Shell-Model Study for Neutron-Rich Nuclei

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In nuclear physics, many models have been developed to demonstrate the nuclear structure properties such as energy, electromagnetic transitions, wave functions and nucleon density distributions. The nuclear shell model was proposed and developed by Maria G. Mayer and J. Hans D. Jensen in 1949. The "magic numbers" and other nuclear properties were successfully addressed and explained with the independent-particle model for nuclei. After the discovery and development of the shell model, some of the stable nuclei can be explained, while the detailed description of higher excited states and nuclei far off $\beta-$ stability and closed shells are still difficult. The shell model provides remarkable regularities in studying the nuclear structure, with continuous progress in the theoretical models and effective interactions, testing the theoretical predictions and new experimental data. With the emergence of powerful computational facilities and advances in technical progress, it is possible to understand the complete spectroscopic characterization of nuclear levels.

This thesis aims to gain knowledge of nuclear structure, collectivity, and isomers in the vast region of the nuclear chart, in particular the ^{132}Sn and ^{208}Pb regions. The relevance of the model space has been discussed and analyzed to learn the evolution of the excitation energies and electromagnetic observables and predicted several missing pieces of information. Further, several new level assignments and isomeric states have been proposed, which can be helpful for experimentalists and shell-model practitioners.

Firstly, we studied the Ca region, and reported shell-model results for $^{47-58}$Ca isotopes in the fp, $fpg_{9/2}$ and $fpg_{9/2}d_{5/2}$ model spaces using realistic NN interaction, to see the importance of $g_{9/2}$ and $d_{5/2}$ orbitals [1]. We have also performed a systematic shell-model study using interactions derived from in-medium similarity-renormalization group (IM-SRG) targeted for a particular nucleus with chiral NN and $3N$ forces. It is shown that the $g_{9/2}$ and $d_{5/2}$ orbitals play an important role for heavier neutron-rich $^{54-58}$Ca isotopes, while it is marginal for $^{47-52}$Ca. We have also examined spectroscopic factor strengths using NN and $NN + 3N$ interactions for recently available experimental data. To reduce the energy of 2^+ state after ^{54}Ca, and to see the importance of $g_{9/2}$ orbital, we have increased the single-particle energy of this orbital by 2 MeV. Results corresponding to the modified single-particle energy show that $g_{9/2}$ orbital is crucial for heavier Ca isotopes. The significant increase of occupancy for the $g_{9/2}$ orbital is obtained above $N = 34$ once we move towards heavier $^{54-58}$Ca isotopes.

In the following work, we have studied the ^{132}Sn region. In this work, available experimental data up to high-spin states of $^{119-126}$Sn isotopes with different seniority (v) have been interpreted with the shell model by performing full-fledged shell model calculations in the 50-82 valence shell composed of $1g_{7/2}$, $2d_{5/2}$, $1h_{11/2}$, $3s_{1/2}$, and $2d_{3/2}$ orbitals [2]. These states are described in terms of broken neutron pairs occupying the $h_{11/2}$ orbital. The high-spin isomers in Sn isotopes are due to seniority (v) = 2, 3, 4, and 5. We have also reported $B(E2)$ values for different transitions for $^{120-126}$Sn isotopes.

Now the study has been extended to the ^{208}Pb region, especially for seniority isomers. This work presents systematic large-scale shell-model calculations for Rn isotopes with $A = 207$ to 216 [3]. For the $^{207-212}$Rn isotopes, we perform calculations with KHH7B

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interaction, while for $^{213-216}$Rn isotopes with KHPE and KHH7B interactions. The calculated energies and electromagnetic properties are compared with the available experimental data. We also suggest spins and parities of several unconfirmed states available from the recent experimental data. A comprehensive study of several isomeric states from the calculated shell-model configurations and half-lives is also reported. For higher mass isotopes $^{213-216}$Rn, it becomes crucial to consider sufficient orbitals below the shell-closure for low-lying states apart from the core-excitation. We found that low-lying states arise from large configuration mixing while high-lying states show less collective behaviour. The isotopes near $N = 126$ shell closure show minor collective nature, and as we move far from the shell-closure, collectivity and configuration mixing increase very rapidly. This shows the importance of the inclusion of a sufficient model space in the ^{208}Pb region to reproduce the energy spectrum correctly. The orbitals $h_{9/2}$ and $i_{13/2}$ are responsible for the isomeric states in the Rn isotopes, and the high-spin isomers are due to seniority $(v) = 1$, 2, 3, 4, 5, 6 and 7.

The spectroscopy of ^{132}Sn and ^{208}Pb, which are very differently located to the valley of stability, both exhibit similarity in many ways. In this work, we have performed a new type of investigation for the similarities between the $N = 82$ ($52 \leq Z \leq 60$) and $N = 126$ ($84 \leq Z \leq 92$) isotones in the framework of the nuclear shell model with well known SN100PN and KHPE interactions, respectively [4]. Similarities between these two isotonic chains have been reported, using the strong resemblance between the high-j orbitals. Apart from the nuclear spectroscopic properties, we have also explained different isomeric states in these two regions. We have reported $B(E2)$, $B(E3)$, g-factor, and quadrupole moments of the isomeric states for comparison in these two isotonic chains. Our study confirms several isomeric states in $N = 82$ and $N = 126$ isotones are due to the breaking of high-j nucleon pairs and well described in terms of seniority quantum number. A similar evolution of excitation energies can be seen between the same seniority states in the Sn and Pb regions. Using the correspondence between the Sn and Pb regions, the high-j orbitals above the shell gaps show similar behavior, eventually deciding other spectroscopic properties.

Apart from the previously mentioned works, the $^{204-210}$Tl isotopes have also been investigated by performing large-scale nuclear shell-model calculations, including configurations allowing both neutron and proton core excitations across the $Z = 82$ and $N = 126$ shell gap [5]. Inspired by the recent high-spin experimental data, the structure of Tl isotopes has been studied for a considerably large model space. The KHHE and KHH7B interactions have been used for $^{204-206}$Tl isotopes and KHH7B and KHM3Y interaction for $^{207-210}$Tl isotopes. The core excitation has been performed using the KHH7B and KHM3Y interactions. The level spectra of $^{204-210}$Tl isotopes are comprehensively described and explained by multi-nucleon couplings of single-particle-hole orbitals within the valence space and by core excitations across ^{208}Pb core. The well-known isomeric states are analyzed in terms of the shell model configurations. With the emphasized effect correlated to the core excitations, the structure of Tl isotopes has been systematically studied with the electromagnetic transition properties.

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References

[1] Bharti Bhoy, P. C. Srivastava and Kazunari Kaneko, J. Phys. G: Nucl. Part. Phys. **47**, 065105 (2020).
[2] P.C. Srivastava, Bharti Bhoy, *et al.*, Prog. Theor. Exp. Phys. **2019**, 103D01 (2019).
[3] Bharti Bhoy, P. C. Srivastava, J. Phys. G: Nucl. Part. Phys. **48**, 125103 (2021).
[4] Bharti Bhoy, P. C. Srivastava, J. Phys. G: Nucl. Part. Phys. **49**, 085101 (2022).
[5] Bharti Bhoy, P. C. Srivastava, *manuscript under preparation.*