Spectroscopic properties of ^{130}Sb , ^{132}Te and ^{134}I nuclei in $^{100-132}\text{Sn}$ magic cores

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Abstract. We have performed shell model calculations by means of Oxbash nuclear structure code using recent experimental single particle (spes) and single hole (shes) energies with valence space models above the ^{100}Sn and ^{132}Sn doubly magic cores. The two-body matrix elements (tbme) of original CD-Bonn realistic interaction are introduced after have been modified taking into account the three-body forces. We have focused our study on spectroscopic properties evaluation of ^{130}Sb , ^{132}Te and ^{134}I nuclei, in particular their energy spectra, transition probabilities and moments have been determined. The getting spectra are in reasonable agreement with the experimental data.

1 Introduction

The effective interaction is a key ingredient for the success of the nuclear shell model. Once a reliable interaction is obtained, we can describe various nuclear properties accurately and systematically, which helps us to understand the underlying structure, and to make predictions for unobserved properties. Structure properties of some nuclei are important inputs for astrophysical r-process model calculations. Particularly, the study of nuclei in the vicinity of doubly magic Sn is indeed a subject of great current experimental and theoretical interest. Experimental information on these nuclei, which have been long inaccessible to spectroscopic studies, is becoming available.

In the last decades, many experimental studies were focused on the discovery of exotic nuclei. In 1948, the ^{134}I isotope was identified by Katcoff et al. [1,2]. Plutonium foils were irradiated with neutrons in the Los Alamos homogeneous pile Fission. In addition, excited levels up to an energy 3691 keV in ^{134}I were measured through the γ rays from the spontaneous fission of ^{252}Cf [3] and in the reaction $^{136}\text{Xe} + ^{208}\text{Pb}$ [4]. In 2009, Coraggio et al. [5] have interpreted the five-observed high-excited states on the basis of a realistic shell-model calculation. They attributed spin-parity assignments to iodine states and they were found very good agreement between the experimental and calculated energies. Very recently, Laouet and Benrachi [6] have performed a study of odd-odd particle-hole nuclei in ^{132}Sn mass region basing on the effect of proton-neutron monopole interaction on the nuclear structure of $N=81$ isotones. The first identification of ^{132}Te was provided by Katcoff et al. in [1]. Besides, Brown et al. [7] have reported shell-model calculation of magnetic moments for selected Sn and Te isotopes, by means a residual interaction based on the CD-Bonn renormalized G-matrix. In a recent paper [8,9], two new levels above 10^+ isomer state have been

experimentally identified in ^{132}Te . Hagebo et al. [10] reported the discovery of ^{130}Sb in 1962. Enriched ^{130}Te targets were irradiated with neutrons produced by bombarding beryllium with a 21 MeV deuteron beam from the Amsterdam cyclotron and ^{130}Sb was formed in (n,p) charge exchange reactions. Covello et al. [11] have performed shell-model calculations for nuclei close to doubly magic ^{132}Sn and ^{100}Sn focusing on particle-hole multiplets. They made realistic effective interactions derived from the CD-Bonn nucleon-nucleon potential. They have found that the agreement between experiment and theory is remarkably good for these calculations for ^{130}Sb . It should be noted that both the experimental and calculated energies are relative to the 8^- state, which has been experimentally observed to be the ground state.

2 Theoretical framework

The two body realistic interactions derived from the N-N force fail to reproduce some nuclear properties [12]. This problem can be solved by the consideration of the monopole interaction [13]. Zuker had shown in [13,14] that a very simple three body monopole term can solve practically all the spectroscopic problems in the p, sd, and fp shells. Those were assumed to need drastic revisions of the realistic two-body potentials. In 2010, Otsuka et al. [15] have also shown that three-body forces are necessary to explain drip line for oxygen isotopes. Therefore, Sarkar have incorporated [12] a simple three-body monopole term as prescribed by Zuker in [13,14]. Poves and Zuker [14] proposed to separate the Hamiltonian of the system into two parts:

$$H = H_m + H_M \quad (1)$$

where H_M and H_m denote respectively the multipole and the monopole Hamiltonians. The monopole Hamiltonian is defined as:

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$$H_m = E_0 + \sum_i \varepsilon_i n_i + \sum_{i \leq j} V_{ij} \frac{n_i (n_j - \delta_{ij})}{(1 + \delta_{ij})} \quad (2)$$

$$V_{ij} = \frac{\sum_J (2J+1) V_{ijJ}^J}{\sum_J (2J+1)}$$

where ε_i corresponds the single particle energies (spes) and n_i , n_j are the valence nucleon numbers in the i and j shells, respectively.

For an inert core of closed shells (Z , N), the monopole term of the proton-neutron interaction can be determined by using differences in binding energies between neighboring nuclei and it given by [16],

$$V_{j\pi j\nu}^{pn} = \frac{1}{2} [BE(Z+1, N+2) - BE(Z, N+2)] - [BE(Z+1, N) - BE(Z, N)] \quad (3)$$

The main aim of this paper is to present some nuclear properties from this study, focusing attention on the proton-neutron multiplets in the ^{130}Sb , ^{132}Te and ^{134}I nuclei in the framework of the nuclear shell model by means of Oxbash nuclear structure code [17].

2.1 Cores ^{100}Sn and ^{132}Sn

For calculations, the CD-Bonn in the proton-neutron formalism and Sn132ph interactions were used. The CD-Bonn interaction in the isospin formalism developed by Machleidt [18, 19] was based on the predictions of Bonn interaction for $j \leq 4$ [18]. Basing on the mass dependence effect, we have modified the two body matrix elements (tbmes) of the original CD-Bonn [19] in order to perform shell model calculations using ^{132}Sn doubly magic nuclei as an inert core. To evaluate these modifications, we

have used $\left(\frac{100}{132}\right)^{1/3}$ mass factor. The resulting two body matrix elements have been changed using the monopole interaction between $\pi g_{7/2}$ and $\nu d_{3/2}$ shells with $V_{lg_{7/2} 2d_{3/2}}^{pn} \approx 150\text{keV}$ to modify $(lg_{7/2} 2d_{3/2})_{J=2-5}^{T=0}$ *tbmes*. The experimental proton spes taken from the spectra of ^{133}Sb and neutron shes taken from ^{131}Sn are used [20, 21] and new interaction named Sn132ph is introduced. The calculations have been realized in the $jj55pn$ valence space. This later consists of five orbitals for both protons and neutrons above the ^{100}Sn inert core. The studied nuclei in this work have 30, 32 and 34 total valence particles with one, two and three proton particles, respectively. Most of the neutron orbitals are completely filled up, and these nuclei contain, respectively, three, two and one neutron holes. Therefore, no truncation was needed for the present calculation.

2.2 Probabilities and moments

The reduced electromagnetic transition probabilities are calculated by the form:

$$B(M_{\sigma\lambda} : J_i \rightarrow J_f) = (2J_i + 1)^{-1} \left| \langle J_f \| M_{\sigma\lambda} \| J_i \rangle \right|^2 \quad (4)$$

In the calculation of the reduced magnetic transition probabilities $B(M1)$, we use the effective factors $g_s^p(\text{eff.})=3.79$, $g_s^n(\text{eff.})=-2.04$, $g_l^p(\text{eff.})=1.102$ and $g_l^n(\text{eff.})=-0.005$. These values are adopted for nuclei in ^{132}Sn mass region [22].

The lowest negative parity states of the studied nuclei are dominated by $\{\pi 1g_{7/2}, \nu 2d_{3/2}; J\}$ and configuration with $j_p = 7/2$ and $j_n = 3/2$. The electromagnetic moments of a state J with different proton and neutron spins can be calculated by means of [23]:

$$\mu_J = \mu_N \frac{J}{2} \left[\frac{\mu_j(p)}{j_p} + \frac{\mu_j(n)}{j_n} + \left(\frac{\mu_j(p)}{j_p} - \frac{\mu_j(n)}{j_n} \right) \frac{j_p(j_p+1) - j_n(j_n+1)}{J(J+1)} \right] \quad (5)$$

$$Q_J = \begin{pmatrix} J & 2 & J \\ -J & 0 & J \end{pmatrix} (-1)^{j_p+j_n+J} (2J+1) \left[\begin{pmatrix} j_p & J & j_n \\ J & j_p & 2 \end{pmatrix} \frac{Q_{j_p}}{\begin{pmatrix} j_p & 2 & j_p \\ -j_p & 0 & j_p \end{pmatrix}} + \begin{pmatrix} j_n & J & j_p \\ J & j_n & 2 \end{pmatrix} \frac{Q_{j_n}}{\begin{pmatrix} j_n & 2 & j_n \\ -j_n & 0 & j_n \end{pmatrix}} \right] \quad (6)$$

Here, $Q_{jp, jn}$ denote respectively single proton/neutron quadrupole moment

$$Q_j(p, n) = -\frac{(2j-1)}{(2j+2)} \langle r^2 \rangle e_{\lambda=2}^{p,n}(\text{eff.}) \quad (7)$$

$e_{\lambda=2}^{p,n}(\text{eff.})$ is the effective charge of the nucleon and $\langle r^2 \rangle$ is the mean square radius of the nucleon in that orbital. Whereas, we have calculated the quadrupole electric moments using $e_p = 1.35e$ and $e_n = 0.9e$ effective charges.

3 Results and discussion

We have performed shell-model calculations by means of the new interactions Sn132ph in $jj55pn$ space model using ^{100}Sn and ^{132}Sn doubly magic cores. The experimental ground states of ^{130}Sb , ^{132}Te and ^{134}I nuclei in ^{132}Sn mass region are dominated by $\pi(1g_{7/2})^1 \nu(1h_{11/2})^{-3}$, $\pi(1g_{7/2})^2 \nu(2d_{3/2})^{-2}$ and $\pi(1g_{7/2})^3 \nu(2d_{3/2})^{-1}$, respectively. Our spectroscopic calculations gave the same configuration for the ground states except for ^{130}Sb .

Fig.1(a) and Fig.1(b) show that the agreement between experimental data and the calculated spectrum using the new interaction Sn132ph is reasonable for the studied nuclei. However, it gives an inversion between the ground state and the first excited one of ^{130}Sb . For ^{132}Te and ^{134}I , it gives an inversion between 8^+ and 10^+ , and 3^+ and 5^+ states, respectively. The CD-Bonnpn interaction gives different energies from the experimental ones.

We have also calculated the electromagnetic properties for ^{130}Sb , ^{132}Te and ^{134}I nuclei, and the results are presented in Tab. 1, Tab. 2 and Tab. 3, in comparison with the available data. The values of electromagnetic properties $B(M1)$, $B(E2)$, τ , μ and Q for the studied nuclei were different in both interactions. Therefore, the calculations of μ and Q moments for ^{130}Sb gave the same values for both interactions. But, for ^{132}Te nucleus, the calculated value of τ was found a very good agreement with experimental one on *Sn132ph* interaction, as shown in table below.

Fig. 1. Calculated energetic spectra using CD-Bonnnpn and Sn132ph interactions in comparison with the experimental ones for ^{130}Sb , ^{132}Te and ^{134}I nuclei.

Table 1. Electromagnetic properties for ^{130}Sb nuclei in the vicinity of ^{132}Sn mass region

J_i	J_f	$B(M1: \mu_N^2)$		$B(E2: e^2\text{fm}^4)$		$\tau(\text{ps})$		$\mu(J_i: \mu_N)$		$Q(J_i: \text{efm}^2)$	
		CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph
3+	2+	0.28	0.611	38	93.357	3.322	3.306	-1.593	-1.171	25.12	22.60
4+	2+	/	/	41.733	83.777	1.469	4.224	-0.6826	-0.4184	30.47	26.41
	3+	1.445	1.435	37.333	70.108	/	/				
5+	3+	/	/	44.927	72.164	25.69	42.22	-0.1419	0.01313	28.65	25.76
	4+	1.552	1.482	142.772	197.427	/	/				

Table 2. Electromagnetic properties for ^{132}Te nuclei in the vicinity of ^{132}Sn mass region

J_i	J_f	$B(E2: e^2\text{fm}^4)$		$\tau(\text{ps})$			$\mu(J_i: \mu_N)$			$Q(J_i: \text{efm}^2)$	
		CD-Bonnnpn	Sn132ph	Exp	CD-Bonnnpn	Sn132ph	Exp	CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph
2+	0+	218.7	335.1	2.64	6.424	3.903	0.70	0.6955	6.793	6.793	27.71
4+	2+	123.4	395.2	/	5.058	4.119	/	2.487	-27.82	-27.82	15.84
6+	4+	197.3	97.49	209E+3	340E+3	5.834 E+3	5.08	4.930	-65.92	-65.92	-60.23
8+	6+	81.36	3.143	/	4.796	29.58	/	-1.076	-45.76	-45.76	20.63
10+	8+	0.0006642	42.119	/	7.426	0.02958	/	-1.712	71.64	71.64	65.71
12+	10+	50.01	78.39	/	8.586	8.313	/	0.9203	33.80	33.80	40.93
14+	12+	0.1436	2.933	/	4.806	0.405	/	3.259	-21.51	-21.51	7.531

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Table 3. Electromagnetic properties for ^{134}I nuclei in the vicinity of ^{132}Sn mass region.

J_i	J_f	$B(+1; \mu_N^2)$		$B(E2: e^2fm^4)$		$\tau(ps)$			$\mu(Ji: \mu_N)$		$Q(Ji:efm^2)$	
		CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph	Exp	CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph	CD-Bonnnpn	Sn132ph
2 ⁺	1 ⁺	0.6204	0.002163	149.52	0.11514	0.04	/	32.92E+03	2.807	2.276	5.833	-26.76
3 ⁺	1 ⁺	/	/	67.84	152.48	22.72	87.02	1333	3.839	2.058	-21.45	-34.43
	2 ⁺	0.2901	2.825E-04	221	3.632							
4 ⁺	2 ⁺	/	/	0.06218	62.222	3.36	0.8121E+5	/	3.044	2.992	-19.06	-5.799
	3 ⁺	0.009428	0.03990	28.34	13.618							
5 ⁺	3 ⁺	/	/	7.051	81.44	/	147.4	1535	3.523	3.377	-8.522	0.5724
	4 ⁺	0.02443	0.01132	251.3	215.1							
10 ⁻	8 ⁻	/	/	101.9	115.6	/	0.8585	1.981	4.897	3.472	-6.533	26.62
12 ⁻	10 ⁻	/	/	4.605	5.924	/	0.4785	1.134	7.216	7.09	-18.01	-18.56
	11 ⁻	1.952	1.963	300.5	285.5							
13 ⁻	12 ⁻	0.8026	0.5275	108.8	76.41	/	0.1426	0.4956	7.684	6.529	-25.66	-14.5
14 ⁻	12 ⁻	/	/	41.9	34.72	/	0.1968	0.2329	7.92	8.00	-28.64	-29.05
	13 ⁻	1.074	0.8296	128.4	125.7							

4 Conclusion

In this work, we focused on the study of the mass effect on the nuclear structure of nuclei far from beta stability. More generally, we have explored in a semi-quantitative manner the nuclear force which lead to modification of shell structure in ^{132}Sn region. The properties were derived from two-body effective interactions including monopole effect in the SM framework, by means of Oxbash nuclear structure code using CD-Bonn the original interaction of the code and carrying out some modifications based on the mass factor and monopole effect to get *Sn132ph* new interaction. The resulting energetic spectra using the new interactions are in good agreement with the available experimental data. For the electromagnetic properties, the obtained values using the original and the new interactions are different the three nuclei. But, for ^{132}Te nucleus, the calculated value of τ of the first excited state using *Sn132ph* interaction is in agreement with experimental one.

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