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# FINE STRUCTURE OF STRENGTH FUNCTIONS FOR GAMOW–TELLER AND FIRST-FORBIDDEN $\beta^{+}$/EC TRANSITIONS

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Тонкая структура силовых функций $\beta^+$/EC-переходов
Гамова–Теллера и переходов первого запрета

Проанализированы экспериментальные данные по измерению тонкой структуры $S_\beta(E)$ в сферических и деформированных ядрах. Применение современных методов ядерной спектроскопии позволило выявить связанное с деформацией ядра расщепление пиков в $S_\beta(E)$ для переходов типа Гамова–Теллера (GT). Экспериментально доказан резонансный характер $S_\beta(E)$ для переходов первого порядка запрета (FF-переходов) как для сферических, так и для деформированных ядер. Показано, что при некоторых значениях энергий возбуждения в ядрах FF-переходы по интенсивности могут быть соизмеримы с GT-переходами.

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Fine Structure of Strength Functions for Gamow–Teller
and First-Forbidden $\beta^+$/EC Transitions

The experimental measurement data on the fine structure of $S_\beta(E)$ in spherical and deformed nuclei are analyzed. The 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.

The investigation has been performed at the Flerov Laboratory of Neutron Reactions, JINR.

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## INTRODUCTION

The probability of the $\beta$ transition 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 $\beta$ transition strength function $S_\beta(E)$. The function $S_\beta(E)$ is one of the most important characteristics of the atomic nucleus [1–3] defined as the distribution of the moduli squared of the matrix elements of the $\beta$-decay type in nuclear excitation energy $E$.

Until recently, experimental investigations of the $S_\beta(E)$ structure were carried out using total absorption gamma-ray spectrometers (TAGS) and total absorption spectroscopy methods, which had low energy resolution. With TAGS spectroscopy, it became possible to demonstrate experimentally the resonance structure of $S_\beta(E)$ for Gamow–Teller $\beta$ transitions [2, 3]. However, TAGS methods have some disadvantages arising from low energy resolution of NaI-based spectrometers. Modern experimental instruments allow using nuclear spectroscopy methods with high energy resolution to study the fine structure of $S_\beta(E)$.

In this work the data on the structure of $S_\beta(E)$ were obtained using nuclear spectroscopy methods of high energy resolution.

For Gamow–Teller transitions, $S_\beta(E)$ has a pronounced resonance structure [1–3]. Until recently, the question of the resonance nature of $S_\beta(E)$ for the first-forbidden $\beta$ transitions remained an open question. In [4], we were the first who show experimentally that $S_\beta(E)$ for the first-forbidden $\beta^+$/EC decay of the deformed nucleus $^{160m}$Ho has a resonance nature.

It has been shown that $S_\beta(E)$ for the first-forbidden $\beta^+$/EC decay of the deformed nucleus $^{160g}$Ho and spherical nucleus $^{147g}$Tb also have a resonance nature. It is shown that at some energies intensities of the first-forbidden $\beta^+$/EC decays are comparable with intensities of the Gamow–Teller transitions. The features of the resonance structure of $S_\beta(E)$ for the first-forbidden (FF) transitions are discussed.

## 1. BETA DECAY STRENGTH FUNCTION $S_\beta(E)$

The strength function $S_\beta(E)$ governs the nuclear energy distribution of elementary charge-exchange excitations and their combinations like proton particle

($\pi p$)–neutron hole ($\nu h$) coupled into a momentum $J^\pi$: $[\pi p \otimes \nu h)]_{J^\pi}$ and neutron particle ($\nu$p)–proton hole ($\pi$h) coupled into a momentum J$^\pi$: $[\nu p \otimes \pi h)]_{J^\pi}$. The strength function of Fermi-type $\beta$ transitions takes into account excitations $[\pi p \otimes \nu h)]_{0^+}$ or $[\nu p \otimes \pi h)]_{0^+}$. Since isospin is a quite good quantum number, the strength of the Fermi-type transitions is concentrated in the region of the isobar-analogue resonance (IAR). The strength function for $\beta$ transitions of the Gamow–Teller type describes excitations $[\pi p \otimes \nu h)]_{1^+}$ or $[\nu p \otimes \pi h)]_{1^+}$. Significant configurations for FF $\beta$ transitions in the Coulomb ($\xi$ approximation) are $[\pi p \otimes \nu h)]_{0^-,1^-}$ or $[\nu p \otimes \pi h)]_{0^-,1^-}$. The residual interaction can cause collectivization of these configurations and occurrence of resonances in $S_\beta(E)$. The position and intensity of resonances in $S_\beta(E)$ are calculated within various microscopic models of the nucleus [1, 5–8].

For the Gamow–Teller $\beta$ transitions, FF $\beta$ transitions in the $\xi$ approximation (Coulomb approximation), and unique FF $\beta$ 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]:

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

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

$$\int\limits_{\Delta E} S_\beta(E)dE = \sum_{\Delta E} 1/(\mathrm{ft}), \tag{3}$$

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

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

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

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

where $Q_\beta$ is the total $\beta$ decay energy, $f(Q_\beta - E)$ is the Fermi function, $t$ is the partial period of the $\beta$ 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 Gamow–Teller transition, $I_i$ is the spin of the parent nucleus, $I_f$ is the spin of the excited state of the daughter nucleus, $D = (6147 \pm 7)$ s. By measuring populations of levels in the $\beta$ decay, one can find the reduced probabilities and the strength function for the beta decay. The reduced probabilities of the beta decays are proportional to the squares of the nuclear matrix elements and reflect the fine structure of the strength function for the beta decay.

The scheme of the states significant for the analysis of strength functions for the Gamow–Teller transitions is shown in Fig. 1. As nuclei with $N > Z$ undergo $\beta^+$/EC decay, there is only one isospin value $T_0 + 1$ at the coupling of the

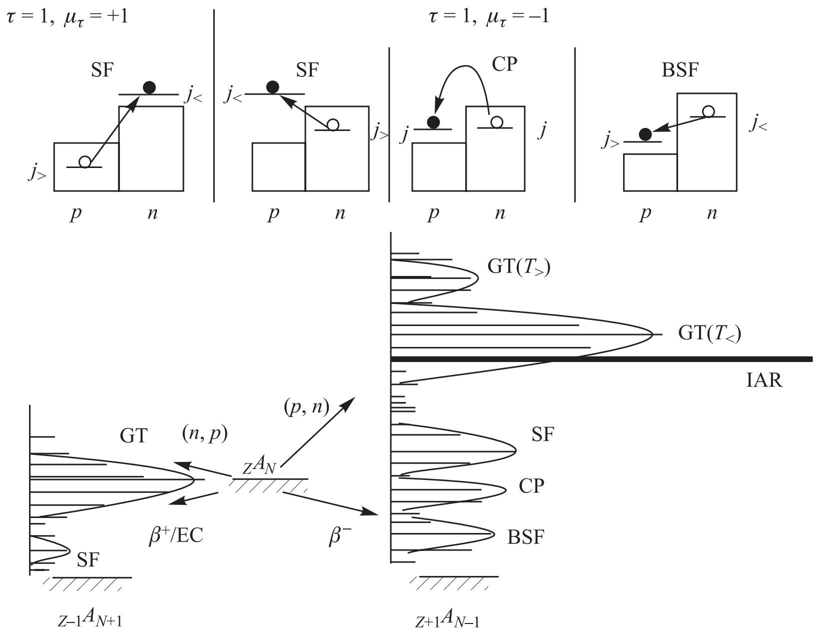


Fig. 1. Diagram of strength functions for the Gamow–Teller $\beta$ transitions and configurtaions that form resonances in $S_\beta(E)$ for the GT transitions. The strength of the Fermi-type transitions is concentrated in the region of the isobar-analogue resonance (IAR)

isospin ($\tau = 1, \mu_\tau = +1$) of the configurations like proton hole–neutron particle $[\nu p \times \pi h]_{1^+}$ with the isospin of the neutron excess $T_0$. The most collective state resulting from excitations like $[\nu p \times \pi h]_{1^+}$ with the isospin $\tau = 1$ and isospin projection $\mu_\tau = +1$ is also called [2] the Gamow–Teller resonance with $\mu_\tau = +1$. While for the $\beta^-$ decay of nuclei with $N > Z$, the Gamow–Teller resonance ($\tau = 1$, $\mu_\tau = -1$) is at energies higher than $Q_\beta$ (Fig. 1) and is energetically inaccessible for population by the $\beta^-$ decay. The Gamow–Teller resonance with $\mu_\tau = +1$ can be populated by the $\beta^+$/EC decay [2]. Now there is no theory that adequately describes strength functions for the $\beta$ decay of deformed nuclei. Theory allows rather correct calculations of positions and relative intensities of peaks in strength functions of the Gamow–Teller transitions for spherical and weakly deformed nuclei [1, 5–8]. As to absolute intensities of peaks in strength functions, the discrepancy between experiment and theory for spherical nuclei can be as large as tens or hundreds of percent. Theory predicts more intense peaks in strength functions than experimentally observed [2, 3, 5]. Macroscopically, collective excitations of the Gamow–Teller type are oscillations of spin–isospin density without a change in the nuclear shape; therefore, the position of the strength function peak in the spherical limit should approximately correspond to the center of gravity of the strength function for the deformed nucleus [2]. The resonance structure of the strength functions for the $\beta$ transitions of the Gamow–Teller type arises from residual spin–isospin interaction and partial $SU(4)$ spin–isospin symmetry in nuclei [2, 3].

For the FF $\beta^+$/EC transitions in the $\xi$ approximation, significant configurations are the configurations like (proton hole)–(neutron particles) coupled into the momentum $0^-$ or $1^-$: $[\nu p \times \pi h]_{0^-, 1^-}$. The question of whether or not there is the resonance structure in the strength function for FF $\beta^-$ or $\beta^+$/EC transitions has remained until recently an open question.

Information on the structure of $S_\beta(E)$ is important for many nuclear physics areas [1–4]. Reliable experimental data on the structure of $S_\beta(E)$ are necessary for predicting half-lives of nuclei far from the stability line, verifying completeness of decay schemes, calculating energy release from decay of fission products in nuclear reactors, calculating spectra of delayed particles, calculating the delayed fission probability and evaluating fission barriers for nuclei far from the $\beta$-stability line, calculating production of various elements in astrophysical processes, and developing microscopic models for calculation of $S_\beta(E)$, especially in deformed nuclei.

## 2. 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 structure of $S_\beta(E)$ for all peaks with the energy no higher than $Q_\beta$. It also becomes possible to obtain qualitatively new information on the fine structure of $S_\beta(E)$ for both Gamow–Teller 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 from the JINR DLNP Phasotron. To this end, a metallic tantalum target with the mass of 5 g was installed with a special device in the Phasotron chamber without breaking the vacuum. Then the target was irradiated with a proton beam for the period of time dictated by the half-life and required amount of the radionuclide whose decay we wanted to investigate. In our experiments the irradiation time varied from tens of minutes to several hours. In all irradiation runs the proton energy was $E_p = 660$ MeV and the intensity was $I_p = 2$ $\mu$A.

After irradiation the target was extracted from the accelerator chamber and delivered to the special laboratory for radiochemical processing. The rare-earth elements produced in the reaction were separated into fractions by the chromatographic technique [11]. The time from the removal of the target till the end of the separation was in general no longer than two hours.

One of the fractions (Tb, Er) was placed into a special ion source ampoule of the electromagnetic mass separator at the YASNAPP-2 complex [12] and was separated into isobars. In the special collection device monoisotopes were deposited (each in its place) in the form of ions on the aluminum tape. The tape was removed from the device and cut into fragments about 1 $cm^2$ in size with one or another monoisotope. The fragments were later used as radioactive sources for measurements at our spectrometers. The entire mass separation process took no more than one hour.

Then spectra of $\gamma$ rays and matrices of $\gamma\gamma t$ coincidences in $\beta$ decays of nuclei under our investigation were measured. In addition, spectra of internal conversion electrons (ICEs) were measured. The measured spectra were used to find energies and intensities of $\gamma$ rays and ICEs, and the data on $\gamma\gamma t$ coincidences allowed their positions between excited states to be found, and thus the decay scheme was constructed. Then intensities of population directly by the $\beta$ decay were determined for each energy level from the balance of its incoming and outgoing $\gamma$ transitions, and reduced half-lives ft entering into expressions (1)–(7) for the function $S_\beta(E)$ were calculated.

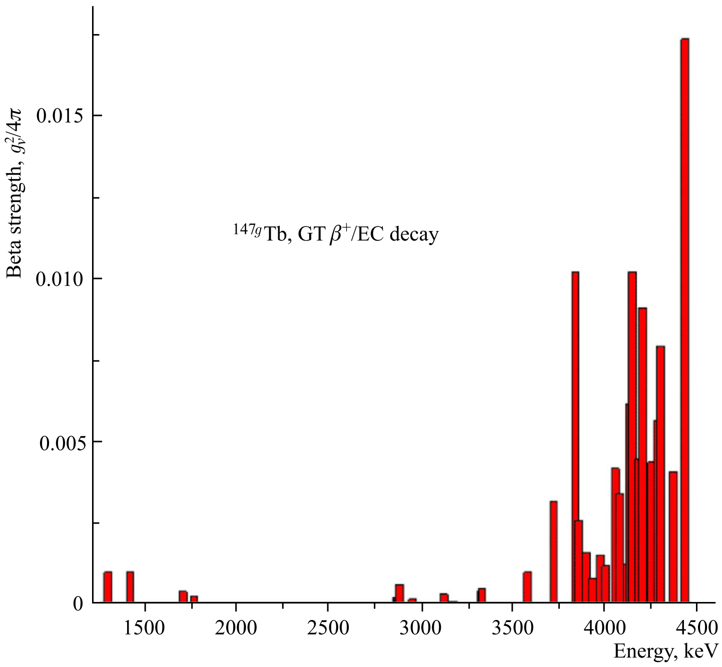


Fig. 2. $S_\beta(E)$ for Gamow–Teller transitions in the $\beta^+$/EC decay of the spherical nucleus $^{147g}$Tb ($T_{1/2} = 1.6$ h, $Q_{\rm EC} = 4.6$ MeV)

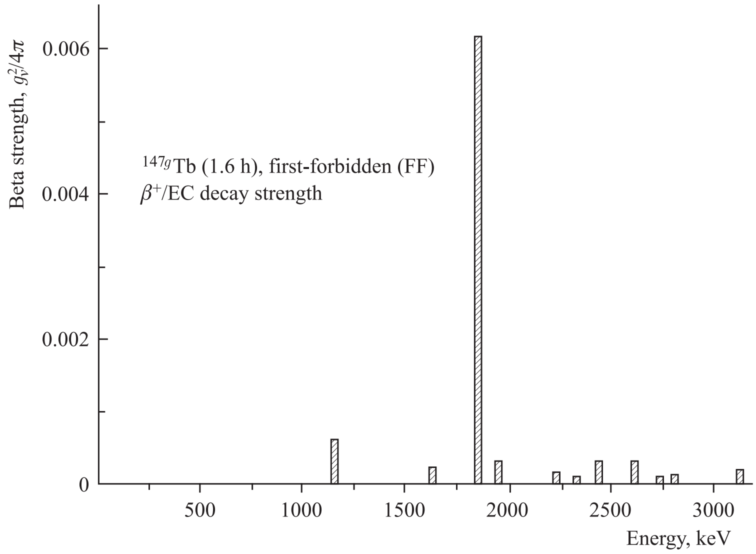


Fig. 3. $S_\beta(E)$ for the first-forbidden transitions in the $\beta^+$/EC decay of the spherical nucleus $^{147g}$Tb ($T_{1/2} = 1.6$ h, $Q_{\rm EC} = 4.6$ MeV)

Using relations (1)–(7) and data [9], we constructed $S_\beta(E)$ for GT transitions (Fig. 2) and FF transitions (Fig. 3) in the$^{147g}$Tb $\beta^+$/EC decay.

The function $S_\beta(E)$ for Gamow–Teller transitions in the $\beta^+$/EC decay of the spherical nucleus $^{147g}$Tb ($T_{1/2} = 1.6$ h, $Q_{\rm EC} = 4.6$ MeV) [5] has a distinct resonance 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 [13]. For the $\beta^+$/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 [14]. Thus, high-resolution nuclear spectroscopy methods, like TAGS, give conclusive evidence of the resonance structure of $S_\beta(E)$ for GT transitions in spherical nuclei.

It follows from Fig. 3 that $S_\beta(E)$ for FF transitions in the $\beta^+$/EC decay of the spherical nucleus $^{147g}$Tb also has a resonance nature. Note also that in the $\beta^+$/EC decay of $^{147g}$Tb the intensity of FF $\beta^+$/EC transitions is higher than the intensity of the Gamow–Teller transitions in the excitation energy region about 2 MeV.

In [10] the authors measured $^{160m,g}$Ho $\gamma$ radiation spectra in the «chain» decay $^{160}$Er (28.6 h) $\to$ $^{160m,g}$Ho $\to$ $^{160}$Dy. The parent isotope $^{160}$Er has a low decay energy $Q_{\rm EC} = 336 \pm 32$ keV; therefore, its presence in the chain hampered identification of only soft-energy $\gamma$ transitions. To calculate reduced probabilities

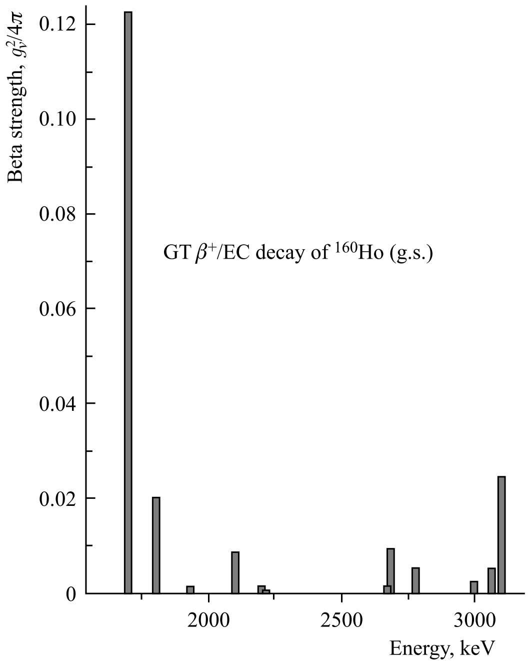


Fig. 4. $S_\beta(E)$ for Gamow–Teller transitions in the $\beta^+$/EC decay of the deformed nucleus $^{160g}$Ho (25.6 min)

for $^{160g,m}$Ho beta transitions (logft), it was necessary to establish the partial period in the $^{160g,m}$Ho $\beta^+$/EC decay branch. In the given calculations the branching coefficient [15] for the $^{160m}$Ho isomer decay $\varepsilon = (\mathrm{EC}/\beta^+)$/total was taken to be $\varepsilon = 0.27(3)$.

On the basis of the data [10] $S_\beta(E)$ are constructed for GT transitions (Fig. 4) and FF transitions [16] (Fig. 5) in the $\beta^+$/EC decay of the deformed nucleus $^{160g}$Ho (25.6 min).

Now there is no microscopic theory that adequately describes strength functions for the $\beta$ decay of deformed nuclei. The strength function for the Gamow–Teller $\beta^+$/EC transitions in the decay of the $^{160g}$Ho nucleus (25.6 min) has a distinct resonance structure (Fig. 4). The strongest peak in the region of 2–3 MeV is identified with the $\mu_\tau = +1$ Gamow–Teller 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 [16] is typical for the $\mu_\tau = +1$ Gamow–Teller resonance [2]. In Fig. 4 the peak for the Gamow–Teller 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 Gamow–

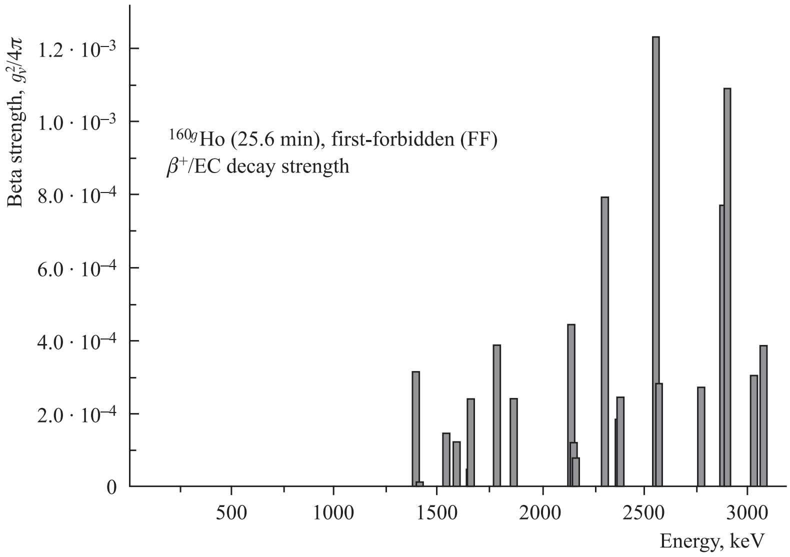


Fig. 5. $S_\beta(E)$ for the first-forbidden transitions in the $\beta^+$/EC decay of the deformed nucleus $^{160g}$Ho (25.6 min)

Teller type are oscillations of spin–isospin density without a change in the nuclear shape. By analogy with the splitting of the peak of the $E1$ giant resonance in deformed nuclei, this splitting can be associated with anisotropy of oscillation of the isovector density component $\rho_{\tau,\mu=1,1}$ [16].

No splitting of this kind is observed for the Gamow–Teller $\beta^+$/EC decay of the spherical nucleus $^{147g}$Tb (Fig. 2).

The resonance structure is observed in $S_\beta(E)$ for FF transitions in the $\beta^+$/EC decay of the deformed nucleus $^{160g}$Ho (25.6 min) (Fig. 5). In the energy region of about 2.5 MeV the FF transitions are more intense than the GT transitions.

In the case of the Gamow–Teller $\beta^+$/EC decay of the isomer $^{160m}$Ho, $S_\beta(E)$ 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 $Q_{\rm EC} = 3346$ keV and not to manifest itself in the $\beta^+$/EC decay of $^{160m}$Ho, and in this case (Fig. 6) we can observe only fragments of the tail of the second component of the split peak in $S_\beta(E)$.

For the Gamow–Teller $\beta^+$/EC decay of the deformed nucleus $^{160m}$Ho the main peak (Fig. 6) 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

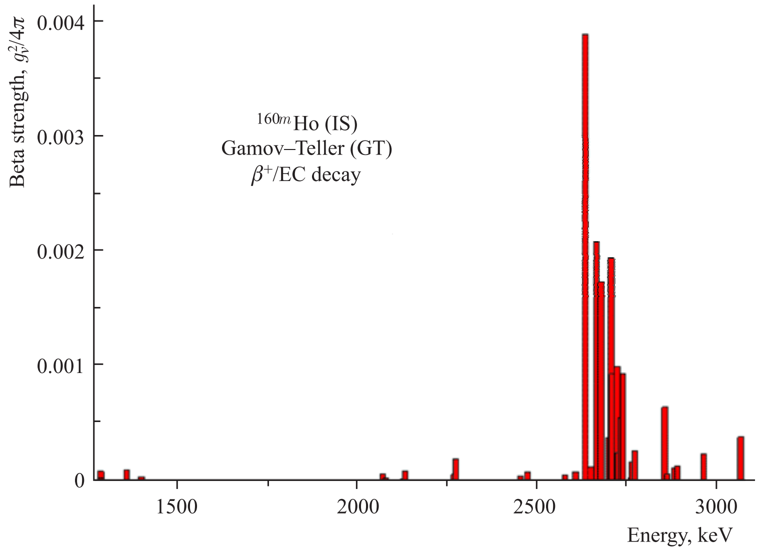


Fig. 6. $S_\beta(E)$ for the Gamow–Teller transitions in the $\beta^+$/EC decay of the deformed nucleus of the isomer $^{160m}$Ho (5.02 h) [4]

quantum number forbidding for the Gamow–Teller $\beta^+$/EC decay of the $^{160m}$Ho isomer.

For the first-forbidden $\beta^+$/EC decays of the $^{160m}$Ho isomer the resonance structure is found to manifest itself (Fig. 7) in the strength function $S_\beta(E)$ [4].

Strong configuration mixing at high excitation energies and densities of states should result in disappearance of the resonance structure in the strength functions $S_\beta(E)$. The approximate symmetry of nuclear interaction prevents some configurations from mixing. For configurations populated by Gamow–Teller $\beta^+$/EC transitions, mixing is weaker because of partial $SU(4)$ spin–isospin symmetry of interaction in the nucleus [2, 3]. For the FF $\beta^+$/EC transitions, resonance structure is also observed in the strength function $S_\beta(E)$ (Figs. 3, 5, 7). The resonance structure of the strength function for the FF $\beta^+$/EC transitions can indicate partial symmetry of interaction in the nucleus, which corresponds to the first forbidding. This means that configurations populated by the FF transitions are also distinguished in approximate quantum numbers among neighboring levels of the daughter nucleus, and no strong configuration mixing occurs.

In the statistical model it is assumed [17] that $S_\beta(E) = \text{const}$ 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.

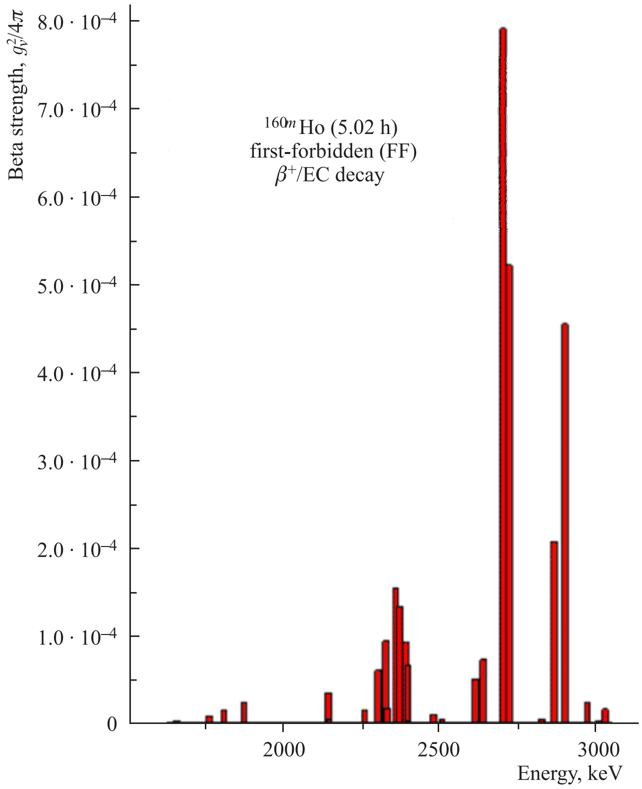


Fig. 7. $S_\beta(E)$ for the first-forbidden transitions in the $\beta^+$/EC decay of the deformed nucleus of the isomer $^{160m}$Ho (5.02 h) [4]

Thus, high-resolution nuclear spectroscopy methods, like TAGS, give conclusive evidence of the resonance structure of $S_\beta(E)$ for the GT transitions in both spherical and deformed nuclei. The high-resolution nuclear spectroscopy methods made it possible to demonstrate experimentally the resonance nature of $S_\beta(E)$ for the FF transitions.

## CONCLUSIONS

The development of experimental technology allows methods of nuclear spectroscopy with high energy resolution to be used for investigating fine structure of $S_\beta(E)$. The most complete investigations of this kind were carried out with some nuclei produced at the YASNAPP-2 complex in Dubna.

High-resolution nuclear spectroscopy methods, like total absorption gamma spectroscopy (TAGS) methods, give conclusive evidence of the resonance structure of $S_\beta(E)$ for the 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 $\beta^+$/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. The obtaining experimental data on the structure of strength functions for the 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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