Vol. 47 (2016) ACTA PHYSICA POLONICA B No 3

COLLECTIVITY ABOVE THE CLOSED ^{78}Ni AND ^{132}Sn CORES*

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(Received November 25, 2015)

We investigate collective features of nuclei with several valence particles outside the closed cores of ^{78}Ni and ^{132}Sn. Using the pseudo-SU(3) model and large-scale shell model diagonalizations, we show that quadrupole collectivity should develop in $N = 54$ and $N = 86$ isotones and that non-axial degrees of freedom may play an important role in both regions.

DOI:10.5506/APhysPolB.47.883

1. Introduction

One of the interests of the nuclear structure is searching for general mechanisms driving the collectivity in different parts of the nuclear chart and understanding them in terms of the underlying shell structure. Recently, it has been predicted that quadrupole collectivity can develop when a few particles are added in the valence space outside the doubly-closed ^{78}Ni [1]. The pseudo-SU(3) limits of the deformed configurations have been estimated showing that also K mixing is possible for four protons/neutrons in the valence space leading to possible non-axial shapes. Large-scale shell model (LSSM) diagonalizations and beyond mean-field calculations with Gogny forces have confirmed the simple model predictions and suggested that the non-axial degrees of freedom should be important especially in ^{86}Ge, while ^{88}Se should be the most axially deformed among the $N = 52$–54 nuclei.

The realization of the pseudo-SU(3) limit in realistic nuclei depends, however, on the underlying shell structure and the possible degeneracy of single-particle orbits. Recent shell model studies of copper isotopes from $N = 40$ to $N = 50$ [2–4] have led to a new estimate of the $p_{3/2}$–$f_{5/2}$ splitting of several hundreds keV. Similarly, the $d_{5/2}$–$s_{1/2}$ levels have been assumed degenerate in the shell model interactions which seems realistic based on the recent study of spectroscopy of ^{79}Zn [5].

* Presented at the XXXIV Mazurian Lakes Conference on Physics, Piaski, Poland, September 6–13, 2015.

The $N = 86$ isotones that can be described in the shell model as a few particles outside the ^{132}Sn core are analogical cases to $N = 54$ nuclei studied recently in Ref. [1]. The spectra of ^{133}Sn and ^{133}Sb show that at least the two lowest orbits in the proton and neutron valence spaces are separated by less than 1 MeV which looks quite favorable for the development of quadrupole collectivity. In this contribution, we remind the main collective features of nuclei just above the ^{78}Ni core and further, we present several preliminary results in the region above ^{132}Sn.

2. Properties of $N = 52, 54$ isotones

The collective properties of $N = 52$ and $N = 54$ isotones have been studied recently in Ref. [1]. In Fig. 1, we compare the reduced $B(\mathrm{E2})$ values between the first excited 2^+ and the ground states obtained in the pseudo-SU(3) symmetry model and in the large-scale shell model diagonalization. As can be noted, except the zinc isotones with 2 protons outside the closed

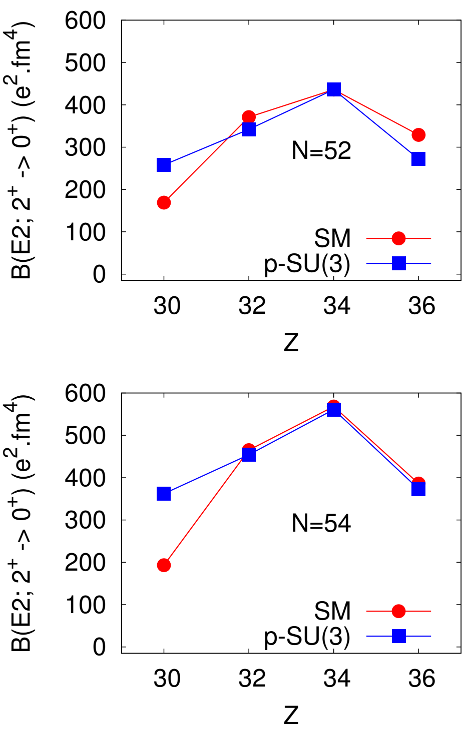

Fig. 1. Pseudo-SU(3) and large-scale shell model diagonalization results for the reduced transition probabilities in $N = 52$ and $N = 54$ isotones.

core, the other nuclei are characterized by a similar transition value in both models. Especially in the $N = 54$ isotones, the two models give very similar values, indicating these nuclei may approach a deformed rotor limit. All theoretical models used in Ref. [1] pointed coherently to the non-axial shape of ^{86}Ge (4 protons and 4 neutrons in the valence space), while ^{88}Se (6 protons and 4 neutrons) has been suggested to have the largest prolate deformation in its ground state ($\beta = 0.25$).

For the moment, the predictions of Ref. [1] are not confirmed experimentally in $N = 54$ isotones. However, recent experiments in $N = 52$ isotones seem to validate the model assumptions. In Refs. [6, 7], the low-spin structure of ^{84}Ge has been studied and it was concluded that the second excited state is 2_2^+, in agreement with theoretical calculations suggesting this state is a head of a quasi-γ band. Recently, a more complete spectroscopy of ^{86}Se has been obtained in Ref. [8] with a possible candidate for the low-lying 3^+ level, in accord with the LSSM calculation. However, experimental determination of electromagnetic properties of these nuclei would be crucial to get a coherent picture of deformation in this region.

3. Nuclei above ^{132}Sn core

The results of large scale shell model calculations presented in the following were obtained using the interaction being currently under development for this region [9, 10]. It is derived from a realistic V_{lowk} interaction (cut-off 2.2 fm^{-1}) based on a N3LO potential [11]. All diagrams through the second order are summed in the Q_{box} expansion in the many-body perturbation theory [12]. We start with the ^{110}Zr core with single particle energies from the GEMO model [13]. Further, to account for the missing contributions from the 3N forces, monopole corrections are applied in order to reproduce the proton and neutron gaps $Z = 50$ and $N = 82$, the spectra of ^{133}Sn and ^{133}Sb as well as low-lying levels of $N = 83, 84$ isotones. As first noted in Ref. [9], most of realistic interactions in this region face a problem to reproduce accurately the trends and magnitude of the recently measured isomeric $6^+ \to 4^+$ transitions in $^{134-138}$Sn. Since our goal is establishing an empirical interaction for a whole region of nuclei, we have slightly reduced $f_{7/2}$ pairing matrix elements to obtain also a good agreement with data for the heavy tins.

With the interaction described above, we have performed calculations for ^{138}Te and ^{140}Xe within the *gds-hpfi* model space, closing the proton $g_{9/2}$ and $h_{11/2}$ orbitals (no excitations of the ^{132}Sn core). The diagonalization of the Hamiltonian matrix has been done using the Strasbourg shell model codes ANTOINE and NATHAN [14, 15]. We use $0.5\,e$ polarization charge for the evaluation of the E2 matrix elements.

As shown in Fig. 2, the agreement between experiment and theory for the known yrast levels in ^{138}Te and ^{140}Xe is excellent. Selected quadrupole properties of both nuclei and of the subsequent ^{142}Ba obtained within this framework are presented in Table I. As in the case of nuclei above ^{78}Ni, the deformation properties of nuclei above ^{132}Sn can be anticipated from the pseudo-SU(3) model. In Fig. 3, we show thus the comparison of values of intrinsic quadrupole moments from both calculations. As can be seen, they agree closely for both, the trend and the magnitude of deformation.

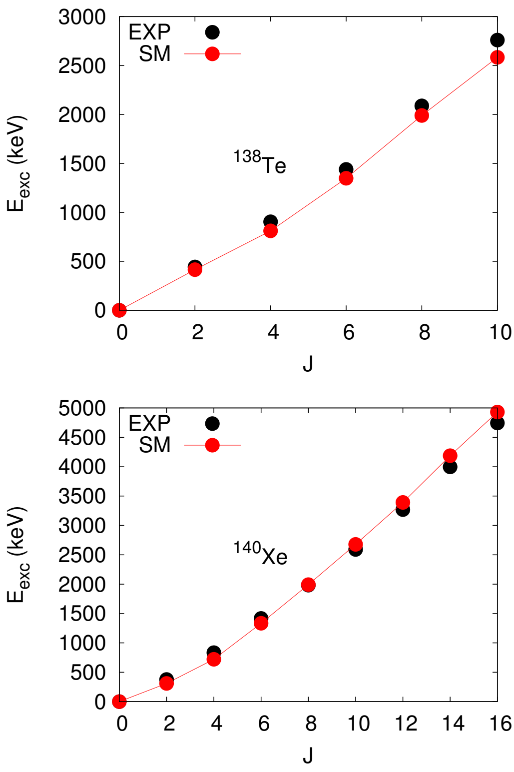

Fig. 2. Yrast states of ^{138}Te and ^{140}Xe obtained from LSSM diagonalization in comparison to known experimental levels from NNDC [16].

^{138}Te with only 2 protons outside the closed shell is the least deformed of the $N = 86$ isotones. The quadrupole transitions through the yrast band are of the order of dozens of W.u. and are of collective nature but still small for what one can expect in deformed nuclei in this mass region. Adding a few more protons to the $g_{7/2}$–$d_{5/2}$ shells should enhance considerably the collectivity leading to strongly deformed shapes and appearance of distinct

TABLE I

Selected quadrupole properties of $N = 86$ isotones obtained from LSSM diagonalization.

Nucleus	$B(\mathrm{E2}; 2^+ \to 0^+)$	$B(\mathrm{E2}; 3^+ \to 2^+_2)$	$Q_{\mathrm{spec}}(3^+)$
^{138}Te	12 W.u.	18 W.u.	$-3.5\,e\,\mathrm{fm}^2$
^{140}Xe	24 W.u.	44 W.u.	$-2.2\,e\,\mathrm{fm}^2$
^{142}Ba	31 W.u.	37 W.u.	$-4.1\,e\,\mathrm{fm}^2$

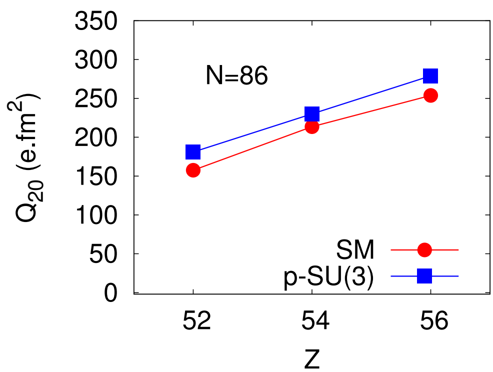

Fig. 3. Intrinsic quadrupole moments of $N = 86$ isotones from LSSM and pseudo-SU(3) calculations.

γ-bands. In ^{140}Xe, the deformation is more pronounced: we obtain quite equal quadrupole moments ($\sim 220\,e\,\mathrm{fm}^2$) calculated from spectroscopic moments and $B(\mathrm{E2})$ transitions up to spin 6^+. This allows us to associate to the yrast band the β deformation parameter of 0.14. The transitions throughout this band are of the order of 20–30 W.u. The $B(\mathrm{E2}, 3^+ \to 2^+_2)$ transition value is of 44 W.u. and spectroscopic quadrupole moments of 2^+_1 and 2^+_2 states are of equal value ($61\,e\,\mathrm{fm}^2$) but opposite signs, a clear sign of triaxiality. There is also a sequence of $2^+_2, 3^+, 4^+_2, 5^+$ states connected by strong transitions that can be identified as a γ-band. As can be seen in Table I, the $B(\mathrm{E2}; 2^+ \to 0^+)$ transition in ^{142}Ba is predicted stronger than in ^{140}Xe, while the $B(\mathrm{E2}; 3^+ \to 2^+_2)$ is less collective. This is in perfect analogy to the $N = 54$ isotones where the triaxiality was maximized in ^{86}Ge (4 valence protons) and the axial deformation was larger in ^{88}Se (6 valence protons).

One should, however, stress that the evolution of collectivity obtained here is sensitive to the single-particle splittings and their evolution due to the monopole interactions, especially between proton $d_{5/2}$ and $g_{7/2}$ orbitals. Therefore, experimental information concerning the collective properties of these nuclei could be used as a benchmark for the shell model interactions in this region. To this purpose, a joined experimental and theoretical study of ^{138}Te and ^{140}Xe has been undertaken and is currently under way [17].

We appreciate financial support of the Polish National Science Center under the contract DEC-2013/09/B/ST2/03485. Discussions with W. Urban are gratefully acknowledged.

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