SHELL EVOLUTION AND SPECTROSCOPIC STUDY OF EVEN–EVEN $Z = 38$ ISOTOPES*

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(Received December 21, 2018)

Dedicated to the memory of the late Profesor Adam Sobiczewski

Study of shell evolution and the appearance of new magic numbers make an important tool to improve and study the monopole effect. In the framework of studying and understanding the role of the latter, shell model calculations have been realized for interpreting and developing the two-body matrix elements of N–N interaction. In this context and in order to reproduce the nuclear spectra of even–even $Z = 38$ isotopes, we have performed these calculations using recent experimental single-particle energies (SPEs), by means of NuShellX@MSU nuclear structure code. The two-body matrix elements (TBMEs) of the using effective interaction were deduced from the $jj44bpn$ realistic interaction for ^{56}Ni mass region. The received results show an acceptable agreement with the available experimental data, which prove the influence of the monopole effect.

DOI:10.5506/APhysPolBSupp.12.605

1. Introduction

The study of nuclei near drip lines and far from beta stability is of great importance, it gives the opportunity to test and develop nuclear models and investigate nuclear properties for such systems. In this context, the Sr isotopes close to ^{78}Ni doubly magic core are good candidates, as they cover masses from the proton drip line to the neutron one.

This region is supposed to be a coexistance shape region ($Z \sim 34$ and $N \sim 40$). However, the study of this feature is not easy, because of a strong mixing depending on shell effects [1].

* Presented at the XXV Nuclear Physics Workshop "Structure and Dynamics of Atomic Nuclei", Kazimierz Dolny, Poland, September 25–30, 2018.

The strontium isotopic chain includes 4 stable discovered isotopes [2]. The radioactive ones were produced via nuclear reactions and induced fission, and the mass spectroscopy leads to identifying the stable ones [2].

This paper aims to study the monopole effect on nuclear structure of even Sr isotopes in order to figure out the collectivity of these nuclides situated on a transitional region between the vibrational and the rotational features.

2. Theoretical framework

The development of the experimental methods in the last decades enables to study systems more and more instable thus getting more data and new magic numbers have appeared ($N = 14, 40\ldots$) [3, 4]. This shows the importance of the 3-body and higher order interactions, which can give SPE modifications and possible shell evolution, as a consequence of the monopole effect [5].

McGrory *et al.* [6] studied $^{42-50}$Ca isotopes using a realistic interaction derived by Kuo and Brown [7]. They detected the monopole anomaly after adjusting the two-body matrix elements (TBME) of the used interaction. Their results showed a dominant interaction of $\nu f_{7/2}$ shell with $\nu p_{3/2}$, $\nu p_{1/2}$ and $\nu f_{5/2}$ ones [6]. Cortes and Zuker gave a theoretical explanation of this anomaly based on the core excitation effect originated from the monopole field. They carried out a spectroscopic study on nuclei in ^{16}O and ^{40}Ca regions considering the monopole effect [8]. Poves and Zuker realized a spectroscopic study on nuclei in ^{40}Ca region. They showed the monopole interaction validity by making application on KB interaction in fp region [9].

The monopole interaction was emphasized for the first time by deriving a simple equation for the mean energies of hole states [10, 11]

$$V_{j_s j_t}^{\tau\tau'} = \frac{\sum_J (2J+1) V_J(j_s j_t)}{\sum_J (2J+1)}\,. \tag{2.1}$$

Here, $\tau/\ \tau'$ refers to proton and/or neutron. $V_J(j_s j_t)$ is the TBME arisen from the $(j_s j_t)$ configuration. For regions with an important neutron excess, isospin operators should be considered.

The monopole term is independent of J values [4, 11]. It corresponds to the mean energy delivered to the nucleus by adding two interacting nucleons, irrespective of their orbits orientation [11, 12]. It contains the fundamental properties of N–N interactions, which influences the evolution of shell closures.

In this work, the proton–neutron, proton–proton and neutron–neutron monopole interactions consideration introduces some modifications on few TBMEs of original interaction $jj44bpn$ [13], and new interaction named $j4bpnm$ is built.

3. Results and discussion

Some calculations are carried out by means of NuShellX@MSU [14] nuclear structure code, using the new interaction. In this work, we have used the full fpg as a single-particle space (SPS). For protons, it contains $\pi(1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$ and $1g_{9/2})$, and for neutrons, the shells $\nu(1f_{5/2}$, $2p_{3/2}$, $2p_{1/2}$ and $1g_{9/2})$ are included. The calculations are realized with full $\pi 2p_{3/2}$ and $\nu 2p_{3/2}$ shells. The SPEs were taken from the experimental data [15] and from Grawe *et al.* [16] for some shells.

The calculated energetic spectra of $^{74-88}$Sr isotopes in comparison with the available experimental data are shown in Fig. 1

From this figure, one can see that the new interaction gives an acceptable agreement with the experimental data. This agreement is perfect for ^{80}Sr and ^{86}Sr isotopes. However, it overestimates the energy levels of 8^+ states by about 1 MeV and 2 MeV for ^{76}Sr and ^{78}Sr isotopes, respectively. For 2^+ and 4^+ states, our interaction leads to obtaining close values to the experimental ones except for ^{88}Sr isotope, in which the differences are around 1 MeV.

One of the parameters used to investigate nuclear structure is the $R_{\frac{4}{2}}$ ratio, which is a signature of the nuclear deformation

$$R_{\frac{4}{2}} = \frac{E\left(4^+\right)}{E\left(2^+\right)}, \tag{3.1}$$

$$E(J) \simeq \frac{200}{\beta^2 A^{\frac{7}{3}}} J\left(J+1\right). \tag{3.2}$$

For the excitation energy $E(J)$, only even Js are allowed. Here, β is the deformation parameter [17, 18].

The $R_{\frac{4}{2}}$ factor for the studied nuclei is presented in Fig. 2. This graph depicts that the calculated factor shows the same behaviour as the experimental one.

The experimental and the calculated $R_{\frac{4}{2}}$ ratios are in the $2.23 \leq R_{\frac{4}{2}} \leq 3.3$ interval (Fig. 2). This corresponds to nuclei in the transitional region between the purely harmonic vibrational system and rotational one [18].

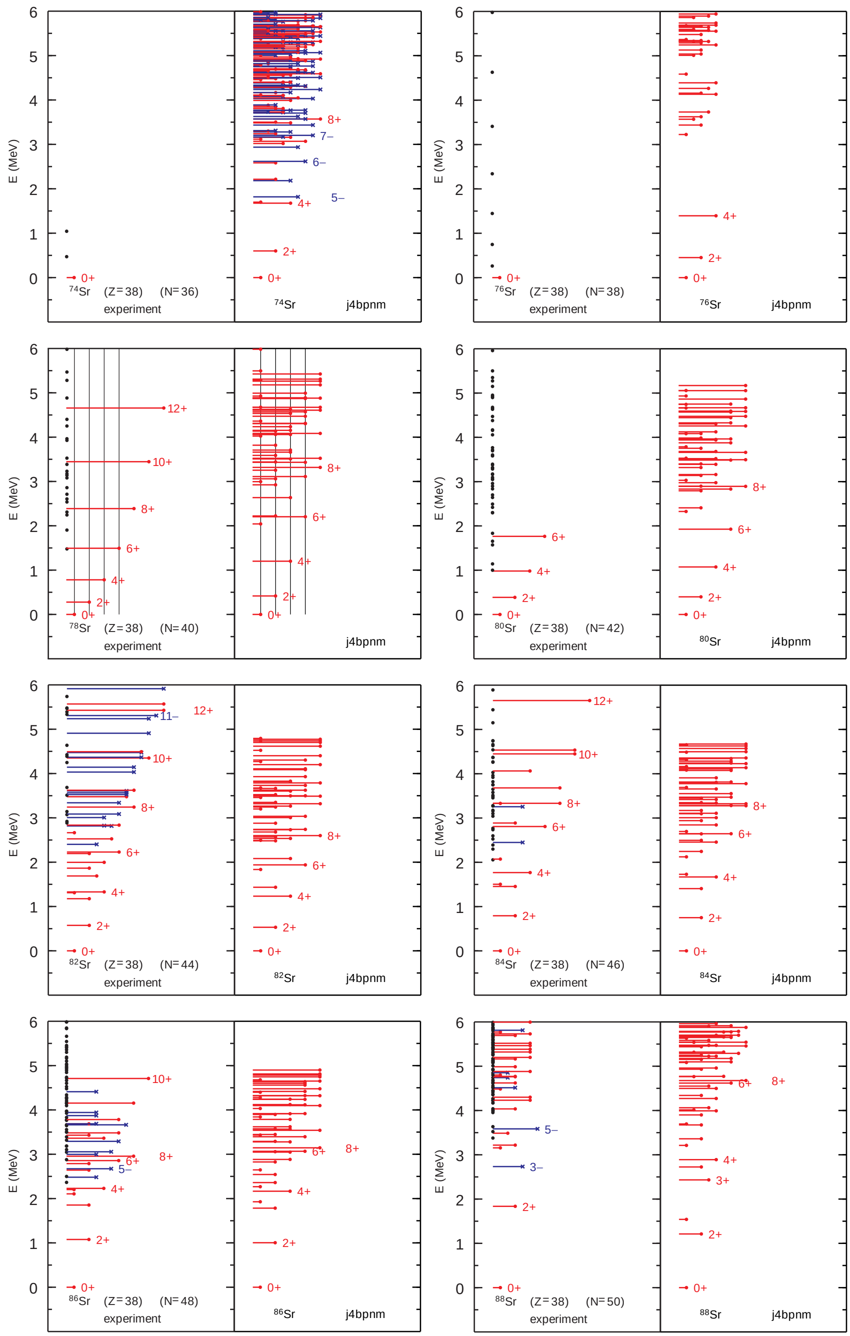

Fig. 1. Calculated energetic spectra of $^{74-88}$Sr isotopes in comparison with the experimental data.

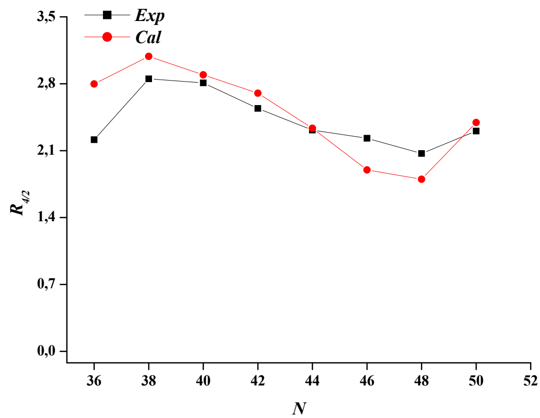

Fig. 2. Calculated $R_{\frac{4}{2}}$ factors for $^{74-88}$Sr isotopes in comparison with the experimental ones.

4. Summary

This study is based on the energetic spectra calculations for $Z = 38$ isotopes, with few protons and neutrons in their valence spaces. The calculations are realized in the framework of the nuclear shell model by means of NushellX@MSU nuclear structure code. Using the *jj44bpn* original interaction of the code, we carried out some modifications based on the proton–neutron, proton–proton and neutron–neutron monopole interactions to get *j4bpnm* new one. The calculations are realized in HPC calculation center in Frères Mentouri Constantine 1 University.

The calculated energetic spectra are in agreement with the experimental data for these even–even isotopes. However, the calculated energy of 2^+ state in ^{88}Sr is located at about 600 keV below the experimental one. This nucleus is a semi-magic isotope where the neutron shells are full.

The 2^+ states evolution shows an agreement with the experimental data. For 4^+ states, the evolution shows the same behaviour as the experimental one, however, the calculations overestimate the energy values for $N = 36$, 38 and 40 nuclei.

The $R_{\frac{4}{2}}$ ratio values are in the interval of the transitional region between the purely harmonic vibrational system and rotational one.

This work was granted access to the HPC resources of UCI-UFMC "Unité de Calcul intensif" of the University Freres Mentouri Constantine 1. Authors of this article thank the organizers of the XXV Nuclear Physics Workshop "Structure and Dynamis of Atomic Nuclei", Kazimierz Dolny, Poland, September 25–30, 2018 for the organization and the support provided during the conference. Special thanks are owed to B.A. Brown for his help in providing us the NuShellX@MSU code (Linux Version).

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