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FINE STRUCTURE OF THE STRENGTH FUNCTION FOR THE β^+/EC DECAY OF THE ^{160m}Ho (5.02 h) ISOMER

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The strength function for the β^+/EC decay of the deformed nucleus of the ^{160m}Ho (5.02 h) isomer is obtained from the experimental data. The fine structure of the strength function $S_\beta(E)$ is analyzed. It has a pronounced resonance structure for Gamow–Teller transitions and is found to exhibit a resonance structure for first-forbidden transitions. It is shown that for some excitation energies of the ^{160}Dy daughter nucleus the probability of first-forbidden β^+/EC transitions in the decay of the ^{160m}Ho isomer is comparable with the probability of Gamow–Teller β^+/EC transitions.

В работе из экспериментальных данных получена силовая функция β^+/EC-распада деформированного ядра изомера ^{160m}Ho (5,02 ч). Проанализирована тонкая структура силовой функции $S_\beta(E)$. Для переходов Гамова–Теллера $S_\beta(E)$ имеет ярко выраженную резонансную структуру. Обнаружена резонансная структура $S_\beta(E)$ для переходов первого запрета. Показано, что для некоторых значений энергии возбуждения дочернего ядра ^{160}Dy вероятность β^+/EC-переходов первого запрета при распаде изомера ^{160m}Ho сравнима с вероятностью β^+/EC-переходов Гамова–Теллера.

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INTRODUCTION

Beta decay of atomic nuclei is a charge exchange process where states whose wave function involves a considerable charge-exchange component are most intensely populated. For the β^- decay this component is made up of configurations like proton particle–neutron hole, and for the β^+/EC decay it is a configuration like neutron particle–proton hole coupled to the moment J^π. The residual nuclear interaction leads to collectivization of the abovementioned configurations, which is experimentally manifested as a resonance structure of the β-transition strength function $S_\beta(E)$ [1].

The β-transition strength function $S_\beta(E)$ is one of the most important characteristics of the atomic nucleus [1–3] defined as a distribution of the modules squared of the β-decay-type matrix elements in nuclear excitation energies E. At the excitation energies E up to Q_β (total energy of β decay) $S_\beta(E)$ determines the character of the β decay and the half-lives ($T_{1/2}$) of the β-decaying parent nuclei, spectra of β particles and neutrinos emitted in their β decay, spectra of γ rays and internal conversion electrons resulting from deexcitation of daughter nucleus states excited in the β decay, and spectra of delayed particles accompanying the β decay. At high excitation energies unattainable in the β decay, $S_\beta(E)$ determines cross sections of charge-exchange nuclear reactions depending on the matrix elements of the β-decay type.

The β-decay probability is proportional to the product of the lepton part described by the Fermi function $f(Q_\beta - E)$ and the nucleon part described by $S_\beta(E)$. Since the Fermi function rapidly decreases with increasing E, the probability of β decays at high excitation energies E (over 2–3 MeV) in medium and heavy nuclei is low. However, from the point of view of the nuclear structure and β-decay description, of greatest interest is the character of $S_\beta(E)$ at excitation energies higher than 2–3 MeV. It is at excitation energies beginning with $E > 2-3$ MeV that there arise resonances caused by the nuclear structure and residual spin–isospin interaction [1–5].

Until recently, total gamma-ray absorption spectrometers and total absorption spectroscopy (TAS) methods have been used $[1, 3, 6, 7]$ for $S_\beta(E)$ measurement. The TAS principle consists in that the γ radiation accompanying the β decay is detected by large NaI crystals in the 4π geometry. If the efficiency of the total γ-ray absorption is high enough, total absorption peaks, whose intensity is only governed by the probability for population of levels in the β decay, can be identified in the spectra. The TAS technique allows population of levels in the β decay of atomic nuclei to be directly measured and data on the $S_\beta(E)$ structure to be obtained. This technique made it possible to prove experimentally the resonance structure of $S_\beta(E)$ for Gamow–Teller β transitions [1–4]. However, TAS methods have some disadvantages bound up with a low energy resolution of NaI-based spectrometers. One or two total absorption peaks can be identified in TAS spectra, uncertainties associated with isobar impurities in the analyzed source often occur, Gamow–Teller and first-forbidden β transitions cannot be discriminated, the fine structure of $S_\beta(E)$ cannot be measured, difficulties often arise in processing of spectra, for instance, in taking account of gamma rays internal conversion and identifying total absorption peaks.

Therefore, it seems important to measure $S_\beta(E)$ using high-resolution γ-spectroscopy methods. It is quite an arduous problem, and these measurements have been impossible until recently. In the last few decades, due to considerable progress in production of monoisotopic radioactive sources and advent of semiconductor HPGe γ-ray detector, combining high energy resolution and tolerable efficiency, it has become possible to measure $S_\beta(E)$ with high confidence and high energy resolution. This allows $S_\beta(E)$ to be thoroughly investigated at a qualitatively new level. The method is based on detection of γ rays by semiconductor HPGe detectors whose standard energy resolution is not worse than 0.2%. The main purpose of the experiments was to measure γ-ray spectra and matrices of $\gamma\gamma t$ coincidences in the β decay of the nuclei under study. Spectra of internal conversion electrons (ICEs) were also measured. Energies and intensities of γ rays and ICEs were found from the measured spectra, their positions between excited states were established from the $\gamma\gamma t$-coincidence data, and thus the decay scheme was constructed. Then intensities of population directly by the β decay were found for each energy level from the intensity balance of incoming and outgoing γ transitions, and reduced half-lives ft entering into expressions (1)–(7) for the function $S_\beta(E)$ were calculated.

By now, high-energy-resolution measurements of $S_\beta(E)$ have been carried out only for the β^+/EC decay of the spherical nucleus ^{147g}Tb ($T_{1/2} = 1.6$ h, $Q_{\rm EC} = 4.6$ MeV) $[3–5, 8]$ and the deformed nucleus ^{160g}Ho (5^+; 25.6 min, $Q_{\rm EC} = 3286(15)$ keV) [9]. These nuclei were chosen for the study because of their quite large $Q_{\rm EC}$, quite large half-lives $T_{1/2}$, and the possibility of effectively producing highly pure monoisotopic radioactive sources of these nuclei at JINR (Dubna).

In this work the strength function $S_\beta(E)$ was obtained from the studies of the β^+/EC decay of the ^{160m}Ho isomer (2^-; 5.02 h, $Q_{\rm EC} = 3346$ keV) by high-resolution nuclear spectroscopy methods. The fine structure of $S_\beta(E)$ was analyzed, and features of $S_\beta(E)$ for Gamow–Teller and first-forbidden β^+/EC transitions are revealed.

1. PRODUCTION AND PREPARATION OF RADIOACTIVE SOURCES

To produce radioactive sources for our experiments, we used the deep spallation reaction of tantalum nuclei interacting with 660-MeV protons of the DLNP Phasotron (JINR). To this end, a metallic tantalum target of mass 5 g was placed in the Phasotron chamber without violation of vacuum using a special device. Then the target was exposed to a proton beam for a certain period of time determined by the half-life and required amount of the radionuclides whose decay we were going to study. In our experiments the exposure time varied from tens of minutes to several hours. In all exposures the energy of protons was $E_p = 660$ MeV and intensity was $I_p = 2$ μA.

After the exposure the target was taken out of the accelerator chamber and transported into the special laboratory, where after radiochemical treatment it was separated into fraction by the chromatographic technique. The time from removal of the target till completion of the separation was generally no longer than two hours.

One of these fractions was inserted into a special ampoule of the ion source of the YASNAPP-2 electromagnetic mass separator [10] and underwent separation into individual isobars. In a special collector the monoisotopes in the form of ions were implanted (each in its place) in an aluminum tape. The tape was taken out of the collector and cut into fragments about 1 cm^2 in size with this or that monoisotope. The fragments were later used as radioactive sources for measurements at our spectrometers. The entire mass-separation process was no more than an hour long.

2. ON THE ^{160m,g}Ho → ^{160}Dy DECAY SCHEME

The most complete scheme of ^{160}Dy levels excited in the decays of ^{160m}Ho (2^-; 5.02 h) and ^{160g}Ho (5^+; 25.6 min) was proposed in [11]. It comprises about 750 γ transitions out of $\sim$ 800 observed by the authors. They measured ^{m,g}Ho γ-ray spectra in the decay «chain» ^{160}Er (28.6 h) $\rightarrow$ ^{160m,g}Ho $\rightarrow$ ^{160}Dy (Fig. 1) with practically equilibrium decays of the isotopes. The parent isotope ^{160}Er has a low decay energy $Q_{\rm EC} = (336 \pm 32)$ keV; therefore, its presence in the chain made it difficult to identify only soft-energy γ transitions.

The wealth of the experimental data [11] on γ transitions in ^{160}Ho was further analyzed in [12], which resulted in a somewhat refined scheme of excited levels in^{160}Dy.

In the table we present a list of ^{160}Dy levels populated by the decay of the ^{160m}Ho isomeric state.

To calculate reduced probabilities of β transitions in ^{160g}Ho (log ft), one should find the partial half-life of ^{160m}Ho against the β^+/EC decay. To this end, the contribution from the γ decay of the ^{160m}Ho (2^-) isomer should be taken into account. In [11] the authors assumed that the sum of total intensities ((5960±130) rel. un. of intensity in Table 1 [11]) of γ

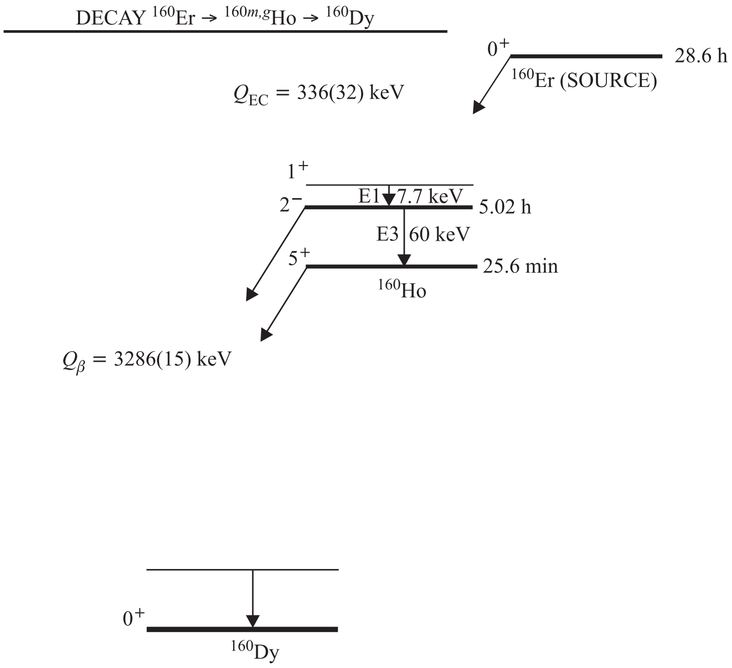

Fig. 1. $^{160}\mathrm{Er} \to {}^{160m,g}\mathrm{Ho} \to {}^{160}\mathrm{Dy}$ decay

transitions to the ground state of ^{160}Dy is 100% of ^{160}Er decays. The isomer decay branching ratio $\varepsilon = (\mathrm{EC}/\beta^+)/\mathrm{total}$, $b = \mathrm{IT}/\mathrm{total}$ was determined in [11] from the comparison of the intensity of the isomeric E3 transition with $E_\gamma = 59.98$ keV ($I_{\mathrm{tot}} = (4390 \pm 310)$ rel. un.) and the total intensity. It turned out that the intensity of the isomeric 59.98-keV transition was $b = 73.6(5.2)\%$ of decays and the intensity of the EC/β^+ decay of ^{160m}Ho (2^-) was $\varepsilon = 26.4(5.2)\%$. Later soft γ radiation of the «chain» of $A = 160$ isotopes was measured using a high-resolution X-ray spectrometer, which resulted [13] in a more accurate branching ratio for the isomeric state ^{160m}Ho (2^-): $b = 0.73(3)$, $\varepsilon = 0.27(3)$.

It is noteworthy, however, that the branching ratios obtained above depend on how well the ^{160m,g}Ho decay schemes are established and how correctly time intervals are taken into account in measurements of the $^{160}\mathrm{Er} \to {}^{160}\mathrm{Ho} \to {}^{160}\mathrm{Dy}$ decay chain spectra. To decrease the effect of the above factors, the authors of [14] found the branching ratio by measuring the intensities of the 59.98-keV γ transition and the Kx(Ho) radiation in the decay of the ^{160}Er parent nucleus: $b = \mathrm{IT}/\mathrm{total} = 0.779 \pm 0.020$. It is obvious that all the three results agree within the error bars. The choice of one or another branching ratio value leads to an increase or a decrease in the amplitudes of all peaks in $S_\beta(E)$ by an identical factor and does not affect the shape of $S_\beta(E)$.

In this work we calculated the partial half-life of the ^{160m}Ho against the β^+/EC decay using the value $b = 0.73(3)$, $\varepsilon = 0.27(3)$ because this branching is recommended by the National Nuclear Data Center database http://www.nndc.bnl.gov/. In the same database, there is a computer program we used to calculate values of log ft.

Levels of ^{160}Dy populated by the β^+/EC decay of ^{160m}Ho (5.02(5) h)

Level energy, keV	Quantum characteristics ($I^\pi K$)	Population by β^+/EC decay of ^{160m}Ho, %	log ft
86.788(5)	2^+0	1.0(2)*	8.9
966.17(1)	2^+2	< 0.3	> 9
1049.12(1)	3^+2	< 0.9	> 8.6
1264.77(1)	2^-2	< 0.2	> 9
1285.62(2)	1^-1	4.2(5)	7.9
1286.71(2)	3^-2	1.2(3)	8.4
1358.67(2)	2^-1	4.4(9)	7.8
1398.98(2)	3^-1	1.5(3)	8.2
1489.49(3)	1^-0	0.4(2)	8.8
1643.3(1)	3^-0	0.6(1)	8.5
1653.7(1)	(2,3)	0.11(8)	9.2
1756.88(4)	$(2)^+$	0.3(2)	8.8
1804.70(2)	1^+1	0.4(3)	8.6
1869.54(3)	2^+1	0.6(2)	8.4
2009.5(1)	$(1,2)^-$	0.07(4)	9.2
2012.72(8)	2^+0	< 0.01	> 10
2068.09(4)	1^-	1.1(1)	8.0
2077.36(4)	3^-3	0.41(9)	8.4
2088.8(1)	(2^-)	0.07(4)	9.2
2090.9(1)	$(2,3)^-$	0.16(3)	8.8
2126.43(7)	3^-	0.33(8)	8.5
2130.6(1)	3^-	1.4(2)	7.8
2138.22(4)	$(2)^+$	0.1(1)	> 9
2140.2(1)	(3)	0.6(1)	8.2
2141.7(1)	(3)	0.09(2)	9.0
2144.5(1)	(2^-)	0.11(1)	8.9
2149.9(1)	(1,2)	0.09(3)	9.0
2191.0(1)	(3^-)	0.037(6)	9.4
2230.5(1)	(2)	0.17(2)	8.7
2245.0(1)	3^+	< 0.004	> 10
2255.7(1)	$(1,2^+)$	0.19(4)	8.6
2267.0(1)	3^-	0.7(3)	8.0
2271.27(4)	2^-	2.4(3)	7.5
2279.0(1)	(3^-)	0.051(9)	9.2
2297.5(1)	$(2)^+$	0.7(1)	8.0
2323.2(1)	$(1,2)^+$	1.0(1)	7.8
2325.3(1)	$(1,2)^+$	0.07(1)	9.0
2327.7(1)	(2^+)	0.20(3)	8.5
2354.6(1)	2^+	1.6(2)	7.6
2367.5(1)	3^+	1.3(2)	7.7
2386.9(1)	$(3)^+$	0.9(1)	7.8
2393.5(1)	(2,3)	0.6(1)	8.0
2396.9(1)	(1,2)	0.030(5)	9.3
2450.22(5)	(1^-)	0.37(6)	8.1

End of Table

Level energy, keV	Quantum characteristics ($I^{\pi}K$)	Population by β^{+}/EC decay of ^{160m}Ho, %	log ft
2469.7(2)	(3)$^-$	0. 7(1)	7.8
2474.9(1)	(3)	0.09(2)	8.7
2503.8(1)	2$^+$	0.04(2)	9.0
2553.6(1)	(3$^-$)	0.06(3)	8.8
2574.4(1)	(1,2,3)$^-$	0.32(5)	8.1
2602.67(5)	(1,2)$^-$	0.44(6)	7.9
2610.0(1)	(2$^+$)	0.27(4)	8.1
2630.3(1)	(1,2)$^+$	0.24(4)	8.1
2630.76(2)	1$^-$	20(2)	6.2
2634.7(1)	(1,2,3)$^+$	0.37(4)	7.9
2645.9(1)	3$^-$	0.7(1)	7.6
2661.50(2)	2$^-$	10(1)	6.5
2674.72(3)	1$^-$	7.8(9)	6.6
2696.5(1)	(2,3)$^-$	1.6(3)	7.2
2697.8(1)	2$^+$	3.3(4)	6.9
2701.09(2)	1$^-$	7.9(9)	6.5
2704.25(3)	2$^-$	3.8(4)	6.8
2717.25(3)	2$^+$	2.0(3)	7.1
2718.91(7)	2$^-$	3.9(5)	6.8
2720.6(1)	3$^-$	1.0(1)	7.4
2729.82(4)	2$^-$	2.0(2)	7.1
2734.72(3)	1$^-$	3.4(4)	6.8
2756.3(3)	(2$^-$)	0.11(1)	8.3
2760.5(1)	(1,2)	0.6(1)	7.5
2767.7(1)	1$^-$	0.9(1)	7.4
2822.2(2)	1$^+$	0.015(4)	9.0
2851.70(4)	1$^-$	1.5(2)	7.0
2858.1(1)	3$^-$	0.14(3)	8.0
2861.1(1)	1$^+$	0.45(6)	7.5
2877.10(4)	1$^-$	0.22(4)	7.8
2879.4(1)	(2)	0.23(4)	7.7
2885.6(1)	(2,3)$^-$	0.25(4)	7.7
2896.3(1)	2$^+$	0.9(1)	7.1
2958.5(1)	3$^-$	0.31(5)	7.4
2969.0(2)	(1,2)	0.03(1)	8.4
3004.4(1)	(1,2)	0.004(1)	9.2
3024.5(1)	(1,2)	0.015(2)	8.6
3061.93(5)	(1,2$^+$)	0.26(4)	7.2

Note. The log ft values were calculated using the partial β^{+}/EC-decay half-life of the ^{160m}Ho isomer $T_{1/2} = 19(2)$ h, $\varepsilon = (\mathrm{EC} + \beta^{+})/\mathrm{total} = 0.27(3)$.

*Under the assumption that β^{+} component with end-point energy $E_{\beta+} = (2280\pm 50)$ keV, $J_{\beta+} = 0.04(1)\%$ belongs to ^{160m}Ho and populates $(2^{+}, 0)$ level.

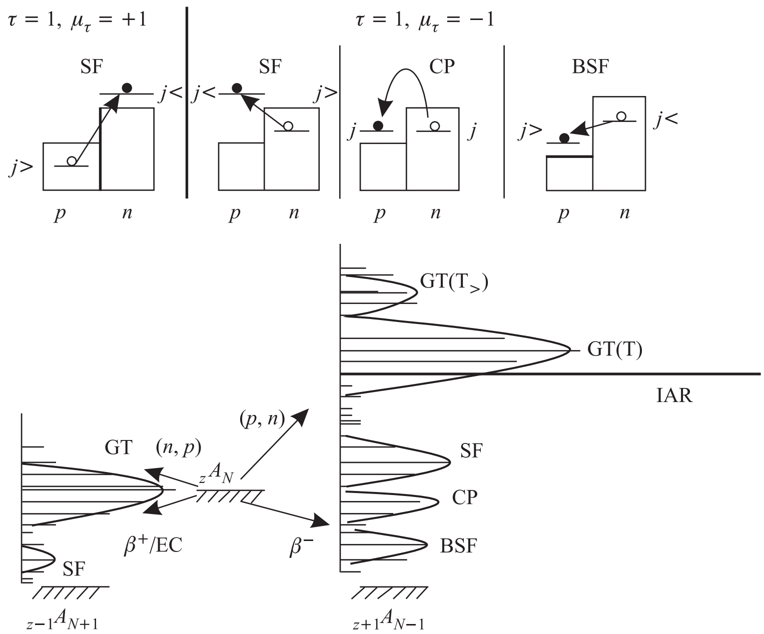

Fig. 2. Schematic view of the strength function for the Gamow–Teller β transitions and configurations responsible for formation of resonances in $S_\beta(E)$

Calculation of ft for the β^+/EC decay of the ^{160m}Ho isomer can be carried out by two methods. In one of them the total half-life of the ^{160m}Ho isomer $T_{1/2}^{\rm tot} = 5.02(5)$ h is used and the overall population of levels in the daughter nucleus ^{160}Dy due to the β^+/EC decay of the ^{160m}Ho isomer is normalized to the value $\varepsilon \times 100\% = 27(3)\%$. In the other the partial half-life of the ^{160m}Ho isomer against the β^+/EC decay $T_{1/2} = 19(2)$ h defined as $T_{1/2} = T_{1/2}^{\rm tot}/\varepsilon$ is used. The overall population of levels in the daughter nucleus ^{160}Dy due to the β^+/EC decay of the ^{160m}Ho isomer is now normalized to 100%. Naturally, both methods should yield identical ft values. The table presents the data for the calculation by the second method because it allows a simpler way to estimate the error caused by the error of the value $\varepsilon = ({\rm EC}/\beta^+)$/total and to round up the results.

In this work we analyzed all excited states of ^{160}Dy known from [11] and singled out those which, according to the angular momentum and parity selection rules, could only be populated by the β^+/EC decay of the isomeric state ^{160m}Ho (5.02 h) with the quantum characteristics $I^\pi = 2^-$. Then we found populations of each of these levels by the β^+/EC decay of ^{160m}Ho and calculated the corresponding reduced probabilities $\log ft$ using the partial half-life of ^{160m}Ho against the β^+/EC decay $T_{1/2} = 19(2)$ h.

3. STRUCTURE OF STRENGTH FUNCTION FOR THE β^+/EC DECAY OF ^{160m}Ho

For the Gamow–Teller β transitions, first-forbidden (FF) β transitions in the ξ approximation, and first-forbidden unique β transitions, their reduced probabilities B(GT), $[B(\lambda\pi = 0^-) + B(\lambda\pi = 1^-)]$, and $[B(\lambda\pi = 2^-)]$, the half-life $T_{1/2}$, the level populations

$I(E)$, the strength function $S_\beta(E)$, and ft are related in the following way [1, 2, 4, 5, 15]:

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

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

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

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

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

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

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

where E is the excitation energy of the daughter nulceus; Q is the total energy of the β decay; $f(Q - E)$ is the Fermi function, $|\langle I_f || \sum t_\pm(k) \sigma_\mu(k) || I_i \rangle|$ 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 daughter nucleus level, and $D = (6147 \pm 7)$ s. Measuring population of levels by the β decay, one can find the reduced probabilities ft and the β-decay strength function $S_\beta(E)$.

The scheme of configurations important for the analysis of the strength functions for the Gamow–Teller (GT) transitions is shown in Fig. 2. The states for the GT transitions are made up of configurations like proton hole–neutron hole coupled to the moment 1^+. In the β^+/EC decay of $N > Z$ nuclei, the isospin $T_0 + 1$ has only one value in the coupling of the isospin ($\tau = 1$, $\mu_\tau = +1$) of the configuration like proton hole–neutron particle $[\nu p \times \pi h]_{1+}$ with the isospin of the neutron excess T_0. The most collective state formed from excitations like $[\nu p \times \pi h]_{1+}$ with the isospin $\tau = 1$ and isospin projection $\mu_\tau = +1$ is also called [2–4] the Gamow–Teller resonance with $\mu_\tau = +1$. And while in the β^- decay of $N > Z$ nuclei the Gamow–Teller resonance ($\tau = 1$, $\mu_\tau = -1$) is (Fig. 2) at the excitation energies above Q_β and is energetically inaccessible for population by the β^- decay, the Gamow–Teller resonance with $\mu_\tau = +1$ can be populated by the β^+/EC decay [2–4]. At present no theory is able to describe adequately strength functions for the β decay of deformed nuclei. Theory allows positions and relative intensities of peaks in Gamow–Teller transition strength function to be rather correctly calculated for spherical and weakly deformed nuclei [3, 16, 17]. The discrepancy between experiment and theory for absolute intensities of peaks in strength functions for spherical nuclei ranges from tens to hundreds of percent. Theory predicts more intense peaks in strength functions than experimentally observed [3, 18, 19]. Macroscopically, Gamow–Teller-type collective excitations are oscillations of spin–isospin density without a change in the nuclear shape; therefore, the position of the peak in the strength function in the spherical limit should approximately agree with the center of gravity of the strength function for the deformed nucleus [2]. The resonance structure of strength functions for Gamow–Teller-type β transitions is due to residual spin–isospin interaction and partial $SU(4)$ spin–isospin symmetry in nuclei [2, 4].

For the first-forbidden (FF) β^+/EC transitions in the ξ approximation (Coulomb approximation) the important configurations are those like proton hole–neutron particle coupled to the moment 0^- or 1^- : $[\nu p \times \pi h]^-_0, ^-_1$. The presence or absence of the resonance structure in the strength functions for the first-forbidden β^- or β^+/EC transitions has been an open question until now. In this work we observed the resonance structure in the strength function for the first-forbidden β^+/EC transitions in the β^+/EC decay of the ^{160m}Ho isomer.

Experimental data on population of ^{160}Dy levels in the β^+/EC decay of ^{160m}Ho are presented in the table. Based on these experimental data, we found the reduced probabilities for the β^+/EC decay of ^{160m}Ho for the Gamow–Teller and first-forbidden transitions (Figs. 3 and 4). The reduced probabilities for the β decay are proportional to the nuclear matrix elements squared and reflect the fine structure of the β-decay strength fucntions.

For the Gamow–Teller β^+/EC transitions in the decay of the ^{160m}Ho isomer, the strength function exhibits a pronounced resonance structure (Fig. 3). 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 2–3 MeV and the ft value for the level at 2630 keV (see table) is typical of the $\mu_\tau = +1$ Gamow–Teller resonance with the asymptotic quantum number forbidding [2].

For the first-forbidden β^+/EC transitions in the decay of the ^{160m}Ho isomer, $S_\beta(E)$ is also found to show a resonance (Fig. 4) structure. At some energies intensities of first-forbidden transitions are comparable with intensities of Gamow–Teller transitions.

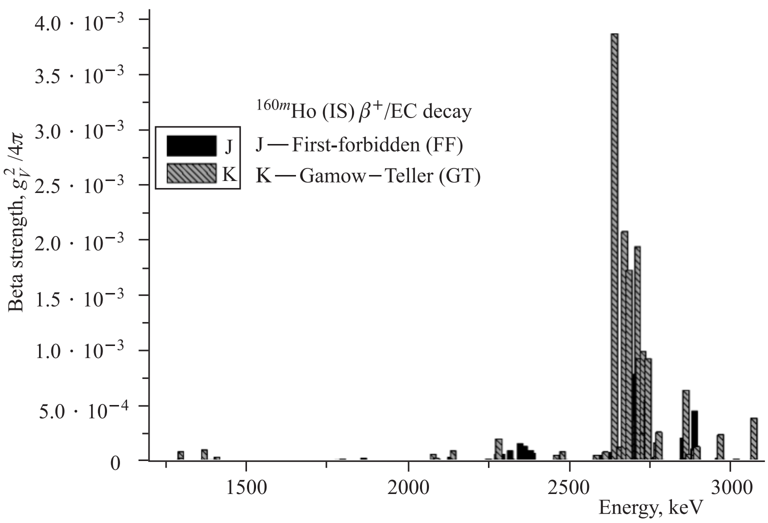

Fig. 3. Structure of the strength function for the β^+/EC decay of ^{160m}Ho

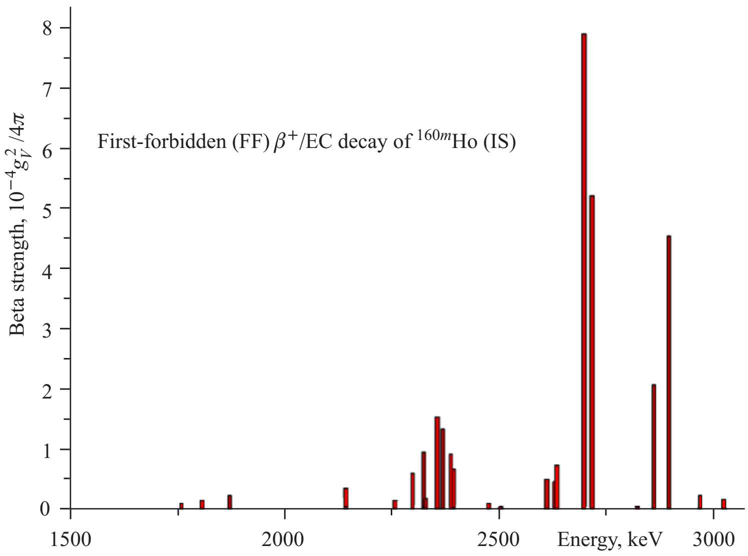

Fig. 4. Structure of the strength function for the β^+/EC decay of ^{160m}Ho for the first-forbidden transitions

4. DISCUSSION

Charge-exchange particle–hole excitations populated by the β decay are related to the oscillation of the $\mu_\tau = \pm 1$ components of the isovector density [20] $\rho_{\tau=1,\mu\tau}$:

$$\rho_{\tau=1,\mu\tau}(r) = \sum_k 2t_{\mu\tau}(k)\delta(r - r_k), \tag{8}$$

where summation is taken over all nucleons k, $\mathbf{t}_{\mu\tau}$ is the spherical component of the nucleon isospin $\mathbf{t}$,

$$\mathbf{t}_{\mu\tau} = \begin{cases} 1/\sqrt{2}(t_x - it_y), & \mu_\tau = -1, \\ t_z, & \mu_\tau = 0, \\ -1/\sqrt{2}(t_x + it_y), & \mu_\tau = +1. \end{cases} \tag{9}$$

Oscillations with $\tau = 0$ correspond to oscillations of the isoscalar (total) density. Oscillations with $\tau = 1$, $\mu_\tau = 0$, $I^\pi = 1^-$ correspond to oscillation of the $\rho_{\tau=1,0}$ component of the isovector density and describe oscillations of protons and neutrons move in antiphase, $E1$-giant resonance. Amplitudes of isovector density oscillations are tensors in isospace and orbital space, which leads to splitting of the $E1$ resonance in deformed nuclei [21, 22].

Oscillations with $\tau = 1$, $\mu_\tau = \pm 1$ describe β^+/EC and β^- decays, and peaks in strength functions for deformed nuclei should also be split.

In [9] we experimentally found splitting of the peak in the strength function for the Gamow–Teller β^+/EC decay of the deformed nucleus ^{160g}Ho, which corresponds to anisotropy of oscillations of the isovector density component $\rho_{\tau,\mu=1,1}$. In the ^{160g}Ho decay the peak for the Gamow–Teller transitions was observed to split into two components [9], the main one at 1694 keV and the other in the region of 2680–3100 keV.

In the Gamow–Teller β^+/EC decay of the ^{160m}Ho isomer 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 in the ^{160g}Ho decay. Therefore, the second component of the peak in $S_\beta(E)$ for the decay of the ^{160m}Ho isomer can have an energy higher than $Q_{\rm EC} = 3346$ keV and not manifest itself in the β^+/EC decay of ^{160m}Ho, and in this case (Fig. 3) we can observe only fragments of the tail of the second component of the split peak in $S_\beta(E)$.

For the Gamow–Teller β^+/EC decay of the deformed nucleus ^{160m}Ho the main peak (Fig. 3) in $S_\beta(E)$ has a smaller amplitude as compared with the main peak [9] in $S_\beta(E)$ for the ^{160g}Ho decay, which results from the asymptotic quantum number forbidding for the Gamow–Teller β^+/EC decay of the ^{160m}Ho isomer.

For the first-forbidden β^+/EC decays of the ^{160m}Ho isomer the resonance structure was found (Fig. 4) to manifest itself in $S_\beta(E)$. Strong configuration mixing at high excitation energies and level densities should result in disappearance of the resonant structure in the strength functions $S_\beta(E)$. The approximate symmetry of nuclear interaction prevents mixing of some configurations. For configurations populated by Gamow–Teller β^+/EC transitions, the mixing is weaker because of partial $SU(4)$ spin–isospin symmetry of interaction within the nucleus [2, 4, 19]. For first-forbidden β^+/EC transitions the resonance structure is also observed in the strength function $S_\beta(E)$ (Fig. 4). The resonance structure of the strength function for first-forbidden β^+/EC transitions may indicate that interaction in the nucleus is characterized by partial symmetry corresponding to the first forbidding. This means that configurations populated by first-forbidden transitions are also distinguished in approximate quantum numbers among the neighboring levels of the daughter nucleus, and strong configuration mixing does not occur.

CONCLUSIONS

The experimental data obtained by the high-resolution nuclear spectroscopy methods for the β^+/EC decay of the isomer ^{160m}Ho (5.02 h) allow the following conclusions:

1. The strength function for the Gamow–Teller β^+/EC decay of the deformed nucleus ^{160m}Ho has a pronounced resonance character. Earlier [3, 5, 8, 9] we performed similar measurements and drew a similar conclusion for the Gamow–Teller β^+/EC decay of the spherical nucleus ^{147g}Tb and the deformed nucleus ^{160g}Ho (5^+; 25.6 min).

2. Until now the resonant character of $S_\beta(E)$ for first-forbidden β transitions has remained an open question. We experimentally established that $S_\beta(E)$ for the first-fobidden β^+/EC decay of the ^{160m}Ho isomer has a resonant character.

3. For some energies the intensities of the first-forbidden β^+/EC transitions are comparable with the intensities for Gamow–Teller transitions.

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