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Disentangling decaying isomers and searching for signatures of collective excitations in β decay

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Abstract. In this contribution we summarize the recent study of the β decay of neutron-rich nuclei with isomeric states close in energy to the ground states. The disentanglement of each pair of β-decaying states was achieved by applying different strategies and using the purification capabilities of the JYFLTRAP double Penning trap system at the Ion Guide Isotope Separator On-Line facility in Jyväskylä. The Total Absorption γ-ray Spectroscopy technique was employed to determine the β intensity probabilities populating the excited states in the daughter nuclei. Previously undetected β intensity was found and we have already evaluated the impact of part of these results on reactor summation calculations. The possibility to populate states associated with the Pygmy Dipole Resonance in the β decay of $^{96\mathrm{gs}}$Y has also been investigated thanks to the sensitivity of our technique to high-lying strength in the daughter nuclei.

1. Introduction

In the region A≈100 some neutron-rich niobium and yttrium isotopes exhibit β-decaying isomeric states close in energy to the ground states. Due to the small energy difference and the similar half-lives, it is often difficult to separate them experimentally in order to study the β decay of each decaying state. In addition to the scarcity of information for many of these cases, the β-intensity probabilities for the known cases have usually been determined with HPGe detectors, which have a modest detection efficiency. This implies an underestimation of the β intensity at high-excitation energies in the daughter nucleus, due to the non-detection of part of the γ-cascades that de-excite these states. This is known as *Pandemonium* effect [1] and becomes more important when one moves away from stability and β-decay energy windows (Q_β) increase. The Total Absorption γ-ray Spectroscopy (TAGS) technique has been shown to be a powerful tool to obtain the β-intensity probabilities free from the *Pandemonium* effect [2]. It is based on the use of large scintillator crystals in almost full solid angle coverage, thus maximizing the detection efficiency. The sum of the γ cascade is detected and the β-intensity distribution is obtained by means of a deconvolution process that uses the response function of the spectrometer. This response function is calculated with Monte Carlo (MC) simulations that are validated with standard calibration sources [3].

The decay data for some of these nuclei are specially important for nuclear reactor studies, since they are relevant fission products and their decay contributes: 1) to the energy released by the radioactive decay of fission fragments in a nuclear reactor, known as decay heat, and 2) to build up the reactor antineutrino spectrum with the antineutrinos emitted in their β decay. The good prediction of the former is essential to safely operate nuclear reactors, while the understanding of the latter is needed for reactor-based antineutrino experiments. A summation approach has proven to be a suitable method to calculate both the reactor decay heat and the reactor antineutrino spectrum. This approach depends on the decay information available in the databases, and the inclusion of TAGS data, free from *Pandemonium* effect, has been shown to improve significantly these calculations [4, 5]. The recent observation of discrepancies in flux [6] and spectral shape [7, 8, 9] when reactor antineutrino experimental spectra are compared with calculations keeps the neutrino physics community on tenterhooks. A recent summation method study has shown the reduction of these discrepancies when the latest TAGS results are taken into account, specially for the flux anomaly [10].

In this work challenging measurements of the β decays of ^{96}Y and ^{98,100,102}Nb have been performed at the Ion Guide Isotope Separator On-Line (IGISOL) facility in Jyväskylä [11]. These cases are summarized in Table 1, where the energy of each isomer is presented. The JYFLTRAP double Penning trap system [12] was used for precision trap-assisted separation, and different strategies were followed to study each pair of β-decaying states separately, as will be commented later. The measurement of the present decays with TAGS technique has been encouraged by the International Atomic Energy Agency (IAEA), and they were assigned high priority for the improvement of the reactor decay heat and antineutrino spectrum summation calculations, as presented in Table 1.

The segmented Decay Total Absorption γ-ray Spectrometer (DTAS) [16] composed of 18 NaI(Tl) crystals was employed in coincidence with a plastic detector for β particles. The nuclei of interest were extracted from JYFLTRAP and implanted on a moving tape located at the center of DTAS and in front of the plastic detector (see Ref. [17] for more details). The analysis methodology of the Valencia group [3, 18, 19] has been applied to obtain the β-intensity distributions from the experimental total absorption spectra, which were reconstructed offline as described in Ref. [20].

Table 1. Cases with isomers studied with DTAS in the last experimental campaign at IGISOL. The β-decay energy window (Q_β) for the decay of the ground state is presented in the second column (from the Atomic Mass Evaluation (AME) 2016 [13]) and the energy of the isomeric state can be found in the third column (according to the NUBASE 2016 evaluation [14]). The priority of the TAGS measurement of these decays for the IAEA [15] is also included, both for reactor decay heat studies (columns fourth and fifth for U/Pu and Th/U fuels, respectively) and for reactor antineutrino spectrum studies (last column).

| Parent nucleus	Q_β [keV]	Energy [keV]	Priority U/Pu	Priority Th/U	Priority $\overline{\nu}_e$
^{96gs}Y	7103(6)	0	2	2	1
^{96m}Y		1540(9)	-	1	-
^{98gs}Nb	4591(5)	0	1	1	1
^{98m}Nb		84(4)	-	-	-
^{100gs}Nb	6396(8)	0	1	1	1
^{100m}Nb		313(8)	-	1	-
^{102gs}Nb	7262(8)	0	2	2	1
^{102m}Nb		94(7)	-	1	-

2. Decays of ^{98,100,102}Nb

Similar strategies were applied for the three niobium cases studied, motivated by the small energy difference between the isomeric state and the ground state in all of them and by the limited beam time for the experiment. Here we will explain the ^{98}Nb system shown in the left panel of Figure 1. The β decay of the low spin state was studied by measuring the β decay of the zirconium parent, which decays only into ^{98gs}Nb and does not populate the isomeric state. The β decay of ^{98}Zr, for which no γ rays are reported in ENSDF [21], was thus treated as a contaminant. We have confirmed this β pure character by setting different time windows offline to the measurement of ^{98}Zr+^{98gs}Nb, in the line of our recent work for ^{100,102}Nb [22]. Finally, a measurement of both decaying states together, ^{98gs}Nb+^{98m}Nb, allowed us to study the high-spin component by considering the decay of ^{98gs}Nb as a contaminant. In order to illustrate this, we show in Figure 2 the experimental spectrum of ^{98gs}Nb+^{98m}Nb, where the ^{98gs}Nb spectrum coming from the ^{98}Zr+^{98gs}Nb measurement is considered as a contaminant.

The TAGS analyses of the decays of ^{100,102}Nb have shown that the previous high-resolution spectroscopy data are affected by the *Pandemonium* effect, and the β intensities for the decay of ^{102m}Nb were obtained for the first time [22]. The impact of these results on reactor antineutrino summation calculations was significant in the region of the reactor antineutrino shape distortion, and they have contributed to the reduction of the discrepancy between the summation calculations and the measured antineutrino spectra [24]. Analogously, the impact of these results on reactor decay heat summation calculations was found to be noticeable, specially 10 s after fission [22].

In the construction of the response function for the TAGS analyses of ^{98gs,m}Nb we have paid special attention to the strong $E0$ transition that de-excites the 0^+ level at 734.6 keV excitation energy in ^{98}Mo. Our preliminary results confirmed the dominance of the ground state to ground state transition in the decay of ^{98gs}Nb, while in the decay of ^{98m}Nb we determined a slight amount of previously undetected β-intensity above 4103.3 keV, the last level in ^{98}Mo known to be populated in this decay. An example of the quality of the analyses is shown in Figure 2
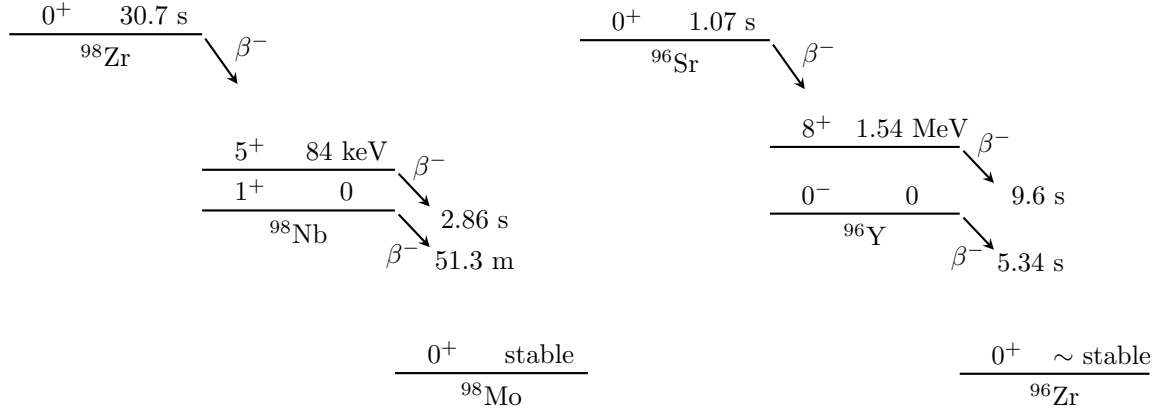
Figure 1. Schemes for the decays of ^{98}Nb (left panel) and ^{96}Y (right panel). Each pair of β-decaying states is shown. The β decay of the grandparents, as well as the final daughter nuclei are also shown. Spin-parity values and half-lives from ENSDF [21, 23] are included and the energy of the isomeric states is also presented [14].
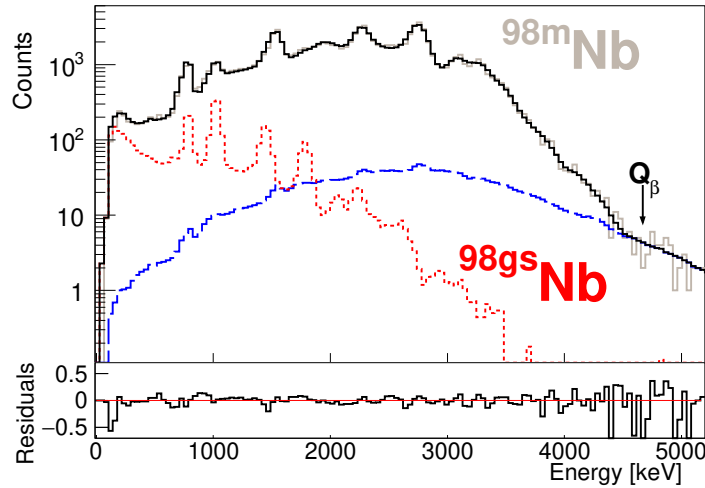
Figure 2. Relevant histograms for the analysis of the decay of ^{98m}Nb: experimental total absorption spectrum (solid grey), summing-pileup contribution (dashed blue), contamination of the ^{98gs}Nb low-spin component (dotted red) and reconstructed spectrum (solid black). The relative deviations between experimental and reconstructed spectra are shown below.
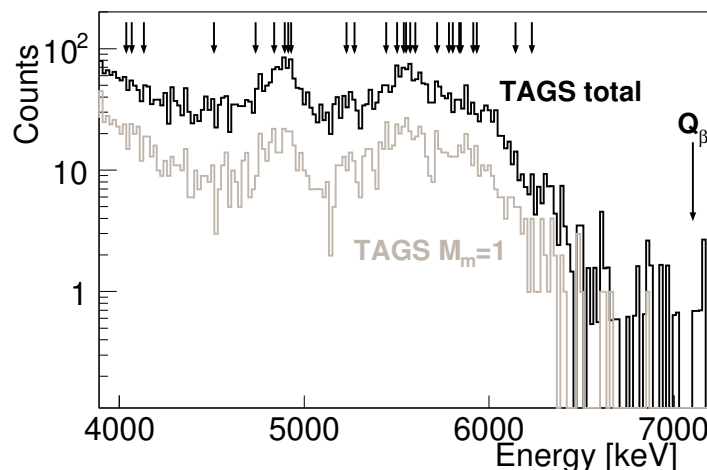
for the decay of ^{98m}Nb. The experimental spectrum is compared with the reconstructed one obtained from the convolution of the β intensities determined in the analysis with the response function.

3. Decay of ^{96}Y

The large energy difference between the isomeric state and the ground state (see Table 1 and right panel of Figure 1) allowed us to distinguish them directly with JYFLTRAP. In the response functions for the TAGS analyses we took carefully into account the strong $E0$ transition from the 0^+ level at 1581.6 keV excitation energy in ^{96}Zr, for which conversion electron emission

competes with pair production. The results obtained confirmed the strong ground state feeding probability in the decay of ^{96gs}Y, and for the decay of the 8^+ isomer previously undetected β intensity was found above 6 MeV.

The production of exotic nuclei with large β-decay energy windows opens the possibility to study collective excitations in β-decay experiments. In particular the search of hints of the Pygmy Dipole Resonance (PDR) has recently attracted a lot of attention [25, 26, 27]. This possibility can be investigated in the β decay of ^{96gs}Y as suggested in [25], since it directly populates 1^- levels, which are associated with low-lying pygmy dipole modes. The advantage of TAGS for these studies is twofold: the sensitivity to high-lying strength in the daughter nuclei [28, 29, 30, 31] and the possibility of detecting the decay of collective modes, preferentially by one or two very energetic γ rays, without *Pandemonium* effect. In addition, the segmentation of DTAS may give us more information about the decay-pattern of such levels. In Figure 3 the high-energy region of the experimental TAGS spectrum for the decay of ^{96gs}Y is shown. We observed broad structures that could be related to the population of potential 1^- levels in this region. The majority of this high-energy spectrum was found to be due to events where energy was deposited only in one crystal (module multiplicity $M_m=1$), which suggests a de-excitation pattern dominated by one γ ray.

Figure 3. Experimental TAGS spectrum for the decay of ^{96gs}Y zoomed at high energies (solid black). The $M_m=1$ gated TAGS spectrum is shown in solid grey. The possible 1^- levels according to ENSDF [23] are depicted with arrows.

4. Conclusions

In this work we have reviewed recent measurements of important fission products for reactor calculations that exhibit isomeric states. The separate study of the β decays of the ground state and the isomeric state for each case required different strategies and was possible thanks to the purification capabilities of the JYFLTRAP system. The recently published results for the TAGS analyses of the decays of ^{100,102}Nb showed a significant impact on reactor summation calculations [24]. The evaluation of the other two cases discussed, ^{98}Nb and ^{96}Y, is ongoing and was additionally complicated by the presence of strong $E0$ transitions. Following the recent interest for the potential study of the PDR in β decay [25], we plan to take advantage of the segmentation of our spectrometer to constrain and characterize the β strength observed at high-excitation energies. All these studies will be very useful for future experimental campaigns of

neutron-rich cases with isomeric states.

5. Acknowledgments

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