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FINE STRUCTURE OF THE $M_T = 1$ GAMOW–TELLER RESONANCE IN $^{147g}\mathrm{Tb} \rightarrow {}^{147}\mathrm{Gd}$ β^+/EC DECAY

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The $M_T = +1$ Gamow–Teller resonance has been observed in $^{147g}\mathrm{Tb} \rightarrow {}^{147}\mathrm{Gd}$ β^+/EC decay. The fine structure of this resonance has been identified and analyzed. Qualitative agreement of the fine structure with the calculated β^+ strength function is obtained using the microscopic quasiparticle-phonon model.

The investigation has been performed at the Dzhelepov Laboratory of Nuclear Problems, JINR.

Тонкая структура $M_T = 1$ резонанса Гамова–Теллера в β^+/EC-распаде $^{147g}\mathrm{Tb} \rightarrow {}^{147}\mathrm{Gd}$

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В β^+/EC-распаде $^{147g}\mathrm{Tb}\rightarrow{}^{147}\mathrm{Gd}$ наблюден резонанс Гамова–Теллера с M_T=+1. Выявлена и проанализирована тонкая структура этого резонанса. Тонкая структура качественно хорошо воспроизводится расчетами силовой функции β-распада, выполненными в рамках микроскопической квазичастично-фононной модели.

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The charge-changing elementary excitations with isospin $T = 1$ and its z projection $M_T = +1$ can manifest in Gamow–Teller β^+/EC decay. The Gamow–Teller $M_T = +1$ resonance is a coherent superposition of such elementary excitations [1] at high energy. In experiments, the $M_T = +1$ Gamow–Teller resonance may manifest as a strong peak in the β^+/EC-decay strength function $S_\beta(E)$ for some nuclei with a high value of decay energy, Q_β, available for the β^+/EC decay [1,2]. The $M_T = +1$ Gamow–Teller resonance can be experimentally identified as a very strong peak in the high-energy part of $S_\beta(E)$. No experimental data for the fine structure of this resonance has been reported yet. Furthermore, no detailed calculation of the fine structure has been published. In this letter we present the first detailed experimental and theoretical study of $M_T = +1$ Gamow–Teller resonance and its fine structure.

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The present work deals with the experimental and theoretical study of the $M_T = +1$ Gamow–Teller resonance for the β^+/EC decay of the $1/2^+$ ground state of the ^{147}Tb nucleus. This nuclide is close to the doubly magic ^{146}Gd nucleus and has quite a high ($Q_{\rm EC} \simeq 4.6$ MeV) total electron-capture energy thus making it an ideal object for theoretical and experimental study of the Gamow–Teller resonance. The ^{147g}Tb ($t_{1/2} \simeq 1.6$ h) can be produced in Z separated (radiochemically) and A separated (by mass separation) form.

The ^{147g}Tb (1.6 h) source was produced in the spallation reaction with tantalum exposed to the internal 660 MeV proton beam from the LNP JINR (Dubna) Phasotron. Half an hour after the exposure, the Tb fraction was separated by chromatographic techniques, and ^{147}Tb nuclides were isolated by mass separation of the terbium fraction at the YASNAPP-2 mass separator [3]. The ^{147}Tb ions were collected on an Al foil and investigated with a total absorption gamma-ray spectrometer in combination with Ge(Li), HPGe detectors [4,5].

The total absorption γ-ray spectrometer (TAS) consists of two NaI(Tl) crystals 200 mm by 110 mm and 200 mm by 140 mm in size. The larger crystal has a 70 mm by 80 mm well into which the nuclei under investigation are supplied and where a Si(Au) detector for $\beta^+{-}\gamma$ coincidence measurements is installed. Details of the experiments and experimental data analysis are described in [4,5].

The combination of the TAS spectroscopy with the high-resolution γ-ray spectroscopy, based on the Ge(Li) and HPGe detectors, allows us to construct in detail the electron-capture strength function, especially at high ($E > 3$ MeV) excitation energy [5].

For beta transitions of the Gamow–Teller type $S_\beta(E)$ can be written as [1]:

$$S_\beta(E) = \frac{B'_\mp(\mathrm{GT}, E)}{D(g_V^2/g_A^2)}\,, \tag{1}$$

$$B'_\mp(\mathrm{GT}, E) = \frac{4\pi}{g_A^2} B_\mp(\mathrm{GT}, E) = \frac{1}{2I_i+1} \left| \langle I_f \| \sum_{k,\mu} t_\mp(k)\sigma_\mu(k) \| I_i \rangle \right|^2 , \tag{2}$$

where I_i and I_f are the spins of the initial and final states, g_A and g_V are the coupling constants of the axial-vector and vector components of the β decay, $D = (6260 \pm 60)$ s, and $t_\mp \sigma$ is the product of the isospin and spin operators giving the respective operators of the Gamow–Teller β^- or β^+/EC decays.

Usually $S_\beta(E)$ is measured in $\mathrm{MeV}^{-1}\mathrm{s}^{-1}$ units, the B(GT) is measured in $g_{\rm A}^2/4\pi$ units, and ft is in seconds. In this case [5]:

$$B(\mathrm{GT}) = D\left(\frac{g_{\rm V}^2}{g_{\rm A}^2}\right) \times \frac{1}{ft}\,, \quad D = (6260 \pm 60)\ \mathrm{s}, \tag{3}$$

$$\int_{\Delta E} S_\beta(E) dE = \sum_{E_i \in \Delta E} \frac{1}{(ft)_i} = \left[D\left(\frac{g_{\rm V}^2}{g_{\rm A}^2}\right)\right]^{-1} \sum_{E_i \in \Delta E} B_i(\mathrm{GT})\,, \tag{4}$$

where ΔE is the energy range, determined by the TAS detector's energy resolution.

In [5] the experimental $S_\beta(E)$ for ^{147g}Tb$\to^{147}$Gd β^+/EC decay has been constructed and a strong resonance in $S_\beta(E)$ at $E \simeq 4$ MeV was observed. For a detailed analysis of this resonance it is more convenient to use the B(GT) values. Using the experimental data [4] about the ^{147g}Tb$\to^{147}$Gd decay and level schemes, we have constructed the B(GT,E)

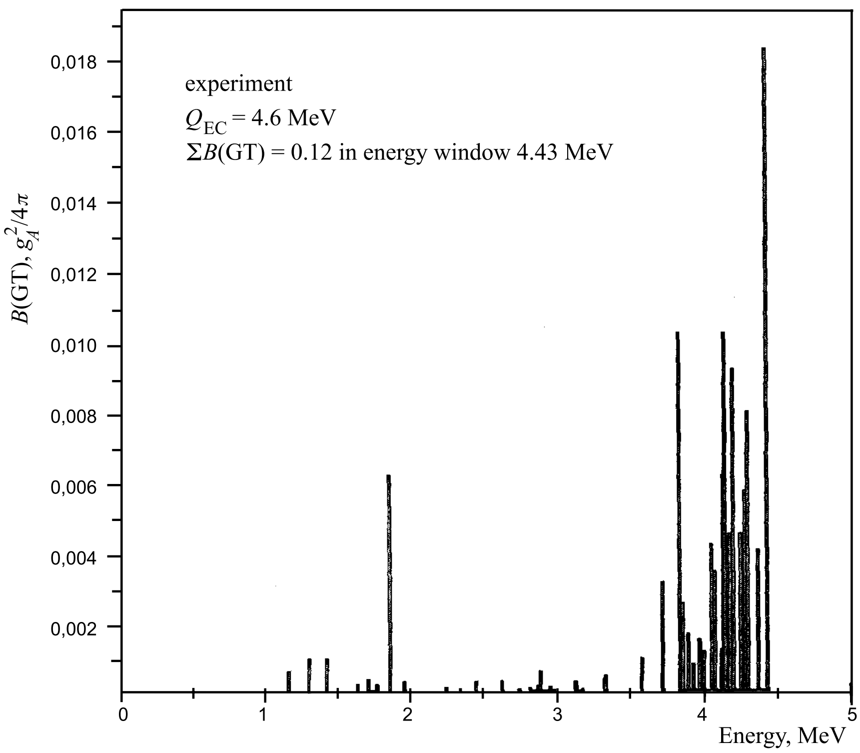

Fig. 1. Strength function for the β^+(EC) decay of ^{147g}Tb deduced from the analysis of the decay scheme in [4]

function in Fig. 1. As one can see from this figure the strong resonance at the $E \simeq 4$ MeV region has a lot of fine structure. If there should be no substantial strength at higher excitation energies this resonance could be identified as a $M_T = +1$ Gamow–Teller resonance.

As it follows from the TAS experiments [5], the strongest resonance within the $Q_{\rm EC}$ window is situated at $E \simeq 4$ MeV (see Fig. 2), in good agreement with Fig. 1. To analyze the energy region $E > Q_{\rm EC}$ and the fine structure of the $M_T = +1$ Gamow–Teller resonance, we have carried out a theoretical calculation of B(GT,E) using the microscopic quasiparticle-phonon model (MQPM) of Ref. 6. In this model we start from realistic effective two-body forces obtained by G-matrix methods from the Bonn one-meson-exchange potential [7]. We have performed the calculations in the 2s-1d-0g-0h valence space for the protons and in the 2s-1d-0g-2p-1f-0h-0$i_{13/2}$ valence space for the neutrons. For the single-particle part of the Hamiltonian we have used the experimental one-particle and one-hole energies with respect to the ^{146}Gd core for the valence neutrons and Woods–Saxon single-particle energies for the protons. Slight adjustments of the proton single-particle energies were done during the BCS calculation described below. It is worth noting that in the work [5] we used just pure Woods–Saxon energies for the single-particle terms of the Hamiltonian and thus the present calculation is more realistic yielding a much better agreement of the calculated energies with the measured low-energy spectrum of ^{147}Gd.

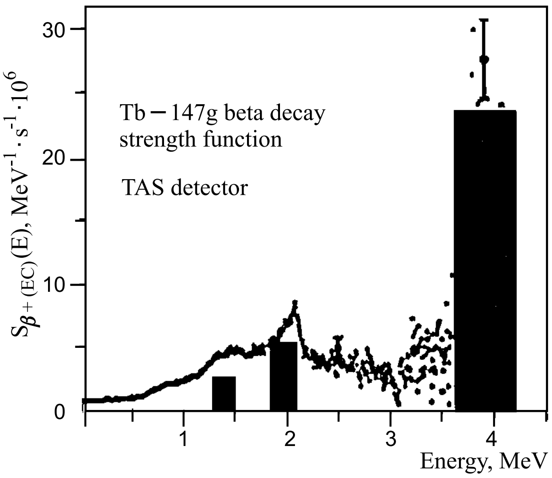

Fig. 2. Strength function for the β^+(EC) decay of ^{147g}Tb deduced from the analysis of the TAS-spectrometer data in [5]

In the MQPM the approximate ground state of the even-even reference nucleus is obtained from a BCS calculation. After the quasiparticle transformation the nuclear Hamiltonian can be written in the form

$$H = \sum_{\alpha} E_a a^{\dagger}_{\alpha} a_{\alpha} + H_{22} + H_{40} + H_{04} + H_{31} + H_{13}\,, \qquad (5)$$

where E_a are the quasiparticle energies and other terms of the Hamiltonian are normal-ordered parts of the residual interaction labeled according to the number of quasiparticle creation and annihilation operators which they contain [8]. The optimal quasiparticle energies and occupation factors are obtained by comparing the results of a BCS calculation with the data for the even-even and even-odd nuclei involved in the calculation.

The states of the odd-proton and odd-neutron nuclei discussed in this work are constructed from one-quasiparticle and three-quasiparticle components where the latter are obtained by combining the quasiparticles with the QRPA (quasiparticle random-phase approximation) phonons of various multipolarities, representing excited states in the ^{146}Gd nucleus. These phonons, in turn, are linear combinations of proton two-quasiparticle and neutron two-quasiparticle states constructed in the adopted valence space. For each value of the angular momentum and parity the spectrum of the ^{146}Gd nucleus is constructed by diagonalizing the QRPA matrix to obtain the above-mentioned linear combinations. Agreement with the experimental excitation energies is good. The mixing of one- and three-quasiparticle components in the wave functions of the ^{147}Tb and ^{147}Gd nuclei was achieved by diagonalization of the $H_{31} + H_{13}$ part of the quasiparticle Hamiltonian (5) in the basis containing the relevant one-quasiparticle and quasiparticle-phonon components. Spurious states were removed by inspection of the norm matrix.

We have constructed the states of the odd mother and daughter nuclei starting from the ^{146}Gd nucleus, ^{147}Gd being a neutron-quasiparticle nucleus and ^{147}Tb being a proton-quasiparticle nucleus. The initial state is the ^{147}Tb ground state which in our calculation

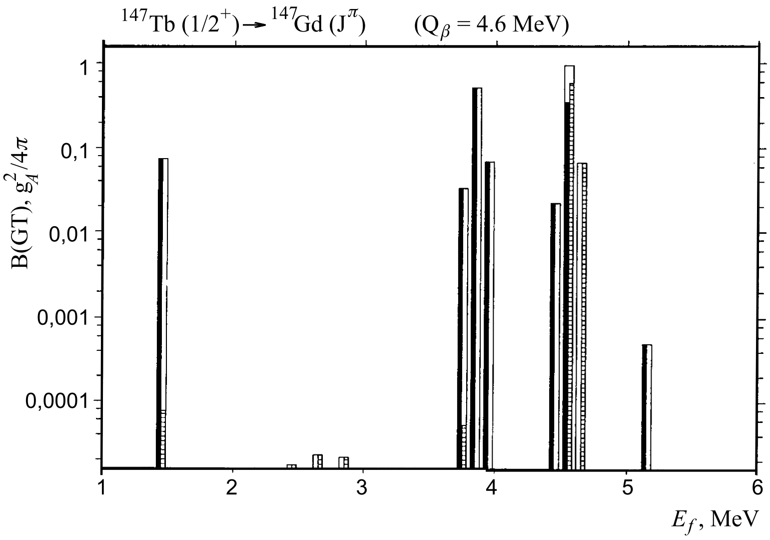

Fig. 3. Calculated strength B'_+(GT,E) of Eq. (2) for the β^+(EC) decay of ^{147g}Tb in a logarithmic scale. Histograms base on a bin size of 100 keV of integrated strength, and the black (striped) part of the total strength (white histogram) corresponds to the $1/2^+$ $(3/2^+)$ final states

has as a dominating component the structure ^{147}Tb(g.s.) = ^{146}Gd $\otimes$ $\pi 2s_{1/2}$ corresponding to the experimentally observed $1/2^+$ ground state of ^{147}Tb [9]. In ^{147}Gd the agreement of the calculated energy spectrum with the experimental one is excellent for excitation energies up to 2 MeV beyond which the experimental spectrum becomes too messy to enable an unambiguous comparison. The good agreement with the experimental energies was achieved by the carefully chosen valence single-particle energies discussed earlier. A convergence of the excitation energies as a function of the adopted multipolarities and the number of related QRPA phonons was obtained to high energies (roughly to 6 MeV in excitation energy) leading to diagonalization and construction of large matrices.

Our relevant theoretical result, namely the strength function of the ^{147}Tb $\to$ ^{147}Gd β^+(EC) decay, has been summarized in Fig. 3. There, the strength B'_+(GT,E) of Eq. (2) has been plotted as a function of excitation energy in a logarithmic scale. The contribution of the $1/2^+$ final states (black part of the histogram) and the $3/2^+$ final states (stripped part of the histogram) have been separated within the summed histogram and a bin size of 100 keV has been used for the summing of the strength. As can be seen from the comparison of this figure and Fig. 1 the qualitative agreement between the theory and the experiment is very good. What is relevant here is that the theory does not predict any significant strength beyond 4.8 MeV of excitation energy supporting the conclusion about the detection of a $M_T = 1$ Gamow–Teller resonance.

In conclusion, one can say that the strength function for the β^+(EC) decay of the ^{147g}Tb (1.6 h) state has a distinct resonance character at high energy confirmed by the theoretical calculations performed on a microscopic level using realistic effective interactions. The fine structure of this resonance has been analyzed both experimentally and in terms of the microscopic quasiparticle-phonon coupling scheme. Both analyses support the identification of the $M_T = 1$ Gamow–Teller resonance in the electron-capture decay of high decay energy.

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