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A study of the nuclear structure in the even–even Yb isotopes

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The nuclear properties of the Ytterbium isotopes and their evolution as the neutron number increases has been a central objective in this work. The medium-to-heavy mass Yb isotopes are known to be well-deformed rotational nuclei which can be populated to very high spins. Spectroscopic information becomes scarcer for neutron-rich nuclei, impeding the understanding of nuclear structure in this mass region, where interesting phenomena, such as shape coexistence [1], have been predicted to exist. The collective behavior of the even-even $^{164-180}_{70}$Yb isotopes was investigated using several well-established theoretical models in synergy with available experimental data. In this work, reduced transition probabilities $B(E2)$ and transition quadrupole moments Q for even-even $^{164-178}_{70}$Yb isotopes have been calculated using the Interacting Boson Model(IBM–1).

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1. Interacting Boson Model (IBM–1)

The Interacting Boson Model (IBM) of Arima and Iachello [2] 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 (Z=70, $94 \leq N \leq 108$). For each Yb isotope the values of the five parameters in the IBM Hamiltonian (Eq. 1), have been determined, so as to obtain the best fit to the available experimental data. The number of bosons is counted from the nearest closed shell. The total number of bosons, N_B, which in the IBM–1 could have been considered as a parameter, is now fixed by the microscopic interpretation of the bosons to be $N_B = N_\pi + N_\nu$, where N_π and N_ν are the proton and neutron boson numbers, respectively. For the IBM calculations we used the extended consistent Q formalism (ECQF) [3], which has been introduced in [4, 5], with the Hamiltonian [6, 7],

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

where $\hat{n}_d = d^\dagger \cdot \tilde{d}$ is the quadrupole boson creation operator, N_B is the number of bosons, c, ζ are free parameters and $\hat{Q}^\chi = (d^\dagger s + s^\dagger \tilde{d}) + \chi(d^\dagger\ \tilde{d})^{(2)}$ is the quadrupole operator. The combinations of $\varepsilon = c(1-\zeta)$ and $\kappa = -c(\zeta/4N_B)$ are also used.

For each N_B ($N_B = 12 - 17$) nearly 20,000 calculations have been carried out with the code IBAR [8]. Results were obtained by fitting five observables to experimental data available for each isotope. Since we consider only ratios for the $E2$ transition rates, the effective boson charge e_B cancels out.

It is well known [9, 10] that specific observables can describe the low–spin structure of the collective even–even nuclei. 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 $B_{2\gamma} = B(E2; 2_\gamma^+ \to 0_1^+)/B(E2; 2_1^+ \to 0_1^+)$, as well as the branching ratio, $R_{2\gamma} = B(E2; 2_\gamma^+ \to 0_1^+)/B(E2; 2_\gamma^+ \to 2_1^+)$, are useful [9]. These observables were used as they are relatively straightforward to measure and involve the bandheads that are relatively simple to identify. The method leaves ζ and χ as free parameters in the range (0.00 to 1.00) for ζ and ($-\sqrt{7}/2$ to 0.00) for χ with step 0.01, where $\chi = -\sqrt{7}/2$ is the limit of SU(3) symmetry.

The IBM calculations can provide results for a large number of observables. These values can be used to gain information for the shape of the nucleus. Generally it is sufficient to use only the deformation parameter $\beta_2 > 0$ and $0^\circ < \gamma < 60^\circ$ to describe the nuclear shape, because for every set of parameters outside this range, it is possible to find parameters inside this range which describe the same shape of the nucleus, with only the orientation in the coordinate system being different.

Figure 1 shows the numerical results for the IBM predictions for γ, compared to experimental values [11], extracted from ratios of the γ bandhead to the first 2^+ state, according to [1, 12, 13],

$$R = \frac{E(2_\gamma^+)}{E(2_1^+)} \tag{2}$$

$$\sin(3\gamma) = \frac{3}{2\sqrt{2}}\sqrt{1 - \left(\frac{R-1}{R+1}\right)^2}. \tag{3}$$

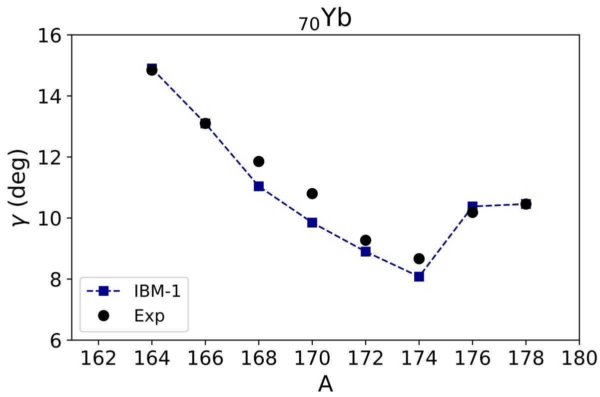

Figure 1: IBM predictions for γ, obtained from Eq. (3), compared to experimental values extracted from ratios of the γ bandhead to the first 2^+ state. Experimental uncertainties are smaller than the data symbols.

2. Results

We present the calculated values of $B(E2; 0_1^+ \rightarrow 2_1^+)$ and quadrupole moments Q and compare them with the experimental ones [11]. For IBM the results have been calculated directly from the model.

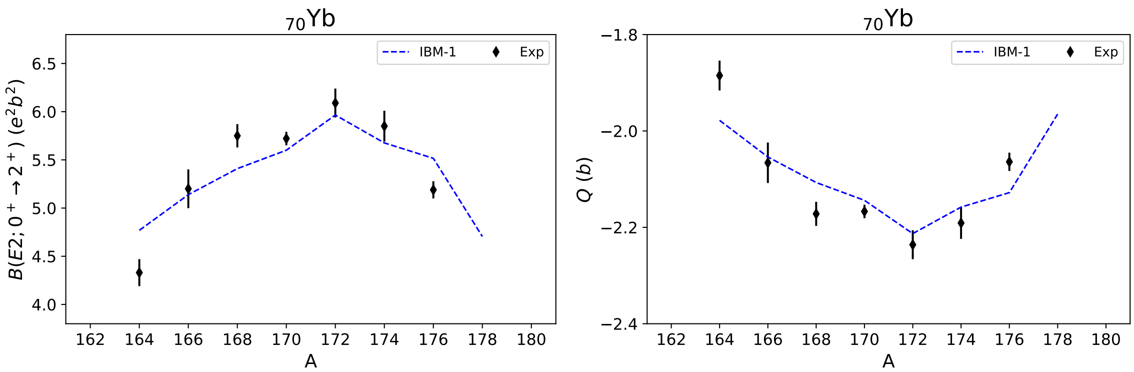

Figure 2: Reduced transition probabilities $B(E2; 0^+ \rightarrow 2^+)$ values and electric quadrupole moments Q values for IBM–1 are compared with experimental ones [11]. Maximum deformation is observed in ^{172}Yb, two neutrons away from the mid–shell closure. The blue dashed lines are used to guide the eye.

3. Conclusion & Future Directions

In the framework of the nuclear collective model, the nuclear observables examined in the present work for a number of permanently deformed prolate Yb isotopes are calculated and shown to be in good agreement with available experimental data. 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 closer to the neutron dripline.

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