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ON THE DIRECT MEASUREMENT OF NUCLEAR γ-RESONANCE PARAMETERS OF LONG-LIVED (≥ 1 s) ISOMERS

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A method for the direct measurement of the γ-resonance width for nuclei with excitation energies $E_0 \leq 100$ keV and lifetimes $\tau_0 \geq 1$ s is discussed. Instead of scanning the energy, as is conventional in Mössbauer spectroscopy, it is proposed to measure the time behaviour of the spontaneous *coherent* emission of γ-quanta by a nuclear ensemble after the cutoff of the exciting radiation flux.

1. Introduction

Isomers with long lifetimes have attracted attention since the first steps of the development of Mössbauer spectroscopy. This interest was caused, first of all, by the aspiration to increase the energy resolution of the method. The isomer ^{67}Zn ($E_0 = 93.3$ keV, $\tau_0 = 1.36 \times 10^{-5}$ s) is the longest-lived one for which the Mössbauer effect was observed and a record value for the γ-resonance energy width Γ was obtained by Potzel et al. [1]: $\Gamma = 5.02 \times 10^{-11}$ eV. For isomers with lifetimes of the order of seconds, e.g. ^{107}Ag ($E_0 = 93.1$ keV, $\tau_0 = 63.9$ s), ^{109}Ag ($E_0 = 88.0$ keV, $\tau_0 = 57.1$ s), no direct measurements of the γ-resonance width have been carried out yet. Nevertheless, these isomers are of great interest, mainly due to the question of the highest energy resolution achievable in Mössbauer spectroscopy. There exists, however, another interesting question: what are the natural limitations on the conservation of the time coherency of a nuclear excited state?

In a solid, the nuclei are strongly influenced by their nearest surroundings. This action can be either static and cause a shift of the resonance energy E_0 (inhomogeneous in a specimen, as a rule) or dynamic and lead to a multiple jumps in energy and phase during the nucleus' excited-state lifetime. The above interactions given rise to, respectively, inhomogeneous and homogeneous γ-resonance broadening with respect to the natural width $\Gamma_0 = \hbar/\tau_0$.

The interaction of nuclei with surroundings in a solid state has a characteristic energy $\sim 10^{-13}$ eV. Therefore, it is natural to expect that the γ-resonance for nuclei with a long-lived excited state ($\tau_0 \geq 1$ s), having a natural width $\Gamma_0 < 10^{-15}$ eV, will be noticeably broadened. It is this large broadening, which makes the observation and study of a nuclear γ-resonance for long-lived isomeric states difficult.

Among the isomers with lifetimes $\tau_0 \geq 1$ s, so far the Mössbauer effect has only been studied on the first excited states of the silver isotopes ^{107}Ag [2] and ^{109}Ag [3–6]. These studies aimed, first of all, at the factual observation of a resonance excitation. Besides the problem of measuring the nuclear γ-resonance cross section and estimating its width Γ was stated.

Attempts to observe the nuclear γ-resonance for ^{107}Ag and ^{109}Ag were first undertaken by Bizina et al. as well as by Alpatov et al. [2,3]. The radiation source and the target were prepared as two specimens of the same material – metallic silver. To excite the nuclei, the source and the target were brought together for some time. In the presence of nuclear γ-resonance an induced activity in the target should arise. Indeed, such an activity was observed when the target was separated from the source. Thus, these experiments have demonstrated the possibility of obtaining a γ-resonance for a long-lived state. Estimates of the γ-resonance width in ^{107}Ag, made by using the experimental data from the target activation, yielded the following result: $\Gamma \simeq 7.5 \times 10^5 \Gamma_0 = 7.5 \times 10^{-11}$ eV.

To achieve a γ-resonance with higher quality, Wildner and Gonser [4] in their later experiments prepared the source and the target as a single unit – a Ag single crystal. Radioactive ^{109}Cd was diffused into the surface layer on one side of the unit. The remaining part served as a resonance absorbing medium. The resonance absorption conditions were varied by changing the specimen temperature. According to the authors' estimate, the γ-resonance width in ^{109}Ag was equal to $\Gamma \simeq 30\Gamma_0 = 3.6 \times 10^{-16}$ eV. In a similar manner the resonance pair was prepared in experiments by Hoy et al. [5,6]. These experiments, however, were improved to record not only the γ-radiation of ^{109}Ag nuclei, but also the fluorescence radiation from the electron capture in ^{109}Cd. This allowed to avoid many uncontrollable changes in recording the γ-radiation intensity. A lowest value of $\Gamma = 20\Gamma_0 = 2.2 \times 10^{-16}$ eV has been achieved in these experiments.

Although the parameters of the ground and first

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excited states of ^{107}Ag and ^{109}Ag nuclei are very close, the values of Γ, obtained in the above-mentioned experiments, differ by four orders of magnitude from each other. Such a significant discrepancy can be explained, obviously, by the different experimental techniques and methods of specimen preparation. One should remember, however, that in refs. [2–6] the γ-resonance widths for silver nuclei were determined by indirect methods and, therefore, some systematic error could arise due to specific experimental conditions. This circumstance makes it necessary to employ direct methods for measuring the γ-resonance parameters of long-lived isomeric states, so that any ambiguity in the determination of Γ be eliminated.

Doppler scanning of the γ-radiation energy in the vicinity of the resonance is a traditional technique in the Mössbauer spectroscopy. But this technique is difficult to apply to nuclei with $\tau_0 \geq 1$ s, since it requires a controllable motion at velocities of ~ 1 Å/s. As the complementarity principle interrelates energy and time, it seems natural to study the time behaviour of the nuclear-resonance interaction process for this purpose. It is clear that the larger the isomer lifetime, the easier to employ the time-domain spectroscopy.

One version of Mössbauer time-domain spectroscopy, based on the delayed-coincidence technique, was proposed by Baldwin [7]. However, this proposal seems to be hardly feasible for long-lived excited states ($\tau_0 \geq 1$ s), because the random coincidences impose a very strong limit on the radioactive-source activity. To overcome this difficulty, Baldwin and Goldanskii [8] proposed to measure the time correlation function. One should note, however, that to determine the resonance parameters, a large amount of statistical data is required in this case.

Another version of Mössbauer time-domain spectroscopy, based on a stepwise phase modulation method, was developed by Ikonen et al. [9,10] and was applied to the ^{67}Zn isotope. This approach can also be used in principle for isomers with longer lifetimes. However, the effect caused by phase modulation is observed against an intense background of incident radiation. Hence, it should be low when thin nuclear targets are applied. But it is just such targets that will be used in the case of long-lived isomers because due to the small cross section, the nuclear γ-resonance absorption length is expected to be comparable to or less than the electron absorption length.

2. On the proposed method

This paper suggests an alternative version of Mössbauer time-domain spectroscopy. It is advantageous just for long-lived isomers ($\tau_0 \geq 1$ s). The essence of the method is as follows: in order to directly determine the nuclear γ-resonance parameters, it is proposed to measure the time dependence of the spontaneous *coherent* emission of γ-quanta by nuclei after the cutoff of the exciting γ-radiation flux. If, after turning off the excitation of the nuclei, γ-quanta re-emitted in an arbitrary direction are recorded, as was done in refs. [2,3], then one can only determine the lifetime τ_0, which is the time interval characterizing the duration of the energy transfer from the excited nuclei to the γ-radiation field. However, the result of such a measurement does not provide any data on the γ-resonance broadening. As far as the re-emission of γ-quanta into coherent channels is concerned, the phase correlation between the waves emitted by the different nuclei becomes essential. In particular, in the absence of a γ-resonance broadening the phases are correlated during the whole nucleus lifetime τ_0. The γ-radiation signal attenuates for the time τ_0 in this case, and it is enhanced coherently *. If, however, inhomogeneous broadening is present, then during the spontaneous decay of an excited nuclear ensemble the mismatch of partial wave phases should exhibit itself gradually due to the spread in frequencies of waves emitted by different nuclei. This should result in a more rapid attenuation of a signal in the coherent channel. Besides, the excited state coherency time can be limited by the presence of time-dependent influences of the nearest surroundings of a nucleus. This fact, obviously, is an additional reason for a faster signal attenuation in the coherent channel. Then the characteristic time of γ-radiation emission into a coherent channel, $\tau = \hbar/\Gamma$, should be less than the natural decay time τ_0. Using the analogy with NMR and EPR, one can say that τ_0 is similar to the longitudinal relaxation time T_1, which is characterized by the rate of approaching thermal equilibrium in the system of spins, while the γ-radiation emission time into the coherent channel τ is similar to the transverse relaxation time T_2, which is determined by the dephasing rate of the spins.

The coherent channels are either the γ-quanta re-emission in the forward direction, or the re-emission into the Bragg angles. The scattering experiments in the forward direction seem to be more simple from the viewpoint of specimen preparation, since single crystals are not needed in this case (as is necessary in the diffraction experiments).

Section 3 of this paper presents a theoretical substantiation of the proposed method. This presentation takes into account the above-mentioned factors which influence the time variation of the coherent spontaneous decay of an excited nuclear system. Only the case of coherent nuclear re-emission in the forward direction

* Here thin nuclear targets are meant, where the effect of the decay speed-up of collective nuclear excitations [11] does not play a noticeable role yet.

is considered here. Section 4 of the paper analyses the possibilities of applying the method in experiments with the isotopes ^{109}Ag and ^{45}Sc, possessing long-lived isomeric states.

3. Theoretical description of the method

Let the plane target containing Mössbauer nuclei be irradiated by a monochromatic wave $\mathscr{A}(E)\exp(-iEt/\hbar)$. At a time $t=0$ the incident radiation is suddenly interrupted. The radiation amplitude at an input surface of the target in this case is described as follows (the target is parallel to the wave front):

$$A'_E(t) = \mathscr{A}(E)\exp(-iEt/\hbar)\theta(-t), \tag{1}$$

$$\theta(t) = \begin{cases} 1, & t \geq 0, \\ 0, & t < 0. \end{cases}$$

The radiation leaving the target at $t > 0$ is a result of the nuclear de-excitation process. As shown in ref. [11], its amplitude $A_E(t)$ is defined by the dependence

$$A_E(t) = \int_{-\infty}^{\infty} dt' G(t-t') A'_E(t'), \tag{2}$$

where $G(t)$ is the response function of the system under study. This function is directly related to the system's spectral function $R(E)$ by a Fourier transformation:

$$G(t) = \int_{-\infty}^{\infty} \frac{dE}{2\pi\hbar} \exp(-iEt/\hbar) R(E), \tag{3}$$

Let us consider the process of coherent re-emission in the forward direction by a system of nuclei contained in a target of thickness l. In this case the spectral function of the nuclear system, $R_A(E, l)$, is expressed in terms of a complex refraction index $n(E)$:

$$R_A(E, l) = \exp[i\kappa l n(E)], \tag{4}$$

$$n(E) = 1 - \frac{1}{2\kappa} \frac{\sigma_R N \eta \Gamma_0/2}{E - E_0 + i\Gamma/2} + \chi_{el}/2, \tag{5}$$

$$\sigma_R = \frac{2\pi}{\kappa^2} \frac{2I_e + 1}{2I_g + 1} \frac{f_{LM}}{1+\alpha}. \tag{6}$$

Here κ is the wave number, σ_R the total resonance absorption cross section at an individual nucleus, N the number of atoms in a unit volume, η the isotopic enrichment, Γ_0 the natural width of an excited nuclear level, Γ the characteristic width of the nuclear γ-resonance taking into account both homogeneous and inhomogeneous broadening in the target: $\Gamma = \Gamma_0 + \Gamma_{hom} + \Gamma_{inhom}$, E_0 is the resonance energy, I_e and I_g are the nuclear spins of the ground and excited states, respectively, α is the internal conversion coefficient, f_{LM} the Lamb–Mössbauer factor of recoilless emission and χ_{el} an addition to the refraction index related to scattering on atomic electrons. The latter's imaginary part equals $\chi''_{el} = \sigma_{ph} N/\kappa$, where σ_{ph} is the photoelectric absorption cross section.

In ref. [11] the response function $G_A(t, l)$, which describes the coherent scattering in the forward direction, was calculated for the case of unbroadened lines. In the situation of interest, when the resonance line is broadened, $G_A(t, l)$ is calculated in a similar way. In such a form it was used for the first time in ref. [9]:

$$G_A(t, l) = \left\{ \delta(t) - \xi(\Gamma_0/\hbar) \frac{J_1\left[2(\xi\Gamma_0 t/\hbar)^{1/2}\right]}{(\xi\Gamma_0 t/\hbar)^{1/2}} \times \exp(-iE_0 t/\hbar - \Gamma t/2\hbar)\theta(t) \right\} \exp(i\phi), \tag{7}$$

$$\xi = \sigma_R N \eta l/4,$$

$$\phi = \kappa l \chi_{el}/2,$$

We shall confine ourselves to considerations for $\xi \ll \Gamma/\Gamma_0$ only. This corresponds to the situation when either the broadening is extremely large, $\Gamma/\Gamma_0 \gg 1$, or the resonance absorption in the target is small, i.e. the parameter ξ is small. In this case one can use, to a good accuracy, a simpler analytical expression for $G_A(t, l)$:

$$G_A(t, l) = \left[\delta(t) - \xi(\Gamma_0/\hbar)\exp(-iE_0 t/\hbar - \Gamma_\xi t/2\hbar) \times \theta(t)\right] \exp(i\phi), \tag{8}$$

$$\Gamma_\xi = \Gamma + \xi\Gamma_0.$$

Proceeding from eqs. (1)–(8) one obtains the following time dependence (for $t > 0$) for the amplitude of the γ-radiation leaving the target after the nuclear excitation cutoff:

$$A_E(t, l) = -i\xi\Gamma_0 \mathscr{A}(E)\exp(i\phi) \times \frac{\exp(-iE_0 t/\hbar - \Gamma_\xi t/2\hbar)}{E - E_0 + i\Gamma_\xi/2}. \tag{9}$$

One should mention two important circumstances which follow from relation (9). The first one, which is crucial, is that the measurement of the time dependence of delayed γ-radiation leaving the target in forward direction results directly in Γ_ξ, and, hence, in Γ. Γ is determined more accurately the better the relation $\xi \ll \Gamma/\Gamma_0$ is fulfilled. The second important aspect is that the time dependence of coherent emission in the forward direction does not depend on the detuning value $E - E_0$, i.e. on the nuclear system excitation conditions – whether it took place at resonance or nearby (in this respect see also the results of ref. [12] and the theorem proven there). This also implies that the time behaviour of emission in forward direction does not depend on the incident γ-radiation spectrum $|\mathscr{A}(E)|^2$. Only the absolute intensity of the re-emitted quanta depends on spectral properties of the incident γ-radiation.

Let us calculate the time dependence of the γ-radiation. For this purpose one should square modulo eq. (9) and average the results over the spectrum of the incident radiation $|\mathscr{A}(E)|^2$. For simplicity we shall assume the latter to have a Lorentz dependence:

$$|\mathscr{A}(E)|^2 = N_\gamma \frac{\Gamma_s}{2\pi} \frac{1}{(E-E_s)^2 + (\Gamma_s/2)^2} \tag{10}$$

with width Γ_s and a maximum at energy E_s. The source spectral function (10) is normalized with respect to a total number N_γ of incident γ-quanta per unit time.

Thus one obtains the following dependence for the intensity of γ-radiation leaving the target:

$$I(t) = N_{\Gamma_0} 4\xi^2 \frac{\Gamma_0}{\Gamma_\xi} \delta_s \exp\left(-\Gamma_\xi t/\hbar - \sigma_{ph} N l\right), \tag{11}$$

with

$$\delta_s = \frac{(\Gamma_s + \Gamma_\xi)\Gamma_s/4}{(E_s - E_0)^2 + \left[(\Gamma_s + \Gamma_\xi)/2\right]^2}.$$

Here $N_{\Gamma_0} = N_\gamma \Gamma_0/\Gamma_s$ is the number of γ-quanta emitted by a source in the band of natural width in the time unit, and δ_s is a factor mainly determined by spectral properties of a source. Under the conditions $E_s \simeq E_0$ and $\Gamma_s \geq \Gamma_\xi$ its value is $\delta_s \approx 1$.

One should point out one more important circumstance which follows from eq. (11). Namely, that the intensity of γ-quanta re-emitted in forward direction is proportional to $\xi^2 = (\sigma_R N \eta l/4)^2$, i.e. to the square of the number of nuclei per unit of scattering target area. This is the manifestation of the enhancement effect of the radiative channel in the coherent spontaneous decay of an excited nuclear system. It follows that in the experiment the target should be chosen as thick as possible in order to obtain as high an intensity of re-emitted γ-quanta as possible (retaining the condition $\xi \ll \Gamma/\Gamma_0$). However, the thickness l of a target has also an upper limit. This limitation is due to the photoelectric absorption in the system under study. The optimal thickness calculated from eq. (11) is $l^* = 2/(\sigma_{ph} N)$. The expression for the time dependence of the radiation intensity for the chosen optimal thickness l^* of the absorber takes the following form in this case:

$$I^*(t) = N_{\Gamma_0} \left[\frac{\sigma_R \eta}{e \sigma_{ph}}\right]^2 \frac{\Gamma_0}{\Gamma_\xi} \delta_s \exp\left(-\Gamma_\xi t/\hbar\right). \tag{12}$$

Thus, one can see that the measurement of the time dependence of the process of re-emission of γ-quanta by a nuclear system in the forward direction directly gives the value of the real width Γ of the nuclear γ-resonance.

One should also mention that a measurement of time dependencies of the re-emission process in the forward direction can provide data for some more complicated spectra, e.g. when the nuclear γ-resonance spectrum contains several lines E_{0i} $(i = 1, 2, \cdots)$, rather than a single one, E_0. This situation occurs very often when nuclei are under the action of intracrystalline magnetic or electric fields. In this case the method makes it possible to determine relative intensities of resonance lines and distances between them. As an illustration we shall consider only the case of two lines of the same intensity, which have transition energies E_{01}, E_{02}. We shall assume the nuclear target to be irradiated by radiation with a wide spectrum $\Gamma_s \gg \Delta E_{Hf} = |E_{01} - E_{02}|$. Simple calculations show that the correct value for the intensity of γ-quanta, re-emitted in forward direction, is obtained if eq. (12) is multiplied by an additional factor of $4\cos^2(\Delta E_{Hf} t/2\hbar)$. This implies that when the nuclear γ-resonance spectrum contains more than one line, the intensity of the re-emitted quanta does not attenuate monotonously, but oscillates in time. Such a behaviour is due to a quantum beat modulation of the decay rate. This effect was first observed under conditions of coherent excitation of ^{57}Fe nuclei ($E_0 = 14.4$ keV, $\tau_0 = 1.41 \times 10^{-7}$ s) by synchrotron radiation pulses [13,14].

In conclusion to this section we point out that the relation $\xi \ll \Gamma/\Gamma_0$, which has been used in deriving the formulae (8–12), is not a necessary condition for realization of the method. If this relation is not met, the mathematical analysis of a measured time dependence (i.e. the determination of a Γ-value and of other γ-resonance parameters) becomes merely more complicated.

4. Numerical estimates for ^{109}Ag and ^{45}Sc

This section deals with the analysis of possibilities of applying the method proposed in this paper. For this purpose the numerical estimates are presented for experiments with the long-lived isomers ^{109}Ag and ^{45}Sc.

In the experimental setup, the source and the nuclear target must obviously be separated in space from each other, so that a gate can be installed between them. The requirements for the duration of the incident γ-radiation cutoff follow from the relation $\tau_{sh} \ll \min\{\hbar/\Gamma, \hbar/\Delta E_{Hf}\}$ and, therefore, depend strongly on the γ-resonance parameters, in particular the width Γ. If one considers a situation close to that achieved in refs. [4–6], $\Gamma \approx 10^2 \Gamma_0$, then a cutoff within a millisecond time interval should be provided. For this purpose even a mechanical shutter might be utilized.

Let us estimate the counting rate of γ-quanta coherently re-emitted by ^{109}Ag nuclei in the forward direction after turning off the exciting γ-radiation flux. Let the γ-quanta source be radioactive ^{109}Cd nuclei diffused into a metallic silver matrix. Suppose the source activity to be 1 mCi, as it was in the experiments of ref. [5]. The beam striking the nuclear target is assumed to be confined in a solid angle of $\Delta\Omega/4\pi = 10^{-3}$. At a source

temperature of 4.2 K, the Lamb–Mössbauer factor equals $f_{LM} = 0.035$ [5]. With an account of the conversion factor ($\alpha = 26.7$ [5]), the number of Mössbauer quanta striking the target under these conditions is equal to ~ 50 quanta/s. Let the target be manufactured of the same metallic silver and also be maintained at helium temperature. The optimal thickness of a target, determined by a photoeffect cross section for quanta with an energy of 88 keV in silver ($N = 5.85 \times 10^{22}$ cm^{-3}, $\sigma_{ph} = 3.7 \times 10^{-22}$ cm^2 [16]), is equal to $l^* = 0.92$ mm. It is natural to suppose that the source emission and the target absorption lines are broadened to the same value: $\Gamma_s \simeq \Gamma$. Besides, the isomeric shift between the source and the target is assumed to be small, i.e. $E_s \simeq E_0$. In these conditions the spectral density of the γ-radiation flux in the band of natural width for ^{109}Ag will be $N_{\Gamma_0} \approx 50(\Gamma_0/\Gamma)$ quanta/s. Then from eq. (12) one finally obtains the value of the intensity of γ-quanta coherently re-emitted in the forward direction (for $\sigma_R = 1.6 \times 10^{-21}$ cm^2 [15] and $\eta = 0.48$):

$$I^*(t) \simeq 15(\Gamma_0/\Gamma)^2 \exp(-\Gamma t/\hbar) \text{ quanta/s}.$$

Thus, for a broadening of $\Gamma/\Gamma_0 \approx 10^2$, the experiment seems to be quite feasible, even if the source activity is accepted to be so low. If the broadening is larger, one can estimate at least a lower limit for Γ.

As a second example we shall consider the γ-resonance of ^{45}Sc nuclei ($E_0 = 12.4$ keV, $\tau_0 = 0.46$ s) [17]. In this case the observation of the γ-resonance is difficult, not only due to its small energy width, but also due to the absence of a suitable parent radioactive nucleus that could be used as a resonant γ-radiation source. Therefore we shall assume the ^{45}Sc nuclei to be irradiated by synchrotron radiation with a white spectrum. According to ref. [18], by using undulators on electron–positron storage rings of the new generation, it will be possible to achieve a γ-quanta flux with a spectral density of about 10^{13} quanta/(s eV) (in the energy range of 12 keV). This means that in this case $N_{\Gamma_0} \approx 0.01$ quanta/s will fall in the band of natural width of γ-resonance in ^{45}Sc. The target is assumed to be made of metallic Sc maintained at a room temperature. In this case $f_{LM} \simeq 0.74$, and according to the tabular data [17], $\sigma_R = 1.0 \times 10^{-20}$ cm^2. Taking into account that $\sigma_{ph} = 3.7 \times 10^{-21}$ cm^2 [16] and $N = 4.27 \times 10^{22}$ cm^{-3}) one obtains the following estimate for the optimal thickness of the Sc target: $l^* = 0.13$ mm. Taking into consideration the above information as well as the fact that Sc is a mono-isotope ($\eta = 1$), one obtains from eq. (12) the following estimate for the intensity of delayed γ-quanta leaving the target in the forward direction:

$$I^*(t) \simeq 0.01(\Gamma_0/\Gamma) \exp(-\Gamma t/\hbar) \text{ quanta/s}.$$

Thus, for a broadening less than 10, the Γ-value can still be estimated. With a larger broadening it will only be possible to estimate a lower limit for Γ.

As can be seen from eq. (11), the counting rate can be essentially enhanced by increasing the nuclear target thickness. But this would be possible if the electronic absorption is reduced. The latter could be achieved in principle by employing the Borrmann effect. Estimates based on the theory of γ-ray propagation through a crystal containing resonance nuclei (see ref. [19] and references therein) show that an enhancement up to 10^2–10^3 could be obtained for the case of a Sc single crystal. So under these conditions a broadening up to $\Gamma/\Gamma_0 \simeq 10^3$–$10^4$ could be revealed.

The Borrmann effect works when the radiation is incident on a crystal in the vicinity of the Bragg angle. Hence, collimated beams are needed in this case. One may hope that the progress in the development of synchrotron radiation sources with high spectral density and collimation will make these experiments feasible. The last results on the coherent excitation of ^{57}Fe nuclei obtained with undulator radiation [20] support these expectations.

5. Conclusion

The method proposed in this paper provides a possibility to directly measure parameters of γ-resonance on nuclei with a long-lived excited state ($\tau_0 \geqslant 1$ s). The essence of the method consists in measuring the time dependence of the spontaneous *coherent* emission of γ-quanta by an excited nuclear ensemble after the cutoff of the exciting γ-radiation. In the case of long-lived isomers, the proposed method can be implemented rather easily. The incident γ-radiation cutoff might be performed by a mechanical shutter operating for time $\tau_{sh} \ll \hbar/\Gamma$. To resolve the hyperfine structure in the nuclear γ-resonance spectrum, the shutter must operate for time $\tau_{sh} \ll \hbar/\Delta E_{Hf}$. We would like to emphasize some positive features in which this method differs from those proposed earlier [7–10]. As the theoretical analysis has shown, the time dependence of a coherent emission process is insensitive to the exciting radiation spectrum. Therefore, both the usual radioactive sources and synchrotron radiation sources can be used. The synchrotron radiation sources are especially interesting in cases where radioactive parent nuclei cannot be used for this purpose. The isotope ^{45}Sc is quite attractive in this respect [17]. Sources with a white radiation spectrum are also attractive due to the fact that their use practically eliminates the problem of tuning to resonance in the target.

The high sensitivity of the method proposed here is one of its most essential advantages. This is due to the fact that only delayed γ-quanta separated from the intensive incident radiation are measured. Hence, in comparison to other time-domain methods, the recorded effect should be larger for the same resonance

cross section σ_R and therefore a larger broadening can be revealed.

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References

[1] W. Potzel, A. Forster and G.M. Kalvius, Phys. Colloq. C37 (1976) 691.
[2] G.E. Bizina, A.G. Beda, N.A. Burgov and A.V. Davydov, Sov. Phys. JETP 18 (1964) 973 [Zh. Eksp. Teor. Fiz. 45 (1963) 1408]; V.G. Alpatov, A.G. Beda, G.E. Bizina, A.V. Davydov and M.M. Korotkov Proc. Int. Conf. on Mössbauer Spectroscopy, Bratislava, Czechoslovakia (Czechoslovakian Atomic Energy Commission, 1973) p. 499.
[3] V.G. Alpatov, A.G. Beda, G.E. Bizina, A.V. Davydov and M.M. Korotkov, Proc. Int. Conf. on Mössbauer Spectroscopy, Bucharest, Rumania (Rumania Acad. Sci., 1977) p. 43.
[4] W. Wildner and U. Gonser, J. Phys. (Paris) 40 (1979) C2-44.
[5] G.R. Hoy, and R.D. Taylor, J. Quant. Spectrosc. Radiat. Transfer 40 (1988) 763.
[6] G.R. Hoy, S. Rezaie-Serej and R.D. Taylor, Proc. Int. Conf. on Mössbauer Spectroscopy, Budapest, Hungary, 1989, Hyperfine Interactions, to be published.
[7] G.C. Baldwin, Nucl. Instr. and Meth. 159 (1979) 309.
[8] G.C. Baldwin and V.I. Goldanskii, Nucl. Instr. and Meth. 169 (1980) 582.
[9] E. Ikonen, P. Helisto, T. Katila and K. Riski, Phys. Rev. A32 (1985) 2298.
[10] E. Ikonen, J. Hietaniemi, T. Katila, J. Linden and I. Tittonen, Hyperfine Interactions 47 (1989) 139.
[11] Yu. Kagan, A.M. Afanas'ev and V.G. Kohn, J. Phys. C12 (1979) 615.
[12] G.V. Smirnov and Yu. V. Shvyd'ko, Sov. Phys. JETP 68 (1989) 444 [Zh. Eksp. Teor. Fiz. 95 (1989) 777].
[13] E. Gerdau, R. Rüffer, R. Hollatz and J.P. Hannon, Phys. Rev. Lett. 57 (1986) 1141.
[14] U. Van Bürck, R.L. Mössbauer, E. Gerdau, R. Rüffer, R. Hollatz, G.V. Smirnov and J.P. Hannon, Phys. Rev. Lett. 59 (1987) 355.
[15] J. Blachot, Nucl. Data Sheets 41 (1984) 111.
[16] E. Strom and H. Israel, Photon Cross Sections from 0.001 to 100 MeV for Elements 1 through 100 (Los Alamos National Laboratory, 1967).
[17] T.W. Burrows, Nucl. Data Sheets 40 (1983) 149.
[18] ESRF Foundation Phase Report (Grenoble, France, February 1987).
[19] Yu. Kagan and A.M. Afanas'ev, Proc. 1971 IAEA Vienna Panel (Vienna, 1972) p. 143; Yu. Kagan, JETP Lett. 20 (1974) 11 [Pis'ma Zh. Eksp. Teor. Fiz. 19 (1974) 722].
[20] J. Arthur, G.S. Brown, D.E. Brown and S.L. Ruby, Phys. Rev. Lett. 63 (1989) 1629.