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## Gamma spectroscopy of even-even Ytterbium isotopes

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**Abstract** The even-even Ytterbium isotopes lack spectroscopic information with the increase of the neutron number, and they are well deformed nuclei, presenting rotational properties. In this mass region of the nuclear chart, predictions have shown rare phenomena related to nuclear structure, such as shape coexistence. In this work the population of excited states were investigated in the even-even Yb isotopes via the 2n-transfer reaction  $^{168-174}\text{Yb}(^{18}\text{O}, ^{16}\text{O})^{170-176}\text{Yb}$ . The measurements were carried out at the 9 MV Tandem accelerator at the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) in Romania. The deduced gamma-ray angular distributions in the ground state bands are found to correspond to E2 transitions, as expected.

**Keywords** gamma spectroscopy, angular distribution, 2n-transfer reaction, ytterbium isotopes

## INTRODUCTION

There are two competitive forces in nuclei; the nuclear attraction and the Coulomb repulsion of which the interplay is the reason behind the creation of the different isotopes leading to the formation of the isotopic table consisted of the different isotopic groups. The even-even Ytterbium  $^{70}\text{Yb}$  isotopes belong to the group of the well-deformed nuclei and they have rotational properties. In the medium mass region where the even-even Ytterbium isotopes belong, interesting phenomena, such as the shape coexistence take place [1-3]. The lack of experimental data on the neutron-rich  $^{178}\text{Yb}$  and  $^{180}\text{Yb}$  was the motivation of the test run on which this work was based [4]. An important aspect of the nuclear structure, which can be studied via gamma-ray spectroscopy, is the investigation of the angular distributions of emitted photons during de-excitations, which is conducted in the reported work.

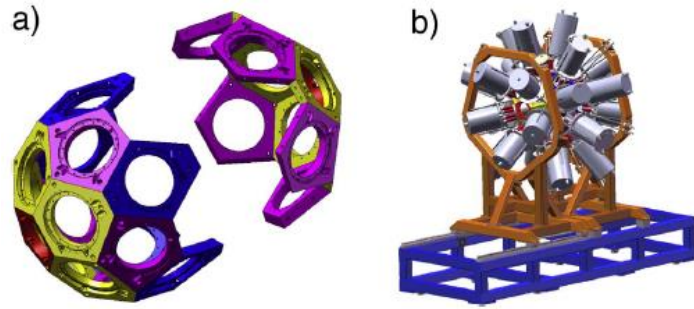
## EXPERIMENTAL DETAILS

In this work the population of excited states were investigated in the even-even Yb isotopes via the 2n-transfer reaction  $^{168-174}\text{Yb}(^{18}\text{O}, ^{16}\text{O})^{170-176}\text{Yb}$ . The experiment was carried out at 9 MV Tandem accelerator of IFIN-HH. Gamma rays and charged particles were detected by the ROSPHERE [5] (15 HPGe detectors + 10 LaBr<sub>3</sub>) and SORCERER [6] (6 Si detectors) detection arrays, respectively. A natural Yb target, consisting of 7 isotopes (Table 1), with a thickness of 2.5 mg/cm<sup>2</sup>, was irradiated at four different  $^{18}\text{O}$  beam energies, i.e. 69, 72, 73 and 74 MeV. Angular distributions were constructed using data recorded from the 15 HPGe detectors (see Figs. 1 and 2) mounted in three rings at angles 37°, 90° and 143°, with respect to the beam direction at 72 MeV beam energy. The Coulomb barrier for the 2n-transfer reaction  $^{176}\text{Yb}(^{18}\text{O}, ^{16}\text{O})^{178}\text{Yb}$  is 71.6 MeV [7]. The deduced gamma-ray angular distributions in the ground state bands are found to correspond to E2 transitions, as expected.

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**Figure 1.** The ROSPHERE detector array.



**Figure 2.** (a) Schematic illustration of the five rings of ROSPHERE [5], with different color for each ring. The rings at relative angles of 37°, 143° have yellow color, the rings in angles 70°, 110° have purple color and the ring at the 90° relative angle has blue color. (b) CAD representation of the detection system of ROSPHERE.

**Table 1.** The isotopic composition of the natural Yb target.

Isotope	Relative Abundances(%)
<sup>168</sup> Yb	0.12
<sup>170</sup> Yb	2.98
<sup>171</sup> Yb	14.09
<sup>172</sup> Yb	21.69
<sup>173</sup> Yb	16.10
<sup>174</sup> Yb	32.03
<sup>176</sup> Yb	13.00

**Table 2.** The list of the transitions studied in this work along with the corresponding photon energies [4].

Isotope	Transition	Energy (keV)	Multipolarity
<sup>170</sup> Yb	2 <sub>1</sub> <sup>+</sup> → 0 <sub>1</sub> <sup>+</sup>	84.25	E2
<sup>170</sup> Yb	4 <sub>1</sub> <sup>+</sup> → 2 <sub>1</sub> <sup>+</sup>	193.13	E2
<sup>172</sup> Yb	2 <sub>2</sub> <sup>+</sup> → 4 <sub>1</sub> <sup>+</sup>	857.64	E2
<sup>172</sup> Yb	4 <sub>1</sub> <sup>+</sup> → 2 <sub>1</sub> <sup>+</sup>	181.53	E2
<sup>172</sup> Yb	6 <sub>1</sub> <sup>+</sup> → 4 <sub>1</sub> <sup>+</sup>	279.72	E2
<sup>174</sup> Yb	4 <sub>1</sub> <sup>+</sup> → 2 <sub>1</sub> <sup>+</sup>	176.64	E2
<sup>174</sup> Yb	6 <sub>1</sub> <sup>+</sup> → 4 <sub>1</sub> <sup>+</sup>	272.92	E2
<sup>176</sup> Yb	4 <sub>1</sub> <sup>+</sup> → 2 <sub>1</sub> <sup>+</sup>	189.69	E2
<sup>176</sup> Yb	6 <sub>1</sub> <sup>+</sup> → 4 <sub>1</sub> <sup>+</sup>	292.60	E2

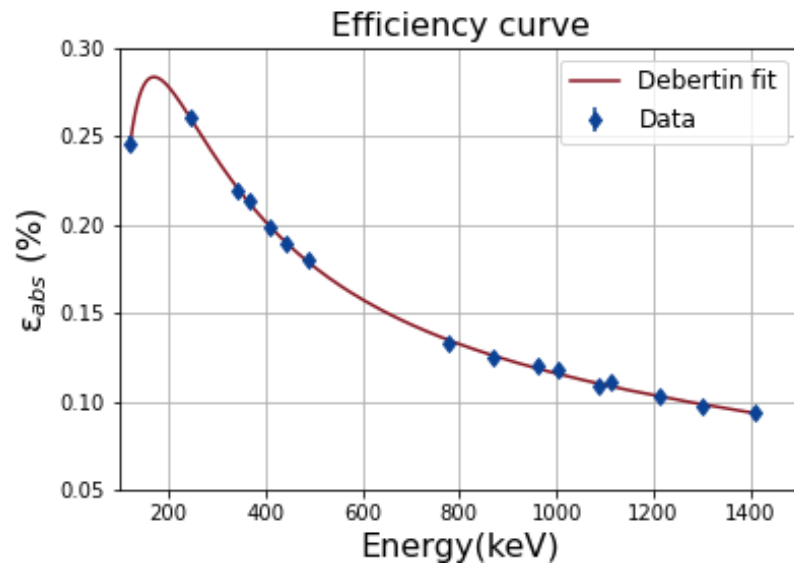
<sup>152</sup>Eu, <sup>56</sup>Co and <sup>133</sup>Ba were used for detector energy calibration. The <sup>152</sup>Eu source was additionally used for efficiency calibration of the HPGe detectors. The Debertin function of Eq. 1 was fitted to the experimental efficiencies, leading to efficiency curves similar to the one shown in Fig. 3.

$$y = A \cdot \ln E + B \cdot \frac{\ln E}{E} + C \cdot \frac{(\ln E)^2}{E} + D \cdot \frac{(\ln E)^4}{E} + F \cdot \frac{(\ln E)^5}{E} \quad (1)$$

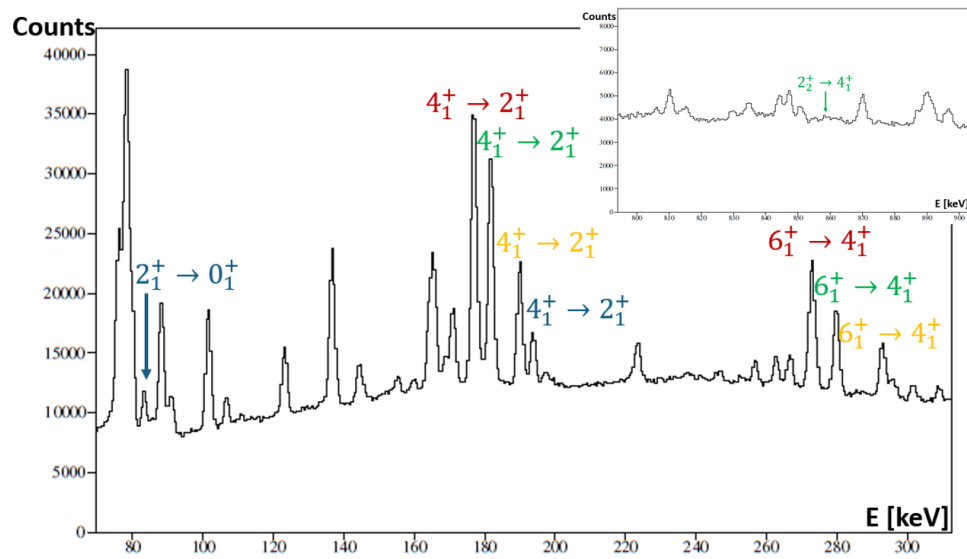
## RESULTS

The data were collected at three different angles (37°, 90° and 143°) relative to the beam direction. In Fig. 4 the  $\gamma$ - $\gamma$  coincidence spectrum is presented, and the transitions of interest are marked with different colors corresponding to each isotope. The origin of every transition was identified by studying the particle- $\gamma$ - $\gamma$  coincidence spectra to isolate the cascade in each isotope inside the ground state band. This was a necessary step in the analysis because the Yb isotopes have very similar  $\gamma$  energies in the g.s. band. By integrating these peaks and using Eq. 2, the angular distributions,  $W(\theta)$ , were reconstructed.

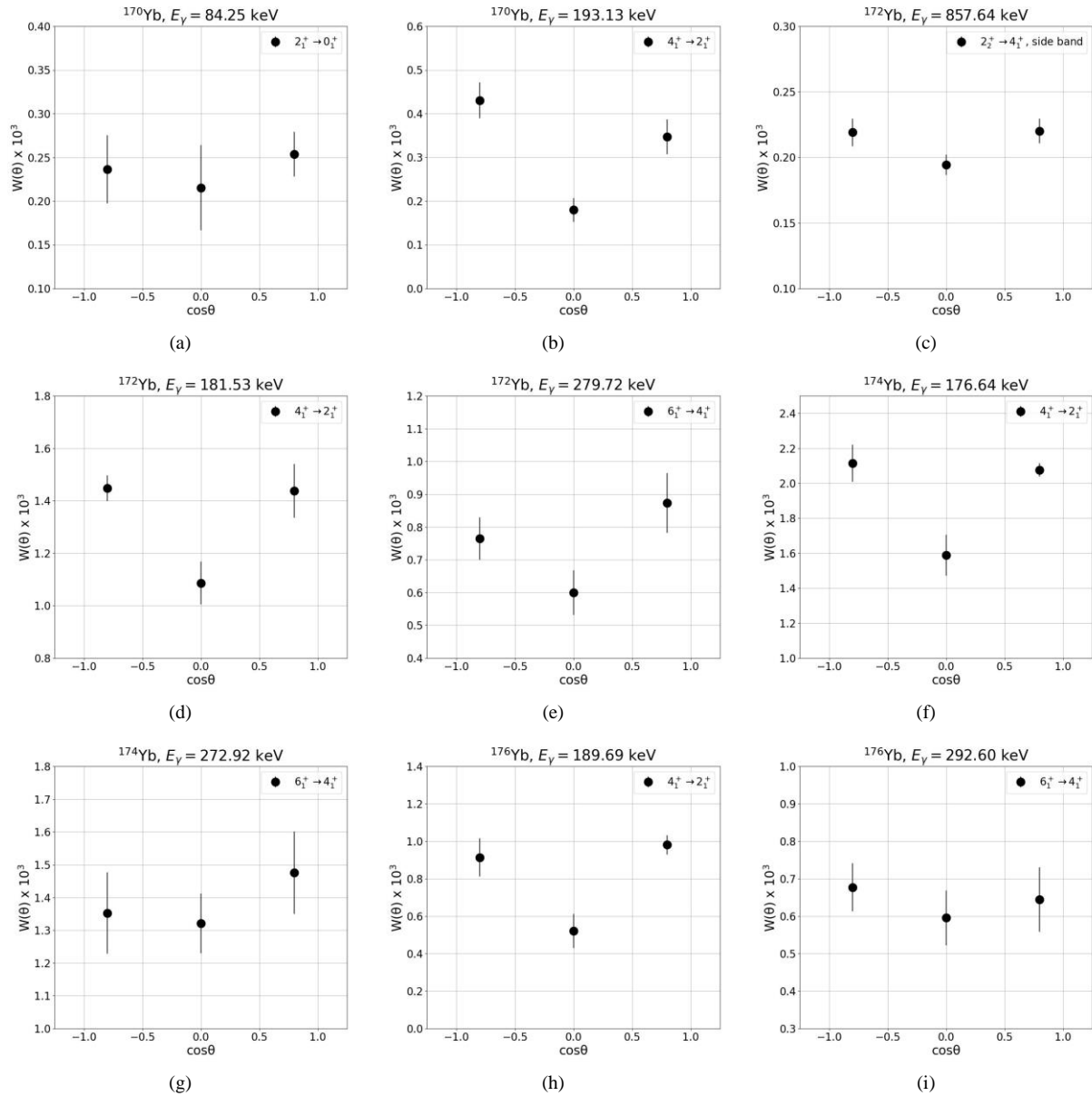
$$W(\theta) = \frac{\text{counts}}{\text{total ring counts}} \quad (2)$$



**Figure 3.** The average efficiency of 15 HPGe detectors using the function of Eq. 1.



**Figure 4.** Typical in-beam spectrum by the HPGe detectors for the 72 MeV lab beam energy. Noted are the energy peaks of the studied transitions (see Table 2), for  $^{170}\text{Yb}$  (blue color),  $^{172}\text{Yb}$  (green color),  $^{174}\text{Yb}$  (red color) and  $^{176}\text{Yb}$  (yellow color).



**Figure 5.** Preliminary angular distributions for the E2 transitions of the isotopes  $^{170,172,174,176}\text{Yb}$ . Transition energies  $E_\gamma$  are obtained from Ref. [4].

## CONCLUSIONS

The angular distributions agree with what is expected for E2 transitions. We observed the transitions  $2_1^+ \rightarrow 0_1^+$ ,  $4_1^+ \rightarrow 2_1^+$ ,  $6_1^+ \rightarrow 4_1^+$  and  $8_1^+ \rightarrow 6_1^+$  of the ground states for the isotopes  $^{170,172,174,176}\text{Yb}$  but we managed to construct the angular distributions only in the nine above cases (see Fig. 5). This happened because some Yb isotopes transitions present overlapping energies [4] so the analysis is not straightforward, and the natural target is difficult to handle. We also managed to observe the side band transition  $2_2^+ \rightarrow 4_1^+$  of the isotope  $^{172}\text{Yb}$  and the angular distribution was constructed as it seen in Fig. 5. The experimental data are still under analysis, and if the statistics permit it, we are planning to incorporate the  $\text{LaBr}_3$  data into the analysis of angular distributions, to measure Yb lifetimes using the fast-timing method, as well as to extract cross sections for the 2n-transfer reaction.

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