

PEAR-SHAPE EFFECTS IN  $^{130-136}\text{Nd}$  ISOTOPES\*

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The yrast positive- and negative-parity level sequences in the spectra of  $^{130-136}\text{Nd}$  isotopes are examined, showing that in all of them alternating-parity band (APB) structures can be identified as an indication for the possible manifestation of octupole collectivity. The selected band-structures are tested for the presence of quadrupole–octupole (QO) (or pear-shape) deformations within the “rigid” and “soft” limits of a collective QO model. It is found that at moderate angular momenta, the APBs in  $^{130-134}\text{Nd}$  exhibit a structure which can be associated with soft QO vibrations and rotation, whereas the APB in  $^{136}\text{Nd}$  shows signs of a stabilization of the QO shape. Besides, the higher APB levels in  $^{134}\text{Nd}$  give an indication for possible QO shape stabilization and suggest a transition behaviour of this nucleus between the two limits of QO collectivity. The study opens a way for further detailed investigation of the shape dynamics in this nuclear region.

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## 1. Introduction

The subject of nuclear octupole deformations has attracted much new interest within the last decade with the experimental confirmation of stable octupole shape in the nucleus  $^{224}\text{Ra}$  obtained in REX-ISOLDE [1], and in the nuclei  $^{144,146}\text{Ba}$  obtained in ANL [2]. From one side, this fresh wave in the field inspires an interest for the search of octupole collectivity in less studied regions and, from another side, motivates the development and application of theoretical models for the interpretation of available and newly obtained experimental data.

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The purpose of this work is to examine the possibility for the presence of axial quadrupole–octupole (QO) (pear-shape) deformation modes in excitation spectra of the neodymium isotopes  $^{130-136}\text{Nd}$ . For this reason: first, we check the possible formation of alternating-parity bands (APBs) in experimental data and second, we apply a collective QO model [3, 4], which with its “rigid” [3] and “soft” [4] versions (limits) allows one to assess the degree of stability of the eventual octupole shape and its effect on the collective dynamics in this nuclear region.

## 2. Quadrupole–octupole model approach

The first version of the model, called QO rotation model (QORM), describes rotations of the general QO shape through a point-symmetry based Hamiltonian [5] and low-energy octupole oscillations in a symmetric double-well potential with angular-momentum-dependent (increasing) barrier in the middle [3], which together provide an explanation of the APB structure typical for the nuclei with the presence of stable QO deformation. This structure is characterized by a strong shift-up of the negative-parity levels with respect to the positive-parity ones at low angular momenta due to the strong penetration through the potential barrier and subsequent ordering of both sequences into a common “octupole” band at high angular momenta, where the increased barrier suppresses the penetration and reduces the oscillation. Since the formation of octupole band corresponds to a stable QO deformation, we call this version of the model “rigid” (see [3] for details of the model).

The second version, called coherent QO model (CQOM), describes simultaneous axial quadrupole and octupole vibrations assumed with the same oscillation frequency, which are non-adiabatically coupled to the rotation motion [4, 6]. The CQOM potential represents a two-dimensional generalization of the double-well octupole potential of QORM in the space of quadrupole and octupole variables. The typical structure of the spectrum based on such a dynamics is characterized by a persistent parity shift, *i.e.* a displacement of the negative-parity sequence with respect to the positive-parity one up to the highest observed angular momenta without forming a single (octupole) rotation band. Since this behaviour is associated with sustainable vibrations without presence of a stable QO shape, we call this version of the model “soft” (see [4, 6] for details of the model).

## 3. Data analysis and model descriptions

The data for the yrast positive- and negative-parity levels in all  $^{130-136}\text{Nd}$  isotopes are taken from the ENSDF [7]. For three of the nuclei,  $^{130-134}\text{Nd}$ , they are available up to angular momentum  $I = 30$ , although in the all four isotopes, the levels with  $I = 1$  and  $I = 3$  are missing. For the three nuclei,

we construct corresponding APBs up to the region of  $I = 20-22$  which may be considered as a reasonable limit of model applicability (see below). In  $^{136}\text{Nd}$ , the APB can be constructed up to  $I = 14$  although the levels with  $I = 10$  and  $I = 12$  are considered to be not safe due to the presence of other states with the same angular momenta and slightly higher energies in neighboring bands. [See band A (up to  $I = 8$ ) and F ( $I = 10-14$ ) for the positive-parity levels and band C for the negative-parity levels of  $^{136}\text{Nd}$  given in [7].]

In Fig. 1, the above considered experimental APB structures in the four Nd isotopes are compared. It is seen that the overall parity-shift effect considerably decreases in the bands with increasing neutron number from  $^{130}\text{Nd}$  to  $^{136}\text{Nd}$ . Moreover, in  $^{136}\text{Nd}$ , it is seen that between  $I = 7$  and 11, the energy shift practically disappears and the levels appear ordered as in the octupole bands inherent for the nuclei with stable octupole deformation. Signs for similar ordering are also observed in  $^{134}\text{Nd}$  but at the much larger angular momenta approaching  $I = 22$ .

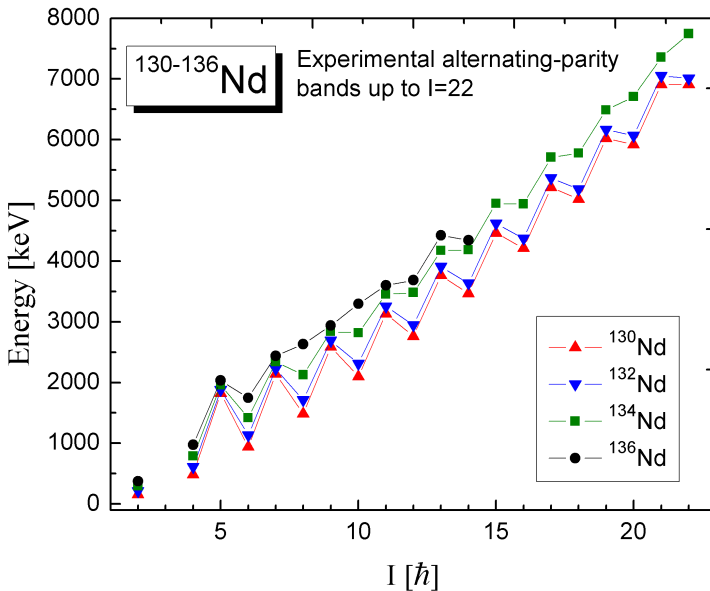


Fig. 1. Experimental alternating-parity bands (APBs) in  $^{130-136}\text{Nd}$  up to  $I = 22$ . Data from ENSDF [7].

Both model versions, QORM and CQOM, were applied independently to the APB of each of the considered Nd isotopes. In  $^{136}\text{Nd}$ , all available experimental levels up to  $I = 14$  were included in the fits, while in  $^{130-134}\text{Nd}$ , the fits were made up to  $I = 20$ . In Fig. 2, the QORM and CQOM de-

scriptions of the APBs in the four isotopes  $^{130-136}\text{Nd}$  are compared with the experimental data. The quality of the model descriptions is characterised by the root-mean-square (RMS) deviations between the theory and experiment given in keV. The parameters of the fits in both models are not given for simplicity and we can say that the obtained values are in the ranges typical for the other applications of the two model versions (see [3, 4, 6]).

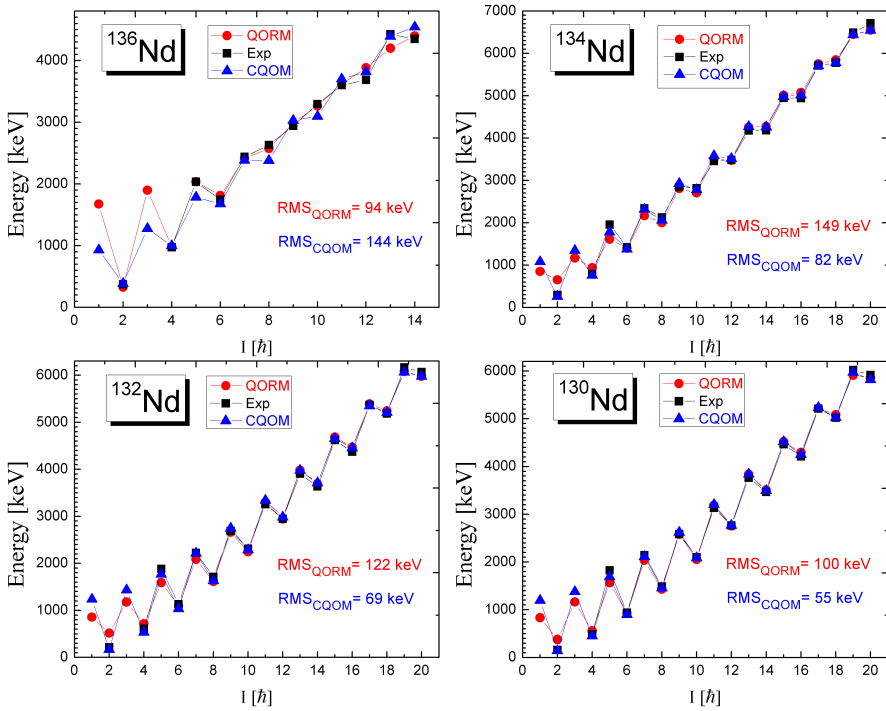


Fig. 2. QORM and CQOM descriptions of  $^{130-136}\text{Nd}$  APBs. Data from ENSDF [7].

For  $^{136}\text{Nd}$ , it is seen, and also confirmed by the obtained RMS factors, 94 keV and 144 keV, respectively, that the rigid QORM limit of the model suggests more reasonable interpretation of this APB for the energy levels up to  $I = 14$ . It is seen that QORM perfectly reproduces the ordering of the experimental levels from  $I = 7$  to  $I = 11$ , whereas CQOM provides a persisting parity shift. On the other hand, the reappearance of the parity effect from  $I = 12$  to  $I = 14$  is only slightly indicated by QORM. Nevertheless, the QORM description quite reasonably reproduces the overall structure of the experimental APB emphasizing the possible formation of an octupole band. Thus, despite of the small amount of data, the model analysis in  $^{136}\text{Nd}$  reveals an APB behaviour similar to the one in the nuclei with recognized octupole deformations [3].

For the isotopes  $^{134}\text{Nd}$ ,  $^{132}\text{Nd}$  and  $^{130}\text{Nd}$ , the QORM and CQOM descriptions are obtained up to  $I = 20$  (see Fig. 2). We see that now the soft CQOM limit of the model already provides better description of the experimental data compared to the rigid QORM. This result suggests that the APBs of these three nuclei can be generally referred to as a manifestation of the soft QO collective mode. Nevertheless, we notice that while for two of them,  $^{132}\text{Nd}$  and  $^{130}\text{Nd}$ , the experimental and theoretical plots demonstrate a well-pronounced parity-shift effect along the all considered APB levels, for  $^{134}\text{Nd}$  the parity-shift essentially decreases towards  $I = 20$ , tending to the formation of a single rotation band. The latter suggests a possible stabilization of the octupole mode in  $^{134}\text{Nd}$  at angular momenta higher than  $I = 20$  (a subject of separate study). In this aspect, the experimental data and the model APB description, presently obtained at moderate energies, suggest an intermediate behaviour of  $^{134}\text{Nd}$  between the rigid (QORM) and the soft (CQOM) limits of the collective QO degree of freedom.

Finally, we remark that the above yet preliminary results suggest a bit stronger manifestation of octupole collectivity than what could be expected for the considered nuclei on the basis of the standard shell model prediction. The latter suggests that in the rare earth region, the octupole degrees of freedom should be favoured close to the nucleon numbers 56 for protons, and 88 for neutrons, which may be called “octupole magic numbers”. The considered  $^{130-136}\text{Nd}$  isotopes, with proton number  $Z = 60$  and neutron numbers  $N = 70-76$ , have four protons above the former and 18–12 neutrons below the latter octupole magic number. Therefore, one can say at least that it is not obvious why pronounced octupole mode, such as the one observed in  $^{136}\text{Nd}$ , appears in this region. A reasonable way to look for clarification of this question is to examine the development of the nuclear shell structure with the related deformation modes. This should be a subject of further work.

#### 4. Concluding remarks

The analysis of data and the performed model calculations presented in this paper suggest that in the  $^{130-134}\text{Nd}$  isotopes the yrast positive- and negative-parity levels can be interpreted as APBs indicating the manifestation of axial QO (pear-shape) deformation degrees of freedom. At moderate angular momenta, the APBs in  $^{130-134}\text{Nd}$  can be associated with the presence of a soft QO mode, whereas in  $^{136}\text{Nd}$ , one observes effects of possible stabilization of the octupole shape. The higher-spin APB structure in  $^{134}\text{Nd}$  suggests a possible transition behaviour of this nucleus between the soft and rigid QO limits at higher energy. The rather pronounced indications of QO collectivity in this nuclear region appear a little bit unexpected regarding

the remoteness of these nuclei from the regions of recognized octupole deformations. Therefore, the obtained results clearly point out the need for further detailed study of the shape dynamics and the underlying shell structure which determine the observed spectroscopic characteristics of the nuclei in this region.

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