# UNUSUAL TRANSITIONS IN NUCLEI*

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The effect of magnetic field reversal on transmission of the Mössbauer radiation through a crystal as well as on the reaction yield is analyzed. The enhancement of coherent radiative channel as well as suppression of incoherent scattering and reactions caused by the field reversal, are discussed.

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We shall concentrate on electromagnetic transitions occurring in nuclei, which are located in an alternating magnetic field. Such situation, unusual for the ordinary nuclear spectroscopy, has been realized in many Mössbauer experiments performed with ferromagnetic absorbers subject to radiofrequency (RF) magnetic field (see *e.g.* [1,2]). Hundreds of such experiments dealt with soft ferromagnets, whose magnetization was easily governed by intensive RF field. This field causes periodical reversals of the magnetization, which lead to periodical reversals of the magnetic field at the nuclei between two values $+\boldsymbol{h}_0$ and $-\boldsymbol{h}_0$. The corresponding step-wise-reversals model has been built in [3-5]. Here we shall briefly discuss our theoretical works [5-10], which explained a number of such experiments and predicted new effects as well.

Let at the moment $t = 0$ the magnetic field at the Mössbauer nucleus reverse from $+\boldsymbol{h}_0$ to $-\boldsymbol{h}_0$. Such reversals repeat with period $T$:

$$\boldsymbol{h}(t) = \boldsymbol{h}_0 f(t) = \boldsymbol{h}_0 f(t+T)\,, \tag{1}$$

where

$$f(t) = \begin{cases} +1, & \frac{-T}{2} < t < 0\,, \\ -1, & 0 < t < \frac{T}{2}\,. \end{cases} \tag{2}$$

Choosing the quantization axis $\zeta$ along $\boldsymbol{h}_0$, one can write down the interaction operator of the nucleus with magnetic field as

$$\hat{V}_f(t) = -\,\gamma_\kappa\,\hat{\boldsymbol{I}}_\zeta\,h_0\,f(t)\,, \tag{3}$$

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where $\hat{\boldsymbol{I}}$ is the spin operator (in units of $\hbar$) of the nucleus, $\gamma_\kappa = g_\kappa \mu_N$ is the gyromagnetic ratio of the nucleus which is a product of the nuclear magneton $\mu_N$ and $g$-factor $g_\kappa$; the subscript $\kappa = g$ for the ground nuclear state and $\kappa = e$ for the excited one.

Then the Hamiltonian of the system (nucleus+crystal+quantized electromagnetic field) will be a periodical function of time, $H(t) = H(t+T)$. The corresponding time-dependent Schrödinger equation is easily solved, giving the scattered electromagnetic wave. In units $i(2\pi\,\hbar\,\omega)^{1/2}$ it is written as:

$$\boldsymbol{E}_{\rm sc}(\boldsymbol{r},t)^j_{\rm coh} = \sum_{\lambda'=\pm 1} \sum_{n=-\infty}^{\infty} f^{(n)}_{\rm coh}(\boldsymbol{k},\boldsymbol{e}_\lambda;\boldsymbol{k'}_n,\boldsymbol{e'}_{\lambda'})^N_j\,\boldsymbol{e'}_{\lambda'}\frac{1}{r}\,{\rm e}^{-i\omega_n(t-r/c)}\,, \qquad (4)$$

where $\boldsymbol{k}$, $\boldsymbol{e_\lambda}$ and $\boldsymbol{k'}$, $\boldsymbol{e'_\lambda}$ are the wave vectors and polarizations of incident and scattered photons, $E=\hbar\omega$ is the energy of incident photon,

$$\omega' = \omega_n = \omega - n\Omega = k_n c \qquad (5)$$

are possible frequencies of scattered photons. The coherent Raman scattering amplitude of $\gamma$-quanta by the nucleus in the $j$-th site with absorption $(n<0)$ or emission $(n>0)$ of $n$ quanta of alternating field with frequency $\Omega$ is given by [5]

$$\begin{aligned} f^{(n)}_{\rm coh}(\boldsymbol{k},\boldsymbol{e}_\lambda;\boldsymbol{k'},\boldsymbol{e'}_{\lambda'})^N_j &= -p_j\frac{{\rm e}^{W_j(\boldsymbol{k})-W_j(\boldsymbol{k'})}}{2\boldsymbol{I}_g+1}c^{-2}\sum_{M_g,M_e}\langle e|\hat{j}^N_{\lambda'}(\boldsymbol{k'})|g\rangle^*\langle e|\hat{j}^N_\lambda(\boldsymbol{k})|g\rangle \\ &\times\sum_{m=-\infty}^{\infty}\frac{a^*_{eg}(m-n)\,a_{eg}(m)}{E-E'_0-m\hbar\Omega+i\frac{\Gamma}{2}}\,, \end{aligned} \qquad (6)$$

where $p_j$ is the probability to find a resonant isotope in the $j$-th site, $\Gamma$ is the width of the resonant level, ${\rm e}^{-W}$ is the Lamb-Mössbauer factor, $|\kappa>=|I_\kappa,M_\kappa\rangle$ is the nuclear wave function,

$$\hat{j}^N_\lambda(\boldsymbol{k}) = \int d\boldsymbol{r}\;{\rm e}^{i\boldsymbol{kr}}\boldsymbol{e}_\lambda\,\hat{\boldsymbol{j}}_N(\boldsymbol{r}) \qquad (7)$$

is the Fourier transform of the nuclear current density operator. Besides, we used the following Fourier coefficients:

$$a_{eg}(n) = \frac{1}{T}\int_{-T/2}^{T/2} dt\;{\rm e}^{-int-\alpha_{eg}|t|}\,, \qquad (8)$$

where

$$\alpha_{eg} = \Big(\gamma_g M_g - \gamma_e M_e\Big)\frac{h_0}{\hbar}\,. \tag{9}$$

Having derived a generalized optical theorem, we got the absorption cross section of $\gamma$-quanta by nuclei. Besides, it was obtained the scattering cross section.

Apart from the periodical reversals of the field we took into account the magnetostrictive vibrations, which are generated in ferromagnets by the RF field. This allowed us to explain with good accuracy the experimental results of Pfeiffer [1].

Moreover, we considered [6] a situation, when an additional constant magnetic field was superimposed along the RF one. Then asymmetric reversals of the field at the nucleus arise, which lead to splitting of the nuclear quasi-energies. This splitting turned out to be the same as the Zeeman splitting of sublevels in the constant magnetic field, being equal to the averaged over time alternating field $\langle \boldsymbol{h}(t)\rangle$. As a result, we explained the observations of Kopcewicz *et al.* [11] of the collapsed line splitting and predicted the splitting of satellites, observed in [8].

Most interesting transient effects arise in the low-frequency case, as $\Omega \to 0$. Then just after the reversal the instantaneous absorption cross section begins to oscillate [5]. During some time intervals the cross section takes negative values, that corresponds to enhancement of the intensity of radiation, transmitted through an absorber.

This has been realized experimentally by Shvyd'ko *et al.* [12], who found that the field reversal cause a short flash of the transmitted radiation, followed by the attenuating oscillations. In this experiment a thick ferromagnetic absorber has been used, and the incident Mössbauer radiation was tuned to the isolated nuclear transition $M_g \to M_e$.

The electromagnetic wave scattered by the $j$-th nucleus, having initial spin projection $+M_g$, into the $\beta$-th channel (in units $i(2\pi\,\hbar\omega)^{1/2}$) is now given by [9,10]

$$\boldsymbol{E}_{\rm sc}(\boldsymbol{r},t)^j_{\alpha\to\beta}=\sum_{\lambda'}\boldsymbol{e}'_{\lambda'}f_{\alpha\beta}\frac{1}{r}\Big\{(1-\theta(t^*))\,\mathrm{e}^{-i\omega' t^*}+\theta(t^*)\,\mathrm{e}^{-i\omega_0'^{-}t^*-\Gamma t^*/2\hbar}\Big\}\,, \tag{10}$$

where $\alpha$ and $\beta$ are initial and final states of the scatter, $t^* = t - r/c$ is the retarded time,

$$\omega'^{\pm}_0 = \frac{E_0'}{\hbar} \pm (\gamma_g M_g' - \gamma_e M_e)\frac{h_0}{\hbar}$$

are the resonant frequencies of transitions $\pm M_e \to \pm M_g'$ in the field $\boldsymbol{h}_0$,

$$\theta(x) = \begin{cases} 1 & x > 0\,, \\ 0 & x < 0\,, \end{cases} \tag{11}$$

$f_{\alpha\beta}$ is the scattering amplitude of $\gamma$-quanta by the Mössbauer isotope $+M_g$ in the constant field $\boldsymbol{h}_0$.

The wave scattered by the nucleus being initially in the state $-M_g$ will be

$$\boldsymbol{E}_{\rm sc}(\boldsymbol{r},t)^j_{-\alpha\to-\beta} = \sum_{\lambda'} \boldsymbol{e'}_{\lambda'} f_{-\alpha,-\beta}\frac{1}{r}\left\{ {\rm e}^{-i\omega' t^*} - {\rm e}^{-i\omega'^+_0 t^* - \Gamma t^*/2\hbar} \right\} \theta(t^*) \,. \quad (12)$$

For the crystal of arbitrary thickness we had to take into account multiple scattering of the waves such as (10) and (12). Adding all waves, generated inside the crystal, we derived the formula for the time-dependent intensity of the beam transmitted through the absorber, which reproduced well the observations of [12] .

The instantaneous differential cross section for scattering of $\gamma$-quanta by the isotope $^{57}$Fe with $\boldsymbol{I}_g = \frac{1}{2}$ in an unpolarized target will be

$$\sigma(\omega,t) = \frac{1}{2}\left(\sigma^{(+)}(\omega,t) + \sigma^{(-)}(\omega,t)\right) \,, \quad (13)$$

where

$$\sigma^{(\pm)}(\omega,t) = \frac{1}{c}\, j_{\rm sc}(\omega,t)^{(\pm)} r^2 \quad (14)$$

are the cross sections at the nuclei being initially in the states $\pm M_g$, and $j_{\rm sc}$ are the corresponding flux densities. The incohorent scattering cross section by the whole target is proportional to (13).

It is useful to introduce the following notations:

$$x = 2\frac{(E - E_0^+)}{\Gamma}, \quad \tau = \frac{\Gamma t^*}{\hbar}, \quad x_0 = 2\frac{(E_0 - E_0^+)}{\Gamma}, \quad E_0^+ = \hbar\omega_0^+ \,. \quad (15)$$

Averaging (14) over the energy distribution of incident $\gamma$-quanta

$$w_e(E) \sim \frac{\frac{\Gamma}{2}}{(E - E_0)^2 + (\frac{\Gamma}{2})^2} \,, \quad (16)$$

one gets the experimentally measured cross sections [10]

$$\bar{\sigma}^{(+)}(t) = \bar{\sigma}^{(+)} \left\{ (1 - \theta(\tau)) + {\rm e}^{-\tau}\theta(\tau) \right\} \,, \quad (17)$$

and

$$\bar{\sigma}^{(-)}(t) = \bar{\sigma}^{(+)} \left\{ 1 - \left[ \cos\left(\frac{x_0\tau}{2}\right) + \left(\frac{2}{x_0}\right) \sin\left(\frac{x_0\tau}{2}\right) \right] {\rm e}^{-\tau} \right\} \theta(\tau) \,, \quad (18)$$

where $\bar{\sigma}^{(+)}$ is a standard cross section of $\gamma$-quanta in the stationary case. From (10), (12), (19) and (20) we can see that prior to the field reversal the scattering proceeds only at the nuclei $+M_g$. After the reversal these nuclei continue to decay generating the exponentially attenuating wave concentrated at the resonant energy $\omega_0^-$, which corresponds to de-excitation transition $M_e \to M_g'$ in the field $-\boldsymbol{h}_0$. On the contrary, the $-M_g$ nuclei begin to absorb incident radiation only at $t > 0$. But their contribution to the radiation yield grows gradually from zero value at $t = 0$ to $\bar{\sigma}^{(+)}$ at $t \gg \tau_N$. Aside of the exact resonance ($x_0 \neq 0$) the function $\bar{\sigma}^{(-)}(\tau)$ oscillates with the period $\delta\tau = 4\pi/|x_0|$. In the case of exact resonance ($x_0 = 0$) this cross section becomes a monotonically growing function of the time:

$$\bar{\sigma}^{(-)}(t) = \bar{\sigma}^{(+)}\left\{1 - (1+\tau)\mathrm{e}^{-\tau}\right\}\theta(\tau)\,. \tag{19}$$

In an unpolarized target with isotopes $^{57}$Fe the averaged cross section for exact resonance is

$$\bar{\sigma}(t) = \bar{\sigma}(0)\left\{1 - \tau\mathrm{e}^{-\tau}\theta(\tau)\right\}\,, \tag{20}$$

where $\bar{\sigma}(0) = \bar{\sigma}^{(+)}/2$ is the value of $\bar{\sigma}(t)$ prior to the reversal.

The function (20) in the interval $0 \le \tau < \infty$ is a sum of monotonically de- creasing ($\bar{\sigma}^{(+)}(t)$) and increasing ($\bar{\sigma}^{(-)}(t)$) functions. Therefore it looks like a well with a minimum at the point $\tau = 1$, where it equals $0.67\,\bar{\sigma}(0)$. This means a suppression of the incoherent process during the time $\sim \tau_N$. The same effect holds for reactions [9]. Perhaps, these effects will facilitate construction of the $\gamma$-ray lasers.

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