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Shell Evolution Effect on Odd A Antimony Isotopes in ^{132}Sn Mass Region

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Abstract. In order to understand the monopole interaction effect on the single particle energies and the shell evolution, we have studied Z=51 isotopes with odd mass number in the vicinity of 132Sn mass region. We have performed some spectroscopic calculations in the framework of nuclear shell model using kh5082 and mkh effective interactions in a truncated space, which is constructed taking into account the evolution of the effective single particle energies in the studied mass region.

Keywords: Monopole interaction, Shell Evolution, Nuclear structure, Odd A Antimony isotopes, Oxbash code, 21.60.Cs; 27.60. +j; 21.30.Fe

1. INTRODUCTION

The structure of odd nuclei, containing few valence particles in addition to a doubly closed shell inert core (*CS*), is an important tool to understand and to develop the theoretical models explaining the N-N interaction [1, 2]. The interaction of the single proton (neutron) in these nuclei with the valence neutrons (protons) provides significant information on proton-neutron part of the nuclear interaction. In fact, Antimony isotopes with one valence proton have a great interest in the determination of the N-N interaction properties, in the aim of giving a unified description of nuclear structure.

In the last fifty years, many experimental studies were focused on the discovery and the measure of odd Antimony isotopes ^{132}Sn mass region [3]. These isotopes were produced using the fission of $^{235\text{-}238}U$ samples [3], or proton beams on tin targets [4]. As cited in Ref. [3], ^{133}Sb was first discovered by Strom et al. (1966). It was produced by thermal neutron induced fission of ^{235}U at the Stanford 10-kW reactor. M. Sanchez-Vega et al. (1999) have investigated the β decay of ^{133}Sn isotope in order to determine the low energy structure of ^{133}Sb [5]. In 2010, B. Sun et al. [6] have studied the core excited isomer ^{133}Sb by applying a novel technique of isochronous mass spectrometry at GSI, and they measured the 4.56 MeV excited state with the half live of 17 μs.

^{135}Sb was observed by Bemis et al. (1964), as mentioned in Ref. [3], following the irradiation of Uranium samples by thermal neutrons in the MIT Reactor. They have observed its first excited stated at the excitation energy of only 282 keV with a preliminarily measured half-life, $T_{1/2}$ = 6.0 *ns* [7]. Coraggio et al. in [8] have studied few valence nucleons neutron rich nuclei with $133 \leq A \leq 137\ and\ 50 \leq Z \leq 52$ when adding proton and neutron pairs in order to follow shell evolution in ^{132}Sn mass region. The calculations were based on the consideration of the monopole effect using V_{low} approximation. They have obtained the same energetic sequences as the available experimental ones. However, the differences between the calculated excited energies and the experience are about 100 keV.

Motivated by these experimental achievements and theoretical studies, we have considered the odd antimony isotopes to reproduce their experimental spectra and to predict the nuclear structure of $^{137\text{-}139\text{-}141}$Sb. The effect of the monopole interaction, on the nuclear structure of odd Sb isotopes and those are far from β stability and near ^{132}Sn mass region, is also evaluated.

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2. THEORETICAL FRAMEWORK

The two body N-N interaction, in which the nucleus contains an inert core without any interactions with the valence particles, fail to reproduce nuclear properties of some isotopic chains [9, 10].

A. Poves and A. Zuker [11] shown that it is required to consider the monopole interactions between the core and the valence particles in order to reproduce the missing nuclear properties. They proposed to separate the Hamiltonian of the system into two parts: a monopole part H_m and a multipole one H_M,

$$\begin{aligned} H &= H_m + H_M \\ H_m &= \sum_s n_s \varepsilon_s + \sum_{s \le t} \left(a_{st} n_{st} + b_{st} T_{st} \right) \end{aligned} \tag{1}$$

s and/or *t* refer to proton and/or neutron orbits. $n_{s,t}$ and $T_{s,t}$ refer, respectively, to the number and the isospin operator [12, 13]. The operators a_{st} and b_{st} are defined in ref. [13] as function of the monopole Hamiltonian diagonal part V_{st}^T. This latter is expressed in term of the average energies over the configurations of *s* and *t* orbits with T=1 for *proton-proton* and *neutron-neutron*, and T=0, 1 for *proton-neutron* parts of H_m [9, 13, 14, 15],

$$V_{st}^T = \frac{\sum_J (2J+1) \left\langle j_s j_t \middle| V_{st} \middle| j_s j_t \right\rangle_J^T \left[1 - (-1)^{J+T} \delta_{st} \right]}{\sum_J (2J+1) \left[1 - (-1)^{J+T} \delta_{st} \right]} \tag{2}$$

The two body matrix elements $\left\langle j_s j_t \middle| V_{st} \middle| j_s j_t \right\rangle_J$ arisen from the interaction between the particles in the orbits *s* and *t* can be extracted from the proton and/or the neutron separating energies of neighbouring nuclei.
The monopole interaction, risen from addition nucleon pairs to proton and/or neutron orbits, lead to modifications or evolution of single particle energies of these orbits [16]. The resulting effective single particle energies (*ESPEs*) are given in terms of single particle energies (*SPE*) ε_S for orbits *s* and of the occupation numbers ($2j_t$+1) of the other orbits *t* [8, 10]:

$$ESPE_s = \varepsilon_s + \sum_t (2 j_t + 1) V_{st}^T \tag{3}$$

Considering a doubly closed shell core (A, Z), the monopole component of the *proton-neutron* interaction can be written [10],

$$V_{j_\pi j_\upsilon}^{pn} = \frac{1}{2} \left[S_p (A+3, Z+1) - S_p (A+1, N) \right] \tag{4}$$

L. Corragio et al. (2013) in ref. [8], have studied shell evolution beyond ^{132}Sn mass region by adding proton or neutron pairs, using V_{low} approach. They have performed spectroscopic calculations for odd mass nuclei in this region. They have found that the dominant terms for the *proton- neutro*n monopole components were, respectively, $V_{j_\pi f_{7/2}}^{pn}$ and $V_{g_{7/2} j_\upsilon}^{pn}$.

In this context and basing on the monopole interaction between $\pi g_{7/2}$ and $\nu f_{7/2}$, we carried out spectroscopic calculations, aimed to estimate some nuclear properties of antimony isotopes near ^{132}Sn mass region, in the framework of the nuclear shell model by means of Oxbash nuclear structure code [17].

The development and the progress in the theoretical approaches describing nuclear systems, in the last few years, give rise to increasing dimension of matrices when solving Schrödinger equation. However, there exists a limit to the maximum dimension of matrices than can be diagonalized, in spite of the powerful used computing devices, especially for large model spaces and many valence particles.

L. Corragio et al. in Ref. [18] pointed out that the truncation of shell model space is one of the powerful methods to simplify the computational problem of large scale shell model calculations. They have studied isotopic chains near ^{100}Sn mass region in truncated spaces and compared the obtained results with those in the full space. They found that it is useful to use the *ESPEs* in order to exclude some subshells from the space model and find a reduced one preserving the reliability of the shell model calculations.

In this context, we have used this method in ^{132}Sn mass region to reduce the computational complexity of large-scale shell calculations. By correcting (*SPEs*) and using the resulting (*ESPEs*), proton-neutron monopole effect consideration introduces some modifications on two body matrix elements (*TBMEs*) of the original interaction *kh5082* (W. T. Chou and E. K. Warburton [19]), and using Eq.4, we have calculated the $V^{pn}_{1g_{7/2}2f_{7/2}} \approx 400\ keV$ to modify $\left(1g_{7/2}2f_{7/2}\right)^{T=0}_{J=0-7}$ TBMEs. By means of the resulting interaction *mkh* some calculations are released.

After the calculation of *ESPEs* resulting from *mkh* interaction, two proton ($3s_{1/2}$ and $1h_{11/2}$) and two neutron ($2f_{5/2}$ and $1i_{31/2}$) subshells were excluded as shown in Fig.1.

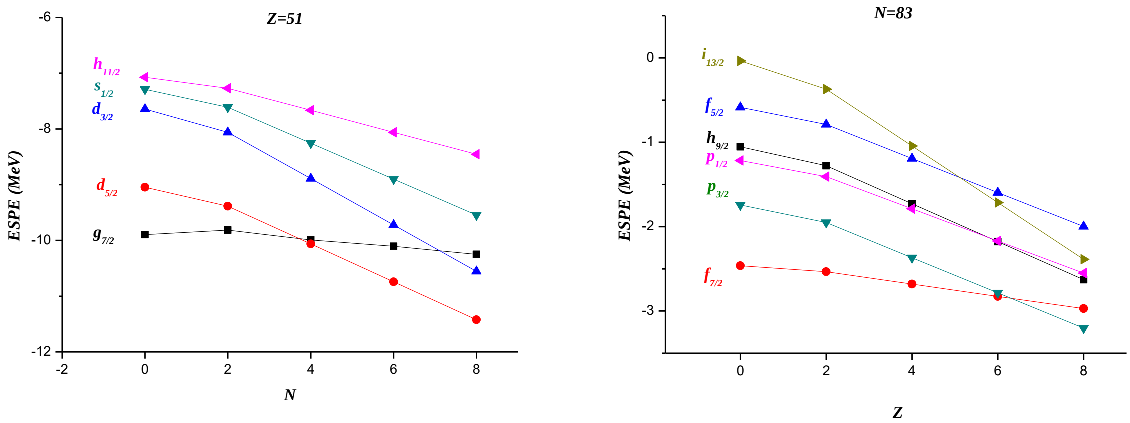

Fig.1 Calculated effective single particle energies of *mkh* interaction as a function of N (left) and Z (right) numbers.

3. RESULTS AND DISCUSSION

We have performed shell model calculations, using the new interaction *mkh* in $\pi(0g_{7/2}, 1d_{5/2}$ and $1d_{3/2})^{Z-50}$ and $\nu(0h_{9/2}, 1f_{7/2}, 2p_{3/}$ and $2p_{1/2})^{N-82}$ truncated space model using ^{132}Sn as a magic core. The experimental single particle energies taken from ^{133}Sb for protons and ^{133}Sn for neutrons is used as a starting point to calculate the effective single particle energies [20, 21] using in the interaction.

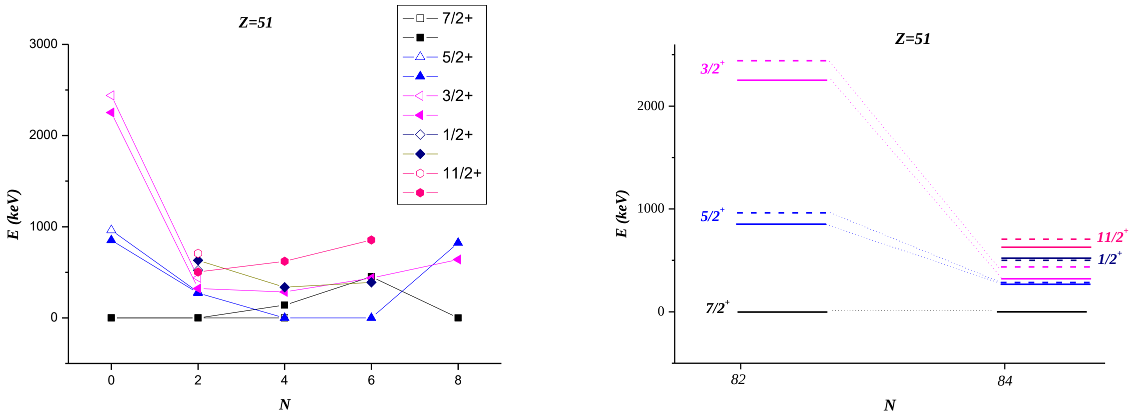

Fig.2. Left: Calculated energetic spectra (full forms) using *mkh* interaction as a function of N in comparison with the experimental ones (opened forms) for odd- even *Sb* isotopes in ^{132}Sn mass region. **Right:** Calculated spectra (discontinued lines) for $^{133\text{-}135}$Sb isotopes in comparison with the experimental (dashed lines) data.

The available experimental ground states of the odd antimony isotopes in ^{132}Sn mass region are dominated by $\pi(1g_{7/2})^1\nu(2f_{7/2})^{2n}$ n= 0,1, or 2. Our spectroscopic calculations gave the same configuration for the ground state for the studied nuclei except for $^{137\text{-}139}$Sb for which we obtained $\pi(2d_{5/2})^1\nu(2f_{7/2})^{4\text{-}6}$. The fig.2 (right) shows that the new interaction lead to reproduce the energetic sequences of $^{133\text{-}135}$Sb isotopes. The differences between the experimental data and the calculated result turn around 100 keV for ^{133}Sb and 150 keV for ^{135}Sb. For ^{137}Sb, it gives $\frac{5}{2}^+$ as a ground state, however the experimental one has the spin $\frac{7}{2}^+$. As shown in Fig.3, our new interaction *mkh* gives closer results than those obtained by the V_{low} [8] interaction in comparison with the available data for the first excited state in ^{135}Sb. But it misses the ground state spin for ^{137}Sb reproduced by V_{low} interaction.

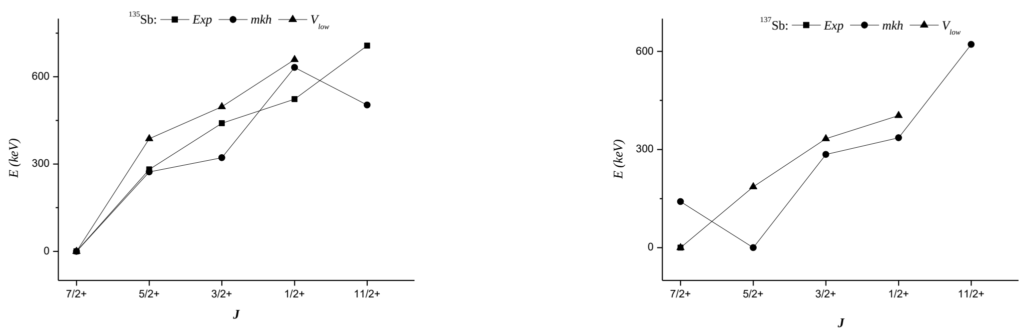

Fig.3. Calculated energetic spectra of $^{135\text{-}137}$Sb by means of V_{low} and mkh interactions in comparison with the experimental data.

4. CONCLUSION

In summary, this study is based on the energetic spectra calculations, for odd- even Z=51 isotopes, with few valence neutrons in there valence spaces. The calculations are carried out in the framework of the shell model in a truncated space, by means of *Oxbash* nuclear structure code. Using *kh5082* the original interaction of the code, we carried out some modifications based on the proton-neutron monopole effect to get mkh interaction. This new interaction gave a reasonable agreement between the calculated and the experimental data for $^{133-135}$Sb, however it cannot reproduce the ground state of ^{137}Sb nucleus.

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