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THE SPECTRUM OF THE MÖSSBAUER RADIATION PASSED THROUGH A VIBRATING RESONANT MEDIUM

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It is well known that the ultrasonic vibrations applied to either the source or the absorber in Mössbauer experiments, influence the spectrum of the radiation passed, resulting in a splitting of the original line into an infinite series of sidebands, spaced equidistantly at multiples of $\Delta f$, the frequency of the external perturbation [1]. This phenomenon can be described adequately either from a wave point of view, in terms of a frequency modulation of the photon wave, or in a corpuscular one — in terms of creation and annihilation of phonons, which interact with the gamma-radiation field.

More complex is the case, when the source is at rest, the radiation is passed through a resonant absorber, vibrating at ultrasonic frequency, and a second absorber serves for analyzing the transmitted radiation. In this case, the vibrating changes its absorption with a period comparable with the lifetime of the excited Mössbauer state, and it must change appreciably the spectral distribution of the emerging radiation. The experiments of Asher et al [2] shows a similar splitting of the spectrum in this case. These authors explain the results using the optical theorem applied to the forward-scattered component of the radiation. However, their approach yields an infinite set of coupled differential equations for the partial amplitudes, which can be solved in a few special cases, when the modulating absorber is thin, in particular. At the same time, it is obvious that the expected effect must be increasing with the modulator thickness.

To avoid this difficulty, one may use the theory, developed by Hamermesh [3] and Harris [4] for the transmission of the Mössbauer radiation through a stationary resonant medium. Thus, we assume a modulator containing resonant nuclei, vibrating at the same frequency, amplitude and phase. Then, in the modulator frame, the time dependence of the source radiation is:

$$\alpha(t) = e^{i\omega t - \frac{t^2}{2}} e^{-iK\xi + i\gamma}$$

Here $\xi = \lambda t$ is the wavenumber of the photon, $A$ — the vibrating amplitude, and $\gamma$ describes the phase of crystal vibrations at $t=0$. The Fourier transform of $\alpha(t)$ is:

$$\alpha(\omega) = \sum_{k=-\infty}^{\infty} J_n(x\gamma) \frac{e^{iK\xi}}{\sqrt{2\pi}} \frac{e^{-i(\omega - \omega_k)\xi}}{\omega - \omega_k + i\epsilon}$$

Now, the spectrum of the emerging radiation is changed due to the dispersive properties of the medium [3]:

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Here D denotes the effective modulator thickness, and \( \hbar \omega_0 \) its resonant energy.

The corresponding amplitude in the time domain is:

\[
\alpha'(t) = \sum_{v} \int \mathcal{J}_v(x, x') e^{i \omega_0 t} e^{-i \omega_0 t} e^{i \omega t} e^{i k_\perp \mathbf{r}} e^{i k \perp \mathbf{r}} J_0(\xi_0 \sin \theta t), \quad /4/ 
\]

or, alternatively:

\[
\alpha'(t) = \sum_{k} \int \mathcal{J}_k(x, x') e^{i \omega_0 t} e^{-i \omega_0 t} e^{i \omega t} e^{i k \perp \mathbf{r}} e^{i k_\perp \mathbf{r}} e^{i k_0 \perp \mathbf{r}} J_0(\xi_0 \sin \theta t), \quad /4'/ 
\]

The choice between /4/ and /4'/ is determined by convergence requirements for the sum over \( n \).

Returning to the lab frame, we have:

\[
\alpha''(t) = \alpha'(t) e^{i x A \sin \mathbf{A} t} \quad /5/ 
\]

Now, we need the Fourier transform of /5/. The corresponding integrals can be carried out, and the result is:

\[
\alpha''(\omega) = \sum_{v} \sum_{k} \mathcal{J}_v(x, x') J_k(x, x') e^{i k_\perp \mathbf{r}} e^{i k_\perp \mathbf{r}} e^{i k_0 \perp \mathbf{r}} J_0(\xi_0 \sin \theta t), \quad /6/ 
\]

or:

\[
\alpha''(\omega) = \sum_{v} \sum_{k} \mathcal{J}_v(x, x') J_k(x, x') e^{i k_\perp \mathbf{r}} e^{i k_\perp \mathbf{r}} e^{i k_0 \perp \mathbf{r}} J_0(\xi_0 \sin \theta t), \quad /6'/ 
\]

Finally, the spectrum of interest is obtained by squaring /6/ and averaging over the initial phase \( \gamma \). The last operation only selects the non-vanishing terms in the sums.

It is seen from /6/ that the spectrum consists a set of equidistant satellites, shifted in energy from the central line by multiples of \( \Omega \). If \( \omega - \omega' = 0 \) i.e. no isomer shift between the source and the absorber, the spectrum is symmetric with respect to \( \omega_0 \). If the modulator is at rest /\( \mathbf{A} = 0 \)/, /6/ represents the self-absorption of the radiation in a thick stationary absorber, and if \( \mathbf{A} = \mathbf{A}_0 \) spectrum is reduced to a natural width single Lorentzian, centered at \( \omega_0 \).

Therefore, a region in amplitudes of the modulator vibration exists, wherein the expected splitting effect is maximal. Numerical calculations indicate that this region is at \( \mathbf{A} \approx \mathbf{I} \).

Figure I represents the calculated spectrum for several amplitudes \( \mathbf{A} /D=5, \omega_0 - \omega' = 0, \mathbf{A} = 10, \mathbf{A} = 2 \) /.

References: