GAMMA-MAGNETIC RESONANCE

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Abstract

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GAMMA-MAGNETIC RESONANCE

IN A SINGLE-DOMAIN FERROMAGNET

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1. Recently, a line of research connected with the action of radio-frequency fields on the spectrum of Mössbauer gamma resonance has been developing intensively. In the author' s work ([1]) the phenomenon of gamma-magnetic resonance was considered; it is a two-quantum process: a Mössbauer nucleus absorbs a gamma quantum and emits or absorbs a radio-frequency photon. This phenomenon was studied theoretically for the example of a ferromagnetic absorber of multidomain structure. The principal contribution to the effect was due to nuclei located in domain walls.

At the same time, it would be of interest to study the effect from nuclei located in a domain. The influence of the latter on gamma-magnetic resonance should become predominant when a saturating constant magnetic field is applied to the ferromagnetic absorber, as a result of which the ferromagnetic specimen becomes single-domain. Our work is devoted to the study of the effect in this structure.

2. The problem may be characterized by the following Hamiltonian:

$$\hat{\mathcal{H}} = \hat{\mathcal{H}}^0 + \hat{\mathcal{H}}^\gamma + \hat{\mathcal{H}}^{rf}, \tag{1}$$

where $\hat{\mathcal{H}}^0$ is the Hamiltonian determining the energy levels of the nucleus (we assume that the ground and excited nuclear levels possess Zeeman splitting in the magnetic field), while $\hat{\mathcal{H}}^\gamma$ and $\hat{\mathcal{H}}^{rf}$ are the Hamiltonians of the interaction of, respectively, the gamma quantum and the radio-frequency photon with the nucleus.

One can calculate the probability of transition of the nucleus from the ground state $|a\rangle$ to the excited state $|b\rangle$, with absorption of a gamma quantum of frequency ω_γ and absorption or emission of a radio-frequency quantum of frequency ω:

$$W_{a\to b} = W^+_{a\to b} + W^-_{a\to b}, \tag{2}$$

$$W^+_{a\to b}(\omega) = W^-_{a\to b}(-\omega), \tag{3}$$

$$W^+_{a\to b}(\omega) = \frac{\pi}{2\hbar^4}\left|\sum_s\left\{\frac{R_{bs}Q_{sa}}{\omega_{s,a}+\omega} + \frac{Q_{bs}R_{sa}}{\omega_{s,a}-\omega_\gamma}\right\}\right|^2 \delta(\omega_{b,a}-\omega_\gamma+\omega). \tag{4}$$

Here $R_{s,s'}$ and $Q_{s,s'}$ are defined by the identities

$$\langle s, n_\gamma - 1|\hat{\mathcal{H}}^\gamma|n_\gamma, s'\rangle = R_{s,s'}\exp(-i\omega_\gamma t),$$

$$\langle s|\hat{\mathcal{H}}^{rf}|s'\rangle = Q_{s,s'}\cos(\omega t).$$

3. Let us now consider the Hamiltonians of the interactions of the perturbations with the nucleus. We direct the constant and alternating magnetic fields respectively along the axes oz' and ox'. In a domain, the alternating field at the nucleus is amplified. This is due to the fact that the effective field at the nucleus in ferromagnets is directed parallel to the magnetization, and its magnitude is equal to the hyperfine field at the nucleus, which reaches the order of 10^5–10^6 Oe. Because of this circumstance, a small change in the direction of the magnetization caused by the application of the alternating component leads to the appearance of an analogous component at the nucleus, many times exceeding

the initial intensity $\overline{\mathbf{H}}_1$. The amplification coefficient is expressed by the formula $\zeta = H_N/H_0$ (2), where H_N and H_0 are the magnitudes of the hyperfine and constant magnetic fields at the nucleus. Usually, the amplification coefficient is of the order of 10^2, but for Rh^{100} nuclei in metallic nickel it reaches 10^3 (3).

Let us now write the Hamiltonian of the interaction of the radio-frequency field with the nucleus:

$$\mathcal{H}_{rf} = (1+\zeta)g\beta_N H_{1x'}\hat{I}_{x'}\cos(\omega t), \tag{5}$$

where $\hat{I}_{x'}$, $H_{1x'}$ are, respectively, the components of the nuclear spin and of the intensity $\overline{\mathbf{H}}_1$ along the axis Ox'.

Let us also write the matrix elements of the Hamiltonian for the interaction of a gamma quantum with the nucleus, assuming the transitions to be magnetic dipole transitions:

$$R_{ba} = \left(\frac{2\pi\hbar c}{V\omega_\gamma}\right)^{1/2}\chi(M)(-)^{m_b-m_a}\begin{pmatrix} j_b & 1 & j_a \\ m_b & M & -m_a\end{pmatrix}\times$$

$$\times \sum_{\gamma=\pm 1} vl_\nu D^{(1)*}_{\nu, m_a - m_b}(\alpha, \beta, \gamma), \tag{6}$$

where (α, β, γ) are the Euler angles defining the coordinate system (x', y', z') with respect to the laboratory system (x, y, z), whose oz axis is directed along the propagation vector of the gamma quantum; l_ν are the spherical projections of the polarization vector in this same coordinate system; D are generalized spherical functions;

$$\begin{pmatrix} j_b & 1 & j_a \\ m_b & M & -m_a \end{pmatrix}$$

are Wigner $3j$-symbols, which are determined by the spins and magnetic quantum numbers of the ground (j_a, m_a) and excited (j_b, m_b) states of the nucleus.

4. If we now substitute (5) and (6) into (4), and then compare the probability of a two-quantum transition with the probability of a one-quantum Mössbauer transition, then, using the theorem on spectroscopic stability, one can find the cross section of the gamma-magnetic transition:

$$\sigma^{(2)+}_{a\to b} = \frac{\sigma_0}{8}(1+\eta)^2 \left(\frac{\beta_N}{\hbar}\right)^2 \left| \sum_{\varepsilon,\nu} \varepsilon \nu H'_{1\varepsilon} f_\varepsilon l_\nu D^{(1)}_{\nu, m_a - m_b - \varepsilon}(\alpha, \beta, \gamma) \right|^2 \times$$

$$\times \frac{\Delta\omega_{\text{izl}}}{\Delta\omega_n^{(2)}} \frac{\left(\Delta\omega_n^{(2)}\right)^2}{\left(\omega_\gamma - \tilde{\omega} + m_b\omega_1 - m_a\omega_0 - \omega\right)^2 + \left(\Delta\omega_n^{(2)}\right)^2}, \tag{7}$$

$$f_\varepsilon = \frac{g_0 \left[(j_a + \varepsilon m_a)(j_a - \varepsilon m_a + 1)\right]^{1/2}}{[\omega\varepsilon + \omega]} \begin{pmatrix} j_b & 1 & j_a \\ m_b & m_a - m_b - \varepsilon & -m_a + \varepsilon \end{pmatrix} +$$

$$+ \frac{g_1 \left[(j_b - \varepsilon m_b)(j_b + \varepsilon m_b + 1)\right]^{1/2}}{[\tilde{\omega} - \omega_1(m_b + \varepsilon) + \omega_0 m_a - \omega_\gamma]} \begin{pmatrix} j_b & 1 & j_a \\ m_b + \varepsilon & m_a - m_b - \varepsilon & -m_a \end{pmatrix}. \tag{8}$$

Here $\Delta\omega_{\text{izl}}$ is the half-width of the incident gamma radiation; $\Delta\omega_n^{(2)}$ is the half-width of the gamma-magnetic resonance; g_0 and g_1 are the g-factors of the ground and excited states of the nucleus; $\omega_0 = -g_0\beta_N H_N/\hbar$; $\omega_1 = -g_1\beta_N H_N/\hbar$; $\tilde{\omega}$ is the distance, in frequency units, between the centers of gravity of the ground and excited nuclear levels;

$$\sigma_0 = 2\pi\lambda^2 \frac{2j_b + 1}{2j_a + 1} \frac{f'}{1 + \alpha},$$

where f' is the Mössbauer factor for the absorber; α is the conversion coefficient;

$$H'_{1\varepsilon} = \sum_{\mu} D^{(1)}_{\mu\varepsilon}(\alpha, \beta, \gamma) H_{1\mu},$$

where $H_{1\mu}$ are the spherical projections of the intensity vector of the alternating magnetic field in the laboratory coordinate system.

To estimate the effect, we choose such a direction of the magnetic fields that

$$\left| D^{(1)}_{\gamma, m_a - m_b - \varepsilon}(\alpha, \beta, \gamma) \right| = 1.$$

This can always be done provided

$|m_a - m_b - \varepsilon| = 1$. Then, if one takes into account that the number of nuclei in the domain is an order of magnitude larger, while the amplification coefficient is an order of magnitude smaller, than in the domain walls, the magnitude of the resonant absorption of gamma quanta in the indicated process will be of the same order as the corresponding absorption in the domain walls and can be experimentally detected on Fe^{57} nuclei in pure iron (see (1)).

5. Apparently, the theory of gamma-magnetic resonance in single-domain and multidomain ferromagnets can be invoked to explain the experiment carried out by Heiman et al. [(4)]. They observed satellites near the positions of Mössbauer lines, which arose when Fe^{57} nuclei introduced into pure iron were acted upon simultaneously by gamma radiation and a radio-frequency field. This experiment was considered in a constant magnetic field directed both perpendicular and parallel to the radio-frequency field. In the first case, when the field strength was increased to 1 kG, the intensity of the satellites changed insignificantly, and upon approaching a field value of 2 kG it tended to zero; whereas in the second case the intensity of the satellites fell rapidly already at a constant field of 50 G.

Let us try to explain these experiments from the standpoint of our theory. Let us first assume that the satellites observed in Ref. [(4)] are due to gamma-magnetic resonance. Then, in a perpendicular radio-frequency field, an increase in the constant magnetic field leads to destruction of the domain walls, and the intensity of the satellites becomes dependent only on the nuclei located inside the domains. However, with a further increase in the strength of the constant field, the intensity of the satellites falls in proportion to $1/H_0^2$. In a parallel radio-frequency field, an increase in the strength of the constant magnetic field leads, through the destruction of the domain walls, to a sharp decrease in the intensity of the satellites, since in this case gamma-magnetic resonance from nuclei located inside a domain is equal to zero.

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Note: Figure translations are in progress. See original paper for figures.