YRAST STRUCTURE ABOVE THE 9.6 s 8^+ ISOMER IN ^{96}Y ISOTOPE *

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High- and medium-spin structures have been investigated in neutron-rich ^{96}Y isotope produced in the cold-neutron-induced fission of ^{235}U and ^{241}Pu targets. The study significantly extended the existing level scheme of this isotope. In the current work, particular attention was devoted to the structure which has been identified above the long 9.6 s, (8^+) isomer, up to the excitation energy of 4813 keV. The angular correlation analysis, together with obtained decay pattern, allowed to propose spin values for some of the newly observed states.

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The onset of deformation in the region near $Z = 40$ and $N = 60$ is considered as one of the most interesting and dramatic shape changes in the nuclear chart. Despite the fact that over the last decades the knowledge about the structures of the nuclei in this region has been significantly extended, still the phenomenon of the onset of deformation as well as its rapidity remains unclear. In the case of yttrium isotopic chain, with $Z = 39$, the

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regular ground-state rotational bands have been observed in the nuclei with $N \geq 60$, while in the lighter isotopes, the ground state is spherical. Also, the laser spectroscopic study showed sudden onset of ground state deformation at $N = 60$ [1]. From all those studies, the ^{98}Y nucleus, with $N = 59$, appeared as a transitional one: in this nuclide, spherical and deformed structures coexist. While the ground state of ^{98}Y is considered spherical, the beta-decaying isomer with $T_{1/2} = 2$ s located in ^{98}Y at 410 keV shows large static deformation. Additionally, in ^{98}Y, a rotational band was identified above the 4^-, 8.1 μs isomer [2, 3]. By measuring half-lives via fast timing technique [4], our collaboration has shown that this rotational band exhibits deformation with $\beta \sim 0.4$ [5], similar to the one reported in yttrium isotopes with $N \geq 60$.

In the instance of ^{96}Y with $N = 57$, the spectroscopic information was very limited — a few low-spin states that were known came from the study of the ^{96}Sr β decay [6]. Also, the presence of a long 9.6 s, (8^+) isomer at 1140(30) keV excitation energy was established [7, 8] in this nucleus. The scientific motivation of the current investigation was then to develop the level scheme of the ^{96}Y isotope in order to search for the deformed structures similar to the ones which were observed in the $N = 59$ ^{98}Y nucleus.

The data for the present study were obtained by employing highly efficient HPGe array installed at the Institute Laue–Langevin in Grenoble, during the experimental campaign named EXILL [9]. The array consisted of eight EXOGAM Clover detectors, six large GASP detectors and two ILL-Clovers mounted about 15 cm from the target position. The reactor neutrons were collimated at the PF1B facility forming a cold-neutrons beam with a flux of $10^8/(\mathrm{s} \times \mathrm{cm}^2)$ which induced fission of the ^{235}U and ^{241}Pu targets. The targets had 675 μg and 300 μg thickness, respectively, with a 25 μm thick Be backing. The events were collected by using fully digital acquisition system in a trigerless mode with a 100 MHz clock. During the off-line analysis, the data were sorted into the 2D and 3D histograms with various time windows. For the purpose of angular correlation study, the EXOGAM clover detectors were mounted in one ring with octagonal geometry. The data have been sorted in terms of three different angles between the detectors *i.e.* 0°, 45°, and 90° (the 135° and 180° are corresponding to 45° and 0°, respectively).

During the analysis, the level scheme of the neutron-rich ^{96}Y isotope has been significantly extended, covering the identification of over 40 new gamma transitions and 22 new states. The detailed description of these results will be a subject of the extended publication [5] while in this work, we concentrate on the new structure identified above the long (8^+) isomer, which is shown in Fig. 1 — we report spin assignments to the states belonging to this structure. Since there is no connection between the part of the level scheme above the

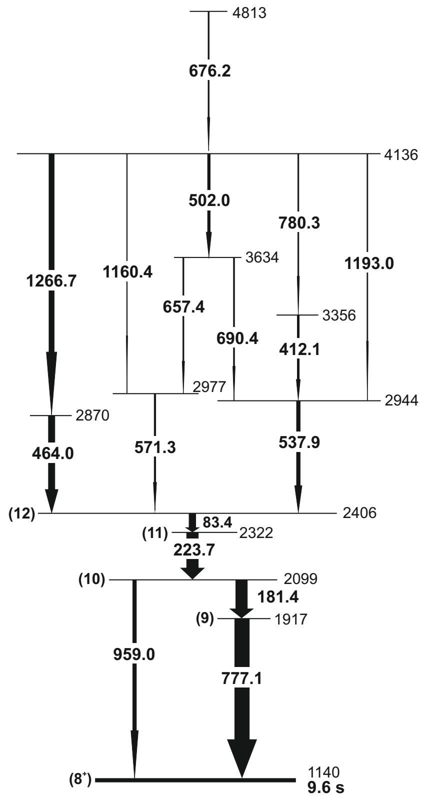

Fig. 1. Partial level scheme of ^{96}Y isotope identified in the current study. The arrow widths reflect the observed transition intensities. See the text for details.

(8^+) isomer and the structure built on the ground state, the identification was based on the cross-coincidence technique described in Ref. [10]. In the present study, the main partners to the ^{96}Y nucleus are the ^{137}I and ^{143}Cs isotopes in the case of ^{235}U and ^{241}Pu targets, respectively — they are associated with 3 neutrons evaporation channel. Gates placed on intense rays in the fission fragments complementary to ^{96}Y displayed both the previously known ^{96}Y transitions and a number of the new gamma rays which were candidates for transitions feeding the (8^+) isomer. In Fig. 2 (a), the lines from ^{96}Y have been observed when the gates are placed on the 400 and 554 keV transitions in the ^{137}I isotope. The other exit channels of the fission reaction are also visible which is manifested by the present of transitions from the ^{95}Y, ^{97}Y, and ^{99}Y nuclei. The analogue situation occurs in instance of ^{241}Pu(f,n) reaction where the same distribution of yttrium isotopes has been obtained by putting gates on the ^{143}Cs nucleus. However, due to the occurrence of four exit reaction channels, the analysis does not provide unambiguously information that the identified transition belongs to the ^{96}Y

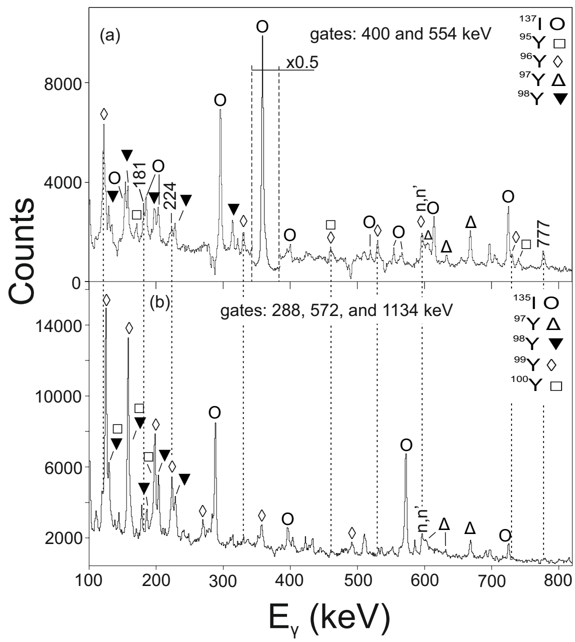

Fig. 2. The cross-coincidence spectra obtained with gates placed on transitions in the ^{137}I (a) and ^{135}I (b) isotopes.

isotope. On the other hand, the number of evaporation neutrons remains more or less the same in instance of different complementary partners in the fission reaction. Therefore, the cross-coincidence relation of ^{135}I nucleus should be strong with the ^{98}Y isotope, which corresponds to $3n$ evaporation channel, while there should be no evidence of transition related to the ^{96}Y nucleus. This situation is illustrated in Fig. 2 (b), where the 288, 572, and 1134 keV lines in the ^{135}I isotope have been selected. The 181 and 777 keV peaks do not have their counterparts in the spectrum in Fig. 2 (b) which is associated with the absence of $5n$ evaporation channel. The detailed analysis of cross-coincidence relations with other isotopes from the iodine isotopic chain with taking into account the intensity balance concludes that indeed the 181, 224, and 777 keV transitions belong to the ^{96}Y isotope and are located above (8^+) isomeric state. Subsequently, the level scheme has been delineated up to nearly 5 MeV excitation energy via study of triple gamma coincidence. The pattern of the level scheme above the (8^+) state is characteristic for the spherical structure.

The spin assignments for some of the identified states have been based on angular correlation analysis as well as observed decay branchings and the well-documented fact that the population of yrast states in fission process is favored [11]. In order to analyze angular correlations between two gamma rays, the formalism described in detail in Ref. [12] has been used where this correlation is expressed as a series of Legendre polynomials *i.e.* $W(\theta) = \Sigma A_k P_k(\cos\theta)$. The experimental A_k coefficients have been compared with theoretical ones in order to test the various hypotheses of transition multipolarity assignments.

In many instances, the analysis provides conclusive confirmation of spin values of intermediate states. This technique can deliver also information about the mixing coefficients δ of the examined transitions. The angular correlation results are juxtaposed in Table I together with spin suggested for the states between which the corresponding transition occurs. The last column in Table I contains the χ^2 function (see Ref. [13] for details) which has been obtained from the difference between experimental A_k/A_0 and calculated $A_k(\delta)/A_0$ values.

TABLE I

Normalized experimental angular correlation coefficients together with mixing coefficients for given transitions and theoretical counterparts.

E_γ–E_γ	Spin hypothesis	A_2/A_0	A_4/A_0	A_{2t}	A_{4t}	δ_1	δ_2	χ^2
224–181	$11 \to 10 \to 9$	0.17(2)	−0.03(4)	0.17	0	0.39(4)	0.47(5)	0.76
83–224	$12 \to 11 \to 10$	0.15(3)	0.02(6)	0.15	0.01	0.43(9)	0.38(6)	0.04

In particular, in Table I, the results of the correlations between 224–181 and 83–224 keV transitions (see Fig. 3) are reported. The analysis shows that all the lines display significant multipolarity mixing with coefficient $\delta \sim 0.4$, while the positive correlations between them specify the same character. Therefore, the $I = (10)$ assignment has been proposed for the 2099 keV level which decays via 181 keV, $\Delta I = 1$ transition to the $I = (9)$ excitation at 1917 keV. In spite of the fact that the character of the 777 and

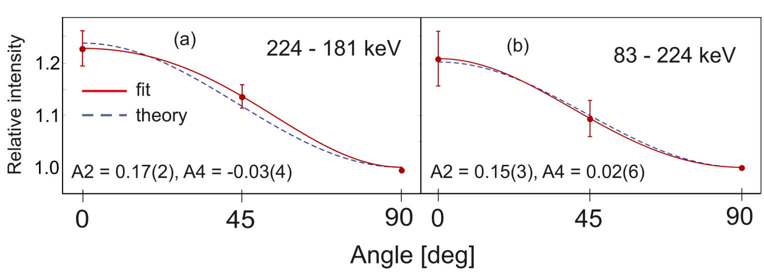

Fig. 3. (Color online) Results of angular correlations analysis in ^{96}Y. The figure includes the energies of the transitions considered in each pair (see Fig. 1) and the obtained A_2 and A_4 values. See the text and Table I for details.

959 keV has not been experimentally determined due to contamination from other nuclei at the required coincidence conditions, the absence of measurable lifetime for the 2099 keV state excludes the multipolarity higher than 2 for the 959 keV transition. Additionally, the yrast character of populated states, which is favored in our reactions, excludes the $I < 10$ and $I < 9$ assignments for the 2099 and 1917 keV levels, respectively. Subsequently, spin $I = (11)$ and (12) can be assigned to the 2322 and 2406 keV levels, respectively. This is in line with the absence of lifetime for the 2406 keV state which deexcitates via low energy 83 keV transition.

In conclusion, in the current work, we presented the level structure newly located above the (8^+) isomer in the neutron-rich ^{96}Y isotope. We reported also results of the angular correlation analysis leading to the multipolarity assignments to a number of transitions belonging to that structure. These results, together with observed decay pattern, indicate the $\Delta I = 1$ multipolatity for the 83, 181, 224, and 777 keV transitions while $\Delta I = 2$ for the 959 keV one. It is apparent that the states of the considered structure have spherical character.

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