Periodic modulation of Mössbauer radiation

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An expression is obtained for the spectral intensity of Mössbauer radiation that is periodically modulated by passage through layers that alternate in time and have different complex refractive indices. The influence of the modulation parameters on the spectral distributions of the modulated radiation is analyzed. It is shown that interference should take place in the process of transition of the isotope from the source to the absorber through the different "temporal channels."

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Amplitude and phase modulation of gamma rays can be effected by periodically altering the properties of the medium between the nuclei of the emitter and the nuclei of the absorber. If the radiation passes through time-alternating layers with complex refractive indices $\alpha_1 + i\beta_1$ and $\alpha_2 + i\beta_2$, then the modulated photon probability amplitude takes the form

$$A(t) = \exp\left[i\left(\omega_0 + i\frac{\Gamma}{2}\right)t\right] B(t+\eta), \tag{1}$$

where $B(t+\eta)$ is the modulation function. The function $B(\eta)$ has the following properties:

$$B(\eta) = \begin{cases} f_1 e^{i\phi_1} & 0 \leqslant \eta < \tau \\ f_2 e^{i\phi_2} & \tau \leqslant \eta \leqslant T \end{cases} . \tag{2}$$

Here $\omega_0 = E/\hbar$, E is the energy, Γ is the width of the excited level of the source nuclei, T is the period of the modulation, τ is the fraction of the period during which the nucleus of the absorber is illuminated through a layer with parameters α_1 and β_1; $f_i = \exp[-(\omega_0/c)\beta_i d_i] = \exp[-k_i d_i/2]$, k_i is the linear absorption coefficient, and d_i is the layer thickness.

Taking the Fourier transform of $A(t)$ and averaging the intensity of the modulated radiation over all values of η, the spectral distribution of the radiation is

$$I(\Delta) \sim \frac{f_1^2 \tau/T + f_2^2(1-\tau/T)}{\Delta^2 + \Gamma^2/4} + \frac{f_1^2 + f_2^2 - 2f_1 f_2 \cos(\phi_1 - \phi_2)}{\Delta^2 + \Gamma^2/4} \tag{3}$$

$$\times \frac{1}{\Gamma T/2}\left[\left(1 - \frac{2\Gamma^2/4}{\Delta^2 + \Gamma^2/4}\right) C(\Delta) - \frac{2\Gamma^2/4}{\Delta^2 + \Gamma^2/4} D(\Delta)\right]\left[1 - 2\cos\Delta T e^{-\Gamma T/2} + e^{-\Gamma T}\right]^{-1},$$

where

$$C(\Delta) = 1 - e^{-\Gamma T} - 2e^{-\Gamma T/2}\left[\cos\Delta\tau \,\mathrm{sh}\frac{\Gamma}{2}(T-\tau) + \cos\Delta(T-\tau)\,\mathrm{sh}\frac{\Gamma}{2}\tau\right],$$

$$D(\Delta) = 4\frac{\Delta}{\Gamma} e^{-\Gamma T/2}\left[\sin\Delta\tau \,\mathrm{ch}\frac{\Gamma}{2}(T-\tau) + \sin\Delta(T-\tau)\,\mathrm{ch}\frac{\Gamma}{2}\tau - \sin\Delta T\right]$$

$$\Delta = \omega_0 - \omega .$$

Under conditions of periodic modulation of the properties of the medium, the photon can proceed from the source to the absorber along two paths that are separated in time: through the layer of the first medium and through the layer of the second medium. Fourier-transformation and averaging of the intensity of the modulated radiation over η corresponds to a transition from periodic alteration of the properties of the medium and modulation of the probability amplitude of the individual photon to a stationary process that corresponds to the real conditions of the experiment. In this stationary process it is impossible to determine which of the possible paths is realized for the detected photon.

As seen from (3), in this process, in contrast to the stationary process without modulation, the spectral distribution of the radiation contains, besides a Lorentz line, also a non-Lorentz part that is symmetrical with respect to ω_0. The intensity of the non-Lorentz part of the spectrum, due to the modulation of the radiation includes, owing to the physical indistinguishability of the possible photon paths, an interference term whose magnitude depends on the phase shift between the two "channels" for the photon.

Thus, in contrast to the previously observed interference phenomena, in coherent interaction of gamma rays with nuclei and with electron shells of atoms (interference of resonant scattering and Rayleigh scattering by electrons, [1] nuclear diffraction, [2] interference of internal conversion of gamma rays and the photoeffect[3]), when the process proceeds simultaneously via two or several "spatial channels," in the case when the radiation is modulated by passage through a medium with optical properties that vary periodically in time, an interference should be observed in the course of transition of the photon from the source to the absorber via the different "temporal channels."

If the radiation is modulated with a chopper that blocks the radiation flux completely ($f_2 = 0$), then the second "channel" for the photon does not exist and there is of course no interference, corresponding to pure amplitude modulation of the photon probability amplitude.

Modulation leads to the appearance of sidebands in the spectrum and to attenuation of the central line.[1)] The sideband position is determined by the value of ΓT. At $\Gamma T \lesssim 1$ the sidebands are distinctly separated, and with increasing ΓT they come closer to the central line; When $\Gamma T \gg 1$, the modulation part of the spectrum has practically no sidebands and the total spectrum turns into a single line that is, however, much weaker than Lorentzian. Figure 1 shows, for $\Gamma T = 2.4$, 3.1, and 22 ($\Gamma\tau = 1$), the calculated Mössbauer absorption spectra of the modulated radiation. At $\Gamma T \lesssim 1$, the intensities of the central line and of the sidebands in the spectrum of the modulated radiation depend on the value of $\Gamma\tau$. Figure 2 shows the calculated resonant-absorption spectra for $\Gamma T = 2.1$ and $\Gamma\tau = 0.2$ and 1. If $\Gamma T \gg 1$, then the value of $\Gamma\tau$ determines the width and intensity of the central line.

The relation between the intensity of the Lorentz line and the modulation part of the spectrum depends essentially on the sign and magnitude of the interference term.

Ruby *et al.*[4] obtained the first clear-cut results in experiments on periodic modulation of gamma radiation with the aid of a mechanical chopper. Similar experiments were performed later by Hauser *et al.*,[5] who noted that, in contrast to[4], they obtained entirely different results even though the experimental conditions were close.

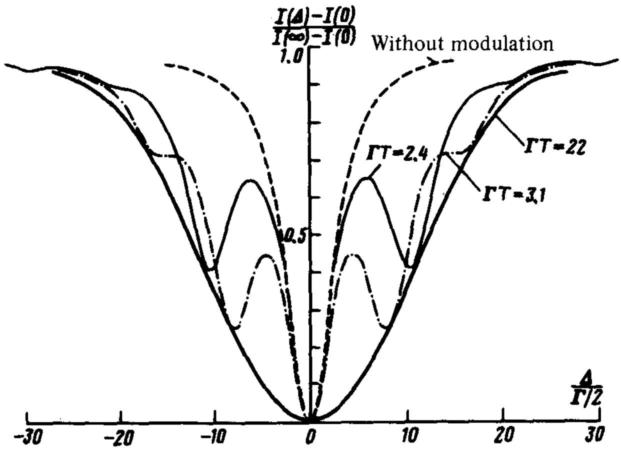

FIG. 1. Mössbauer absorption spectra of modulated radiation in Fe^{57} at different values of ΓT ($\Gamma\tau = 1$; $f_2 = 0$).

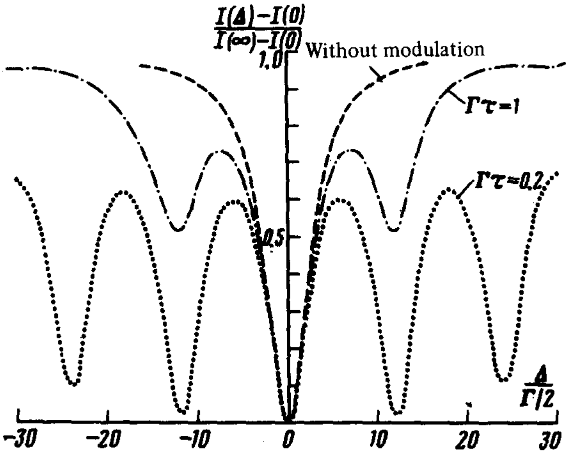

FIG. 2. Mössbauer spectra of absorption of modulated radiation in Fe^{57} at $\Gamma T = 2.1$ and different values of $\Gamma\tau$ ($f_2 = 0$).

The explanation of the "contradiction" of the results of[4] and[5] lies in the following. In[5] the authors, when comparing the experimental data with calculation, used the expression obtained by them for the spectral distribution of the modulated Mössbauer radiation. This expression reflects only pure amplitude modulation; the phase modulation and its influence on the character of the spectrum are not taken into account at all.

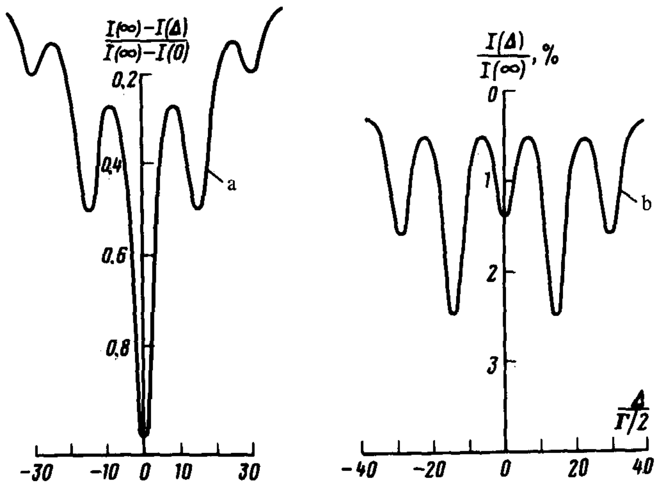

FIG. 3. Mössbauer spectra of the absorption of modulated radiation in Fe^{57}: a) $\Gamma T = 2.1$; $\Gamma\tau = 0.54$; $f_2^2/f_1^2 = 0.05$; $\phi_1 - \phi_2 = 0.86(\pi/2)$. b) $\Gamma T = 1.82$; $\Gamma\tau = 0.42$; $f_2^2/f_1^2 = 0.25$; $\phi_1 - \phi_2 = 0.89\pi$.

Inasmuch as in the experiments of[5] only 5% of the radiation passed through the "second channel," and the value of $\phi_1 - \phi_2$ apparently differed little from $\pi/2$, the experimental absorption spectrum turned out to be close to that calculated for pure amplitude modulation. (In the general case, even at $f_2^2/f_1^2 = 0.05$ the interference term can amount to as much as 50% of the total modulation part of the spectrum.) Of course, in the case of pure amplitude modulation, the spectrum in the experiments of Ruby *et al.* should have the same form as the spectrum in[5], but in the former experiments they had $f_2^2/f_1^2 = 0.25$, an appreciable fraction of the radiation passed through the "second channel," and the interference could give rise to a strong influence of phase modulation.

The Mössbauer absorption spectra for the experimental parameters of[4] and[5] were calculated by using expression (3). These experimental distributions, at $\phi_1 - \phi_2 = 0.86(\pi/2)$ for[5] and $\phi_1 - \phi_2 = 0.89\pi$ for[4] (see, e.g.,[2)] Fig. 3) are close to the corresponding experimental spectra in[5] and[4]. The difference between the spectra in Fig. 3 is due to phase modulation. The character of the spectrum was determined by the interference in the course of the passage of the photon from the source to the absorber via the different "temporal channels."

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[1)] The non-Lorentz part of the radiation spectrum is symmetrical with respect to the interchange of τ and $T - \tau$.

[2)] The calculation was carried out for the values $\Gamma T = 2.1$ and $\Gamma\tau = 0.54$, corresponding to a modulator-disk speed of 2713 rpm in[5], and at values $\Gamma T = 1.82$ and $\Gamma\tau = 0.42$, corresponding to 500 rpm for the modulator disk in[4]. In the experiment of Ruby *et al.* the layers of the modulator disk had a thickness variable in the period, and effective values were used in the calculation for d_i and correspondingly for f_i and $\phi_1 - \phi_2$.

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