Reviewing Nuclear Structure Properties of Even-Even Yb Isotopes

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Abstract. The medium-to-heavy mass ytterbium isotopes ($_{70}\text{Yb}$) in the rare-earth mass region are known to be well-deformed nuclei. Spectroscopic information becomes scarcer as the neutron number increases, impeding the understanding of nuclear structure in this mass region, where interesting phenomena, such as shape coexistence, have been predicted [1]. The lack of any experimental information on the structure of the neutron-rich ^{178}Yb and ^{180}Yb have greatly motivated this study, which can offer useful information for the collective behavior of neutrons and protons, the evolution of shape and shape coexistence. A test run was performed to investigate the population of excited states and a first measurement of the unknown 2_1^+ lifetime of ^{178}Yb by means of a two neutron-transfer reaction $^{176}\text{Yb}(^{18}\text{O}, ^{16}\text{O})^{178}\text{Yb}$ using the ROSPHERE [2] array at IFIN-HH, Romania. From the theoretical point of view, in this work, the reduced transition probabilities $B(E2)$ and transition quadrupole moments Q have been calculated using the IBM-1 and various other theoretical models, including the recently developed Proxy and Pseudo SU(3) model [3]. Good agreement was found between available adopted data [4] and theoretical predictions for $^{164}\text{--}^{180}\text{Yb}$ isotopes.

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KEY WORDS: nuclear structure, Ytterbium isotopes, IBM-1, Proxy SU(3), lifetimes.

1 Introduction

The Yb isotopes around mass 170 are known to exhibit distinct rotational properties and can be populated to very high spin. Typically, deformed nuclei can be schematically subdivided into prolate, oblate, and triaxial nuclei according to the size of the three principal axes of rotation in the ellipsoid. Meanwhile, experiments and theories have revealed some exotic shapes. It is known that many nuclei in the rare earth area are well deformed for example with quadrupole deformation β_2 greater than 0.2 in ground or in low-lying states. The reduced electric quadrupole transition probabilities $B(E2)$'s and related quantities have given valuable information for the collective behavior of deformed nuclei.

In this work, the well-deformed even-even $^{164-180}\text{Yb}$ nuclei, are taken as test cases in an investigation of their rotational properties, through calculation of various observables with the use of different theoretical models. In addition, we report on preliminary results from a recent experiment to study nuclear structure in these isotopes.

We mainly focus on the calculation of $B(E2)$ values for the 0^+ ground state to the first 2^+ state transition and related quadrupole moments Q . We extend this work to mass number equal to 180, presenting results for Yb isotopes considering previous works for the neutron-rich nuclei in this region [5]. The results are compared to available experimental data [4, 6].

A partial energy spectrum of the ground states for Yb isotopes that were studied in this work is presented. For $^{178,180}\text{Yb}$ no experimental data are available for the lifetimes and energy levels of the ground state, respectively.

Figure 1. (Color online) Ground-state band spectra of $^{164-180}\text{Yb}$.

2 Related Quantities & Theoretical Models

2.1 Related quantities

The intrinsic electric quadrupole moment, Q_0 , is defined in the intrinsic frame of the nucleus. Any deviation from spherical shape is linked to Q_0 , which is in turn related to the reduced electric transition probability $B(E2)$, where the up-pointing arrow represents excitation in Eq. (1).

$$Q_0 = \left[\frac{16\pi}{5} \frac{B(E2) \uparrow}{e^2} \right]^{1/2} \text{ (in barns)}, \quad (1)$$

$$Q(I, K) = \frac{3K^2 - I(I+1)}{(I+1)(2I+3)} Q_0, \quad (2)$$

$$\beta_2 = \left(\frac{4\pi}{3ZR_0^2} \right) \left[\frac{B(E2) \uparrow}{e^2} \right]^{1/2}. \quad (3)$$

The $B(E2)$ values carry information about the structure of the low-lying levels of the nuclei and are basic experimental quantities, which do not depend on nuclear models [4]. The quadrupole moment is an excellent tool to study nuclear deformations. By definition, the nuclear electric quadrupole moment describes the effective shape of the ellipsoid of nuclear charge distribution. A non-zero value of the quadrupole moment Q indicates that the charge distribution is not spherically symmetric. In the collective nuclear model, the relation between the observable (spectroscopic) electric quadrupole moment $Q(I, K)$ and the intrinsic electric quadrupole moment Q_0 is presented in Eq. (2), where I is the total spin of the nucleus, and K is the total projection of I onto the z -axis in the symmetry axis of the nucleus [7]. Another quantity that is quite useful because of its easy visualization, despite being model-dependent, is the deformation parameter, β_2 ; see Eq. (3). Nine models were used in this work in order to extract $B(E2; 0^+ \rightarrow 2^+)$'s and quadrupole moments through the deformation parameter.

2.2 Theoretical modeling

The Interacting Boson Model (IBM) of Arima and Iachello [8] has been employed to make a schematic study of the Yb isotopes. The main idea of the IBM is to describe the low-lying collective states of several medium and heavy mass nuclei. In this work we apply the model to the even-even Yb isotopes with mass number from 164 to 178. For each Yb isotope the values of the five parameters in the IBM Hamiltonian Eq. (4), have been determined to obtain the best fit to the experimental energy spectrum.

$$H(\zeta) = c \left[(1 - \zeta) \hat{n}_d - \frac{\zeta}{4N_B} \hat{Q}^x \cdot \hat{Q}^x \right], \quad (4)$$

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where $\hat{n}_d = d^\dagger \cdot \tilde{d}$ is the quadrupole boson creation operator, $N_B = N_\pi + N_\nu$ is the number of bosons, c , ζ are free parameters and $\hat{Q}^x$ is the quadrupole operator. The combinations of $\varepsilon = c(1 - \zeta)$ and $\kappa = -c(\zeta/4N_B)$ are also used.

Based on these values, we can extrapolate to isotopes for which no experimental data exist and provide guidance for future experiments. Especially, energy and $B(E2)$ ratios are used to fit all isotopes and determine the IBM parameters running nearly 20'000 calculations with IBAR program [9]. The most useful are in a notation $R_{4/2} = E(4_1^+)/E(2_1^+)$, $E(0_2^+)/E(2_1^+)$, $E(2_\gamma^+)/E(2_1^+)$, where the 2_γ^+ state is the bandhead of the quasi- γ band in rotational nuclei. Also for the electromagnetic transition probabilities the $B(E2)$ ratio $B_{2\gamma} = B(E2; 2_\gamma^+ \rightarrow 0_1^+)/B(E2; 2_1^+ \rightarrow 0_1^+)$ as well as the branching ratio, $R_{2\gamma} = B(E2; 2_\gamma^+ \rightarrow 0_1^+)/B(E2; 2_\gamma^+ \rightarrow 2_1^+)$ are useful [10].

In Figure 2 are the results for specific ratios that can explain low spin structure collective behavior of even-even nuclei. The ratio $R_{4/2}$ that is the most important observable, proves that Yb isotopes with mass number close to 170 are rotational nuclei with a ratio close to 3.33. Other observables are also presented in these graphs and for ^{174}Yb where the maximum amount of bosons

Figure 2. (Color online) Experimental (symbols) [6] and IBM-1 (blue lines) calculated ratios are compared for even-even $^{164-178}\text{Yb}$ isotopes. The blue lines are used to guide the eye. Error bars are smaller than the data points for some ratios.

Figure 3. (Color online) (top) Reduced transition probabilities $B(E2; 0^+ \rightarrow 2^+)$ values, and (bottom) electric quadrupole moments Q for all models are compared with experimental ones [4].

is achieved, maximum collectivity is occurred. For $B(E2)$ ratios more data are needed through new experiments in order to study furthermore the nuclear structure of these isotopes.

Further, the results for $B(E2)$'s of the ground state transition and quadrupole moments through nine well established theoretical models are compared with the available experimental data [4, 6] (see Figure 3 for a list of the models.). An overall good agreement was found between available adopted data and theoretical predictions. We realized that depending on the model, the maximum of deformation is observed in either ^{170}Yb or ^{172}Yb isotopes, whereas the maximum value is observed experimentally for mass number equals to 172, two neutrons away from the mid-shell in 174. Results from Proxy-SU(3) and Pseudo-SU(3)

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Figure 4. (Color online) Energy (left) and mean life time (right) of the 2_1^+ state against mass number A of $^{164-180}\text{Yb}$ isotopes by a local fit to the experimental values. Blue circles are extrapolated values for ^{180}Yb and ^{178}Yb , respectively. Experimental uncertainties are smaller than the data symbols.

models seem to require a scaling factor although the trend line is acceptable.

Lastly, using a local fit we attempted a prediction for the mean lifetime of the 2^+ state of ^{178}Yb and the energy of the 2^+ of ^{180}Yb , for which no experimental data exist yet (see Figure 4). Using a 2nd degree polynomial, we extrapolated the available experimental data to find the values shown in Table 1. The fitting of experimental data points was obtained by random sampling and taking the 1σ (68%) coverage. The fourth column in this table refers to Raman's Global Best Fit for the mean lifetime τ_{2+} [11]. Knowledge of the energy of the 2^+ state is all that is required to predict the corresponding lifetime and the $B(E2)$.

Table 1. Extrapolated values and Raman's global fit values for ^{178}Yb and ^{180}Yb .

A	Energy E_{2+} (keV)	Local fit τ_{2+} (ns)	Global fit [11] τ_{2+} (ns)
178	84.0 (3)	2.58 (7)	2.8 (5)
180	96.90 (33)	—	—

3 Experimental Setup & Results

3.1 Experimental Setup

A measurement was performed to investigate the population of excited states and a first measurement of the unknown first 2^+ lifetime of ^{178}Yb by means of a two neutron-transfer reaction $^{176}\text{Yb}(^{18}\text{O}, ^{16}\text{O})^{178}\text{Yb}$.

An ^{18}O beam impinged on a natural Yb target (2.5 mg/cm^2) consisting of seven stable Yb isotopes at energies 68-74 MeV. The emitted γ rays were recorded in the RoSPHERE array [2] at IFIN-HH, Romania. The array comprises 15

Figure 5. (Color online) View of the RoSPHERE array [2] (left), and the SORCERER particle detector [12] (right).

HPGe and 10 LaBr₃(Ce) detectors. The particle detector SORCERER [12] was additionally mounted to enable particle identification.

In this experiment the ground states of almost all Yb isotopes in the target were populated with the 2n-transfer reaction at spins up to 8⁺. An estimation of the lifetime of the 2₁⁺ state in ¹⁷⁸Yb using the fast-timing technique was obtained. A major challenge in this experiment was to overcome problems arising from the target composition which involves significant percentages of other Yb isotopes,

Figure 6. (Color online) γ -particle spectrum at 72 MeV beam energy.

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along with ^{176}Yb , such as overlapping energy peaks etc.

3.2 Results

From the recorded data, γ - γ spectra were constructed (Figure 6). The spectra show a complicated form due to γ -rays with similar energies from the Yb isotopes, as well as background rays from the tantalum shielding. To resolve the situation particle- γ - γ spectra were further produced (see example in Figure 7). Despite the lower statistics, the coincident spectra are much cleaner.

Figure 7. (Color online) Particle- γ - γ spectrum at a beam energy of 72 MeV and a gate on the 83 keV γ ray of ^{178}Yb .

Besides spectroscopy performed with the HPGe detectors, the $\text{LaBr}_3(\text{Ce})$ detectors were used to apply the fast-timing technique to measure lifetimes in Yb isotopes. Despite overall low statistics, coincidence spectra (Figure 8) were used to propose a lower limit of the lifetime of the unknown 2_1^+ state in ^{178}Yb , $t_{1/2} = 0.42$ (20) ns, by calculating the time difference for the delayed and the anti-delayed spectrum. Despite significantly different from the estimated value in Table 1 the present result can serve as a lower limit for a more precise measurement in the future. It should be noted that the tabulated value is produced by a rather simple extrapolation, and as such its validity needs to be scrutinized further experimentally.

Figure 8. (Color online) The $\gamma\text{--}\gamma\text{--}\Delta T$ spectrum for the 2_1^+ state of ^{178}Yb .

4 Conclusions

The nuclear properties of the Ytterbium isotopes and their evolution as the neutron number increases has been the major subject in this work, at both a theoretical and an experimental level. The collective behavior of the even–even $^{164\text{--}180}\text{Yb}$ isotopes was investigated by means of calculations using several well–established theoretical models in synergy with available experimental data. We conclude that in the framework of the nuclear collective model, the nuclear observables examined in this work for a number of permanently deformed Yb isotopes are calculated in agreement with available experimental results. In addition, predictions have been made for some observables of $^{178,180}\text{Yb}$ isotopes for which no experimental data currently exist. Also, the experimental setup and preliminary results from the experiment that took place in IFIN–HH, Romania had been presented for transitions in the ground state band and a lower limit of the lifetime of the 2_1^+ state in ^{178}Yb . Besides the detailed calculations and comparisons with various theoretical models that extend previous ones, we hope this work can serve as a reference point for future experimental and theoretical work in this mass region, which will provide useful information towards understanding the nuclear structure as one moves towards the neutron dripline.

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