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Translated by W. F. Brown, Jr.

Dynamics of interphase boundaries in antiferromagnets

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(Submitted 8 January 1980)
Zh. Eksp. Teor. Fiz. 79, 581–588 (August 1980)

The nonlinear dynamics of an antiferromagnet in the intermediate state, in which a collinear and a flopped phase of the antiferromagnet can coexist, is investigated theoretically. The motion of an individual interphase boundary is considered with account taken of the magnetic dipole interaction. The scattering of two domain walls and their bound states are investigated. The steady-state motion of a domain wall is studied with account taken of relaxation under the influence of an external magnetic field. The possibility of observing this phenomenon in experiment is discussed.

PACS numbers: 75.30.Kz, 75.60.Ch, 75.50.Ee

It is known that in antiferromagnets (AFM) there can exist 180° domain walls (DW) that have many features in common with the domain walls of ferromagnets. The most substantial difference between the DW in these magnets is that the 180° DW in AFM are not topological DW and are therefore metastable.

However, as shown by V. Bar'yakhtar *et al.*,[1] near first-order transition points there can exist in AFM a thermodynamically stable domain structure with 90° DW (intermediate state of AFM). These DW are of great interest primarily because they are separate essentially different phases of the AFM (the collinear phase $\Phi_{\parallel}$ and the flopped phase $\Phi_{\perp}$). Since the susceptibilities of these phases differ substantially, when the external magnetic field (or some other external parameter) is changed, the phase-equilibrium condition is violated and the 90° DW goes into motion. Thus, the question arises of experimental and theoretical study of the dynamics of the interphase boundaries in AFM under the influence of an external magnetic field.

Investigations of this kind are being quite intensively pursued in recent years in connection with the study of the motion of DW in ferromagnets and in ferrites. However, the motion of DW in AFM has a number of fundamental differences. It was shown in Ref. 2 that the limiting velocity of a 180° DW in an AFM is of exchange order of magnitude ($\sim Ja/\hbar$. where J is the exchange integral) and exceeds considerably the limiting velocity of DW in ferromagnets. At the same time, in the simplest model of a purely uniaxial AFM without allowance for the magnetic dipole interaction, considered by I. Bar'yakhtar and the author,[2] a 90° interphase DW cannot move at all, i.e., its limiting velocity is zero.

This result is understandable, since a 90° DW separates the phases $\Phi_{\parallel}$ and $\Phi_{\perp}$, in which we have respectively $\mathbf{m}=0$ and $\mathbf{m}=m_0\mathbf{n}\neq 0$, where $\mathbf{n}$ is a unit vector along the chosen axis of the crystal (the z axis). Consequently, when the DW moves a change should take place in the value of the z-projection of the total magnetization $I_z=\int m_z dx$, namely $\dot{I}_z=VM_0$.[3] At the same time, I_z commutes with the Hamiltonian of the uniaxial AFM without allowance for the magnetic dipole interaction or the anisotropy in the basal plane [see (3)], i.e., $\dot{I}_z=0$, which leads to the condition $V=0$ for a 90° DW. Thus, to study the motion of a 90° DW it is necessary to go outside the framework of the model of Ref. 2.

In the present paper we consider the dynamics of a 90° DW in a uniaxial AFM with account taken of the magnetic dipole interaction. We obtain a solution that describes a moving DW, and an expression for the limiting velocity of the DW. We investigate the study-state motion of the DW under the influence of an external magnetic field with account taken of the relaxation. We obtain more complicated solutions, which describe the interaction of the 90° DW, and also dynamic antiferromagnetic solitons.

1. EFFECTIVE EQUATIONS OF THE MAGNETIZATION DYNAMICS

We consider an AFM with two equivalent sublattices whose magnetizations will be designated $\mathbf{M}_1$ and $\mathbf{M}_2$, $|\mathbf{M}_1|=|\mathbf{M}_2|=M_0$. It is convenient to describe the nonlinear synamics of the AFM in terms of the normalized vectors of antiferromagnetism $\mathbf{l}$ and magnetization $\mathbf{m}$:

$$\mathbf{l}=(\mathbf{M}_1-\mathbf{M}_2)/2M_0,\quad \mathbf{m}=(\mathbf{M}_1+\mathbf{M}_2)/2M_0, \tag{1}$$

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which are connected by the obvious relations

$$\mathbf{lm}=0, \quad \mathbf{l}^2+\mathbf{m}^2=1. \tag{2}$$

We write down the energy of the AFM in terms of m and l in the form

$$W\{\mathbf{m},\mathbf{l}\}=M_0^2\int d\mathbf{r}\{2\delta\mathbf{m}^2+(\alpha-\alpha')(\nabla\mathbf{l})^2+(\alpha+\alpha')(\nabla\mathbf{m})^2 -(\beta-\beta')l_z^2-(\beta+\beta')m_z^2-b(1-l_z^2)^2-2(\mathbf{mh})-(\mathbf{mh}_m)\}.$$

Here δ and α, α' are respectively the constants of the homogeneous and inhomogeneous exchanges, β, β', and b are the AFM anisotropy constants; $\mathbf{h}=\mathbf{H}/M_0$, H is the external field, which we assume parallel to the z axis; $\mathbf{h}_m$ is the field of the magnetic dipole interaction, which is determined by the equations of the magnetostatics. Inasmuch as for a flat domain wall $\mathbf{M}_i=\mathbf{M}_i(x-vt)$, $\mathbf{h}_m$ in the form

$$\mathbf{h}_m=-8\pi m_x\mathbf{e}_x. \tag{4}$$

The character of the ground state of an AFM and static DW is determined by minimizing (3). It is easy to verify that at $H<H_1$ the collinear phase of the AFM $\Phi_\parallel$ is stable, corresponding to the value $\mathbf{m}=0, \mathbf{l}\parallel\mathbf{H}$. At $H>H_2$, the flopped phase $\Phi_\perp$ is realized, in which $\mathbf{l}\perp\mathbf{H}$, $\mathbf{m}=m_0\mathbf{n}\neq 0$. The fields H_1 and H_2 are defined by the formulas

$$H_1=M_0[(\beta-\beta')(2\delta+\beta-\beta')]^{1/2}, \quad H_2=M_0[(\beta-\beta'-2b)(2\delta-\beta-\beta')]^{1/2}.$$

We assume henceforth that $b\delta+\beta(\beta-\beta')>0$; the phase transition $\Phi_\parallel\rightleftarrows\Phi_\perp$ takes place at $H=H_{tr}$ (H_{tr} is the transition field),

$$H_{tr}=M_0[(\beta-\beta'-b)(2\delta-\beta-\beta')]^{1/2}$$

and is of first order; at the point $H=H_{tr}$ there can be realized 90° DW which separate the phases $\Phi_\parallel$ and $\Phi_\perp$.

The magnetization dynamics equations are determined by the functional (3) of the AFM energy (see Ref. 4) and can be written in the form[1)]

$$\dot{\mathbf{m}}/gM_0+(\alpha-\alpha')[\mathbf{l}\Delta\mathbf{l}]+(\alpha+\alpha')[\mathbf{m}\Delta\mathbf{m}]+[\mathbf{mh}] +[\beta-\beta'-2b(1-l_z^2)]l_z[\mathbf{ln}]+(\beta+\beta')m_z[\mathbf{mn}]-8\pi m_x[\mathbf{me}_x]=0, \tag{5}$$

$$\dot{\mathbf{l}}/gM_0+2\delta[\mathbf{ml}]+(\alpha-\alpha')[\mathbf{m}\Delta\mathbf{l}]+(\alpha+\alpha')[\mathbf{l}\Delta\mathbf{m}]+[\mathbf{lh}] +[\beta-\beta'-2b(1-l_z^2)]l_z[\mathbf{mn}]+(\beta+\beta')m_z[\mathbf{ln}]-8\pi m_x[\mathbf{le}_x]=0. \tag{6}$$

It will be convenient to proceed as follows. Assuming that $\mathbf{m}^2\ll\mathbf{l}^2\approx 1$, and using Eq. (6), we can express m only in terms of the vectors l and $\dot{\mathbf{l}}$, namely (c8):

$$\mathbf{m}=\frac{[\mathbf{h}-\mathbf{l}(\mathbf{lh})/l^2]+[\dot{\mathbf{l}},\mathbf{l}]/gM_0l^2}{2\delta+\beta\cos 2\theta-\beta'}+\frac{8\pi h}{(2\delta)^2}l_xl_z(\mathbf{e}_x-\mathbf{l}l_x). \tag{7}$$

When writing this equation we have assumed that $b\ll\beta,\beta'$; $\beta\sim\beta'\sim 4\pi$, and confine ourselves to terms of order $(\beta/\delta)^{1/2}$ and $(\beta/\delta)^{3/2}$, since it is precisely with this accuracy that is necessary to write down the equations in investigations of the AFM near the phase transition $\Phi_\parallel\rightleftarrows\Phi_\perp$ (Refs. 1 and 2) (we recall that in this case $H\approx H_{tr}$). Since $(\alpha-\alpha)|\Delta\mathbf{l}|\ll(\beta-\beta')$ in 90° DW (see formula (16) below), no account was taken in (7) of terms with special derivatives of l.

Eliminating m from Eq. (5) with the aid of relation (7), we can obtain the equation of dynamics of AFM in terms of only the vector l. It is convenient to write this equation in terms of the angle variables for l:

$$l_z=l\cos\theta, \quad l_x+il_y=l\sin\theta e^{i\varphi},$$
$$l^2=1-\mathbf{m}^2\approx 1-\frac{(H-\dot{\varphi}/g)^2\sin^2\theta}{(2\delta M_0)^2}, \tag{8}$$

in which it takes the form

$$(gM_0)^2 2\delta(\alpha-\alpha')[\Delta\theta-(\nabla\varphi)^2\sin\theta\cos\theta] -[\ddot{\theta}-\dot{\varphi}^2\sin\theta\cos\theta]-2gH\dot{\varphi}\sin\theta\cos\theta +\sin\theta\cos\theta g^2(H^2-H_{tr}^2)-2B(\varphi)\sin 2\theta\cos 2\theta=0, \tag{9}$$

$$(gM_0)^2 2\delta(\alpha-\alpha')\nabla(\sin^2\theta\nabla\varphi)-[\sin^2\theta(\dot{\varphi}-gH)]^{\cdot} +(4\pi/\delta)(gH)^2\sin^2\theta\cos^2\theta\sin\varphi\cos\varphi=0. \tag{10}$$

The dot denotes here differentiation with respect to time, and the following notation is introduced

$$2B(\varphi)=(gM_0)^2[b\delta+(H^2/2\delta M_0^2)(\beta+4\pi\cos^2\varphi)], \tag{11}$$

or at $H\approx H_{tr}$

$$B(\varphi)=B(1+\varepsilon\cos^2\varphi), \quad B=(gM_0)^2[b\delta+\beta(\beta-\beta')], \quad \varepsilon=\frac{4\pi(\beta-\beta')}{b\delta+\beta(\beta-\beta')}. \tag{12}$$

We assume that $B>0$; the transition is then of first order and 90° DW can exist.[1] The parameter $\varepsilon>0$ characterizes the intensity of the magnetic dipole interaction in the AFM. It is seen that as $H\to 0$ we have $\varepsilon\to 0$ [see (11)], but near the phase transition the value of the parameter ε depends essentially on the value of the fourth-order anisotropy constant b. Without allowance for b, the value of ε is determined by the ratio of the relativistic constants ($\varepsilon=4\pi/\beta$) and can be either larger or smaller than unity. On the other hand if $\beta^2/\delta\ll b\ll\beta$, then $\varepsilon\approx 4\pi(\beta-\beta')/b\delta\ll 1$. Since we have no data on the value of b in real antiferromagnets, we shall analyze the equations for an arbitrary value of the parameter ε.

2. MOTION OF SOLITARY 90° DW

The motion of a solitary DW corresponds to a solution of Eqs. (9) and (10) of the type of a simple magnetization wave, i.e., $\theta=\theta(x-vt)$, where v is the DW velocity. The interphase 90° DW boundary exists at the phase-transition point, i.e., at $H=H_{tr}$. It is easy to verify that at $H=H_{tr}$ Eqs. (9) and (10) have a solution corresponding to $\varphi=\text{const}, \theta=\theta(x-vt)$. In fact, if it is assumed that $\nabla\varphi=\dot{\varphi}=0$, then Eq. (9) takes the form

$$2x_0^2(1-v^2/c^2)\theta''=(1+\varepsilon\cos^2\varphi)\sin 2\theta\cos 2\theta, \tag{13}$$

$$x_0^2=(gM_0)^2\delta(\alpha-\alpha')/2B=\delta(\alpha-\alpha')/2[b\delta+\beta(\beta-\beta')], \tag{14}$$

where x_0 coincides with the thickness of the 90° DW at rest,[1] $c=gM_0[2\delta(\alpha-\alpha')]^{1/2}$ is the minimum phase velocity of the spin waves of the AFM at $H=0$ and coincides with the limiting velocity of the 180° DW.[2]

Integrating (13), we can easily obtain

$$x_0^2(\varphi)(2\theta')^2=\sin^2 2\theta, \tag{15}$$

where $x_0(\varphi)$ is the thickness of the moving DW,

$$x_0(\varphi)=x_0/(1+\varepsilon\cos^2\varphi)^{1/2}. \tag{16}$$

allowance for the factor $1-v^2c^2$ in the 90° DW would be an exaggeration of the accuracy.

Substituting the relation (15) in (10) we find that the latter becomes algebraic and determines the dependence of the angle φ on the DW velocity v. The function $\varphi(v)$ can be written in the form

$$\varepsilon\cos 2\varphi=-(v/\omega_0x_0)^2\pm[(v^2/\omega_0^2x_0^2-\varepsilon)^2-(2v/\omega_0x_0)^2]^{1/2},$$
$$\omega_0=2B/gH=gM_0[b\delta+\beta(\beta-\beta')][2\delta(\beta-\beta')]^{-1/2}, \tag{17}$$

where ω_0 coincides with the frequency of the homogeneous antiferromagnetic resonance at $H=H_{tr}$ and $\varepsilon=0$. It is easily seen that a DW at rest corresponds to two values of the angle φ, namely $\varphi=\pi/2$ and $\varphi=0$. The magnetization m at the center of the DW is correspondingly parallel to e_y [the minus sign in (17)]. In analogy with DW in ferromagnets, we shall call these 90° DW quasi-Bloch walls ($\varphi=\pi/2$) and quasi-Néel DW ($\varphi=0$), respectively.

Analyzing (17), we easily find that the velocity cannot exceed v_c:

$$v_c=\omega_0 x_0[(1+\varepsilon)^{1/2}-1]=\frac{gM_0(\alpha-\alpha')^{1/2}}{(2(\beta-\beta'))^{1/2}} \times[(b\delta+(\beta-\beta')(\beta+4\pi))^{1/2}-(b\delta+\beta(\beta-\beta'))^{1/2}], \tag{18}$$

which has the meaning of the limiting velocity of the stationary motion of a 90° DW of an AFM. This velocity v_c is much less than the limiting velocity of a 180° DW at $H=0$, and vanishes at $\varepsilon=0$.

Calculating the energy of the moving 90° DW, we easily obtain

$$E=E_0(1+\varepsilon\cos^2\varphi)^{1/2},\quad E_0=M_0^2((\alpha-\alpha')[b\delta+\beta(\beta-\beta')]/\delta)^{1/2}; \tag{19}$$

here E_0 is the energy of the 90° DW at rest, and the $\varphi(v)$ dependence is determined by expression (17). It is seen that the energy more favored at a given value of the velocity is the quasi-Bloch DW, which corresponds to a lower value of a magnetic dipole energy.

At low velocities, expression (19) becomes much simpler:

$$E(v)=E_0+\frac{1}{2}m_* v^2,\quad m_*=\frac{(b\delta+\beta(\beta-\beta'))^{1/2}}{2\pi g^2(\delta(\alpha-\alpha'))^{1/2}}. \tag{20}$$

Here m_* is the effective mass per unit area of the 90° DW, which at $b=0$ is $(\beta\delta)^{1/2}/4\pi$ times larger than the effective mass of the 180° DW of the AFM at $H=0$. The expression for m_* [see (20)] differs from the expressions given earlier (Refs. 4 and 5).

The expressions obtained above corresponded to the motion of 90° DW "by inertia" without allowance for relaxation processes and for factors that cause this motion. Such a factor can be the difference between H and H_{tr}. It is of interest to calculate the dependence of the velocity of the steady-state motion of a 90° DW under the influence of an external field, i.e., at $H\neq H_{tr}$. We take the relaxation processes into account phenomenologically, by introducing into the Landau-Lifschitz equation the dissipative term in the Gilbert form

$$(\dot{\mathbf{M}}_i)_r=-(\lambda/M_0)[\mathbf{M}_i\dot{\mathbf{M}}_i]. \tag{21}$$

Allowance for dissipation leads to the appearance of a viscous-friction force that acts on the moving DW. Equating this force to the magnetic-pressure force acting on the DW at $H\neq H_{tr}$, we get the velocity of the steady-state motion of the DW under the action of an external field with account taken of the relaxation, i.e, $v(H)$. It can also be verified that the condition that the forces be equal coincides with the condition that the system (9), (10) have a solution at constant φ. For $v(H)$ we easily obtain

$$v=\frac{\varepsilon\omega_0 x_0}{\lambda}(\Delta H)\left\{1+\frac{\varepsilon}{2}\left[1\mp\left(1-\left(\frac{\Delta H}{\lambda}\right)^2\right)^{1/2}\right]\right\}^{-1/2}, \tag{22}$$

$$\Delta H=|H^2-H_{tr}^2|/2\pi H_{tr}M_0 \approx|H-H_{tr}|/\pi M_0.$$

The minus sign corresponds to a stable quasi-Bloch DW, and the plus sign to an unstable quasi-Néel DW, and a plot of $v(H)$ is shown in the figure. It is easily seen that the stationary motion of the DW exists only for small deviations of the field H from H_{tr} ($\Delta H<\lambda$), i.e., at $|H^2-H_{tr}^2|<2\pi\lambda M_0 H_{tr}$. At larger values of ΔH, there is realized a nonstationary motion of the type of the Slonczewski oscillations in ferromagnets (see Ref. 6), or the structure of the moving DW becomes more complicated.[7]

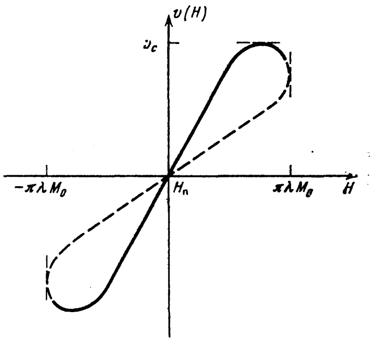

FIG. 1. Velocity of interphase domain boundary (90° DW) as a function of the external magnetic field. Positive values of the velocity correspond to motion of the DW towards the phase $\Phi_{\parallel}$, and negative towards the phase $\Phi_{\perp}$. The solid line corresponds to a stable quasi-Bloch 90° DW, and the dashed line to an unstable quasi-Neel 90° DW.

3. INTERACTION OF INTERPHASE BOUNDARIES IN AFM

In the preeceding section we considered the solution of Eqs. (9) and (10) in the form of a solitary wave. This solution corresponds to the condition $\varphi'=\dot{\varphi}=0$, which describes a solitary 90° DW. However, Eqs. (9) and (10) admit of the approximate existence of a larger class of solutions, including two-soliton solutions, which describe the interaction of two 90° DW. As will be shown below, at $H\approx H_{tr}$ we have $\dot{\varphi},\dot{\theta}\lesssim\omega_0$, i.e., $\dot{\varphi},\dot{\theta}\ll gH$ [see (17)]. We can then leave out some time derivatives from Eq. (9) and (10).

It can be verified that in this approximation these equations have a one-dimensional solution of the same type as was obtained in a ferromagnet[8]

$$\varphi=\varphi(t),\quad \theta=\theta(x,t).$$

This solution can be written in the form

$$\operatorname{tg}\varphi=-\operatorname{tg}\varphi_0\operatorname{th}(vt/x_0(v)),$$
$$\operatorname{tg}\theta=\frac{(\varepsilon)^{1/2}\omega_0 x_0}{v}\frac{\{\cos^2\varphi_0+\operatorname{sh}^2(vt/x_0(v))\}^{1/2}}{\operatorname{ch}(x/x_0(v))}, \tag{23}$$

where $x_0(v)$ is determined by formula (16), and the parameters φ_0 and v are connected by the relation (17).

It is easy to verify that as $t\to-\infty$ (or $t\to+\infty$) this solution describes two DW in the phase $\Phi_{\parallel}$, which come closer together (or move apart) with a velocity v. In fact, as $t \to -\infty$ we obtain two 90° DW moving towards each other with equal velocities

$$\mathrm{tg}\,\theta=[(\varepsilon)^{1/2}\omega_0 x_0/v]\exp\{-(x+vt)/x_0(v)\},\quad x>0, \qquad (24)$$
$$\mathrm{tg}\,\theta=[(\varepsilon)^{1/2}\omega_0 x_0/v]\exp\{(x-vt)/x_0(v)\},\quad x<0.$$

At $t=0$, the DW stop, and the distance between them depends on their velocity. The distribution of the magnetization at the instant of the maximum approach of the DW is determined by the formula

$$\mathrm{tg}\,\theta=\frac{(\varepsilon)^{1/2}\omega_0 x_0\cos\varphi_0}{v\,\mathrm{ch}(x/x_0(v))},\quad \frac{\partial\theta}{\partial t}=0\quad \text{for } t=0. \qquad (25)$$

The DW next begin to diverge, and as $t \to +\infty$ the solution (23) describes two DW that move apart in opposite direction with velocity v.

The distance Δx between the DW at the instant of shortest approach ($t=0$) is determined by the velocity of the DW

$$\Delta x \approx x_0 \ln[(\varepsilon)^{1/2}\omega_0 x_0\cos\varphi_0/v].$$

If $\Delta x \gg x_0$, then at the instant of the closest approach the DW do not lose their individuality, and their form is little distorted. In particular, if $\varepsilon \ll 1$, then for Bloch DW that approach each other at arbitrary velocity we have $\Delta x \gtrsim x_0|\ln\varepsilon| \gg x_0$. On the other hand if $\Delta x \lesssim x_0$, then the DW become strongly deformed as they come closer together and lose their shape is restored as $t \to +\infty$.

It is similarly possible to obtain a solution that describes the interaction of two 90° DW in the phase $\Phi_\perp$. It is of the form

$$\mathrm{tg}\,\varphi=+\mathrm{tg}\,\varphi_0\,\mathrm{th}(vt/x_0(v)),$$
$$\mathrm{ctg}\,\theta=\frac{(\varepsilon)^{1/2}\omega_0 x_0}{v}\frac{\{\cos^2\varphi_0+\mathrm{sh}^2(vt/x_0(v))\}^{1/2}}{\mathrm{ch}(x/x_0(v))}. \qquad (26)$$

This solution can be investigated in analogy with (23), and we shall not dwell on it further.

It can be verified that the energy corresponding to the solutions (23) or (26) is equal to $2E(v)$, i.e., it is larger than double the energy of the DW at rest. Thus, these solutions describe the scattering of two 90° DW. Making in solutions (23) and (26) a formal limiting transition to imaginary values of the velocity

$$\varepsilon v/x_0(v) \to i\omega,$$

it is easy to obtain a solution corresponding to the bound state of two DW in the phases $\Phi_\parallel$ or $\Phi_\perp$. In this bound state, the magnetization of the AFM executes periodic motion with frequency ω, and its deviation from the equilibrium value is localized in space.

Thus, these solutions describe localized antiferromagnetic solitons in the phases $\Phi_\parallel$ or $\Phi_\perp$. For the soliton in the phase $\Phi_\parallel$ we easily obtain

$$\mathrm{tg}\,\varphi=-[(\Omega+\varepsilon)/\Omega]^{1/2}\,\mathrm{tg}\,\omega t,$$
$$\mathrm{tg}\,\theta=\frac{\omega_0(1-\Omega)^{1/2}}{\omega}\frac{[\Omega+\varepsilon\sin^2\omega t]^{1/2}}{\mathrm{ch}((1-\Omega)^{1/2}x/x_0)}, \qquad (27)$$

where the parameter Ω is connected with the frequency of the soliton by the relation $\omega=\omega_0[\Omega(\Omega+\varepsilon)]^{1/2}$ and varies in the interval $(0,1)$. As $\Omega \to 1$ the frequency ω approaches from below the limit of the spin-wave frequencies in the AFM at $H=H_{tr}$, i.e., $\omega \to \omega_0(1+\varepsilon)^{1/2}$, and the amplitude of the soliton tends to zero like $(1-\Omega)^{1/2}$. On the other hand if $\Omega \to 0$, which corresponds to $\omega \to 0$, then the solution (27) describes the vibrational motion of two 90° DW that move periodically away from each other to a distance $\Delta x \sim x_0|\ln\Omega|$. At the instant of closest approach of the DW, which the condition $\sin\omega t=0$ corresponds, the character of the solution depends on the parameter ε. If $\varepsilon \gtrsim 1$, then the DW approach each other to a distance of the order of x_0, and become strongly deformed. On the other hand if $\varepsilon \ll 1$, then the distance between the DW at the instant of shortest approach is of the order of $x_0|\ln\varepsilon| \gg x_0$, and at $\Omega \ll \varepsilon \ll 1$ the DW does not lose its individuality in the course of its oscillations, and the distance between the DW varies periodically in the range from $x_0|\ln\varepsilon|$ to $x_0|\ln\Omega|$.

The solution describing the soliton in the phase $\Phi_\perp$ is obtained from (27) by making the substitutions $\omega \to -\omega$ and $\tan\theta \to \cot\theta$; its analysis is similar.

Notice must be taken of the substantial difference between the interaction considered in this section of a 90° DW, and the interaction of a 180° DW. In the collinear phase of an AFM, at $H=0$, the solution describing two 180° DW that move towards each other with velocity v is described by the formula[2]

$$\varphi=\text{const},\quad \mathrm{tg}\frac{\theta}{2}=\frac{c}{v}\frac{\mathrm{sh}(vt/x_\pi(v))}{\mathrm{ch}(x/x_\pi(v))},$$

where $c=gM_0[2\delta(\alpha-\alpha')]^{1/2}$ is the limiting velocity of the 180° DW, $x_\pi(v)$ is the thickness of the 180° DW, $x_\pi(v)=[(\alpha-\alpha')/(\beta-\beta')(1-v^2/c^2)]^{1/2}$.

This interaction must be interpreted as interpenetration of DW; in particular, at $t=0$ the angle $\theta\equiv 0$ at all values of x, i.e., the AFM is in a homogeneous state (the memory of the DW remains only via the derivative of θ with respect to time, which is maximal at $t=0$). In contrast, at the instant of closest approach of 90° DW (at $t=0$) they stop [see (25)], and then begin to move in opposite directions. Thus, in contrast to 180° DW in AFM, one must speak not of the interpenetration of DW, but of scattering of 90° DW by each other. Analogous differences can be revealed also in the properties of antiferromagnetic solitons in the $\Phi_\parallel$ phase at $H=0$ [see formula (48) of Ref. 2] and at $H=H_{tr}$ [see (27)].

4. DISCUSSION OF RESULTS

The reported investigation has demonstrated the substantial difference between the nonlinear dynamics of AFM in the region of the existence of the intermediate state, from the previously considered case[2] of weak magnetic fields. This difference manifests itself both in the dynamic properties of an individual 90° DW, and in the interaction of two 90° DW. In particular, the limiting velocity of a 90° DW v_c is determined only by relativistic interactions [see (18), in the estimates that follow we assume that $b=0$], and is smaller by a factor $(\beta\delta)^{1/2}/4\pi$ than the limiting velocity of the 180° DW, the effective mass of the 90° DW is substantially larger (by a factor $(\beta\delta)^{1/2}/4\pi$) than the mass of the 180° DW, and so on.

A preceding paper[9] dealt with the motion of interphase boundaries produced in orthoferrities in the case of spin reorientation, $H=0$. The corresponding equations are Lorentz-invariant, and the characteristic velocity coincides with the minimal phase velocity of the spin waves c. In our problem there must of necessity be present a strong magnetic field that upsets the Lorentz invariants of the equations and leads to a nontrivial dependence of the DW structure on its velocity.

An important singularity of the problem of the motion of 90° DW is that when the external field deviates from H_{tr}, induced motion of the DW must arise. Thus, it is possible to investigate experimentally the dynamics of nonlinear waves in AFM, and this can be of interest for the physics of antiferromagnetism. Such an experiment can be carried out, e.g., in accordance with the scheme proposed by Chetkin *et al.*,[2] the only difference being that the AFM sample should be placed in a constant magnetic field close to H_{tr} (e.g., 6 kOe for $CuCl_2 \cdot 2H_2O$ or 94 kOe for MnF_2). The DW velocity is linear in ΔH as $\Delta H \to 0$, but when ΔH is increased the velocity $v(H)$ saturates, i.e., nonlinear motion of the DW should set in. The transition to the most interesting nonlinear regime occurs at sufficiently low value of $(H-H_{tr}) \sim \pi\lambda M_0$ [see (22)], e.g., at $H-H_{tr}\sim 10$ Oe, if $\lambda \sim 10^{-2}$ and $M_0 \sim 10^3$ G.

The author thanks V.G. Bar'yakhtar, V.M. Eleonskii, V.V. Eremenko, A.M. Kosevich, N.F. Kharchenko for helpful discussions of the work, and I.V. Bar'yakhtar for help and discussions.

[1] $[\mathbf{mh}] \equiv \mathbf{m}\times\mathbf{h}$, etc.

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Translated by J. G. Adashko

Investigation of mictomagnetic MnBi alloys

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(Submitted 16 January 1980)
Zh. Eksp. Teor. Fiz. **79**, 589–599 (August 1980)

MnBi alloys in the mictomagnetic state were obtained and subjected to x-ray-diffraction, microstructural, and differential-thermal analysis. The electric, magnetic, and elastic properties were investigated, as well as the effect of high hydrostatic pressure (up to 10 kbar) on the temperature dependences of the magntization. It was established that the mictomagnetism arises in two-phase system consisting of the high-temperature MnBi phase and Bi. New data were obtained on the magnetic phase transitions and on the influence of hydrostatic compression on the mictomagnetic and superparamagnetic properties of MnBi. Exchange interactions in the investigated alloys are discussed on the basis of these new data.

PACS numbers: 75.30.Kz, 75.50.Cc, 62.50. + p, 75.30.Et

INTRODUCTION

The physics of magnetic phenomena has recently been enriched with new concepts (spin glass, mictomagnetism,[1] speromagnetism, asperomagnetism[2]) that describe various disordered states of a spin system. Despite the intensive theoretical and experimental investigations, many aspects of the magnetic behavior of these systems remain unclear, to a considerable degree because of insufficient knowledge of the mechanism of the exchange spin coupling in each concrete case.

We report in this paper the production and investigathat of MnBi alloys whose magnetic properties differ radically from those hitherto known (for MnBi) and recall the mictomagnetic Cu-Ni and Au-Fe systems that were extensively investigated by Beck.[1] According to his ideas, mictomagnetism is determined by the presence of ferro- and antiferromagnetic clusters that are randomly frozen in a nonmagnetic spin-glass matrix. When the temperature is lowered in the region of T_0 (the freezing temperature of spin glass) a transition from the superparamagnetic to the mictomagnetic state takes place. The characteristic symptoms of this state are: a) the absence of hysteresis or saturation of the magnetization; b) very large changes in the magnetic parameters, depending on the magnetic annealing of

 0038-5646/80/080297-07$02.40