Resonance structure of the Gamow–Teller (GT) and first-forbidden (FF) β^+/EC decay strength functions

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Abstract. The experimental measurement data on the fine structure of $S_\beta(E)$ in spherical and deformed nuclei are analyzed. Modern nuclear spectroscopy methods allowed the split of the peaks caused by nuclear deformation to be revealed in $S_\beta(E)$ for transitions of the Gamow–Teller (GT) type. The resonance nature of $S_\beta(E)$ for first-forbidden (FF) transitions in both spherical and deformed nuclei is experimentally proved. It is shown that at some nuclear excitation energies FF transitions can be comparable in intensity with GT transitions.

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1. Introduction

The probability of the β transition to the nuclear level with excitation energy E is proportional to the product of the lepton part described by the Fermi function $f(Q_\beta - E)$ and the nucleon part described by the β transition strength function $S_\beta(E)$ [1-3]. Until recently, experimental investigations of the $S_\beta(E)$ structure were carried out using total absorption gamma-ray spectrometers (TAGS), which had low energy resolution. With TAGS spectroscopy, it became possible to demonstrate experimentally the resonance structure of $S_\beta(E)$ for GT β transitions [2, 3]. Modern experimental instruments allow using nuclear spectroscopy methods with high energy resolution to study the fine structure of $S_\beta(E)$ [4]. Information on the structure of $S_\beta(E)$ is important for many nuclear physics areas [1–4].The position and intensity of resonances in $S_\beta(E)$ are calculated within various microscopic models of the nucleus [1, 5–8].

In this work data on the structure of $S_\beta(E)$ were obtained using nuclear spectroscopy methods of high energy resolution. Features of the resonance structure of $S_\beta(E)$ for GT and FF transitions are discussed.

2. Beta decay strength function $S_\beta(E)$

For the GT β transitions, FF β transitions in the ξ approximation, and unique FF β transitions the reduced probabilities B(GT), $[B(\lambda\pi = 0^-) + B(\lambda\pi = 1^-)]$, and $[B(\lambda\pi = 2^-)]$, half-life $T_{1/2}$, level populations I(E), strength function $S_\beta(E)$, and ft values are related as follows [4]:

$$d(I(E))/dE = S_\beta(E)\, T_{1/2}\, f(Q_\beta - E) \tag{1}$$

$$(T_{1/2})^{-1} = \int S_\beta(E) f(Q_\beta - E)\, dE \tag{2}$$

$$\int_{\Delta E} S_\beta(E) dE = \sum_{\Delta E} 1/(ft) \tag{3}$$

$$B(GT,E) = [D(g^2_V/4\pi)]/ft \tag{4}$$

$$B(GT,E) = g^2_A/4\pi \left| \langle I_f \,\|\, \sum t_\pm(k)\, \sigma_\mu(k) \,\|\, I_i \rangle \right|^2 /(2I_i+1) \tag{5}$$

$$[B(\lambda\pi = 2^-)] = 3/4\, [D\, g^2_V/4\pi]/ft \tag{6}$$

$$[B(\lambda\pi = 0^-) + B(\lambda\pi = 1^-)] = [D\, g^2_V/4\pi]/ft \tag{7}$$

where Q_β is the total β decay energy, $f(Q_\beta - E)$ is the Fermi function, t is the partial period of the β decay to the level with the excitation energy E, $|\langle I_f \| \sum t_\pm(k)\, \sigma_\mu(k) \| I_i \rangle|$ is the reduced nuclear matrix element for the GT transition, I_i is the spin of the parent nucleus, I_f is the spin of the excited state of the daughter nucleus, D = (6147 ± 7) s.

3. Investigation of the structure of $S_\beta(E)$ using high-resolution nuclear spectroscopy methods

Methods of nuclear spectroscopy with high energy resolution yield detailed information on the fine structure of $S_\beta(E)$ for both GT and FF transitions. In the experiments [5, 9, 10], radioactive sources were produced using the reaction of deep spallation of tantalum nuclei in interaction with 660-MeV protons. Experimental data for A=160 are summarized in [11]. Rare-earth elements produced in the reaction were separated into fractions by the chromatographic technique [12]. One of the fractions (Tb, Er) was placed into a special ion source ampoule of the electromagnetic mass separator at the YaSNAPP–2 complex [13] and was separated into isobars. Then spectra of γ rays and matrices of γγt coincidences in β decays of nuclei under our investigation were measured. In addition, spectra of internal conversion electrons (ICEs) were measured. For γ rays and γγt coincidences measurements we used the following detectors: HpGe (19%): $\Delta E\gamma$ = 1.8 keV (^{60}Co); HpGe (28%): $\Delta E\gamma$ = 1.9 keV (^{60}Co); HpGe (50%): $\Delta E\gamma$ = 2.0 keV (^{60}Co); HpGe (2 cm^3): $\Delta E\gamma$ = 580 eV for γ120 keV. For ICE measurements we used mini-orange: ΔEe = 2.3 keV (^{207}Bi); β spectrograph: ΔEe = 0.03–0.05%. The intensities of population directly by the β decay were determined for each energy level from the balance of its incoming and outgoing γ transitions, and reduced half-lives ft entering into expressions (1)–(7) for the function $S_\beta(E)$ were constructed.

The function $S_\beta(E)$ for GT transitions in the β^+/EC decay of the spherical nucleus ^{147g}Tb ($T_{1/2}$ = 1.6 h, Q_{EC} = 4.6 MeV) [5] has a distinct resonance (Fig.1) at the excitation energy in the region of 4 MeV. Theoretical calculations [5] correctly describe the energy but yield a several times higher intensity of the resonance. This is typical of many nuclei investigated by the TAGS method [14]. For the β^+/EC decay of the ^{147g}Tb nucleus the experimentally observed value turns out to be smaller than the theoretical value because only the tail of the peak in $S_\beta(E)$ was observed in [5,15]. Thus, high-resolution nuclear spectroscopy methods, like TAGS [5], give conclusive evidence of the resonance structure of $S_\beta(E)$ for GT transitions in spherical nuclei. It follows from Fig. 2 that $S_\beta(E)$ for FF transitions in the β^+/EC decay of the spherical nucleus ^{147g}Tb also has a resonance nature. Note also that in the β^+/EC decay of ^{147g}Tb the intensity of FF β^+/EC transitions is higher than the intensity of GT transitions in the excitation energy region about 2 MeV. The experimental values of B(GT) for the peak at $E \approx$ 4 MeV for ^{147g}Tb which we evaluated from the TAGS data, $B(\mathrm{GT})_{[\mathrm{TAGS}]}$, and from the decay scheme data, $B(\mathrm{GT})_{[\mathrm{DS}]}$, make a ratio $B(\mathrm{GT})_{[\mathrm{TAGS}]}/B(\mathrm{GT})_{[\mathrm{DS}]}$ that does not differ from unity within the experimental error [15]. This agreement of the B(GT) values points to sufficient completeness of the decay scheme proposed in [9] and correctness of the $S_\beta(E)$ measurement by the TAGS technique for the peak at $E \approx$ 4 MeV [5]. By using TAGS it is impossible to discriminate between GT and FF β transitions. Also it is impossible to indicate all total absorption peaks and, as a consequence, to make a proper interpretation of the TAGS spectra [3,15] in the energy region around 2 MeV for ^{147g}Tb.

Application of TAGS to the study of the decay of "chain" ^{160}Er(28.6 h) → ^{160m,g}Ho → ^{160}Dy does not allow us to extract $S_\beta(E)$, because one of the conditions for TAGS application is using of the monoisotope source [3,15]. The difference in half life of ^{160m}Ho and ^{160g}Ho does not help TAGS spectra interpretation in this case. In analysis we used the branching coefficient [16] for the ^{160m}Ho isomer decay $\varepsilon = (\mathrm{EC}/\beta^+)/\mathrm{total}$ was taken to be ε = 0.27(3). On the basis of the data [10-11] $S_\beta(E)$ are constructed for GT transitions (Fig. 3) and FF transitions [17] (Fig. 4) in the β^+/EC decay of the deformed nucleus ^{160g}Ho (25.6 min). The strength function for the GT β^+/EC transitions in the decay of the ^{160g}Ho nucleus (25.6 min) has a distinct resonance structure (Fig. 3). The strongest peak in the region of 2–3 MeV is identified with the $\mu_\tau = +1$ GT resonance because evaluations by the model described in [2] predict this resonance in the region of 2–4 MeV and the ft value for the 1694-keV level [17] is typical of the $\mu_\tau = +1$ GT resonance [2]. In Fig. 3 the peak for the GT transitions is seen to split into two components, one in the region 1700–2200 keV and the other in the region 2680–3100 keV. Macroscopically, collective excitations of the GT type are oscillations of spin–isospin density without a change in the nuclear shape [2]. By analogy with the splitting of the peak of the E1 giant resonance in deformed nuclei, splitting of the GT peak in deformed nucleus (Fig.3) can be associated with anisotropy of oscillation of the isovector density component $\rho_{\tau,\mu=1,1}$ [17]. No such splitting is observed for the GT β^+/EC decay of the spherical nucleus ^{147g}Tb (Fig. 1).

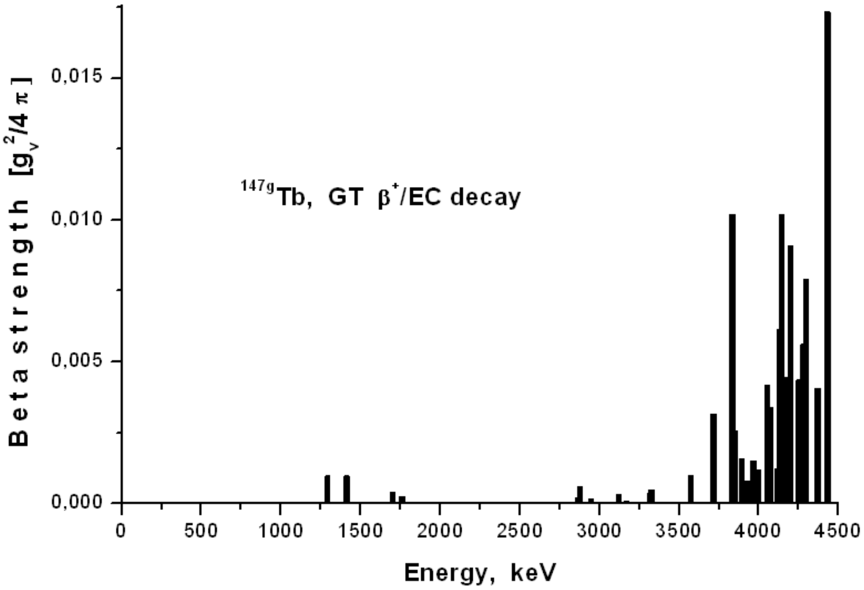

Figure 1. $S_\beta(E)$ for GT transitions in the β^+/EC decay of the spherical nucleus ^{147g}Tb.

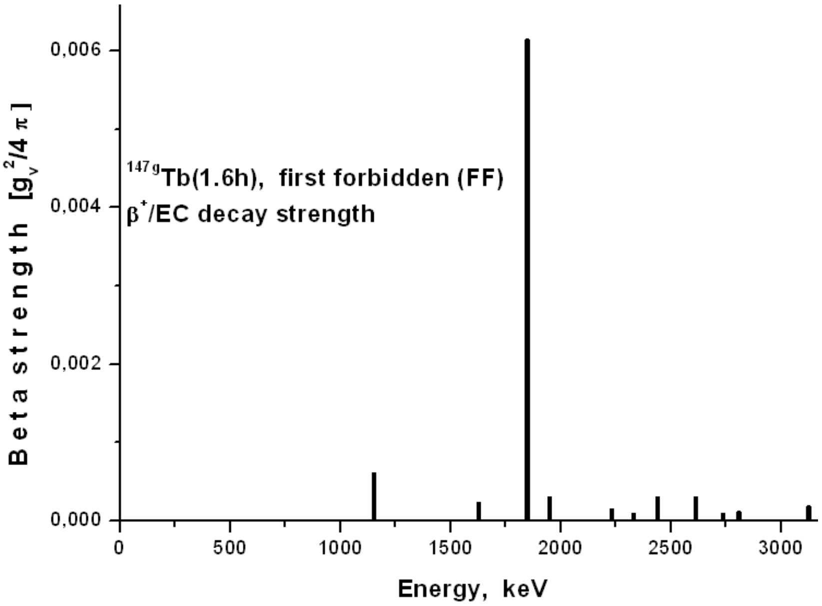

Figure 2. $S_\beta(E)$ for FF transitions in the β^+/EC decay of the spherical nucleus ^{147g}Tb.

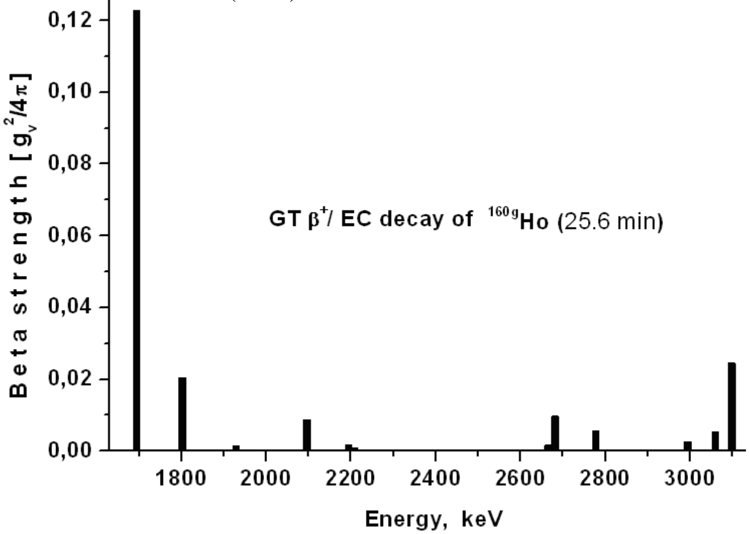

Figure 3. $S_\beta(E)$ for GT transitions in the β^+/EC decay of the deformed nucleus ^{160g}Ho.

The resonance structure is observed in $S_\beta(E)$ for FF transitions in the β^+/EC decay of the deformed nucleus ^{160g}Ho (25.6 min) (Fig. 4). In the energy region about 2.5 MeV the FF transitions are more intense than the GT transitions. In the case of the GT β^+/EC decay of the isomer ^{160m}Ho (Fig.5), $S_\beta(E)$ has a pronounced resonance structure [4]. The main peak in $S_\beta(E)$ is at the excitation energy 2630 keV of the daughter nucleus ^{160}Dy, which is about 1 MeV higher than for the decay of ^{160g}Ho. Therefore, the second component of the peak in $S_\beta(E)$ for the decay of isomer ^{160m}Ho can have the energy higher than Q_{EC} = 3346 keV and not to manifest itself in the β^+/EC decay of ^{160m}Ho, and in this case (Fig. 5) we can observe only fragments of the tail of the second component of the split peak in $S_\beta(E)$.

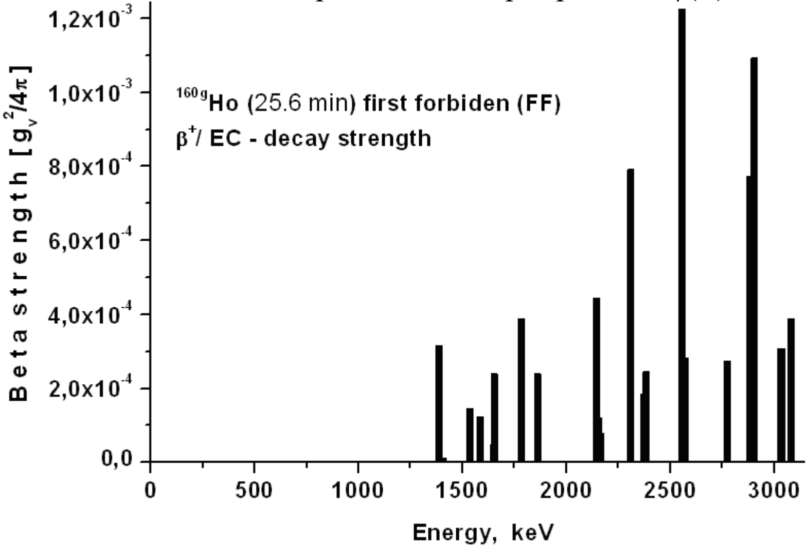

Figure 4. $S_\beta(E)$ for FF transitions in the β^+/EC decay of the deformed nucleus ^{160g}Ho.

For the GT β^+/EC decay of the deformed nucleus ^{160m}Ho the main peak (Fig. 5) in $S_\beta(E)$ has a smaller amplitude as compared with the main peak [4] in $S_\beta(E)$ for the decay of ^{160g}Ho, which results from the asymptotic quantum number forbidding for the GT β^+/EC decay of the ^{160m}Ho isomer. For the FF β^+/EC decays of the ^{160m}Ho isomer the resonance structure is found to manifest itself (Fig. 6) in the strength function $S_\beta(E)$ [4].In the statistical model it is assumed [18] that $S_\beta(E)$ = Const or $S_\beta(E) \approx \rho(E)$, where $\rho(E)$ is the density of the excited states of the daughter nucleus. The experimental data unambiguously indicate that the statistical model is not suitable for calculation of $S_\beta(E)$ for both GT and FF transitions.

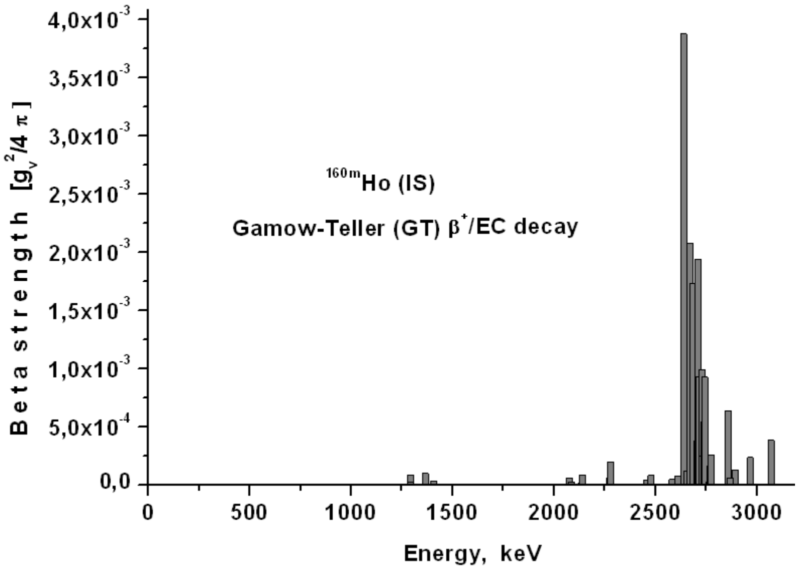

Figure 5. $S_\beta(E)$ for GT transitions in the β^+/EC decay of the deformed nucleus of the isomer ^{160m}Ho (5.02 h) [4].

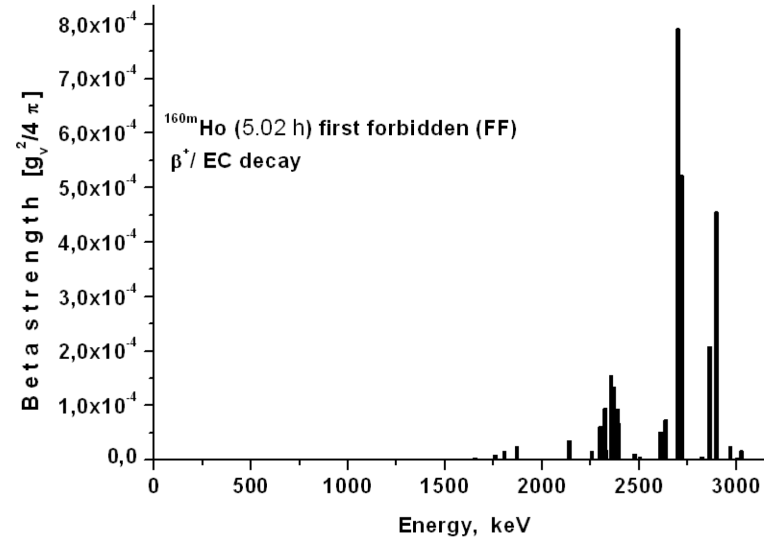

Figure 6. $S_\beta(E)$ for FF transitions in the β^+/EC decay of the deformed nucleus of the isomer ^{160m}Ho (5.02 h) [4].

4. Conclusions

High-resolution nuclear spectroscopy methods, like total absorption gamma spectroscopy (TAGS) methods, give conclusive evidence of the resonance structure of $S_\beta(E)$ for GT transitions in both spherical and deformed nuclei. High-resolution nuclear spectroscopy methods made it possible to demonstrate experimentally the resonance nature of $S_\beta(E)$ for FF transitions and reveal splitting of the peak in the strength function for the Gamow–Teller β^+/EC decay of the deformed nucleus ^{160g}Ho into two components. This splitting indicates anisotropy of oscillation of the isovector density component $\rho_{\tau,\mu=1,1}$.

Now it seems crucial to develop theoretical models and methods for calculation of $S_\beta(E)$ with allowance for deformation of atomic nuclei. To obtain experimental data on the structure of strength functions for transitions of the Gamow–Teller type and first-forbidden transitions in spherical and deformed nuclei is very important for further improvement of theoretical approaches to the calculation of $S_\beta(E)$.

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