the data taken from[2,3] and with the new experiments in Fig. 2. The curve runs close to the results obtained by static measurements at pressures of $P<10$ kbar, but differ by 1.5–2 orders of magnitude from the data characterizing the viscosity of water behind the shock wave front. The agreement between the predictions of the hole theory of liquids and the experimental data is achieved by assuming that $\alpha=1$ at high pressures, i.e., the vacancy volume is equal to the volume of a molecule. This value of α corresponds to the upper curve in Fig. 2. According to[3] and in agreement with[14], the dramatic increase in the viscosity of water behind the shock wave front is due to partial or complete freezing. In our view, the more probable reason is the formation at high pressures of strongly interacting molecular associations in the liquid phase.

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Conditions for parametric excitation of spin waves in a sample with regular domain structure

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A theoretical and experimental investigation has been made of parametric excitation of spin waves in a single-crystal nickel ferrite sample in the presence of a domain structure. The results of the theory developed by Pil'shchikov (Sov. Phys. JETP **39**, 323, 1974) are used. A computer is used to determine the dependence of the threshold field on the constant field and to obtain the spectrum of the stable spin waves for the case of parallel and perpendicular pumping. It is shown that the conditions for the instability of the spin waves are determined by the following: 1) singularities of the spectrum of the spin waves in the domains, 2) the conditions for the excitation of homogeneous precession in samples with a domain structure. The experimental data obtained at 9400 and 3050 MHz confirm the main conclusions of the theory.

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INTRODUCTION

A theory of the instability of spin waves (SW) in a ferrite sample with a domain structure (DS) was proposed in[1]. The calculation of the threshold field $h_{\rm thr}$ was carried out for a spherical single-crystal sample of cubic symmetry with a negative first anisotropy constant ($K_1<0$) at arbitrary orientation of the pump field. It was proposed that a sample magnetized by an external constant field (H) applied along the [110] axis has a two-phase plate-like DS with domain walls perpendicular to the (001) plane and making an angle α with the [110] axis.[2] In this case the magnetization in the constant field is due only to the rotation of the magnetization in the domains, without a change in their relative volumes.

The following assumptions were used in the calculations: a) the domain walls do not move; b) there is no interaction between the SW of neighboring domains; c) the SW in each domain are regarded as plane waves (the boundary conditions on the sample boundaries and on the domain walls are disregarded). For a perpendicular DS ($\alpha=90°$), in the case of three types of pumping (parallel $\mathbf{h}\parallel\mathbf{H}$, perpendicular and symmetrical $\mathbf{h}\perp\mathbf{H}$ and $\mathbf{h}\parallel[1\bar{1}0]$, and perpendicular antisymmetrical $\mathbf{h}\perp\mathbf{H}$, $\mathbf{h}\parallel[001]$), expressions were obtained for the homogeneous precession (formulas (16)–(19) of[1])1) and an approximate qualitative analysis of $h_{\rm thr}(H)$ was carried out.

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On the basis of the results of[1] we can identify the main factors that determine the conditions for spin-wave instability in domains.

1. At any orientation of the pump field **h**, there is realized for the SW in the domains an oblique or perpendicular pump direction relative to the static magnetic moment in the domains,[2)] and consequently lowering of the threshold field is possible when the positive resonance approaches the principal resonance in the sample with the DS.

2. The threshold field and the spectrum of the unstable SW, just as in a sample magnetized to saturation, are determined by the spectrum of frequency-degenerate SW with the frequency equal to half the pump frequency, and by the conditions for the excitation of the homogeneous precession at different orientations of the external high-frequency field.

We report in this paper the first results of an experimental verification of the theory developed in[1]. The theory and experiment were compared for single-crystal nickel ferrite, the choice of which was governed by the following considerations:

a) The data on the magnetic resonances of homogeneous and inhomogeneous magnetostatic modes demonstrate that the model of plate-like perpendicular DS[3–5] is valid in high-grade single crystals of nickel ferrite in a wide range of magnetizing fields.

b) Owing to the large magnetization and to the anisotropy field in this ferrite, the frequencies of the parallel homogeneous resonance are quite high, making it possible to make the pump frequency equal to the frequency of this resonance in the microwave band.

c) Nickel ferrite has a relatively narrow absorption curve; thus, in conjunction with the large magnetization, makes it possible to investigate threshold phenomena at relatively low pump levels.

The theoretical and experimental results were obtained for spherical samples with parameters $4\pi M = 3200$ G, $|K_1|/M = 265$ Oe, and gyromagnetic ratio $\gamma = 3.1$.

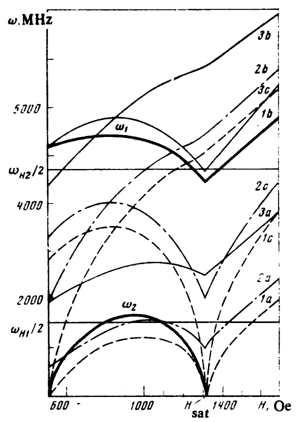

FIG. 1. Spin-wave spectrum in a nickel ferrite sample. $H < 1330$ Oe is the region of existence of the domain structure. Curves 1—for $Dk^2 = 0$, curves 2—for $Dk^2 = 10^2$, curves 3—for $Dk^2 = 5 \cdot 10^2$; a—at $\theta_k = 0$, $\varphi_k = 0$, b—at $\theta_k = \pi/2$, $\varphi_k = 0$, c—at $\theta_k = \pi/2$, $\varphi_k = \pi/2$.

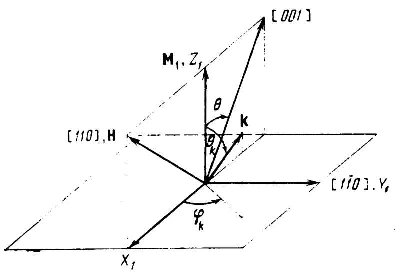

FIG. 2. Local system of coordinates for the domain.

1. SPIN-WAVE SPECTRUM IN SPHERICAL SAMPLE MAGNETIZED ALONG THE [110] AXIS

The SW spectrum was calculated from the dispersion relation using the formulas of[6] for a sample magnetized to saturation, and the formulas of[1] for the domains. In the analysis of the dependence of the threshold field on the external constant field H, it is convenient to represent the SW spectrum in the form $\omega(H)$.

Figure 1 shows the SW spectrum for a nickel ferrite, where k, θ_k, and φ_k are the wave number and the polar and azimuthal angles of the SW wave vector (see Fig. 2). Figure 1 shows also plots of $\omega(H)$ for the homogeneous-precession frequency in the case of perpendicular (ω_1) and parallel (ω_2) excitation.[1,2,7,8] The frequencies equal to half the pump frequencies (ω_{H1}, ω_{H2}) used in the experiment are also marked.

It is seen from the plots in Fig. 1 that the spectrum of the SW in the domains differs strongly from the spectrum in a sample magnetized to saturation. Whereas in the saturation region ω_k increases with increasing H for all values of k, in the domains this dependence can be either monotonic or nonmonotonic (with a maximum) for different values of k. Because of these peculariarities, the upper limit of the SW spectrum in the domain region, at fields close to the saturation field, corresponds to SW with $\theta_k = \pi/2$, $\varphi_k = 0$ (just as in the saturated region), and in weak fields it corresponds to SW with $\theta_k = \varphi_k = \pi/2$.

It is interesting to note that in the presence of domains there can exist two field regions in which a given frequency is degenerate with SW having the same k. It should be borne in mind, however, that at different H the starting magnetization **M** in the domain can be differently oriented relative to the crystallographic axes, and consequently SW with identical **k** propagate in different crystallographic direction.

2. THRESHOLD FIELD AND SPECTRUM OF UNSTABLE SPIN WAVES

The theoretical plots of $h_{\text{thr}}(H)$ and the spectrum of the unstable SW (for pump frequencies 3050 and 9400 MHz) were obtained by numerical computer minimization of the threshold fields ((13), (16)–(19) in[1]) relative to θ_k, φ_k, k for each value of the field H. It was assumed in the minimization that $\Delta H_k = \text{const}$.

Figures 3–5 show the results of the minimization of the threshold fields h_{thr} and θ_k, φ_k, Dk^2 (D is the ex-

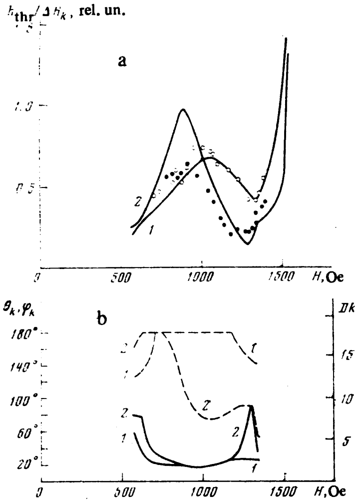

FIG. 3. Plots of $h_{thr}/\Delta H_k$, θ_k, φ_k, Dk^2 against H ($\mathbf{h}\perp\mathbf{H}$, frequency 3050 MHz); curves 1—symmetrical pump, 2—antisymmetrical pump. Figure a: solid lines—theory, points—experiment; ○—for curve 1, ●—for curve 2; Figure b—solid lines for θ_k, dashed for φ_k, Dk^2 is close to 0.

change constant). The values of h_{thr} in the saturation region were obtained by minimizing the expressions given in[9] for the threshold field.

Frequency 3050 MHz. In the wide range of fields (800–1100 Oe), the degenerate SW are those close to the lower limit of the spectrum ($\theta_k \approx 0$) (Fig. 1). It is known that at any pump-field orientation the spin waves having these θ_k have very high threshold-field values. Degenerate SW with θ_k from 0 to 90° appear at different φ_k and k (Fig. 1) and having a lower threshold (Fig. 3b) only in fields close to the saturation field, as well as in weak field ($H < 800$ Oe).

Consequently, the $h_{thr}(H)$ curve have a maximum in the field interval 800–1100 Oe (Fig. 3a) at all the pump-field orientations. The indicated singularities of the SW spectrum determine the maximum of the threshold field even in the case of parallel pumping, when the frequency of the principal resonance ω_2 ($\omega_{2max} \approx 1700$ MHz) is close

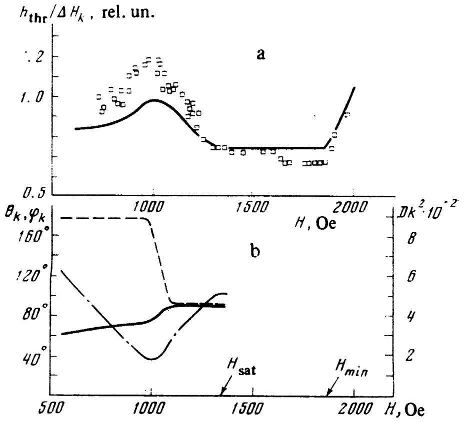

FIG. 4. Plots of $h_{thr}/\Delta H_k$, θ_k, φ_k, Dk^2 against H($\mathbf{h}\parallel\mathbf{H}$, frequency 9400 MHz). Figure a: solid line—theory, ⊐—experiment; figure b: solid line for θ_k, dashed for φ_k, and dash-dot for Dk^2.

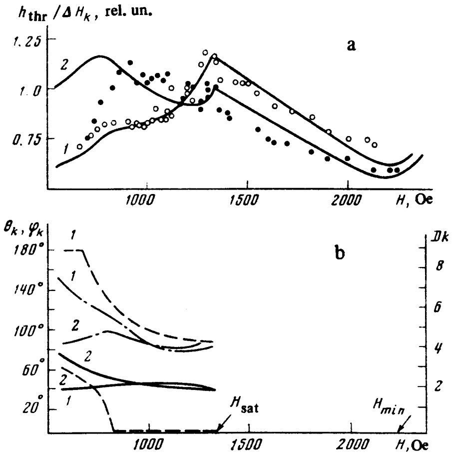

FIG. 5. Plots of $h_{thr}/\Delta H_k$, θ_k, φ_k, Dk^2 against H($\mathbf{h}\perp\mathbf{H}$, frequency 9400 MHz). The symbols are the same as in Fig. 3.

enough to the pump frequency (Fig. 1), which should lead to a lowering of the threshold field at $H \approx 900$ Oe.

Frequency 9400 MHz (Figs. 4 and 5). In the case of parallel pumping ($\mathbf{h}\parallel\mathbf{H}$) the pump frequency is far from the FMR frequency ω_2 (Fig. 1). Consequently, the threshold field is determined in the main by the SW spectrum. In fields close to the saturation field, **h** turns out to be almost parallel to **M**. The degenerate SW are those with $\theta_k \simeq \varphi_k \approx \pi/2$ (Fig. 4b) with minimum threshold. With decreasing field, θ_k of the degenerate SW decreases, and this leads, as is known from experiments on parallel pumping in samples magnetized to saturation, to an increase of the threshold field.

In weak fields, the pump becomes perpendicular to **M**, and some of the degenerate SW have a relatively low threshold ($\theta_k \approx 65°$, $\varphi_k \approx 180°$). As a result, $h_{thr}(H)$ has a maximum at $H \approx 1000$ Oe (Fig. 4a).

In the case of perpendicular pumping ($\mathbf{h}\perp\mathbf{H}$), the pump frequency is much closer to the FMR frequency ω_1 (Fig. 1), so that homogeneous precession exerts a much greater influence on h_{thr}.

The conditions for the excitation of homogeneous precession at different RF field orientations are determined by the ellipticity of the precession of the magnetization. In the saturation field, the ellipticity is due mainly to anisotropy. The major axis of the ellipse is parallel to [001], and the excitation intensity is maximal when **h** is directed along this axis. With decreasing magnetizing field, owing to rotation of the magnetization vector of the domains, the ellipticity due to the anisotropy decreases, and that due to the demagnetizing field at the domain walls increases. The RF magnetization component parallel to the [001] axis decreases. Accordingly, with decreasing constant field the intensity of the homogeneous precession for antisymmetrical excitation ($\mathbf{h}\parallel[001]$) decreases monotonically. For symmetrical excitation ($\mathbf{h}\parallel[110]$) the picture is reversed—the excitation intensity of the homogeneous precession increases with decreasing H.

In the case of antisymmetrical perpendicular pumping

($\mathbf{h} \parallel [001]$) in fields close to the saturation field, the pump is perpendicular to the vector **M** and the degenerate SW are those with $\theta_k \approx 40$, which have a relatively low threshold. In this field, the $h_{thr}(H)$ dependence is determined by the conditions for the excitation of homogeneous precession, the intensity of which decreases with decreasing H. As a result, h_{thr} increases. In weak field, the pumping becomes parallel to **M**, and among the degenerate SW there appear waves with relatively large $\theta_k \approx 60-65$, i.e., with low thresholds at this pump. This decreases the threshold field. Consequently, the $h_{thr}(H)$ dependence for antisymmetrical pumping has a maximum at $H \approx 800$ Oe (Fig. 5a).

In the case of symmetrical pumping we have ($\mathbf{h} \parallel [1\bar{1}0]$) at all H, $\mathbf{h} \perp \mathbf{M}$, i.e., the pump is always perpendicular. In the entire magnetizing-field range, degeneracy with SW with $\theta_k \approx 40$ is possible, i.e., with the same waves as for antisymmetrical pumping in strong fields. The intensity of the homogeneous precession in strong fields, however, is weaker than for antisymmetrical pumping, and increases with decreasing H. Consequently, $h_{thr}(H)$ decreases monotonically with decreasing H (Fig. 5a).

3. EXPERIMENTAL RESULTS

A check on the main conclusions of the theoretical calculations was carried out by comparing the theoretical and experimental $h_{thr}(H)$ dependences. It must be borne in mind, however, that the theoretical $h_{thr}(H)$ were obtained by minimizing the expression for the threshold field at $\Delta H_k = \text{const}$. One can therefore not expect full agreement of the absolute theoretical and experimental values of the threshold fields. It is important to establish a correspondence in the course of these relations themselves and the presence of the most characteristic singularities for different types of pumping.

The principal measurements of the threshold fields were made on samples of 2.8 mm diameter at a frequency 3050 MHz and 1.24 mm at a frequency 9400 MHz. Results similar to those shown in Figs. 3–5 were obtained also for other high-grade samples of nickel single crystals. The threshold fields were determined from the distortion of the wave form of the rectangular pulse passing through the resonator with the sample. To prevent heating of the sample the pump generators operated with a pulse duration 1 μsec and a repetition frequency 10 Hz. The sample was oriented in the (110) plane and was placed in the resonator in such a way that the [110] axis (rotation axis) was parallel to the field **H**.

Figures 3a–5a show the experimental plots of $h_{thr}(H)$. For comparison, the experimental curves were made to coincide with the theoretical curves at the point corresponding to the saturation field. It follows from Figs. 3a–5a that the experimental plots of $h_{thr}(H)$ agree qualitatively with the theoretical ones. We note first that at both pump frequencies there is a clearly pronounced dependence of the threshold field on the RF field orientation at a fixed value of the constant field, and in a large field interval ($H > 900$ Oe) the difference of h_{thr} for symmetrical and antisymmetrical pumping is close to the theoretical one.

At 9400 MHz and $\mathbf{h} \parallel \mathbf{H}$ there is a strongly pronounced maximum of the threshold field in the region of fields close to theoretical. For the case $\mathbf{h} \perp \mathbf{H}$, the experimental plots of $h_{thr}(H)$ also agree with the theory for symmetrical and antisymmetrical pumping. As follows from the theory, in the case of symmetrical pumping $h_{thr}(H)$ decreases monotonically in the domain region with decreasing H, and in the case of antisymmetrical pumping it goes through a maximum. Notice should be taken here of the good agreement between the experimental data and the theoretical ones for the case of symmetrical pumping.

The plots of $h_{thr}(H)$ at the frequency 3050 MHz were obtained only for the case $\mathbf{h} \perp \mathbf{H}$ (at $\mathbf{h} \parallel \mathbf{M}$ the instability could be observed in a very narrow field interval). For this case, the experimental $h_{thr}(H)$ curves are also approximately in agreement with the theoretical ones. Both for symmetrical and antisymmetrical pumping, the plots of $h_{thr}(H)$ go through a maximum, and in the case of symmetrical pumping, just as at 9400 MHz, the experimental data agree well with the theoretical ones.

From a comparison of the theoretical and experimental results it follows that the theory proposed in[1] describes for the most time correctly the conditions of parametric excitation of spin waves in single crystals with domain structure.

In conclusion, the authors thank É. V. Rubal'skaya for supplying the high-grade single-crystal samples.

1)The term $2B_k \cos\varphi_k$ in the expression for T' in[1] should be preceded by a minus sign.

2)The terms "parallel" and "perpendicular" pumping ($\mathbf{h} \parallel \mathbf{H}$, $\mathbf{h} \perp \mathbf{H}$) were first introduced in the literature for a saturated sample for which it was assumed that $\mathbf{M} \parallel \mathbf{H}$. Actually, the conditions for the instability of the SW are determined by the orientation of **h** relative to **M**. This circumstance must be taken into account when considering excitation of SW in domains in which **M** and **H** do not have the same direction.

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