136Sn and three-body forces

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Abstract. New experimental data on 2+ energies of 136,138Sn confirm the trend of lower 2+ excitation energies of even–even tin isotopes with N > 82 compared to those with N < 82. However, none of the theoretical predictions using both realistic and empirical interactions can reproduce experimental data on excitation energies as well as the transition probabilities (B(E2; 6+ → 4+)) of these nuclei, simultaneously, apart from the ones whose matrix elements have been changed empirically to produce mixed seniority states by weakening the pairing. We have shown that the experimental result also shows good agreement with the theory in which three-body forces have been included in a realistic interaction. The new theoretical results on transition probabilities are discussed to identify the experimental quantities which will clearly distinguish between different views.

Keywords. Shell model; neutron-rich nuclei; nuclear structure; B(E2) values; 90 ≤ A ≤ 149.

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1. Introduction

Nuclei around doubly closed 132Sn lie on or close to the path of astrophysical r-process flow. Structure of these nuclei, particularly the binding energy (BE), low-lying excited states and β decay rates at finite temperatures are important ingredients for calculating nucleosynthesis. However, these nuclei usually are experimentally inaccessible by common techniques of nuclear spectroscopy. So far, experimental investigations have been performed using spontaneous fission sources, thermal-neutron-induced fission deep inelastic reactions, fragmentation and fission at intermediate and relativistic energies. Reactions with neutron-rich radioactive ion beams are expected to generate very important, reliable database for these nuclei.

So far the experimental status [1] was not at all satisfactory for Sn isotopes beyond 132Sn. Spectroscopic information, such as BE and low-lying spectrum, is known experimentally only for 134Sn. Half-lives of 135–137Sn were measured using the β–n decay process. Lifetimes of these nuclei are very small and production rates are also very low,
thus presenting challenges to spectroscopic studies. Reliable theoretical results are therefore necessary and useful, especially as inputs to calculations for astrophysical processes. Being close to the doubly closed neutron-rich $^{132}$Sn nucleus, this region has been considered as a fertile ground for testing nuclear shell model (SM) with interactions suited for nuclei far from stability.

2. Evolution of our endeavours

We have started working in this mass region in the early 2000, with a systematic study [2] utilizing the available interactions. We have used the then available version of the shell model code OXBASH [3]. The interactions [4] used by us were KH5082 and CW5082. The SM calculations were carried out in the Z50N82 model space (figure 1). The earlier workers realized that there are many points of similarity between the spectroscopy of the doubly closed shell regions around the stable $^{208}$Pb and neutron-rich $^{132}$Sn. The two interactions mentioned above are such $(1 + 2)$-body nuclear interaction Hamiltonians where interactions of $^{208}$Pb region are scaled down to the next lower available doubly magic domain, i.e., in the $^{132}$Sn region. Most of our results satisfactorily explained the available experimental data for several neutron-rich isotopes of $^{52}$Te, $^{53}$I, $^{54}$Xe, $^{55}$Cs, $^{56}$Ba with $N = 82$ and 83. However, we found that, for $N \geq 84$ isotones, the interactions were not as successful and seemed to be inappropriate. The energy levels were overpredicted for these neutron-rich nuclei [5]. So, the limitations of the two interactions in predicting experimental observables in $N \geq 84$ isotones, clearly indicated the necessity of changing particularly the $n–n$ two-body matrix elements (tbmes) of the interactions.

2.1 Construction of the new Hamiltonian

Keeping in mind the conclusion of our first work in this mass region, we attempted a simple modification of the CW5082 interaction [4]. The CW5082 Hamiltonian was modified using the available information on binding energies, low-lying spectra of two-nucleon nuclei: $A = 134$ isobars of Sn, Sb and Te isotopes. The energies of the single-particle orbitals of valence space above the $^{132}$Sn core have been replaced by the experimental ones. The details of this modification procedure are discussed in [5]. The

![Figure 1](image)

**Figure 1.** The valence space for protons (p) and neutrons (n) above the $^{132}$Sn core.
new Hamiltonians work remarkably well in predicting binding energies, low-lying spectra and electromagnetic transition probabilities for $N = 82, 83$ and even for $N \geq 84$ isotones of Sn, Sb, Te, I, Xe and Cs nuclei. Out of the total 2101 tbes, only 26 tbes are modified in SMPN interaction. Twelve of them are $n-p$ tbes, four are $p-p$ and the rest (10) are $n-n$ tbes. Six of these neutron–neutron matrix elements are diagonal elements coupled to $0^+$ spin. These matrix elements are reduced, implying pairing reduction in this neutron-rich domain. The modified two-body matrix elements of the SMPN are tabulated in [6].

2.2 Comparison with realistic interaction

The success of this new interaction (figure 2) prompted us to apply it for several new datasets obtained by experimentalists [7–9]. In the mean time, few other groups have worked with the CD-Bonn potential-based realistic interactions [10–12]. Their results also agreed well with many of the available data. So our next aim is to compare the results obtained by the empirically modified interactions with those obtained by the realistic interactions.

We have used the CD-Bonn potential-based realistic CWG [10] and the empirical SMPN interactions. These Hamiltonians are used in this neutron-rich region and have the

![Figure 2](image)

**Figure 2.** Comparison of the experimental and theoretical energy spectra of $^{136}$Te.
same set of single-particle energies of the valence orbitals but different sets of two-body interaction matrix elements. The SM calculations [13] were carried out in the Z50N82 model space (figure 1) with the SMPN and CWG Hamiltonians using the OXBASH and NuShell codes [3].

The calculations have been done [13] for $^{138}$Sn ($T_z = +3.0$) with six neutrons, $^{138}$Te ($T_z = +1.0$) with four neutrons and two protons, $^{138}$Xe ($T_z = -1.0$) with two neutrons and four protons and finally, $^{138}$Ba ($T_z = -3.0$) with six valence protons. Untruncated shell model calculations for six valence nucleons in this basis space usually involve matrices of large dimensions. Calculated energy eigenvalues of the levels with the SMPN and CWG Hamiltonians are in good agreement with the experimental ones up to the highest observed level in $^{138}$Te (figure 3), $^{138}$Xe and $^{138}$Ba [13] (including the non-yrast levels in $^{138}$Xe, Ba). In the CWG results all the energy eigenvalues of the excited states are systematically underpredicted by about 100–150 keV. For neutron-rich ones like $^{138}$Te, both these calculations reproduced reasonably well the vibrational spectrum of this nucleus (figure 3) is indicated by the value $R_4 = E(4^+_1)/E(2^+_1) = 2.04$. In both the results, the lowest proton and neutron orbitals have the maximum occupation. The CWG wave functions have comparatively larger occupation in other orbitals also, indicating larger configuration mixing.

2.3 Predictions for neutron-rich heavy Sn isotopes

It was remarkable that for $^{136,138}$Sn, where the experimental level schemes were not known until recently, the two results [13] differ dramatically (figures 4–6). The energies of the first three excited states $2^+_1$, $4^+_1$ and $6^+_1$, for $^{138}$Sn with the CWG Hamiltonian appear at about twice of those predicted by SMPN.

![Figure 3. Comparison of the experimental data and the theoretical predictions for excitation energies in $^{138}$Te.](image)
In $^{138}$Sn, multiplet structure with $\nu 2f_{7/2}$ is more clear in SMPN results for $0^+$ to $6^+$ states. Six neutrons, or in other words, two neutron holes in $\nu 2f_{7/2}$ can couple to $J_{\text{max}} = 6$. Thus for generating the $8^+$ state a pair of neutrons must be promoted to a higher-lying single-particle orbital. This leads to an energy gap of about 2.0 MeV, in the spectrum between the first $6^+$ and $8^+$ states, as shown in the SMPN results (figure 6). This gap is about 0.8 MeV for CWG. This structural difference is also demonstrated clearly in the calculated $B(E2; 4^+ \rightarrow 2^+)$ and $B(E2; 2^+ \rightarrow 0^+)$ values with SMPN and CWG [14] (table 1).
The calculated excitation spectra of $^{138}\text{Sn}$ using SMPN, CWG3M and CWG interactions. Results are compared with the experimental data.

While comparing [13] the structure of the states in $^{138}\text{Ba}$ having six valence protons with that of $^{138}\text{Sn}$ having the same number of neutrons, it is found that the protons in this valence space are more efficient in generating configuration mixing. This is essentially

Table 1. Comparison of the calculated $B(E2)$ ($e^2\text{fm}^4$) values for major transitions connecting the positive-parity yrast levels till $12^+$ for $^{136,138}\text{Sn}$. The experimental values of $B(E2; 6^+_1 \rightarrow 4^+_1)$ for $^{136,138}\text{Sn}$ is 24(4) and $\simeq 17$ $e^2\text{fm}^4$, respectively [20]. Effective neutron charge $e_n = 0.64$.

| $I_i$ | $I_f$ | CWG [10] | CWG3M [14] | SMPN [5] |
|------|------|----------|-----------|--------|
| $^{136}\text{Sn}$ | | | | |
| 2    | 0    | 125      | 88        | 90     |
| 4    | 2    | 86       | 81        | 43     |
| 6    | 4    | 14       | 45        | 14     |
| 8    | 6    | 53       | 48        | 46     |
| 10   | 8    | 0.0097   | 0.0948    | 0.0954 |
| 12   | 10   | 91       | 77        | 69     |
| 6    | 4(2) | 52       | 16        | 45     |
| $^{138}\text{Sn}$ | | | | |
| 2    | 0    | 184      | 73        | 69     |
| 4    | 2    | 0.3286   | 45        | 44     |
| 6    | 4    | 12       | 21        | 20     |
| 8    | 6    | 1.05     | 0.20      | 0.73   |
| 10   | 8    | 138      | 104       | 81     |
| 12   | 10   | 60       | 56        | 44     |
due to close spacing between $\pi(gds)$ single-particle orbitals that permit $\pi-\pi$ residual interaction to easily scatter protons to various single-particle states.

The structure of the wave function shows [13,14] that the CWG interaction favours large configuration mixing thus conserving seniority as far as possible. In contrast, SMPN favours the purer structure of the low-lying states and shows characteristics of $\nu(2f_{7/2})$ multiplets. Interestingly, this structural difference has a dramatic effect on the transition rates (especially, $B(E2; 2^+ \rightarrow 0^+)$) calculated with these two interactions for both $^{136,138}$Sn [14].

In [13], energies, wave functions and $B(E2, 0^+_{g.s.} \rightarrow 2^+_{1^-})$ values are compared for the yrast $0^+$ and $2^+$ states of the three Sn isotopes. It was found that although the $E(2_{1}^+)$ energy increases with increasing neutron number in Sn isotopes for $N \geq 84$, $B(E2)$ values corresponding to the SMPN calculations do not increase as expected. This feature was already observed experimentally in the neutron-rich $^{136}$Te isotope in this mass region. Origin of an anomalously low $B(E2, 0^+_{g.s.} \rightarrow 2^+_{1^-})$ value found in this nucleus was traced to a reduced neutron pairing above the $N = 82$ shell gap. Interestingly, similar behaviour is also seen near the $N = 20$ shell closure for neutron-rich Mg and Ne isotopes [13]. It seems to be a unique feature observed in neutron-rich nuclei. In this domain, a comparatively lower value of $E(2_{1}^+)$ does not necessarily imply a larger $B(E2)$ value indicating collectivity. This feature is predicted theoretically with the SMPN interaction for $N \geq 84$.

### 2.3.1 The shell closure at $N = 90$ for the Sn isotope and its origin

In a subsequent work [14], with SMPN interaction, the prediction for $E(2_{1}^+)$ of $^{140}$Sn appears to be much larger than expected. The comparison of the high $2_{1}^+$ energy of $^{140}$Sn with examples from other neutron-rich domains [14] clearly shows that $N = 84-88$ spectra with SMPN manifest the effect of gradually filling up the $\nu(2f_{7/2})$ orbital, which finally culminates in a new shell closure at $N = 90$.

To understand how the shell closure at $N = 90$ develops as the number of valence neutrons increases from $^{132}$Sn, the effective single-particle energies (ESPE) for the neutron orbitals for the two Hamiltonians are compared [14]. To investigate the specific component of interaction which is responsible to generate this new shell gap, the two-body matrix elements of both CWG and SMPN are spin-tensor decomposed [14,15] into central, antisymmetric spin-orbit (ALS), spin-orbit (LS) and tensor parts [14]. For SMPN, the central and ALS parts for $2f_{7/2}-2f_{7/2}$ tmbes account for the majority of the downward shift of the ESPE of $2f_{7/2}$ with increasing valence neutron number ($n$). Variation in ALS part is primarily responsible for this shell gap observed at $N = 90$ [14].

While analysing our results, we had to understand the implication of the ALS term. Bare nucleon–nucleon force does not contain ALS term. A characteristic feature common to many empirical effective interactions is the strong ALS components in the tmbes. It indicates important contributions from higher-order renormalization or many-body effects to the effective interactions. In empirical SMPN such many-body effects might have been included in some way through the modification of important tmbes using the experimental data.

However, it has been observed experimentally that $N = 90$ is suitable for the onset of deformation for nuclei above Sn (like Xe, Ba, etc.). Therefore, the energy of the deformed configuration also reduces. The presence of valence protons above the inert
core is essential for the onset of collectivity. The ESPEs for SMPN which indicate the features of a shell closure for \( Z = 50 \) at \( N = 90 \), have also been analysed to indicate the possibility of onset of deformation at \( N = 90 \) with increasing \( Z \). If the ESPEs for proton orbitals for \( N = 90 \) are plotted, substantial reduction of the \( 1g_{7/2} \) and \( 2d_{5/2} \) energy gap is observed with increasing \( Z \), which may favour the onset of collectivity [14].

3. The three-body forces and its implication

In our earlier work ([14,15], and references therein) we have discussed that realistic interactions fail to reproduce some shell closures for neutron-rich nuclei. Otsuka et al [16] showed that a three-body delta-hole mechanism can explain these shell gaps and three-body forces are necessary to explain why the doubly-magic \(^{24}\text{O}\) nucleus is the heaviest oxygen isotope.

Zuker [17] demonstrated earlier that a very simple three-body monopole term can eliminate the limitations of the realistic two-body potentials. According to his prescription, we have included corrections in the relevant terms of CWG to incorporate the three-body effects. The correction factor will be effective for nuclei for which the valence neutron number \((n) = 3\) or more. It is amazing that although CWG does not predict a shell closure at \(^{140}\text{Sn}\), the updated CWG including three-body forces, named as CWG3M, also predicts a shell gap for \( N = 90 \). The \( E(2^+; 1) \) energy of \(^{140}\text{Sn}\) predicted by CWG3M \((1.889 \text{ MeV})\) is close to that predicted by SMPN \((1.949 \text{ MeV})\) [14,15,18]. This also indicates that three-body effect may play an important role for shell evolution in neutron-rich \( \text{Sn} \) isotopes above \(^{132}\text{Sn}\), as also observed in sd and pf shells.

4. The new results on \(^{136,138}\text{Sn}\) and their interpretations

Very recently, experiments were carried out at the RIKEN radioactive isotope beam factory (RIBF) [19,20] to study the neutron-rich isotopes of \( \text{Sn} \). In one of the experiments, the first \( 2^+ \) excited state in the neutron-rich tin isotope \(^{136}\text{Sn}\) was identified at 682(13) keV by measuring \( \gamma \)-rays in coincidence with the one-proton removal channel from \(^{137}\text{Sb}\) [19]. In another experiment, delayed \( \gamma \)-ray cascades, originating from the decay of isomeric states at \( I = 6^+ \), in the very neutron-rich, semimagic isotopes \(^{136,138}\text{Sn}\) were observed following the projectile fission of a \(^{238}\text{U}\) beam at RIBF, RIKEN. The measured \( E_1(2^+_1) \) value of \(^{136}\text{Sn}\) was found to be much higher than the neighbouring \( N = 86 \) isotones, indicating a good \( Z = 50 \) shell closure. The excitation energies remain almost constant in \(^{134}\text{Sn}, 136\text{Sn}\) and \(^{138}\text{Sn}\), suggesting that the seniority \( -2 \) coupling scheme holds beyond \( N = 82 \) up to 88 [19]. They found that the predicted and the experimental \( B(E2; 6^+ \rightarrow 4^+) \) values [20] agree for \(^{138}\text{Sn}\) with both empirical and realistic interactions. However, for \(^{136}\text{Sn}\) the results with their realistic interaction, differ by a factor of \( >5 \). Three other shell-model calculations, using realistic and empirical interactions, also failed to reproduce this value for \(^{136}\text{Sn}\) by at least a factor of 2 [20]. To interpret these data better, the authors incorporated an empirical modification to the \( 2f_{7/2}^2 \) matrix elements, probably the zero-coupled ones, equivalent to reduced pairing, which generates a seniority-mixed \( 4^+_1 \) state, reproducing all the available experimental data better. The authors proposed the wave functions of these isomeric states [20] to be predominantly a fully aligned pair of \( f_{7/2} \) neutrons.
5. Motivation of the present work

From the experimental data on odd–even staggering of masses, Saha Sarkar and Sarkar [21] showed that the variation of pairing as a function of neutron number plays an important role in many distinctive features like occurrence of new shell closures, shell erosion, anomalous reduction of energy of the first $2^+$ state and slower increase of $B(E2; 2^+_i \rightarrow 0^+_j)$ in neutron-rich even–even nuclei of different mass regions. Recently, Holt et al [22] indicated that it is essential to include $3N$ contributions to the pairing interaction for a quantitative description of nuclear pairing gaps at regions away from stability. It is usually found that inclusion of a three-body effect improves the predictive power of realistic interactions. In our earlier work, we have already included three-body effects in realistic CWG interaction to construct CWG3M. Our aim is to study the importance of three-body forces in the interpretation of the new data.

6. Shell model calculations

In this work we have used the CD-Bonn potential-based realistic CWG [10] and the empirical SMPN [5] along with the CWG3M [14] interaction. All these Hamiltonians have the same set of single-particle energies of the valence orbitals but different sets of two-body interaction matrix elements. The SM calculations [13] were carried out in the Z50N82 model space using the OXBASH code [3].

7. Results

We have compared these new results with our theoretical ones calculated using CWG, SMPN and CWG3M interactions as shown in figures 4–6. The calculated $B(E2)$ values for all the $E2$ transitions connecting the yrast band till $12^+$ state are tabulated in table 1. To complete the information the $B(E2)$ for $6^+_1 \rightarrow 4^+_2$ for $^{136}$Sn nucleus are also tabulated.

7.1 Energy

If we keep in mind the usual errors obtained in shell model predictions, for $^{136}$Sn, one cannot choose between these three interactions. However, the predicted and the experimental energy spectra for both $^{136,138}$Sn (figures 4–6) show that best agreement is reached with the theory in which three-body forces are included in a realistic interaction (CWG3M).

7.2 Transition probabilities

The measurement of transition probabilities and its comparison with theory, is the best way to validate a theoretical prediction. As discussed in [13,21], the depressed $E(2^+_1)$ energies in neutron-rich nuclei arise due to weakening of pairing, unlike near stability, where low $E(2^+_1)$ indicates collective deformed state manifested through strong $B(E2; 2^+_1 \rightarrow 0^+_1)$. Therefore, anomalous reduction of energy of the first $2^+_1$ state and
slower increase in $B(E2; 2_1^+ \rightarrow 0_1^+)$ in the neutron-rich even–even nuclei is a distinctive feature arising out of reduced pairing. It has been discussed earlier [13] that apart from differences between the $E(2_1^+)$, the most dramatic difference lies in the transition probabilities of the $2_1^+ \rightarrow 0_1^+$ transition using CWG and SMPN interactions.

In this work, it is found that the $B(E2)$ values for the $6^+$ isomers in $^{136,138}$Sn are almost similar with CWG and SMPN. Although the CWG3M results are closer to CWG and SMPN predictions for $^{138}$Sn, it is totally different for $^{136}$Sn. However, if one carefully studies the results, it is evident that the $4_1^+$ and $4_2^+$ characters with CWG3M (manifested through $6^+$ to $4^+$ $B(E2)$s) are opposite to those predicted by SMPN and CWG. Simpson et al [20] have discussed that with the new empirically modified interaction, the improved results correspond to a mixed seniority $4_1^+$ state. So it seems that this mixing is to some extent overdone in CWG3M results, completely reversing the nature of the two $4^+$ states. This is not unexpected as we have already pointed out that the three-body corrections included in CWG3M is a simple one. It includes an overestimation of the up-sloping trend of $\nu(3p_3/2)$ effective single-particle energy. On the other hand, the $B(E2)$s for the $2_1^+$ states are similar for both the isotopes with CWG3M and SMPN, whereas it is almost double with CWG. This structural difference is also manifested in the anomalously low value of the calculated $B(E2; 4^+ \rightarrow 2^+)$ with CWG compared to those with SMPN and CWG (table 1). The stark difference between the structure of $2_1^+$ state predicted by CWG and SMPN/CWG3M is responsible for this anomaly. The $2_1^+$ state primarily has a multiplet structure with $2f_7/2$ partition contributing $\simeq 79–80\%$ in SMPN/CWG3M calculations. On the other hand, the largest contribution of $23\%$ arises from $2f_7/2$ partition in CWG.

8. Conclusion

The SMPN and CWG3M include the contributions of reduced pairing and three-body effects. Wang et al [19] and Simpson et al [20] indicated that reduced pairing is responsible for the anomalous results in these nuclei. Three-body forces were found to play an important role in reduced pairing in this mass region. Our results clearly show that the most sensitive probe to confirm this claim will be the measurement of transition probabilities, at least the $B(E2; 2_1^+ \rightarrow 0_1^+)$ values. Thus, the importance of pairing will be confirmed from the transition probability measurement in these neutron-rich isotopes of Sn. For better understanding of the three-body effects, improved three-body corrections should be included in the realistic interactions.

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