Sound absorption in an antiferromagnet in the vicinity of a spin-flop field

V. G. Bar'yakhtar and B. A. Ivanov

Donets Physico-technical Institute, Ukrainian Academy of Sciences
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The mechanism of sound absorption in an antiferromagnet in the intermediate state is investigated. It is shown that the sound absorption is considerably increased as a result of the motion of the domain walls.

A sharp, narrow peak has been observed experimentally (see[1]) in the plot of sound absorption vs the magnetic field near a spin-flop field H_f. This phenomenon, as it appears to us, can be explained if we take into account the existence of an inhomogeneous intermediate state near the spin flop.[2] The presence of deformations in the crystal, due to the sound wave, leads as we shall show below, to a change in the surface energy of the 90-degree domain boundary, and, by virtue of this, to a rearrangement of the domain structure, while the motion of the domain boundary leads to dissipation of the sound-wave energy.

The energy of the 90-degree domain boundary in the 1 l of elastic stresses can easily be obtained by adding the energy of magneto-elastic coupling W_{me} to the usual magnetic energy W of the antiferromagnet (see[3], Sec. 4):

$$W_{me}=\int \rho_0\Lambda_{ik}\frac{\partial u_i}{\partial x_k}d^3x, \qquad (1)$$

$$\begin{aligned}\rho_0\Lambda_{ik}/M_0^2={}&\delta_1[\mathbf{m}^2-(\mathbf{mn})^2]\delta_{ik}+\delta_2[m_0^2-\mathbf{m}^2]n_in_k\\&+\delta_3[m_0^2-(\mathbf{mn})^2]n_in_k+\delta_4[m_0^2n_in_k-m_im_k]\\&+\delta_5[m_0^2n_in_k-{}^1/_2(\mathbf{mn})(m_in_k+m_kn_i)]-\Lambda_{ik}^0\\&-{}^1/_2(\delta_2+\delta_3+\delta_4+\delta_5)m_0^2(\mathbf{ln})^2(l_in_k+n_il_k),\end{aligned}$$

where Λ_{ik}^0 is a constant tensor added to satisfy the equations

$$\Lambda_{ik}(0,\mathbf{n})=\Lambda_{ik}(m_0\mathbf{n},\ (1-m_0^2)^{1/2}\mathbf{v})=0,$$
$$m_0=h/2\delta,\quad \mathbf{v}\perp\mathbf{n},\quad 2\mathbf{m}=(\boldsymbol{\mu}_1+\boldsymbol{\mu}_2)\mu_0^{-1},$$
$$2\mathbf{l}=(\boldsymbol{\mu}_1-\boldsymbol{\mu}_2)\mu_0^{-1},\quad \mathbf{h}=\mathbf{H}_0/M_0,$$

H_0 is the external field, which we shall assume to be equal to H_f, $\delta_1-\delta_5$ are magneto-elastic constants, and the rest of the notation is standard.[3,4]

By minimizing the total energy of the antiferromagnet $W + W_{me}$, we obtain equations which describe the 90-degree domain boundary in the field of given elastic deformations:

$$\mathbf{m}=(0,\ m\cos\theta,\ m\sin\theta),\quad \mathbf{l}=(0,\ (1-m^2)^{1/2}\sin\theta,\ -(1-m^2)^{1/2}\cos\theta),$$
$$m(x)\approx(h_\pi/h_e)\sin\theta(x),$$
$$(\alpha-\alpha')\left(\frac{d\theta}{dx}\right)^2-\beta\frac{h_\pi^2}{h_e^2}\sin^2 2\theta-\frac{1}{2}\Lambda_{ik}(m,\theta)\frac{\partial u_i}{\partial x_k}=0 \qquad (2)$$

(we limit ourselves to the case of a longitudinal acoustic wave of low frequency $\omega \ll \omega_1$, where ω_1 is the frequency of free vibrations of the domain boundaries[5]).

By solving Eq. (2) with account of (1), we can easily find the surface energy of the domain boundary in the deformation field $\mathbf{u}(\mathbf{r}, t)$:

$$\sigma(\mathbf{u})=\sigma_{sur}\left(1+\frac{f_x}{\beta}\frac{\partial u_x}{\partial x}+\frac{f_y}{\beta}\frac{\partial u_y}{\partial y}+\frac{f_z}{\beta}\frac{\partial u_z}{\partial z}\right), \qquad (3)$$

where σ_{sur} is the surface energy without account of deformations,[2]

$$f_x=\delta_1\frac{\beta}{2\delta},\quad f_y=(\delta_1-\delta_4)\frac{\beta}{2\delta},\quad f_z=(\delta_1+\delta_3+\delta_4+\delta_5)\frac{\beta}{2\delta}, \qquad (4)$$

i.e., in the field of a longitudinal sound wave $u_i(\mathbf{r}; t)$ the density of the surface energy of the portion of the boundary at the point $\mathbf{r}$ and the time t is equal to

$$\sigma(\mathbf{r},t)=\sigma_{sur}(1+f\mathbf{ku}(\mathbf{r},t)/\beta),$$

where f is the effective constant of magneto-elastic coupling (see (2), (4)).

Using this formula, we can easily establish the fact that the mean size of the domain d at the point $\mathbf{r}$ and at the time t is equal to[6]

$$d(\mathbf{r},t)=d_0\left(\frac{\sigma(\mathbf{r},t)}{\sigma_{sur}}\right)^{1/2}\approx d_0+\frac{1}{2}fd_0\mathbf{ku}(\mathbf{r},t)=d_0+X(\mathbf{r},t),$$

where $d_0 = (\sigma_{sur}l_z/\xi M_0^2)^{1/2}$ is the equilibrium size of the domain, X can be interpreted as the shift of the domain from its position of equilibrium. If $(g\Delta H)^{-1}$ is the damping time for free vibrations of the domain boundary, $\mu_{\pi/2}S$ the total mass of the domain boundary,[5] N the number of domains for $h = h_f$ ($N \gg 1$), s the velocity of sound, then we have for the sound damping decrement

$$\Gamma=g\Delta H\frac{N\mu_{\pi/2}S}{\rho_0 V}\left(\frac{d_0}{2s}\right)^2\omega^2. \qquad (5)$$

We note that Γ (5) depends weakly on the temperature at $T \ll T_N$, T_N is the Neel temperature of the antiferromagnet, in contrast with the damping decrement γ_{pp} due to phonon-phonon collisions:

$$\gamma_{pp}=\Theta_D\left(\frac{\omega}{\Theta_D}\right)^2\left(\frac{T}{\Theta_D}\right)^3,$$

where Θ_D is the Debye temperature.

The damping at low temperatures ($T \approx 4-70°K$) was measured in[1]. Assuming $\Delta H \sim 10$ Oe and $T \sim 10°K$, we can easily obtain the following for reasonable values of the parameters in (5) (see[2,4,5]):

$$\Gamma\sim10^3\gamma_{pp}.$$

The region of sharp increase in the sound absorption[1] coincides with the region of existence of the intermediate state.[2] Thus the sharp peak in the absorption obtained by experiment (see[1]) finds a satisfactory explanation.

To explain the results, various mechanisms were adduced[1], including the absorption of sound by the usual nonequilibrium domains.[7] It is seen from (5) that the "domain" decrement of attenuation is proportional to the ratio of the "total effective mass of the domain boundaries" to the mass of the crystal $N\mu_{\pi/2}S/\rho_0V$, i.e., the existence of a thermodynamical equilibrium domain structure with $N \gg 1$ is necessary for effective sound absorption.

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