under his direction for a discussion. Finally, I take pleasure in thanking É. B. Amitin, A. I. Larkin, E. V. Matizen, and F. I. Khomskiĭ for a discussion of the work.

[1)] This phenomenon is discussed in the Gehrings' review.[2] We emphasize that when the exchange is via acoustic phonons the total effect is due to the presence of a gap in the spectrum of the elastic fluctuations. We note also that the presence of the gap in the spectrum extends the region of validity of the Landau theory to cover the entire vicinity of the phase transitions.[3,4]

[2)] The separation of the contribution of the acoustic oscillations to the thermodynamic potential and the ensuing effective interaction in the form (8) correspond to diagonalization of the part of the Hamiltonian H with $\mathbf{k} \neq 0$.

[3)] If the nonlinearity of the phonon spectrum is of importance to the short-wave part of the momenta corresponding to the considered lattice of two-level systems, then the effective interaction via the phonons also contains a contribution that depends on the distances between the lattice points.

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Theory of dislocation retardation in antiferromagnets

V. G. Bar'yakhtar, V. V. Gann, E. I. Druinskiĭ, A. I. Zhukov, and V. F. Klepikov

Physicotechnical Institute, Ukrainian Academy of Sciences

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We investigate dislocation retardation in antiferromagnets as a result of "Cerenkov" generation of spin waves and their scattering by the moving dislocations, as a function of the ground state of the antiferromagnet. It is established that the retardation force has a velocity threshold in the magnon generation mechanism; the influence of the magnetic field on the threshold velocity is investigated. The dependence of the retardation force on the temperature, velocity, and orientation of the dislocation is studied. It is shown that in the presence of a non-activation branch in the spin-wave spectrum the retardation force is anomalously large. The general character of the temperature dependence of the retardation force of the dislocations in antiferromagnetic dielectrics and metals is investigated. It is shown that interaction with the spin waves can make a substantial contribution to the dislocation retardation force in antiferromagnets at low temperatures.

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1. INTRODUCTION

It is well known that many properties of solids (plasticity, brittle fracture, microhardness) and also some kinetic phenomena (sound absorption, internal friction, width of ferromagnetic resonance line, etc.) are determined by the dislocations in the crystal. At low tempertures, when the diffusion processes are suppressed, the principal role in the dislocation retardation is played by their interaction with the quasiparticles of the crystal. The interaction of dislocations with phonons and conduction electrons has been sufficiently well investigated (see, e.g., the reviews[1,2]). With metals as the example, it was shown that the restructuring of the quasiparticle spectrum in the superconducting transition exerts a substantial influence on the dependence of the retardation force on the dislocation velocity.[2] The interaction of the dislocations with spin waves and the ensuing additional magnon retardation mechanisms of dislocations in ferromagnets were considered in Refs. 3–5.

Antiferromagnets are typical examples of crystals that are particularly rich in phase transitions, which have been well investigated both experimentally and theoretically.[6] The spin-wave spectra in antiferromagnets are also highly diverse, so that interest attaches to an investigation of the interaction of magnons with dislocations[7] and of the influence of the ground state on the retardation force.

The present paper is devoted to a theoretical study of the influence of magnons on the mobility of dislocations in antiferromagnets. It is shown that dislocation motion with even constant velocity leads to a coherent magnon emission if the dislocation velocity v exceeds the

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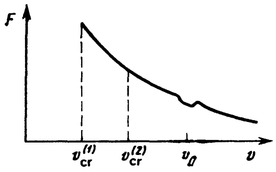

Fig. 1. Schematic dependence of the dislocation retardation force due to Cerenkov generation of spin waves in the absence of damping. The critical velocities $v_{cr}^{(1)} = v_{cr}(H^{(1)})$ and $v_{cr}^{(2)} = v_{cr}(H^{(2)})$ correspond to different values of the magnetic field $(H^{(1)} > H^{(2)})$.

minimum phase velocity v_{cr} of the spin waves.

The mechanisms of "Cerenkov" emission of magnons by a dislocation makes the main contribution to the magnon retardation in the velocity region $v \geq v_{cr}$. The retardation force due to this mechanism is produced jumpwise at $v = v_{cr}$, then decreases with increasing dislocation velocity (see Fig. 1).

When account is taken of the thermal motion of the magnetic moments of the sublattices, it turns out that because of scattering processes in which two or more magnons take part, the contribution of the magnons to the retardation force becomes different from zero also at $v > v_{cr}$. The increment added by these processes to the friction force at $v < v_{cr}$ turns out to be small. Magnon damping blurs the jump on the plot of the retardation force against the velocity, and this plot itself becomes smoother (Fig. 2).

It is known that the external magnetic field determines the activation of the magnons and can influence their phase velocity. This makes it possible to control, with the aid of an external magnetic field, the total "intensity" of the retardation force, the quantity $v_{cr} = v_{cr}(H)$, and the discontinuity of the retardation force at $v = v_{cr}(H)$. It is important to note that the influence of the external magnetic field on the retardation of the dislocations in antiferromagnets differs qualitatively from its influence on the retardation of the dislocations in ferromagnets. In ferromagnets, the increase of the magnetic field leads to a decrease of the retardation force and to an increase[1)] of v_{cr}.[5] In antiferromagnets with magnetic anisotropy of the "easy axis" type, the increase of the magnetic field in phase with the antiparallel arrangement of the magnetic moments leads to a decrease of the activation energy, to a decrease of v, and to an increase of the friction force (see Fig. 1).

In the phase with flopped magnetic moments, the increase of the magnetic field leads to a decrease of the phase velocity of the spin waves, and in a number of

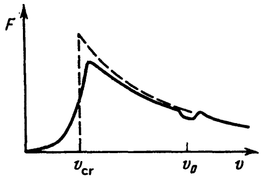

FIG. 2. Dependence of the dislocation retardation force due to the Cerenkov generation of damped spin waves (solid line). The dashed line shows the same plot without damping.

cases to an increase of the discontinuity of the retardation force with increasing magnetic field at $v = v_{cr}(H)$. The retardation force, generally speaking, depends on the direction of the dislocation velocity relative to the crystal axes and to the magnetic field. The anisotropy effect is most pronounced in those antiferromagnet phases in which the spin-wave spectrum has no activation. Thus, for example, in an antiferromagnet with flopped magnetic moments the retardation force is anomalously large when the dislocations move along the magnetic field.

An analysis carried out in the present paper shows that the magnetic field can exert a substantial influence on the plastic properties of antiferromagnets.

2. RETARDATION FORCE OF MOVING DISLOCATION

To describe the interaction of dislocations with spin waves we start from the following expression for the Hamiltonian of an antiferromagnet (AFM):

$$\mathcal{H} = \mathcal{H}_s + \mathcal{H}_{sd}, \tag{2.1}$$

where $\mathcal{H}_s$ is the energy of the spin subsystem:

$$\mathcal{H}_s = \int_{(V)} dr \left\{ \frac{\alpha}{2}\left[\left(\frac{\partial \mathbf{M}_1}{\partial x_i}\right)^2 + \left(\frac{\partial \mathbf{M}_2}{\partial x_i}\right)^2\right] + \alpha' \frac{\partial \mathbf{M}_1}{\partial x_i}\frac{\partial \mathbf{M}_2}{\partial x_i} + \delta \mathbf{M}_1\mathbf{M}_2 - \frac{\beta}{2}[(\mathbf{n}\mathbf{M}_1)^2 + (\mathbf{n}\mathbf{M}_2)^2] - \beta'(\mathbf{n}\mathbf{M}_1)(\mathbf{n}\mathbf{M}_2) - (\mathbf{M}_1 + \mathbf{M}_2)\mathbf{H}\right\}. \tag{2.1a}$$

Here α, α', and δ are the exchange constants; $\mathbf{M}_1$ and $\mathbf{M}_2$ are the magnetic moments per unit volume of the sublattices; β and β' are the magnetic anisotropy constants, $\mathbf{n}$ is a unit vector directed along the easy magnetization axis, and V is the volume of the crystal.

In the energy of the magnetoelastic interaction $\mathcal{H}_{sd}$ we shall take into account both the homogeneous and inhomogeneous magnetostrictions:

$$\mathcal{H}_{sd} = \int_{(V)} dr \left[\gamma_{ik}(\mathbf{M}_1; \mathbf{M}_2) w_{ik}(\mathbf{r}, t) + \gamma^{jj'}_{ik,sp} \frac{\partial \mathbf{M}_j}{\partial x_i}\frac{\partial \mathbf{M}_{j'}}{\partial x_k} w_{sp}(\mathbf{r}, t)\right]. \tag{2.1b}$$

We assume the antiferromagnet to be isotropic in terms of the magnetostriction properties. We then write

$$\gamma_{ik}(\mathbf{M}_1; \mathbf{M}_2) = \gamma_1(M_{1i}M_{1k} + M_{2i}M_{2k}) + \gamma_2(M_{1i}M_{2k} + M_{1k}M_{2i}) + \delta_{ik}[\delta\gamma_3\mathbf{M}_1\mathbf{M}_2 + \gamma_4(M_1^2 + M_2^2)], \tag{2.2a}$$

$$\gamma^{jj'}_{ik,sp} = \alpha^{jj'}[{}^1/_2\beta_1(\delta_{is}\delta_{kp} + \delta_{ip}\delta_{ks}) + \beta_2\delta_{ik}\delta_{sp}], \tag{2.2b}$$

where $\alpha^{11} = \alpha^{22} = \alpha_1$; $\alpha^{12} = \alpha^{21}\alpha_2$; the quantities γ_i, β_1, and β_2 are dimensionless and are of the order of unity; $j, j' = 1, 2$.

At a dislocation velocity much larger than the speed of sound the distortion tensor w_{ik} can be regarded as a given function of the coordinates and time: $w_{ik} = w_{ik}(\mathbf{r} - \mathbf{r}_0 - \mathbf{v}t)$ ($\mathbf{r}_0$ is the initial coordinate of the dislocation core and $\mathbf{v}$ is dislocation velocity). We neglect here the reaction of the magnetic subsystem on the elastic fields in the crystal. In addition, we consider those AFM in which the phase velocity of the spin waves is much less than the speed of sound; we shall therefore neglect "relativistic" effects in the dislocation motion.

It is known that the force acting on a dislocation is determined by the tensor of the stresses on the dislocation axis in accordance with the Peach-Koehler formula:

$$F_i = -\varepsilon_{ike}\tau_k\tilde{\sigma}_{se}b_s, \qquad (2.3)$$

where $\tilde{\sigma}_{se} = \sigma_{se} - \frac{1}{3}\sigma_{ll}\delta_{se}$, b_s is the Burgers vector component, τ_k is a unit vector along the dislocation axis, and σ_{se} is the elastic stress tensor. In magnetically ordered crystals σ_{se} is determined not only by the distortion tensor but also, owing to magnetostriction, by the magnetic moments of the sublattices

$$\sigma_{se} = \sigma_{se}^{0} + \sigma_{se}^{m}(\mathbf{M}_j).$$

The presence of dislocations leads to deviations of the magnetic moments from their equilbrium values $\mathbf{M}_{0j}$, so that $\mathbf{M}_j = \mathbf{M}_{0j} + \mathbf{m}_j(\mathbf{r}, t)$; therefore

$$\sigma_{se}^{m}(\mathbf{M}_j) = \sigma_{se}^{m}(\mathbf{M}_{0j}) + \sum_{j'} \frac{\partial\sigma_{se}^{m}(\mathbf{M}_{0j})}{\partial\mathbf{M}_{j'}} \mathbf{m}_{j'}(\mathbf{r}, t)\Big|_{\mathbf{r}=\mathbf{r}_0+\mathbf{v}t}, \qquad (2.4)$$

where the first term describes the stresses in the crystal due to the homogeneous magnetization, the second is connected with the transfer of energy from the dislocation to the magnetic subsystem, i.e., to the onset of the friction force F_i^m:

$$F_i^m = \varepsilon_{ike}\tau_k \sum_{i} \frac{\partial\sigma_{se}(\mathbf{M}_{0j})}{\partial\mathbf{M}_j} \mathbf{m}_j(\mathbf{r}, t)\Big|_{\mathbf{r}=\mathbf{r}_0+\mathbf{v}t} b_s. \qquad (2.5)$$

In this formula the value of the deviation $\mathbf{m}_j$ is taken on the dislocation axis.

To find the deviations $\mathbf{m}_j$ it is necessary to use the equations of Landau and Lifshitz:

$$\partial\mathbf{m}_j/\partial t = g[\mathbf{M}_{0j} \times \mathbf{H}_j^{eff}], \qquad (2.6)$$

where the effective fields are defined by

$$\mathbf{H}_j^{eff} = -\delta\mathscr{H}/\delta\mathbf{m}_j.$$

The presence of moving dislocations leads to the appearance in $\mathbf{H}_j^{eff}$ of a term proportional to the components of the distortion tensor $w_{ik}(\mathbf{r} - \mathbf{r}_0 - \mathbf{v}t)$. Since the Fourier components of the tensor $w_{ik}(\mathbf{k}, \omega)$ are proportional to $\delta(\omega - \mathbf{kv})$, the solution of (2.6) takes the form

$$\mathbf{m}_j(\mathbf{k}, \omega) = \mathbf{f}_j(\mathbf{k}, \omega)\delta(\omega - \mathbf{kv})e^{-i\mathbf{k}\mathbf{r}_0}.$$

The deviation on the dislocation axis is then equal to

$$\mathbf{m}_j = \frac{1}{(2\pi)^4}\int d\mathbf{k}\,\mathbf{f}_j(\mathbf{k}, \mathbf{kv}). \qquad (2.7)$$

Formulas (2.4)–(2.7) solve the problem of finding the friction force. The function $f_j(\mathbf{k}, \omega)$ has poles at $\omega = \varepsilon_j(\mathbf{k})$, while $f_j(\mathbf{k}, \mathbf{kv})$ has a singularity at

$$\mathbf{kv} = \varepsilon_j(\mathbf{k}). \qquad (2.8)$$

This equation determines the wave vectors of the spin waves that can be radiated by a moving dislocation. Equation (2.8) has a solution only at $v > v_{cr}$, where v_{cr} is the minimal velocity of the spin waves; therefore the structures of $\mathbf{m}_j$ at $v > v_{cr}$ and $v < v_{cr}$ are principally different. The distribution of the magnetization at $v < v_{cr}$ does not differ qualitatively from the distribution around the immobile dislocations; $\mathbf{m}_j$ on the dislocation axis is equal to zero in this case.[8] At $v > v_{cr}$ the quantity $\mathbf{m}_j$ remains finite as $r \to \infty$ and describes the propagating spin waves.

The friction force determines the energy losses per unit time in the course of the dislocation motion:

$$\dot{Q} = \mathbf{Fv}. \qquad (2.9)$$

In nonequilibrium thermodynamics there are well developed methods for the calculation of the energy dissipation $\dot{Q}$. A second independent method of calculating the magnon retardation force can therefore be proposed.

We represent the magnetoelastic energy (2.1b) in terms of the spin-wave creation and annihilation operators[6]:

$$\mathscr{H}_{sd} = \sum_{\mathbf{k},\mathbf{q},j,j'} e^{-i\mathbf{qv}t}\{\Phi_j(\mathbf{q})c_{j,-\mathbf{q}} + \Psi_{j,j'}(\mathbf{k},\mathbf{q})c^{+}_{j,\mathbf{k}+\mathbf{q}}c_{j',\mathbf{k}}$$

$$+\chi_{jj'}(\mathbf{k},\mathbf{q})c^{+}_{j,\mathbf{k}}c^{+}_{j',-\mathbf{k}+\mathbf{q}}\} + \text{H.c.} \qquad (2.10)$$

The scattering amplitudes Φ, Ψ, and χ are linear in the components $w_{ik}(\mathbf{q})$. The dependence of $\mathscr{H}_{sd}$ on the time is due to the dislocation motion.

The expression for the energy dissipation per unit dislocation length L is of the form

$$\dot{Q} = -\frac{1}{L}\sum_{i,f}\omega_{if}(\nu_{if} - \nu_{fi}), \qquad \omega_{if} = \omega_i - \omega_f, \qquad (2.11)$$

where ν_{if} is the probability of the transition in the magnetic subsystem from the state i to the state f under the influence of the perturbation; ω_{if} is the transition energy.

Using (2.10) and (2.11), we represent the dislocation energy loss due to the magnon retardation mechanisms in the form

$$\dot{Q} = -\frac{2\pi}{L}\sum_{\mathbf{q},j}(\mathbf{qv})|\Phi_j(\mathbf{q})|^2\delta[\varepsilon_j(\mathbf{k}) - \mathbf{qv}]$$

$$-\frac{2\pi}{L}\sum_{\mathbf{k},\mathbf{q},j,j'}(\mathbf{qv})|\chi_{jj'}(\mathbf{k},\mathbf{q})|^2[1 + n(\varepsilon_j(\mathbf{k}))$$

$$+n(\varepsilon_{j'}(\mathbf{k}-\mathbf{q}))]\delta[\varepsilon_j(\mathbf{k}) + \varepsilon_{j'}(\mathbf{k}-\mathbf{q}) - \mathbf{qv}]$$

$$-\frac{2\pi}{L}\sum_{\mathbf{k},\mathbf{q},j,j'}(\mathbf{qv})|\Psi_{jj'}(\mathbf{k},\mathbf{q})|^2[n(\varepsilon_j(\mathbf{k}))$$

$$-n(\varepsilon_{j'}(\mathbf{k}+\mathbf{q}))]\delta[\varepsilon_j(\mathbf{k}) - \varepsilon_{j'}(\mathbf{k}+\mathbf{q}) - \mathbf{qv}]. \qquad (2.12)$$

The first term in (2.12) corresponds to the energy lost by the moving dislocation on account of the "Cerenkov" radiation of the spin waves. The second term describes the energy losses in the course of radiation of two magnons by the moving dislocation (this process, just as the "Cerenkov" radiation, has a threshold). The third term describes the energy loss due to the scattering of the thermal magnons by the moving dislocation. The last process, in contrast to the preceding ones, has no velocity threshold and makes a contribution at all dislocation velocities. The emission of two magnons is a process of second order compared with the Cerenkov radiation and can therefore be omitted. The process of magnon scattering by dislocations depends substantially on the temperature, and its contribution to the energy dissipation is small compared with the contribution of the "Cerenkov" radiation in terms of the parameter T/Θ_N; at $v < v_{cr}$, however, when there is no "Cerenkov" radiation, the scattering of the magnons by the dislocations must be taken into account.

3. AFM WITH MAGNETIC ANISOTROPY OF THE EASY AXIS TYPE

We consider the motion of a screw dislocation in an AFM with anisotropy of the easy axis type ($\beta-\beta'>0$). We dwell first on the case when the magnetic field is oriented along the anisotropy axis z and is weaker than the flopping field $H_1=M_0[(2\delta+\beta-\beta')(\beta-\beta')]^{1/2}$. If the Burgers vector of the dislocation is directed along the magnetic field, and the dislocation moves perpendicular to the direction of the magnetic field, then the retardation force due to the "Cerenkov" generation of spin waves is equal to

$$F=\frac{gM_0^4b^2\tilde{\gamma}^2\delta}{H_1v}\theta\left(\frac{v}{v_{cr}}-1\right), \tag{3.1}$$

where θ is the Heaviside function,

$$v_{\kappa}=v_0(1-H^2/H_1^2)^{1/2}, \quad v_0=gM_0[2\delta(\alpha-\alpha')]^{1/2}, \quad \tilde{\gamma}=\gamma_1-\gamma_2.$$

Expression (3.1) takes into account the excitation of the magnons with a dispersion law $\varepsilon_1=(\varepsilon_0^2+v_0^2k^2)^{1/2}-gH$, where $\varepsilon_0=gH_1$. Starting with the velocity

$$v>v^*=v_0\left[1+\left(\frac{\alpha+\alpha'}{\alpha-\alpha'}\right)^{1/2}\frac{H}{\delta M_0}\right]$$

a second spin-wave branch is excited

$$\varepsilon_2=(\varepsilon_0^2+v_0^2k^2)^{1/2}+gH.$$

The expression for the retardation force is described in this case mainly by formula (3.1). The inclusion of the second branch of the wave leads to the appearance of the singularity in the dependence of F on v; this is shown in Fig. 1. The jump of the force F at $v=v^*$ is estimated from the formula

$$\Delta F|_{v=v^*}\approx\frac{1}{8}\frac{gM_0^3b^2\tilde{\gamma}^2}{v^*}\left(\frac{\alpha+\alpha'}{\alpha-\alpha'}\right)^{1/2}. \tag{3.2}$$

We consider now an AFM in a phase with a flopped magnetic moment. If the dislocation is oriented along the magnetic field and moves perpendicular to the plane of the magnetic moments, then at $v>v_{cr}$ only the upper branch of the spin waves is excited, and the retardation force is determined by the formula

$$F_1=\frac{gM_0^3}{2v}[(\gamma_1+\gamma_2)\eta^2-\tilde{\gamma}\nu^2]^2b^2\left\{\frac{\alpha+\alpha'}{[(\alpha+\alpha')^2\eta^2+(\alpha^2-\alpha'^2)\nu^2]^{1/2}}+\left[\frac{2\delta}{2\delta\eta^2-(\beta-\beta')\nu^2}\right]^{1/2}\right\}\theta\left(\frac{v}{v_{cr}}-1\right), \tag{3.3}$$

where

$$\eta=H/H_2, \quad H_2=2\delta M_0, \quad \nu=(1-\eta^2)^{1/2}, \quad H_1/H_2\leqslant\eta\leqslant1,$$
$$v_{cr}=gM_0\{[[2\delta\eta^2-(\beta-\beta')\nu^2](\alpha+\alpha')]^{1/2}+[2\delta[(\alpha+\alpha')\eta^2+(\alpha-\alpha')\nu^2]]^{1/2}\}.$$

We note that when H approaches H_1 for dislocations with disorientation the friction force increases substantially and its value at the phase-transition point is

$$F_1=\frac{1}{2v}gM_0^3\tilde{\gamma}^2\frac{\delta}{[\beta(\beta-\beta')]^{1/2}}b^2\times\theta\left(\frac{v}{v_{cr}(H_1)}-1\right). \tag{3.3a}$$

If the dislocation having the same orientation moves in the plane of the magnetic moments, then at $v>v_{cr}$ the upper branch of the spin waves is excited, as before, and the friction force is

$$F_2=\frac{1}{2v}gM_0^3(\gamma_1+\gamma_2)^2b^2\eta^2\times\left\{\left[\frac{(\alpha+\alpha')\eta^2+(\alpha-\alpha')\nu^2}{\alpha+\alpha'}\right]^{1/2}+\left[\frac{2\delta\eta^2-(\beta-\beta')\nu^2}{2\delta}\right]^{1/2}\right\}\theta\left(\frac{v}{v_{cr}}-1\right). \tag{3.4}$$

Comparing (3.3) with (3.4), we see that the slowing-down force is anisotropic, since $F_2/F_1\sim\eta^2$ and in magnetic fields $H_1<H\ll H_2$ the force F_1 greatly exceeds F_2.

In the case when the dislocation lies in the basal plane perpendicular to the magnetic-moment-flopping plane ($\boldsymbol{\tau}\perp\mathbf{n}$) and moves along the direction of the magnetic field, the retardation is due to generation of the lower branch of the spin waves, and the retardation force is

$$F=\frac{gM_0^3\tilde{\gamma}^2b^2\nu^2}{2v}\frac{gH_2}{\Delta}\theta\left(\frac{v}{v_{cr}}-1\right), \tag{3.5}$$

where Δ is the magnetostriction gap in the dispersion law of the spin waves, and $v_{cr}=v_0\nu$. The retardation force (3.5) greatly exceeds the dislocation retardation force of the parallel to the magnetic field.

4. AFM WITH MAGNETIC ANISOTROPY OF THE EASY PLANE TYPE

We consider the retardation of dislocations in an AFM with magnetic anisotropy of the easy plane type ($\beta-\beta'<0$), when the external magnetic field is located in the basal plane xy and is directed along the x axis.

If the dislocation is directed along z ($\boldsymbol{\tau}\parallel\mathbf{n}$), then at $\mathbf{v}\parallel y$ the retardation force is obtained from the formula

$$F_y=\frac{gM_0^3(\gamma_1-\gamma_2)^2b^2\nu^3}{2v}\left(\frac{2\delta}{\beta'-\beta}\right)^{1/2}\theta\left(\frac{v}{v_{cr}}-1\right), \tag{4.1}$$

and at $\mathbf{v}\parallel x$ we have

$$F_x=\frac{gM_0^3(\gamma_1+\gamma_2)^2b^2\eta^2}{2v}\left[\eta+\left(\eta^2+\frac{\alpha-\alpha'}{\alpha+\alpha'}\right)^{1/2}\right]\theta\left(\frac{v}{v_{cr}}-1\right). \tag{4.2}$$

If the dislocation lies in the basal plane, is oriented along x, and moves along the anisotropy axis, then the retardation force due to the "Cerenkov" generation of the spin waves is

$$F_z=\frac{gM_0^3[(\gamma_1+\gamma_2)\eta^2-\tilde{\gamma}^2\nu^2]^2b^2}{2v}\times\left\{\left[\frac{\alpha+\alpha'}{(\alpha+\alpha')\eta^2+(\alpha-\alpha')\nu^2}\right]^{1/2}+\frac{gH_2}{\Delta}\right\}\theta\left(\frac{v}{v_{cr}}-1\right), \tag{4.3}$$

where $\Delta=(g^2H_2^2\eta^2+\Delta_s^2)^{1/2}$ is the gap in the spin-wave dispersion law, and Δ_s is the magnetostriction gap. In formulas (4.1)–(4.3) at $H\ll H_2$ the critical velocity is equal to $v_{cr}=v_0\nu$. We note also that in this case the retardation force for dislocations located in the basal plane turns out to be proportional to the large quantity gH_2/Δ.

5. INFLUENCE OF THE MAGNON SCATTERING MECHANISM ON THE DISLOCATION DYNAMICS

We now analyze the contribution made to the retardation force by the mechanism of spin-wave scattering by dislocations; this mechanism is described by the last term of (2.12). For dislocations moving with low velocities $v\ll v_{cr}$, this term can be described at $T\gg\varepsilon_0$ and

$H=0$ in the form

$$Q=-\frac{2\pi}{4aT\Theta_N L}\sum_{\mathbf{k},\mathbf{k}',j,j'}(\mathbf{qv})^2|\Psi_{jj'}(\mathbf{k},\mathbf{k}')|^2\frac{\delta(k-k')}{\mathrm{sh}^2[\varepsilon_j(\mathbf{k})/2T]}, \tag{5.1}$$

where

$$\Psi_{11}(\mathbf{k},\mathbf{k}')=\Psi_{22}(\mathbf{k},\mathbf{k}')=\frac{gM_0}{2}\{[(\gamma_1+\delta\gamma_3)w_{ee}(\mathbf{q})+(2\gamma_2-3\gamma_1)w_{zz}(\mathbf{q})$$
$$+2\alpha_1(k_e k_m' w_{em}(\mathbf{q})\beta_1+\beta_2\mathbf{kk}'w_{ee}(\mathbf{q}))](u_\mathbf{k}u_{\mathbf{k}'}+v_\mathbf{k}v_{\mathbf{k}'})$$
$$+2[(\gamma_2+\delta\gamma_3)w_{ee}(\mathbf{q})-\gamma_2 w_{zz}(\mathbf{q})+2\alpha_2(\beta_1 k_e k_m' w_{em}(\mathbf{q})+\beta_2\mathbf{kk}'w_{ee}(\mathbf{q}))]u_\mathbf{k}v_{\mathbf{k}'}\}; \tag{5.1a}$$

$$\Psi_{21}(\mathbf{k},\mathbf{k}')=\Psi_{12}^*(\mathbf{k},\mathbf{k}')=\frac{gM_0}{2}(w_{xx}(\mathbf{q})-w_{yy}(\mathbf{q})$$
$$-2iw_{xy}(\mathbf{q}))[\gamma_1(u_\mathbf{k}v_{\mathbf{k}'}+v_\mathbf{k}v_{\mathbf{k}'})+\gamma_2(u_\mathbf{k}u_{\mathbf{k}'}+v_\mathbf{k}v_{\mathbf{k}'})], \tag{5.1b}$$

$\mathbf{k}'=\mathbf{k}+\mathbf{q}$, u_k and v_k are the amplitudes of the canonical transformation, and $w_{ik}(\mathbf{q})$ are the Fourier components of the distortions.

We shall analyze (5.1) for the case of screw and edge dislocations.

Retardation of screw dislocations. In this case the main contribution to (5.1) is made by the scattering-amplitude components that are due only to the inhomogeneous magnetostriction. The scattering amplitudes for a screw dislocation are of the form

$$\Psi_{11}=\Psi_{22}=gM_0 k_e k_m' w_{em}(\mathbf{q})\beta_1[\alpha_1(u_\mathbf{k}u_{\mathbf{k}'}+v_\mathbf{k}v_{\mathbf{k}'})+2\alpha_2 u_\mathbf{k}v_{\mathbf{k}'}]. \tag{5.2}$$

Noting that the expression in the square brackets (5.2) is equal to $(\alpha_1-\alpha_2)/ak$, and substituting (5.2) in (5.1), we get

$$Q=(Fv),\quad F=B_s(T/\Theta_N)^5 v, \tag{5.3}$$

where $B_s=\beta_1^2 b^2 a^{-5}C(\mathbf{n},\boldsymbol{\tau})$ is the coefficient of dislocation retardation by spin waves, $C(\mathbf{n},\boldsymbol{\tau})\sim 1$ and depends on the orientation of the dislocation relative to the direction of the easy axis $\mathbf{n}$. If the dislocation is oriented and moves parallel to $\mathbf{n}$,

$$C(\mathbf{n},\boldsymbol{\tau})=3\cos^2(\widehat{\mathbf{vn}}).$$

If the dislocation lies in a plane perpendicular to $\mathbf{n}$, then

$$C(\mathbf{n},\boldsymbol{\tau})={}^1/_8\sin^2(\widehat{\mathbf{v\tau}})[2\sin^2(\widehat{\mathbf{v\tau}})-\cos^2(\widehat{\mathbf{vn}})].$$

Retardation of edge dislocations. In this case the contribution of the scattering-amplitude components, due to the inhomogeneous magnetostriction, turns out to be of the same order as the contribution due to the homogeneous magnetostriction. Substituting (5.1a) in (5.1) we find that the retardation force of an edge dislocation is given by (5.3), where

$$B_s=b^2a^{-5}(\beta^2+\gamma_3^2)C_1(\mathbf{n},\boldsymbol{\tau}),\quad \beta=(\beta_1^2+\beta_2^2)^{1/2},\quad C_1(\mathbf{n},\boldsymbol{\tau})\sim 1. \tag{5.4}$$

Thus, the dislocation retardation force due to scattering of the spin waves depends little on the form of the dislocation (edge or screw) or on its orientation, and can be estimated from formula (5.3). We note also that formula (5.3) at $H=0$ is valid in the indicated temperature limit $T\gg\varepsilon_0$ for an antiferromagnet of any type, both easy axis and easy plane.

6. INFLUENCE OF RELAXATION PROCESSES ON THE RETARDATION FORCE

In the preceding sections we disregarded in the calculation of the retardation force the relaxation processes in the magnon system, and therefore the retardation force increased jumpwise at $v=v_{cr}$. Allowance for the damping of the spin waves should make the dependence of the retardation force on the velocity smoother. The influence of the relaxation processes will be considered using as an example an antiferromagnet of the easy axis type in a phase with antiparallel magnetic moments. The finite relaxation time τ will be taken into account phenomenologically, by replacing the δ functions in the expressions for the energy dissipation (2.12) by the Lorentz function

$$\delta(\omega-\varepsilon)\to\frac{1}{\pi}\frac{\tau}{\tau^2(\omega-\varepsilon)^2+1}. \tag{6.1}$$

Leaving out the rather cumbersome intermediate calculations, we write down the expression for the retardation force of a dislocation in the approximation $\varepsilon_1\tau\gg 1$ and $(H_1-H)/H_1\ll 1$:

$$F=\frac{2gM_0^4\tilde{\gamma}^2b^2\delta}{\pi H_1 v}\left[\mathrm{arctg}\,\Omega\tau-\mathrm{arctg}\left(\Omega\tau\frac{v_{cr}^2-v^2}{v_{cr}^2}\right)\right], \tag{6.2}$$

where $\Omega=\varepsilon_1(0)$. A plot of the retardation force against the velocity is shown in Fig. 2. It follows from (6.2) that the width of the smearing of the "step" is determined by

$$\Delta v=\left(\frac{\Theta_N}{\Omega}\right)^{1/2}\frac{a}{\tau}. \tag{6.3}$$

The phenomenological parameter τ in (6.3) can be governed by different magnon-interaction processes. We shall assume the principal process to be the scattering of the magnons by one another and by the dislocations. The relaxation time for the first of these processes will be estimated from the formula[9]

$$1/\tau_{ss}\approx\Theta_N(T/\Theta_N)^5, \tag{6.4}$$

while that of the second from[10]

$$1/\tau_{sd}=\Theta_N(T/\Theta_N)^2\xi^{1/2}a, \tag{6.5}$$

where ξ is the dislocation density. Comparison of (6.4) with (6.5) shows that in the temperature region $T\ll(\xi^{1/2}a)^{1/3}\Theta_N$ the main contribution to the relaxation is made by processes of scattering of spin waves by dislocations; in this case τ^{-1} is determined by formula (6.5).

At $v\ll v_{cr}$ the retardation force is linear in v:

$$F=\frac{2gM_0^4\tilde{\gamma}^2b^2\delta}{\pi H_1\Omega\tau v_{cr}^2}v,\quad v\ll v_{cr}. \tag{6.6}$$

Thus, the retardation force due to the mechanism of the "Cerenkov" generation with allowance for the relaxation differs from zero also in the velocity region $v<v_{cr}$, i.e., where the dislocations are slowed down by magnon scattering processes. We compare now the contributions of the two mechanisms to the retardation force at $v\ll v_{cr}$. For the scattering mechanism, the force is described by formula (5.3), while for the Cerenkov generation mechanism with allowance for relaxation it is described by formulas (6.6) and (6.5). The ratio of the force F_s due to the scattering of the magnons by the dislocation to the force F_c due to the "Cerenkov" generation of the spin waves with allowance for the relaxation is estimated in the temperature region $T\ll(\xi^{1/2}a)^{1/3}\Theta_N$ in the following manner:

$$\frac{F_s}{F_c}=\frac{4\pi\varepsilon_0^2a^{-3}(1-H/H_1)^2}{gM_0^3\delta^{1/2}\tilde{\gamma}^2}\frac{(T/\Theta_N)^3}{\xi^{1/2}a}. \tag{6.7}$$

At the characteristic values $gM_0 = 10^{10}$ sec^{-1}, $a \sim 3\times10^{-8}$ cm, $\delta \sim 10^4$, $\tilde{\gamma} \sim 3$, and $\xi \sim 10^{10}$ cm^{-2} the ratio (6.7) is of the order of

$$\frac{F_s}{F_c} \sim \left(1-\frac{H}{H_1}\right)^2 \left[10\frac{T}{(\xi^{1/2}a)^{1/3}\Theta_N}\right]^3 \ll 1.$$

Consequently, at $T \ll (\xi^{1/2}a)^{1/3}\Theta_N$ and $v \ll v_{cr}$ the principal role in the magnon retardation of the dislocation is played by the Cerenkov generation of the spin wave; the resultant force is given by

$$F_c = \frac{2gM_0^4\tilde{\gamma}^2 b^2\delta}{\pi H_1 \Omega v_{cr}^2}\Theta_N \left(\frac{T}{\Theta_N}\right)^2 \xi^{1/2} av. \qquad (6.8)$$

In the temperature region $T \gg (\xi^{1/2}a)^{1/3}\Theta_N$ and at $v \ll v_{cr}$ the forces F_s and F_c depend in equal fashion on the temperature and velocity, and both mechanisms make approximately the same contribution to the total slowing-down force $F \sim (T/\Theta_N)^5 v$.

7. DISCUSSION OF RESULTS

We consider now the general character of the temperature-velocity dependences of the dislocation retardation force in antiferromagnetic dielectrics and in metals at $T \ll \Theta_D$, using as an example an AFM of the "easy axis" type, $H \leq H_1$.

A. Dielectrics

In this case the dynamics of the dislocations is determined by two mechanisms, which cause the onset of two components of the retardation force: F_c—the retardation force due to generation of spin waves, and F_p—the phonon retardation force.[1] At $v \ll v_{cr}$ we have then

$$F_c = B_c\left(\frac{T}{\Theta_N}\right)^2 v, \quad B_c = \frac{2gM_0^4\tilde{\gamma}^2 b^2\delta\Theta_N\xi^{1/2}a}{\pi H_1\Omega v_{cr}^2}, \quad T \ll (\xi^{1/2}a)^{1/3}\Theta_N, \qquad (7.1)$$

$$F_p = B_p\left(\frac{T}{\Theta_D}\right)^3 v, \quad B_p = \frac{1}{2\pi^2}k_D^3. \qquad (7.2)$$

Comparison of these two equations shows that at the characteristic values

$$B_c \approx 10^{-8}(1-H/H_1)^{-2}\ g/\text{cm}\cdot\text{sec}, \quad B_p \sim 10^{-4}\ g/\text{cm}\cdot\text{sec}$$

the magnon contribution becomes predominant in the temperature region

$$\frac{T}{\Theta_D} < \left(\frac{\Theta_D}{\Theta_N}\right)^2 \frac{B_c}{B_p},$$

i.e., at $\Theta_D \sim 10^2$K, $\Theta_N \sim 10$ K, $T \ll \Theta_D/[10^2(1-H/H_1)^2]$. Thus, in magnetic fields $H \sim H_1$ and at temperatures $T \leq 10$ K the retardation of "slow" dislocations ($v \ll v_{cr} \sim \Theta_N a[1-(H/H_1)^2]^{1/2}$) is due mainly to radiation of damped spin waves.

At $v \gtrsim v_{cr}$ the magnon retardation force is determined by the formula (3.1) and does not depend on the temperature. At the characteristic values of the parameters near $v \sim v_{cr}$

$$F_c \approx 10^{-2}\left[1-\frac{H^2}{H_1^2}\right]^{-1/2}, \quad F_p \approx 10^3\left(\frac{T}{\Theta_D}\right)^3\left(1-\frac{H^2}{H_1^2}\right)^{1/2}, \qquad (7.3)$$

i.e., at $T \ll 10^{-2}[1-H^2/H_1^2]^{-1/3}\Theta_D$ we have $F_c \gg F_p$.

Consequently, the slowing down of the "fast" dislocations ($v \gtrsim v_{cr}$) in the temperature region $T \ll 10^{-2}[1-H^2/H_1^2]^{-1/3}\Theta_D$ is determined by the magnon mechanism.

B. Metals

At low temperatures in metals it is necessary to take into account, besides the magnon and phonon components of the slowing-down force, also the electron component[11]

$$F_e = \begin{cases} \frac{1}{2}\omega_H\tau B_e v, & q_m\tau v \ll 1 \\ \omega_H B_e q_m^{-1}\ln(q_m\tau v), & q_m\tau v \gg 1 \end{cases} \qquad (7.4)$$

where $\omega_H = gH$ is the cyclotron frequency, $B_e \sim bn\varepsilon_F/v_F \sim 10^{-5}$ g/cm-sec; $q_m = 2k_F$; ε_F, v_F, and k_F are the Fermi energy, velocity, and momentum; n is the conduction-electron concentration.

Comparison of Eqs. (7.1), (7.2), and (7.4) shows that at $v \ll v_{cr}$ in the temperature region $T \ll T_e = k_p^{-1}(gH_1\tau B_e)^{1/3}\Theta_D \sim 10-10^2$ K the electron contribution becomes predominant. Outside this region of temperatures, the retardation of the slow dislocations is determined by the phonon mechanism.

In the case $v \gtrsim v_{cr}$ and $T \ll T_e$, by virtue of the retardation, contributions are made by the temperature-independent electron and magnon retardation mechanisms. At typical values of the parameters near $v \approx v_{cr}$ we have

$$F_c \approx 10^{-2}(1-H/H_1)^{-1/2}, \quad F_e \approx 10^{-1}\ln(q_m\tau v_{cr}). \qquad (7.5)$$

Consequently in the magnetic-field region $(H_1-H)/H_1 \leq 10^{-2}$ the force of the magnetic retardation due to spin-wave radiation is comparable with the electronic retardation force.

Thus, the interaction with the spin waves can make an appreciable contribution to the dislocation retardation force in antiferromagnets at low temperatures.

[1]A different dependence of the retardation force on the magnetic field was obtained in Ref. 3, where the spatial dispersion of the spin waves was not taken into account.

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