at some instant of time prior to the instant of echo formation. In the general case, the echo signal was seen to decrease when a definite pump power was reached. We investigated the dependence of the influence of the pump on the amplitude, duration, time position, and carrier frequency of the pump pulse.

Figure 2 shows the dependence of the echo intensity on the pump pulse amplitude at $\omega_H = 2\omega_n$ under the condition that the pump pulse is turned on $\tau = 400$ μsec earlier than the first echo-forming RF pulse. As seen from Fig. 2, the dependence has threshold whose value increases rapidly with increasing external magnetic field.

To determine the value of the threshold, we plotted the echo intensity against the pump pulse duration τ_H at a fixed delay and for several values of the pump-pulse amplitude (Fig. 3). The threshold was calculated with τ_H extrapolated to infinity. Unfortunately, the measurement errors, due primarily to the small signal/noise ratio for the echo and to the instability of the echo in the presence of the pump, made it possible to determine only the upper limit of the pump threshold $h_H^{\text{thr}} \leq 1$ Oe in an external magnetic field 120 Oe. The dependence of the influence of the parameteric pulse on the delay τ is exponential with a time constant close to 100 msec.

The plots of Figs. 2 and 3 were obtained for the case when the pump pulse was turned on first, and the pump frequency was equal to double the NMR frequency. At a detuning ±5 MHz from the frequency $2\omega_n$, the character of the influence of the pump on the echo did not change qualitatively. However, to obtain identical effects it was necessary to apply much stronger pumps.

Figure 4 shows the dependence of the pump threshold determined from the plots of the type shown in Fig. 2 on the detuning $\Delta\omega_H = \omega_H - 2\omega_n$ at a fixed pump-pulse duration. At an appreciable detuning $\Delta\omega_H/2\pi = 15$ MHz, when no action of the preliminary pump pulse was not observed, the parametric pulse applied after the first resonant pulse decreased the echo signal. The dependences of the echo intensity on the pulse duration and amplitude had the same character and character and characteristic scale as the preliminary pump pulse without deturning. An influence on the stimulated echo pulse was observed only when the pump pulse was turned on between the first and the second or after the third resonant pulse.

The small magnetic-field interval, 80–300 Oe, in which the measurements were made was due to the small signal/noise ratio of the echo in the 0–80 Oe re-

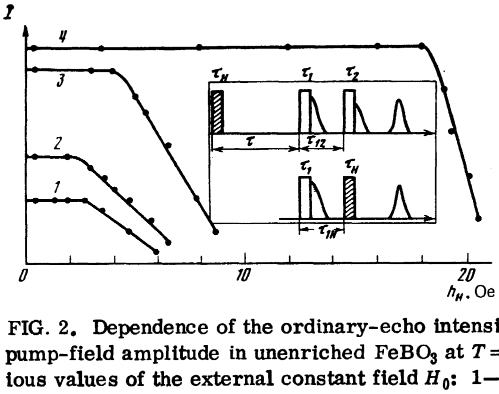

FIG. 2. Dependence of the ordinary-echo intensity on the pump-field amplitude in unenriched $FeBO_3$ at $T = 77$ K, for various values of the external constant field H_0: 1—100 Oe, 2—120 Oe, 3—160 Oe, 4—200 Oe, $\tau_H = 6$ μsec, $\tau = 400$ μsec, $\tau_1 = 3$ μsec, $\tau_2 = 6$ μsec, $\tau_{12} = 250$ μsec. (τ_1, τ_2, τ_H – are the respective durations of the first, second, and pump pulses). The inset shows the sequence of turning on the resonant and parametric (shaded) pulses.

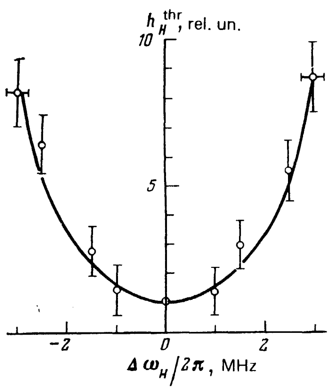

FIG. 4. Threshold pump field in unenriched sample vs. the detuning of the pump frequency relative to the doubled NMR frequency: $\Delta\omega_H = \omega_H - 2\omega_n$, $H_0 = 100$ Oe.

gion and to the strong increase of the required pump power in fields $H_0 > 200$ Oe (Fig. 2).

It should be noted that it was possible to observe in the experiment the influence of the parametric pumping not only at $h_H \parallel H_0$ but also at $h_H \perp H_0$. The resultant plots were approximately of the same form as those shown in Figs. 2 and 3.

In contrast to the earlier data,[5] we succeeded in observing an influence of the pump not only in enriched samples, but also in unenriched ones. It turned out that the pump threshold does not depend on the degree of enrichment, but is very strongly dependent on the sample quality—the maximum threshold is observed in the most perfect crystals.

We consider now the behavior of the so-called parametric echo. If a pump pulse is applied following the resonant RF pulse at exactly double the NMR frequency, it is possible to produce an echo signal at the instant $2\tau_{1H}$, where τ_{1H} is the spacing between the pulses. The echo obtained with a similar experimental setup by Bun'kov and Gladkov[4] on the ^{55}Mn nuclei in $MnCO_3$ was named parametric. We shall adhere to this terminology, although the nature of the parametric echo in our case is entirely different.

The behavior of the parametric echo correlates with the pumping results described above, as exemplified by the following experiment (Fig. 5). The pump pulse is used (a) to suppress the ordinary echo, in which case it is applied ahead of the resonant pulses, and (b) as a second pulse to produce the parametric echo. It is seen from Fig. 5 that the appearance of a parametric echo corresponds to the pump amplitude when a decrease of the ordinary echo becomes noticeable. The conditions for the observation of parametric echo on Fig. 5 were chosen to be optimal. The maximum intensity of the parametric echo is then equal to the intensity of the ordinary echo. As a rule, however, the parametric echo is less intense than the ordinary one.

Figure 6 shows plots of the parametric-echo intensity against the pump-pulse amplitude for an enriched samples. The measurements were made at different values of the external magnetic field. The duration of the first pulse was 3 μsec and was constant. The amplitude, however, was chosen to obtain maximum induction after the pulse. In fields $H_0 > 200$ Oe the intensity of the parametric echo changes from triggering to triggering.

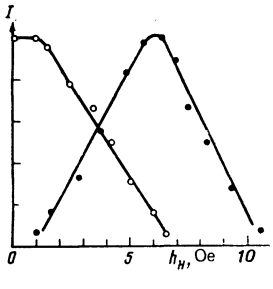

FIG. 5. Intensity of ordinary echo (○) and of parametric echo (●) vs. the pump-field amplitude in an unenriched sample: $H_0 = 100$ Oe, $\tau_1 = 3$ μsec, $\tau_H = \tau_2 = 6$ μsec, $\tau_{12} = \tau_{14} = 250$ μsec.

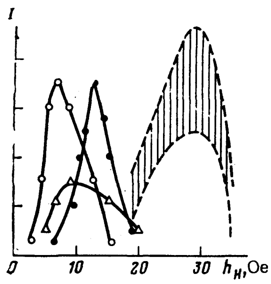

FIG. 6. Dependence of the intensity of parametric echo in an enriched sample at $T = 77$ K on the pump-field amplitude for different values of the magnetic field H_0: Δ – 100 Oe, ○ – 150 Oe, ● – 200 Oe, dashed– 250 Oe, $\tau_H = 6$ μsec, $\tau_{1H} = 250$ μsec, $\tau_1 = 3$ μsec.

The shaded region marks the measurement limits. Similar relations were obtained for unenriched samples, but no parametric echo could be observed in fields $H_0 > 200$ Oe.

With increasing delay between the resonant pulse and the pump pulse, the parametric-echo intensity decreases exponentially with a time constant T_2 (500 μsec for the enriched sample and 3 msec for the unenriched one).

If the pump pulse is applied first and the resonant pulse second, no echo signal is produced. It should be noted in this connection that there is no induction after the pump pulse both in the case of action on a nuclear system at equilibrium and on a system edcited by a resonant radio pulse. Nor could a stimulated-echo signal be obtained if at least one of the three pulses was parametric. In addition, the amplification characteristic of parametric echo in crystals with large dynamic frequency shift[7] was absent. Under no conditions could be obtain an exch amplitude larger than the induction amplitude after the first pulse.

Inasmuch as the interpretation of the parametric phenomena is subsequently connected with excitation of magnetoelastic oscillations. Some additional experiments were performed. Thus, at 77 K the sample was placed in glycerine to decrease its acoustic Q factor. The pump threshold was increased thereby threefold. Cleaving the sample also raised the threshold.

To estimate the lifetime of the oscillations induced by the pump pulse, we compared the action of a pump pulse of duration τ_H and of two pump pulses of duration $\frac{1}{2}\tau_H$ and separated by an interval τ. It turned out that the action of two pulses $(\frac{1}{2}\tau_H + \frac{1}{2}\tau_H)$ becomes equivalent to the action of one pulse (τ_H) if $\tau \leq 1$ μsec.

INTERPRETATION OF RESULTS AND THEORY

To explain the parametric NMR phenomena observed in $FeBO_3$ namely parametric echo and excitation of the nuclear spin system by a pump pulse, the following model can be proposed. During the time of action of the parallel pumping pulse, elastic (more acurately, coupled magnetoelastic) oscillations are excited, on account of the magnetoelastic interaction, at half the pump frequency. It is known that in this case the elementary excitations are generated by pairs with wave vectors **k** and **−k** and add up to form a standing wave or a superposition of standing waves if the parametric-resonance conditions are satisfied for waves with different **k**. The magnetoelastic oscillations induce, via the hyperfine interaction, oscillations of the local fields at the nuclei, and consequently excite the nuclear spin system if the resonance condition $\omega_H/2=\omega_n$ is satisfied. This resonant excitation of the nuclear spin system is in essence spatially inhomogeneous in amplitude and in phase. The crystal breaks up into regions of approximately equal volume (provided that the sample dimensions are much larger than the elastic-oscillation wavelength), in which the phases of the local RF fields are shifted[1)] by π. This inhomogeneous out-of-phase excitation leads to a number of singularities in the observation of the pulsed responses of the nuclear system. For example, a parametric pulse produces no induction or stimulated echo, but does give rise to a two-pulse echo. In our case this echo is produced by the Hahn mechanism. The action of a preliminary parametric pulse on an ordinary echo signal is due to the decrease of the z-projection of the initial nuclear magnetization.

Ozhogin and Yakubovskii[3] presented a quantum-mechanical analysis of the general case of parametric excitation of magnetoelastic oscillations in parallel-pumped weak ferromagnets and obtained an expression for the parametric-instability threshold. In our case it must be recognized that the frequency of the excited modes is much lower than the frequency of the antiferromagnetic resonance (AFMR):

$$\omega\ll\omega_{e_1}, \tag{1}$$

$$\omega_{e_1}=\gamma_e[H(H+H_D)+2H_EH_a]^{1/2}, \tag{2}$$

where H_E, H_D, and H_a are the effective exchange and Dzyaloshinskii magnetic fields and the anisotropy field in the easy plane.

To describe parametric excitation of magnetoelastic oscillations we strat from the following expression for the magnetostriction energy[8,9a]:

$$F=\frac{G_1}{M_0^2}L_xL_yu_{xy}+\frac{G_3}{M_0^2}L_xL_yu_{zx}, \tag{3}$$

where G_1 and G_2 are the magnetostriction constants, M_0 is the magnetization of the sublattice, u is the strain tensor, the x and y axes are directed along $\mathbf{M}=\mathbf{M}_1+\mathbf{M}_2$ and $\mathbf{L}=\mathbf{M}_1-\mathbf{M}_2$ (Fig. 1), and the z axis coincides with the difficult axis. We have retained in (3) the terms responsible for the interaction of the elastic degree of freedom with only the low-frequency spin-wave branch (in our case, $\omega_{e1}\ll\omega_{e2}$). In addition, it is assumed that the sample is saturated and the external field is directed along a twofold axis in the easy plane.

The magnetoelastic interaction (3) leads to a "mutual repulsion" of the elastic branches and of the spin-wave branch, and subject to condition (1) we obtain for the lower branch of the magnetoelastic oscillations

$$\omega=\omega_0(1-\gamma_eH_E\Omega_{\rm me}^{(i)}/\omega_{e_1}^2)^{1/2}, \tag{4}$$

where ω_0 is the unperturbed frequency of the elastic oscillations, $\Omega_{\rm me}^{(i)}=8\gamma_eG_i^2/M_0c_i\,(i=1.3)$ is the characteristic frequency of the repulsion of the magnetoelastic branches, and c_1 and c_3 are suitable combinations of the elastic constants.

The frequencies of the normal modes of the elastic oscillations (4) or the speed of sound ($\omega=vk$) thus depend on the applied magnetic field via the AFMR frequency (2). This makes possible parallel pumping:

$$H(t)=H_0+h_H\cos\omega_Ht, \tag{5}$$

$$\omega(t)=\omega(H_0)+\frac{\partial\omega}{\partial H_0}h_H\cos\omega_Ht. \tag{6}$$

Modulation of the external field (5) when the threshold is exceeded, $h_H>h_H^{\rm thr}$, leads to parametric instability for those normal modes of the magnetoelastic oscillations, for which the paramagnetic-resonance condition $\omega=\omega_H/2$ is satisfied. The parametric excitation is described by a Mathieu equation (see, e.g., Ref. 10), one of the solutions of which constitutes exponentially growing oscillations.

For the exponential growth rate of the amplitude of the magnetoelastic oscillations (for the normal mode with frequency ω) and for the threshold of the parametric instability we obtain, introducing the damping α,

$$\Omega=[(\eta h_H)^2-(\omega-\omega_H/2)^2]^{1/2}-\alpha>0; \tag{7}$$

$$\text{at}\quad \omega=\omega_H/2:\quad \Omega=\eta h_H-\alpha,\quad h_H^{\rm thr}=\alpha/\eta; \tag{8}$$

$$\eta=\frac{1}{2}\frac{\partial\omega}{\partial H_0}=\frac{\gamma_e}{4}\frac{\gamma_e^2(H_D+2H_0)H_e\Omega_{\rm me}}{\omega_{e_1}^4}\frac{\omega_0^2}{\omega}. \tag{9}$$

The magnetoelastic oscillations produce an inhomogeneous local RF field at the nuclei, with a value determined by the expression[9b]

$$H_1=2H_n\frac{\gamma_eH_E\omega_{\rm me}^{(1)}}{\omega_{e_1}^2}u_{xy}+2H_n\frac{\gamma_eH_E\omega_{\rm me}^{(3)}}{\omega_{e_1}^2}u_{zx}, \tag{10}$$

where $\omega_{\rm me}^{(i)}=\gamma_eG_i/M_0$ and $H_n=AM_0$ is the constant hyperfine field.

For numerical estimates we can use the results of Ref. 11, from which we get in a constant field $H_0=120$ Oe the values $\eta=\frac{1}{2}\partial\omega/\partial H_0=0.2\cdot10^6$ rad/sec-Oe and $G_3=14\times10^6$ erg/cm^3. Using these values and assuming a damping $\alpha=10^6$ sec^{-1}, we obtain the threshold value $h_H^{\rm thr}=5$ Oe, which is of the same order as the experimental $h_H^{\rm thr}=1$ Oe. Using Eq. (7) and the dependence of $h_H^{\rm thr}$ on the detuning $\Delta\omega_H$ (Fig. 4), we can also estimate the parameter $\eta=(1-2)\times10^6$ rad/sec-Oe. From (10) we find that elastic oscillations with $\|u\|\sim10^6$ are needed to rotate the nuclear magnetization through an angle $\theta\approx\pi/2$ in a time $\tau=1$ μsec.

For the constant G_1 responsible for the excitation of modes with strain-tensor components in the easy (x,y) plane there are no reliable data. If $G_1>G_3$, then it is just these modes which are observed under parametric pumping; This can explain some discrepancy between the cited estimates and the experimental results.

As noted earlier, during the time of the pump pulse the RF field at the nuclei is of the standing-wave type. At a distance equal to half the wavelength the phase shifts jumpwise by π. Thus, if a sufficiently large number of half-waves fits inside the crystal, then the number of spins acted upon by the field with phase φ will approximately coincide with the number of spins acted upon by a field with phase $\varphi+\pi$. If we disregard the spatial inhomogeneity of the RF field amplitude, which affects only the dependences of the amplitudes of the pulsed responses on the duration and amplitude of the pump, then we can use a simple model that describes the singularities of such a symmetrical inhomogeneous excitation of the nuclear spin system. The nuclear spins can be broken up into two parts, which are acted upon during the time of the pump pulse by out-of-phase RF fields during the time of the pulse, and by in-phase fields during the time of action of an ordinary resonant pulse. If a sequence of resonant and parametric pulses act on such a system, then we obtain in each part induction signals as well as signals of the Hahn two-pulse echo type and of the stimulated echo type. The receiving system, however, senses only the combined signal. After this addition there are left only the in-phase signals, and the out-of-phase signals cancel each other. Therefore a parametric pulse does not produce an induction signal. The phase of the two-pulse Hahn echo is given by $\varphi=-\varphi_1+2\varphi_2+\varphi_0$, where φ_1 and φ_2 are the phase shifts of the first and second pulses. Therefore if the second pulse is parametric, then its echo will be observed, since the phase shift of the echo in the first region is φ, and in the second $\varphi+2\pi$. The phase shift of the stimulated echo is equal to $\varphi=-\varphi_1+\varphi_2+\varphi_3+\varphi_0$, and consequently if one of the three pulses is parametric, no stimulated echo is observed, inasmuch as in the first region the phase shift is φ and in the second $\varphi\pm\pi$. If the number of pulses is two, however, then the stimulated echo will have the same phase in both parts of the sample. The last statement is valid only in the case when the two parts in each parametric pulse the breakups into two parts coincide, i.e., the standing waves have the same configuration. If there is no correlation in these breakups, then the second parametric pulse can not reconstruct the stimulated echo.

A more rigorous analysis can be carried out by using the formalism of the Cayley-Klein parameters α and β.[12] The transformation $\varphi_i\to\varphi_i+\pi$ corresponds to the parameter transformation

$$\alpha_i\to\alpha_i,\quad \beta_i\to-\beta_i. \tag{11}$$

For example, the complex amplitudes of the induction, two-pulse, and stimulated echo signals are given by

$$-2\alpha_1\beta_1,\quad 2\alpha_1^*\beta_1^*\beta_2^2,\quad \alpha_1^*\beta_1^*\alpha_2^*\beta_2\alpha_3\beta_3. \tag{12}$$

Using the transformation (12), we easily determine the pulse responses that are preserved and those that vanish (are cancelled) for any sequence of resonant and parametric pulses (Fig. 7).

We have considered above the manner in which the echo is formed by ordinary resonant and parametric pulses. His model, however, can always be used in the presence of alternating-field resonant pulses acting out of phase on two equal spin volumes, i.e., the considered scheme is of interest in itself.

DISCUSSION

The presented interpretation and estimates explain, on the whole, the principal observed effects. The most important results reduce to observation, with the aid of NMR, of parametric excitation of magnetoelastic oscillations, and to observation of spatially inhomogeneous excitation of a nuclear spin system. At the same time, certain details have not yet been explained. In particular, some of the echo signals admissible by the scheme of Fig. 7 have not yet been observed in experiment, although there are no examples in which echo signals forbidden by this scheme have been observed. This circumstance may indicate that the conditions for the excitation of magnetoelastic oscillations are not reproducible from pulse to pulse, and that several modes are excited simultaneously. That the initial conditions of the parametric excitations are not reproducible is indicated, in particular, by the experimental observation of instability of the amplitude of the parametric echo from on triggering of a train of pulses to another (Fig. 6).

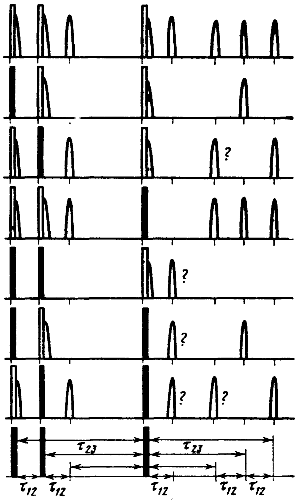

FIG. 7. Diagram illustrating the model of symmetrical inhomogeneous excitation. The echo signals are shown for various sequences of the resonant (light) and parametric (dark) pulses. The echo signals that could not be observed in experiment are marked.

There is no unambiguous explanation for the low intensity of the ordinary echo signal in weak external fields.[5] It should be noted that this fact is observed as a rule in samples in which parametric oscillations are easily excited. It is possible that the low intensity of the signals in samples having a domain structure is due to excitation of magnetoelastic oscillations on account of the motion of the domain walls. In this case, under unfavorable conditions, the phase relation of the echo is violated and the signal weakens, but it can be assumed that under favorable conditions the wall motion produces in the domain magnetoelastic oscillations that lead to formation of an echo from the nuclei in the domains, although the external RF field will excite the domain walls directly.

In this article we hardly touched upon experiments on the influence of nonresonant parametric pumping. We note only that in the case of large detuning $\Delta\omega_H$ parametrically excited magnetoelastic oscillations can upset the echo phasing conditions on account of the additional inhomogeneous local fields, and can lead also to strong acceleration of the irreversible transverse relaxation, an effect similar to the previously investigated influence of parametric pumping of spin waves on NMR in $Y_3FE_5O_{12}$.[13]

An essentially new group of phenomena is to be expected in research at low temperatures. The point is that for liquid-helium temperatures and below, account must be taken, in the formation of echo signals, of the influence of the dynamic frequency shift and of the nonlinear effect due to the high intensity of the nuclear signals in $FeBO_3$, particularly in signals enriched with the magnetic isotope ^{57}Fe. The first experiments performed by us have indeed shown that parametric pumping takes place at $T=4.2$ K, but no parametric echo is observed.

We wish to note in conclusion that the here-revealed possiblility of investigating magnetoelastic oscillations with the aid of nuclear echo may be quite useful for the determination of the magnetoelastic constants as well as to study the above-threshold state in parametric excitation.

The authors thank A. P. Paugurt for helpful discussions and for help with the experiments.

[1)]This statement is valid also when several normal modes are excited, since the phase of the excited oscillations is rigidly connected with the phase of the pump field.

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Hopping photoconductivity of disordered systems

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The action of electromagnetic radiation on the static hopping conductivity of disordered systems, due to the change of the hopping probability in the radiation field, is considered. The model of a weakly doped compensated semiconductor is used. Expressions are obtained for the relative change of the conductivity, with multiphoton processes taken into account.

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1. At sufficiently low temperatures the conductivity of certain disordered systems, such as doped compensated semiconductors, amorphous semiconductors, and others, is due to carrier transfer between localized states (called hopping conduction[1,2]) (see also Refs. 3 and 4). In view of the random scatter of the scatter of the energies of the localized states, the transfers of carriers between them are inevitably accompanied by absorption or emission of acoustic phonons. If, however, the system is the field of electromagnetic radiation, then photons participate in the carrier transfer rather than phonons, and this produces a photocurrent.[5] For a monochromatic wave, however, owing to the indicated scatter of the localized-state energies, the contribution to the conductivity from the hops in which only photons take part is small compared with the contribution of the hops stimulated simultaneously by photons and phonons. The influence of these processes on the static hopping conductivity in the region of relatively low frequencies of the radiation was investigated in Ref. 6, and the method proposed there makes it possible to take multiphoton processes into account.

Hopping conduction was observed experimentally in extremely purified and compensated n-InSb.[7] A detailed exposition of the results of that study is contained in Ref. 8. The authors describe their own interpretation of the observed photoconductivity, but they use some phenomenological parameters (e.g., the time that the electron participates in the photocurrent, the light absorption coefficients) whose connection with the characteristics of the semiconductor has not been established. In Refs. 9 and 10 was investigated hopping photoconductivity of strongly doped uncompensated semiconductors, and also of amorphous semiconductors in the band-bending model. The photoconductivity considered in Refs. 6, 9, and 10 is due to the change of the

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