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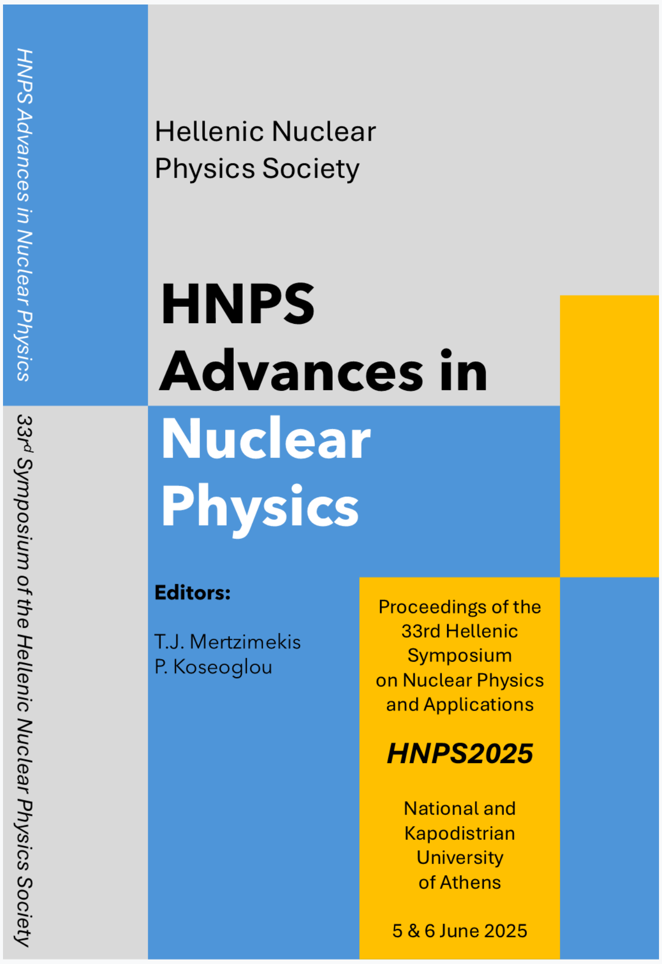

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ARTICLE

Gamma ray spectroscopic analysis around the $N = 104$ mid-shell for ^{176,177}Yb and ^{182}W nuclei

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Abstract

Even-even Yb and W isotopes around the N=104 mid-shell region are known to present deformation. The ground-band states of these nuclei are well described by the SU(3) symmetry, indicating a rigid-rotor character. Excited states of even-even isotopes in the region, namely ^{176}Yb and ^{182}W, were populated through Coulomb excitation and fusion-evaporation reactions, in an experiment performed at IFIN-HH in Măgurele, Romania. The gamma-spectroscopy of these nuclei will be presented in this contribution. Additionally, gamma spectroscopy results for the even-odd ^{177}Yb nucleus, populated by the 1-neutron transfer reaction mechanism, will be presented. Contradictory to the collective description of the ground-band excitations in ^{176}Yb and ^{182}W isotopes, the excited states of this nucleus can be described by single-particle excitations. The gamma-spectroscopy analysis of this data contributes to the evaluation of the available data in this mass region, while ongoing work is expected to provide further insights for the nuclear structure of these rare-earth isotopes.

Keywords: nuclear structure; gamma-spectroscopy; ^{176}Yb; ^{177}Yb; ^{182}W

1. Introduction

Nuclei in the rare-earth region, characterized by proton numbers 50–82 and neutron numbers 82–126, are of particular interest because they illustrate the evolution of nuclear shapes and the interplay between collective motion and single-particle behavior. In this region, the proxy-SU(3) model predicts a clear dominance of prolate nuclear shapes [1, 2], and isotopes of Yb and W around $N = 104$

display clear signs of quadrupole deformation, making them ideal systems to study these effects.

A good example is the case of ^{176}Yb and ^{177}Yb. The even-even nucleus ^{176}Yb mainly shows collective excitations, while the odd-mass ^{177}Yb features the role of individual particle motion. In the Nilsson model [3, 4], the structure of odd-A nucleus is determined by its single unpaired nucleon. The energy levels form rotational bands built on single-particle states calculated in the deformed potential. In collective excitations, the nucleus behaves as a coherent system. A key observable is the ratio $R_{4/2} = \frac{E(4^+)}{E(2^+)}$, which indicates the degree of collectivity: $R_{4/2} = 2.0$ for spherical vibrators, 2.5 for gamma unstable nuclei and 3.33 for well-deformed rotors [3]. Looking at these nuclei side by side shows how the addition of a single neutron can change the overall structure.

In this work, gamma-ray spectroscopy data was analyzed to study the isotopes of interest. In the present work the states of interest were populated for the first time through Coulomb excitation, 1n-transfer and fusion-evaporation reactions using a ^{9}Be beam.

2. Experimental Details

The following reactions are investigated:

Coulomb excitation reaction:

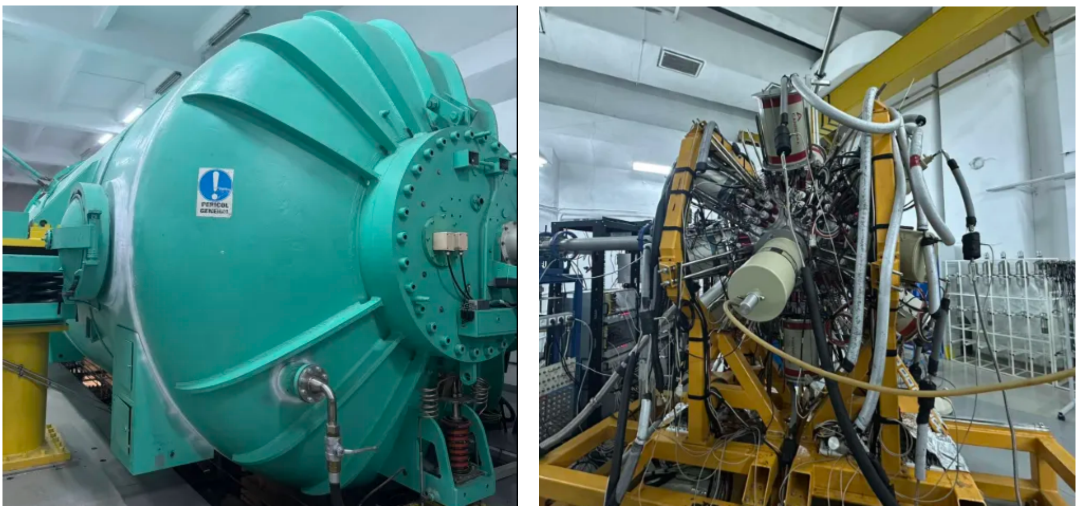
$$^{176}\mathrm{Yb}(^{9}\mathrm{Be},\ ^{9}\mathrm{Be}')\ ^{176}\mathrm{Yb}^{*}$$

Single-neutron transfer reaction:

$$^{176}\mathrm{Yb}(^{9}\mathrm{Be},\ ^{8}\mathrm{Be})\ ^{177}\mathrm{Yb}^{*}$$

and fusion-evaporation reaction:

$$^{176}\mathrm{Yb}(^{9}\mathrm{Be},\ 3n)\ ^{182}\mathrm{W}^{*}$$



(a) (b)

Figure 1. The 9MV Tandem accelerator lab and the ROSPHERE array at IFIN-HH with the 10 HPGe and 15 LaBr3(Ce) detectors.

The experiment was carried out at the Horia Hulubei National Institute of Physics and Nuclear Engineering (IFIN-HH) in Bucharest, Romania. A highly enriched 96% ^{176}Yb metallic target was used. The target was bombarded with a ^{9}Be beam of 38 MeV. The resulting gamma-ray decays were measured using the ROSPHERE detector array (see Figures 1a, 1b) [5], which consists of 10 HPGe and

15 $LaBr_3(Ce)$ detectors. The HPGe detectors were positioned in two rings, at 37° and 143° relative to the beam axis, while the $LaBr_3(Ce)$ detectors were arranged in three rings located at 70°, 90° and 110°. In addition, the SORCERER particle array [6], consisting of six solar-cell particle detectors, was used allowing the application of particle-gamma coincidence techniques. In this contribution only the analysis of the HPGe data will be shown.

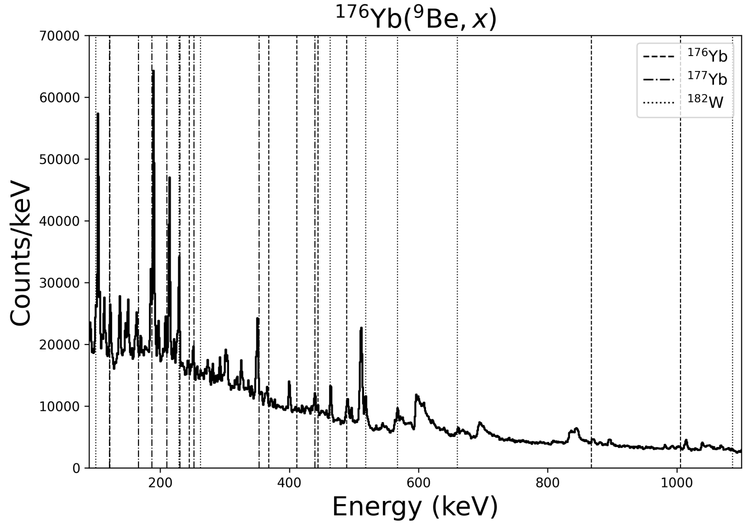
3. Results and Discussion

In Figure 2a, the total (ungated) spectrum is shown, in which peaks corresponding to each of the three studied isotopes can be clearly identified. To investigate the individual isotopes, a gate condition was applied on the $2^+_1 \rightarrow 0^+_1$ decay energies, while for the ^{177}Yb the gate was set on the $11/2^+ \rightarrow 9/2^+$ transition. The resulting spectra are shown in Figures 2b, 2c, and 2d. The gate conditions allow the selective study of each isotope by isolating the relevant transitions. The level schemes presented in Figures 3a, 3b and 3c were constructed using multiple gate conditions on known de-excitation energies and the labeling of the side bands follows the adopted data [7]. No new excited states or transitions were identified in the present experiment. All levels and de-excitation energies shown in Figures 3a, 3b and 3c correspond to previously known states reported in the literature.

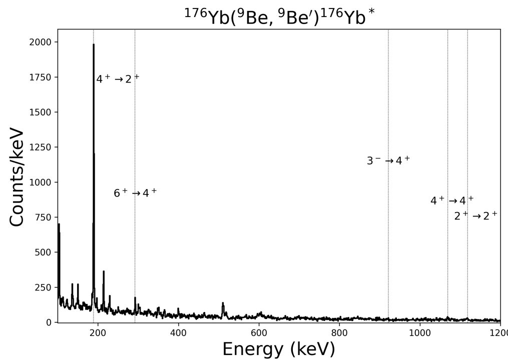
Starting with the even-even ^{176}Yb isotope, excited through the Coulomb excitation reaction, in the gated spectra of the $2^+_1 \rightarrow 0^+_1$ decay (see Figure 2b), transitions belonging to the ground-state band are observed, along with transitions originating from side bands. Specifically, the 2^+ state of band 3 populates the 2^+ level of the ground state band, while the 4^+ state of band 4 decays to the corresponding 4^+. Overall, up to six side bands were successfully populated and then identified via multiple gamma-gate conditions performed in the data with the highest state being 1610 keV. For the ground band, the highest spin level populated is the 8^+_1. The transitions observed can be seen in Figure 3a. The energies of the ground state band follow a rotational pattern, and the ratio $R_{4/2} = \frac{E(4^+)}{E(2^+)}$ is 3.312 according to NuDat, consistent with a deformed shape. These observations indicate that ^{176}Yb exhibits rotational behavior.

Regarding ^{177}Yb, an even–odd nucleus studied via a single neutron transfer reaction, its excited states do not exhibit collective behavior but can be described as single-particle excitations due to the presence of the unpaired neutron. Transitions from only one band in ^{177}Yb were observed. In the literature the band is signed as the $\nu\frac{9}{2}$[624] band [8]. All known states of ground state band have been populated (up to the $\frac{23}{2}^+$ state) though the 1n-transfer reaction. In experiments which used different reaction mechanisms, mainly side bands were populated [9]. The absence of levels belonging to other bands may be attributed to limited statistics, which prevented their clear identification in the present data set or their nature and the population mechanism that was used in the present experiment (1n-transfer reaction).

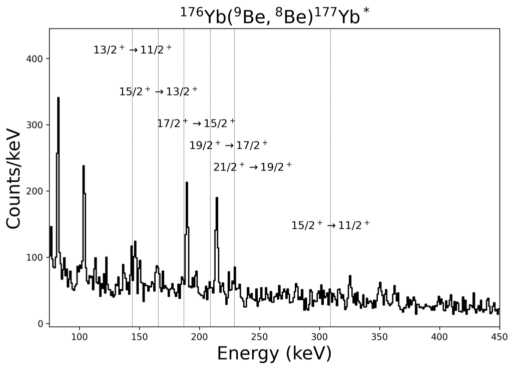
Lastly, among the tungsten isotopes $^{172-186}$W, the nucleus ^{182}W is identified as the most deformed, as demonstrated by its rigid-rotor $R_{4/2}$ value [10]. In particular, the isotope ^{182}W is a well-deformed rotor, as indicated by the calculated ratio $R_{4/2} = \frac{E(4^+)}{E(2^+)} \approx 3.291$. The fusion–evaporation reaction has proven to be effective in populating side bands, reaching the 11^+ state of Band 5 at an excitation energy of 2492.8 keV as shown in Figure 2d. In the observed spectra, up to three side bands can be identified. With the applied gate, as presented in figure 3c, the entire main band is visible, along with the 2^+ state of band 2 that decays to the 2^+_1 level of the ground state band, and the 5^+ state of band 3, which populates the 4^+_1 state of the ground state band.



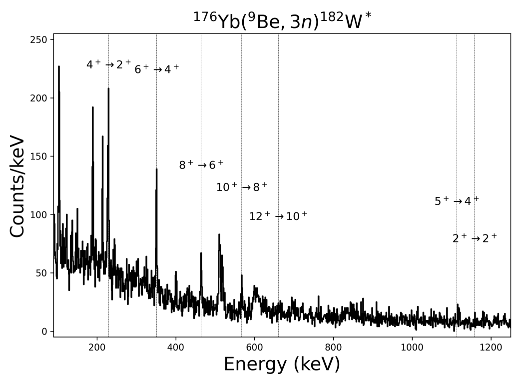
(a) Total (ungated) gamma-ray spectra in which the three isotopes of interest were identified. The indicated gamma energies (dashed lines) are retrieved from the NuDat database [7].



(b) Spectra gated on the $2_1^+ \rightarrow 0_1^+$ transition of the ground-state band of ^{176}Yb. The observed peaks correspond to gamma-ray transitions of the decay from higher energy levels.

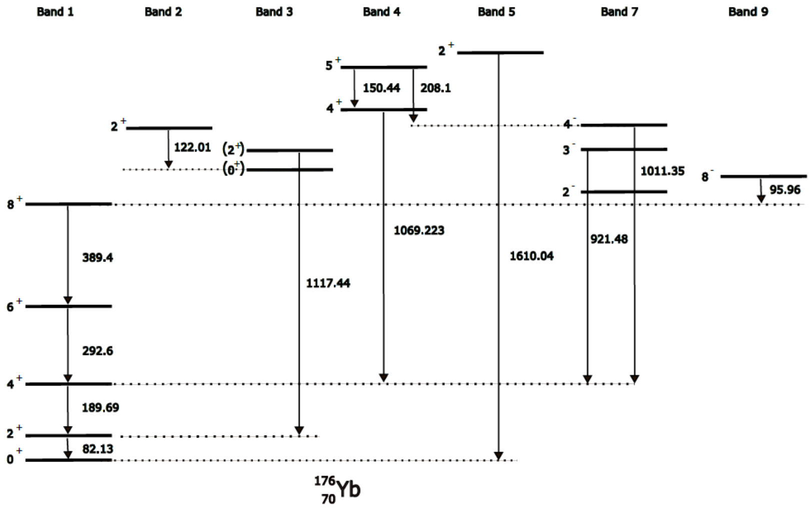


(c) Spectra gated on the $\frac{11}{2}^+ \rightarrow \frac{9}{2}^+$ transition of the ground-state band of ^{177}Yb. The observed peaks correspond to gamma-ray transitions of the decay from higher energy levels.

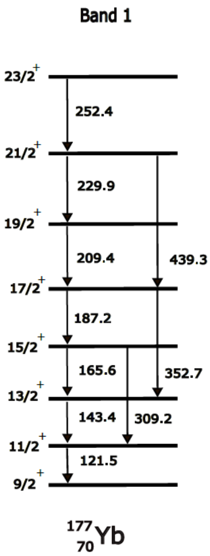


(d) Spectra gated on the $2_1^+ \rightarrow 0_1^+$ transition of the ground-state band of ^{182}W. The observed peaks correspond to gamma-ray transitions of the decay from higher energy levels.

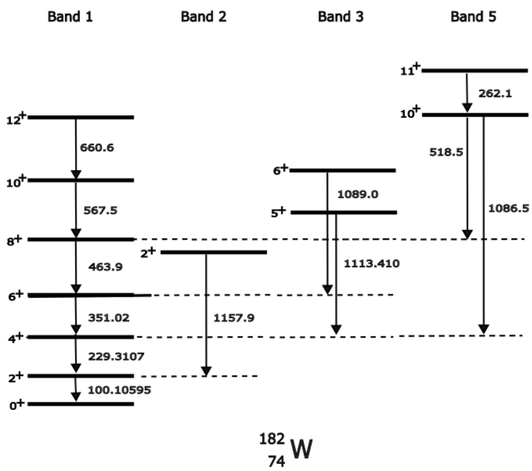
Figure 2. Total ungated spectrum showing the three isotopes (a); spectra gated on the $2_1^+ \rightarrow 0_1^+$ transition of ^{176}Yb isotope (b), and of ^{177}Yb gated on the $11/2^+ \rightarrow 9/2^+$ transition (c); spectrum gated on the $2_1^+ \rightarrow 0_1^+$ transition of ^{182}W (d).



(a) Level scheme from the analysis for ^{176}Yb. The gamma-rays observed are shown. This data are preliminary.



(b) Level scheme from the analysis for ^{177}Yb. The gamma-rays observed are shown.



(c) Level scheme from the analysis for ^{182}W. The gamma-rays observed are shown.

Figure 3. Level schemes of the three studied nuclei, constructed from experimental data and presented with theoretical values from NuDat [7].

4. Conclusion

Overall, the reaction ^{176}Yb+^{9}Be was used to populate excited states in ^{176}Yb, ^{177}Yb and ^{182}W. Gamma-ray spectroscopy was applied to construct the corresponding level schemes based on known excited state energies from the literature [7]. No new excited states or transitions were identified in the current analysis.

The extracted level schemes confirm rotational behavior for ^{176}Yb and a well-deformed rotor for ^{182}W. For the even-odd nucleus ^{177}Yb, the observed states correspond exclusively to the $\nu\frac{9}{2}[624]$ band and exhibit single-particle behavior rather than collective features.

The preliminary analysis and results presented in this contribution will serve as a reference point in the analysis of the $LaBr_3$(Ce) data which were additionally collected during the measurements.

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