TIME DELAY IN THE RESONANCE SCATTERING OF SYNCHROTRON RADIATION BY NUCLEI IN A CRYSTAL

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The time dependence of delayed radiation has been found when the pulse of synchrotron radiation undergoes the resonance Bragg scattering by nuclei in a crystal that have an isomeric Mössbauer level. A strong acceleration of the decay discovered is connected with a collective character of the nuclear excitation. A possibility to conserve the angle direction as well as the intensity and the resonance structure in the delayed reflected radiation is analysed.

1. Recently a great interest has been arisen in direct excitation of low-lying isomeric nuclear levels in the synchrotron radiation (SR) field with realisation of the Mössbauer effect [1–2]. The problem of selecting a resonance with the line-width of about 10^{-8} eV from the continuous radiation spectrum of about tens of kilovolts may be put due to unique time and angle characteristics of SR produced by present-day devices. Indeed, the duration T of a pulse of SR is two or three orders of magnitude shorter than the time interval T_1 between the pulses. Therefore, using isomeric states having the life-time τ_0 in the interval

$$T \ll \tau_0 < T_1 ,$$

one has a possibility to single out the delayed resonance Mössbauer radiation.

On the other hand, a small angular divergence of SR in the plane normal to the electron orbit allows us to use the Bragg scattering by a single crystal containing the appropriate isotope with the isomeric levels. As it has been shown [3–5], in the resonance scattering by the system of nuclei the suppression effect of nuclear reaction inelastic channels arises. As a consequence a complete reflection can be realized.

Along with selecting of Mössbauer radiation it is necessary to decrease sharply the total number of the scattered quanta. For this purpose the Bragg reflection by the magnetically ordered single crystal which has a purely nuclear resonance scattering can be used [6–8]. This is the basis, in particular, of the joint experiment of Kurchatov Institute of Atomic Energy and Novosibirsk Institute of Nuclear Physics, which is under preparation now [9].

2. First of all the question arises, whether it is possible to use the time delay without the loss of the angle direction of the reflected radiation. The contradiction of this requirement may be seen, for example, from the fact that the usual delay with the time of order τ_0 characteristic for isolated nuclei is accompanied by the scattering into 4π. On the contrary, the resonance Bragg scattering preserve the angle collimation but in this case the reflection occurs actually without delay (see below).

3. Let the radiation with a frequency $\tilde{\omega}$ fall on the crystal for a time T at a definite angle θ. Then the amplitude of the electric field has the form

$$E_{\tilde{\omega}}(t) = \mathcal{E}_{\tilde{\omega}}\, e^{-i\tilde{\omega}t}\psi(t) , \qquad (1)$$

where $\psi(t)$ equals one in the interval $0 < t < T$ and zero out of the interval. The amplitude of the scattered wave field may be written as

$$E'_{\tilde{\omega}}(t) = \mathcal{E}_{\tilde{\omega}} \int_{-\infty}^{\infty} dt'\, G(t-t')\psi(t')\, e^{-i\tilde{\omega}t'} , \qquad (2)$$

$$G(t) = \int_{-\infty}^{\infty} \frac{d\omega}{2\pi} R(\omega) e^{-i\omega t} . \quad (3)$$

Here $R(\omega)$ is the amplitude of crystal reflection of the monochromatic wave with the frequency ω.

Suppose the quanta to be within the frequency interval $\Delta\omega \gg 1/T$ near the resonance frequency ω_0. Proceeding from amplitude (2) to the intensity and summing over the whole range $\Delta\tilde{\omega}_0$ we find

$$I_\alpha(t) = 2\pi \frac{N_\alpha}{\Delta\tilde{\omega}} \frac{1}{T} \int_0^T dt' |G_\alpha(t-t')|^2 . \quad (4)$$

Here we have introduced the parameter $\alpha = 2\sin 2\theta_B \cdot \psi$ connected with the angle of deviation $\psi = \theta - \theta_B$ from the Bragg angle θ_B in the scattering plane. We suppose that the distribution with respect to α is determined by a small vertical divergence of SR. The quantity N_α in (4) is defined by $\int N_\alpha d\alpha = N_0$ where N_0 is the total number of quanta per one pulse of SR.

Assume that the hyperfine structure (HFS) is well resolved and the geometry corresponds to a separation of dynamical set of four equations into two independent sets for each polarization [5]. Then the Bragg reflection amplitude for a thick crystal, corresponding to the individual HFS component, can be written as

$$R_\alpha(\omega) = -\frac{b_{10}}{|b_{10}|} \frac{\eta}{\tau_0} \frac{1}{\omega - z_0 + \sqrt{(\omega - z_0)^2 - (\eta/\tau_0)^2}} , \quad (5)$$

$$z_0 = \omega_0 - (\eta/p + i/2)/\tau_0 ,$$
$$\eta = 1/(y - iy_0), \quad y_0 = 2\chi_0''/|b_{10}| , \quad (6)$$
$$p = 2|b_{10}|/(b_{00} + b_{11}) .$$

Here we use the abbreviations $b_{\alpha\beta}$ ($\alpha, \beta = 0, 1$) and $\chi_0 = \chi_0' + i\chi_0''$ which can be defined by representing the coefficients $g_{\alpha\beta}$ in the dynamical theory equations [5] in the form

$$g_{\alpha\beta} = -b_{\alpha\beta} \frac{\Gamma/2}{\hbar(\omega - \omega_0) + i\Gamma/2} + \chi_0 \delta_{\alpha\beta} ,$$

where the second term describes the interaction with electrons. Then

$$y = \frac{\alpha - 2\chi_0'}{|b_{10}|} = \frac{2\sin 2\theta_B}{|b_{10}|} \left(\psi - \frac{\chi_0'}{\sin 2\theta_B}\right) , \quad (7)$$

and the condition for a maximum of the Bragg reflecting intensity is $y = 0$ instead of $\alpha = \psi = 0$.

Substituting (5) into (3) we find after some calculations

$$G_\alpha(t) = \frac{i}{\tau_0} \frac{b_{10}}{|b_{10}|} \exp\left\{-i\omega_0 t - \frac{t}{2\tau_0}\right\}$$

$$\times \frac{J_1(\eta(t/\tau_0))}{(t/\tau_0)} \exp\left\{i \frac{\eta}{p} \frac{t}{\tau_0}\right\} \theta(t) , \quad (8)$$

where $J_1(x)$ is the Bessel function.

4. Consider the times greater than T. In this case we have approximately for the intensity (4)

$$I_\alpha(t) \approx \frac{2\pi}{\tau_0} \frac{N_\alpha}{(\Delta\tilde{\omega}\tau_0)} \exp\left\{\frac{-t}{\tau_0}\right\}$$

$$\times \left|\frac{J_1(\eta(t/\tau_0))}{(t/\tau_0)}\right|^2 \exp\left\{-\frac{2\eta'' t}{p\tau_0}\right\} . \quad (9)$$

Usually $y_0 \ll 1$ for the crystal enriched by the resonance isotope. Let the deviation from the Bragg condition be small, namely, $y_0 < |y| \ll 1$. Then at $t > |y|\tau_0$ the time dependence of the intensity of delayed radiation takes the form

$$I_\alpha(t) \sim |y| \frac{e^{-t/\tau_0}}{(t/\tau_0)^3} \cos^2\left(\frac{t}{|y|\tau_0} - \frac{3\pi}{4}\right) . \quad (10)$$

The principal change in the decay law is connected with the collective character of absorption of each photon by the system of resonance nuclei in a crystal, with formation of a nuclear exciton in the intermediate state. Such the collective (spread over the crystal) excitation decays through the elastic channel, i.e. with γ-quantum emission, essentially faster than in the case of an isolated nucleus. The time-integrated reflected intensity Q_α is concentrated then within the interval $t \lesssim |y|\tau_0$ and is equal to

$$Q_\alpha \approx \frac{N_\alpha}{(\Delta\tilde{\omega}\tau_0)} \frac{1}{|y|} . \quad (11)$$

Let us consider the case of the strictly realized Bragg condition, $y = 0$, and suppose firstly that the electron absorption is absent ($\chi_0'' = 0$). Then it is easy to see from (8) that $G(t) \sim \delta(t)$, i.e. the delay effect is completely absent. This is connected with the fact that a decrease of the nuclear scattering amplitude when deviating from the resonance and an increase of the effective thickness of reflecting layer compensate each other. The existence of small electron absorption, limiting the contribution of far wings of the resonance, restores the small delay ($\sim y_0\tau_0$).

When $|y| > 1$ for the entire time region the usual law of delay restores

$$I_\alpha(t) \sim \frac{1}{y^2} e^{-t/\tau_0} . \qquad (12)$$

However in this case the value of reflected intensity is strongly decreased. One sees now that it is necessary to use the angle interval which satisfies the condition $|y| \sim 1$ to realize the time delay with conserving the intensity.

5. In the case when the angle divergency $\Delta\psi$ of the incident beam is large so that $\Delta y \gg 1$ or crystal has saic structure along the specimen plane, one finds after integration of (9) over ψ ($t > y_0\tau_0$)

$$\bar{I}(t) \approx \frac{16}{3\tau_0} \frac{N_{res}}{\Delta y} \frac{e^{-t/\tau_0}}{(t/\tau_0)} , \quad N_{res} = \frac{\int N_\alpha \, d\alpha}{(\Delta\tilde{\omega}\tau_0)} . \qquad (13)$$

Once again the acceleration of the decay takes place owing to the collective character of resonance excitation. However, weakening the role of the resonance wings leads to the logarithmic increasing of the integral intensity at small t. In accordance with (13), in this case the intensity reduces in Δy times.

6. The acceleration of the excited state decay and the heightened role of the resonance wings lead to broadening the frequency distribution of the delayed reflected radiation as compared with the usual case. Because of this we are faced with an extremely serious problem of loss of resolution in using this radiation for Mössbauer type experiments. To analyze the ques- t is necessary to solve the problem of the transmission of SR-pulse, after the Bragg reflection, through the crystal-absorber having the same nuclei but with a $\Delta\omega_0$ shift in the resonance frequency. This problem has been solved. Referring to the more extended paper for details we formulate here only the basic qualitative results:

(a) When $|y| \ll 1$ the dependence on $\Delta\omega_0$ turns out to be very weak, the resonance structure in the reflected radiation is actually absent.

(b) When $|y| \gtrsim 1$ and $t \ll \tau_0$ the resonance structure vanishes again due to the uncertainty principle. It restores with increasing t and appears to be sufficiently narrowed when $t \gtrsim 0.5\,\tau_0$. However there are noticeable oscillations on the wings.

(c) For the Mössbauer type experiments it is necessary to use the integral-over-time intensity in which the finite interval $> 0.3\,\tau_0$ just after the SR pulse must be excluded. The condition $\Delta y \gtrsim 1$ defines the expedient angle divergency in the incident beam.

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