Ab initio study on evolution of single-particle states in island of inversion

Subhrajit Sahoo* and Praveen C. Srivastava†

Department of Physics, Indian Institute of Technology Roorkee, Roorkee 247667, India

Introduction

The region of the nuclear chart where neutron-rich nuclei with $N \approx 20$ show various exotic features that are incompatible with the $N = 20$ shell closure is known as the "island of inversion" [1]. In this region, the ground states of nuclei exhibit dominant contributions from intruder orbitals due to a significant reduction in the energy gap at $N = 20$ between the *sd*- and fp shell. Over recent years, this region has garnered much attention within the nuclear physics community, both for understanding shell evolution away from the stability line and for the development of sophisticated shell-model interactions.

The keys to understanding the $N = 20$ shell closure and its transition into the "island of inversion" region lies in analyzing the evolution of neutron orbitals or particularly the single-particle states representing them. Significant effort has been made to explaining the properties of nuclei in this region using phenomenological interactions. However, to understand these properties starting from the $2N$ and $3N$ nuclear forces or from *ab initio* effective interactions have been extremely challenging [2]. In the present article, we have investigated the evolution of single-particle states in the $N = 21$ isotones to understand the evolution of $N = 20$ shell gap through *ab initio* effective interactions. These effective interactions were derived from realistic nuclear forces nonperturbatively using the In Medium Similarity Renormalization Group (IMSRG) approach. Additionally, we discuss the collective properties, intruder contributions, and multi-particle-hole excitations associated with these single-particle states in detail.

Formalism

In the IMSRG approach [3], the Hamiltonian in the large Hilbert space is evolved through the flow equation given by

$$\frac{dH(s)}{ds} = [\eta(s), H(s)]\,, \tag{1}$$

where 's' is called the flow parameter and $\eta(s)$ is known as the anti-hermitian generator. This generator $\eta(s)$ performs the necessary unitary transformation to obtain an effective Hamiltonian for the chosen model space. The Hamiltonian in the second quantized form is expressed as

$$H = E_0(s) + \sum_{ab} f_{ab}(s)\{a_a^\dagger a_b\} + \frac{1}{4}\sum_{abcd} \Gamma_{abcd}(s)\{a_a^\dagger a_b^\dagger a_d a_c\}.$$

Here E_0, f_{ab}, and Γ_{abcd} represent the zero-, one- and two-body terms of the Hamiltonian, respectively, and are normal ordered with respect to an ensemble reference state. To make the computations tractable, the Hamiltonian is truncated at two-body level but includes the contributions of $3N$ forces through normal ordering. This is known as IMSRG(2) approximation. By choosing an appropriate generator [2], the multi-shell effective interactions (VS-IMSRG) are decoupled for valance space spanning *sd*- shell for protons and *sd*- shell with $f_{7/2}$ and $p_{3/2}$ orbitals for neutrons in order to study the "island of inversion" nuclei.

Results and Discussion

We have shown some preliminary results of the work in Fig. 1. The ground states in

*Electronic address: `s_sahoo@ph.iitr.ac.in`

†Electronic address: `praveen.srivastava@ph.iitr.ac.in`

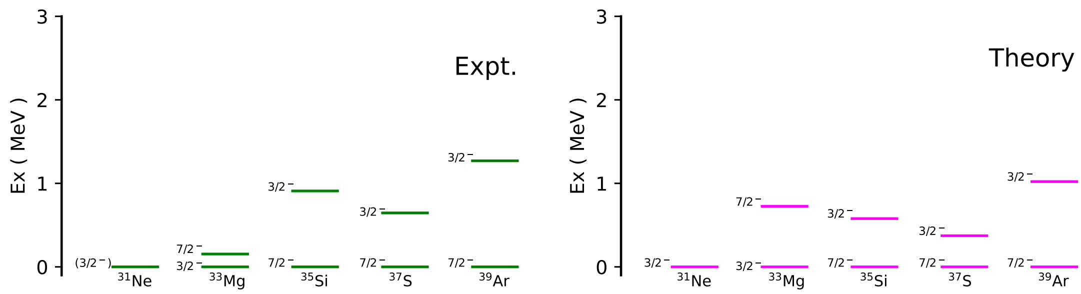

FIG. 1: Low-lying excitation spectra in $N = 21$ isotones.

$N = 21$ isotones are well reproduced from VS-IMSRG interactions. The excited states are also in good agreement with the experimental counter parts. However, in contrast to experimental data, the energy spacing between $3/2^-$ and $7/2^-$ state in ^{33}Mg is enhanced in VS-IMSRG calculations. When the $N = 20$ shell closure persists, the expected ground state is $7/2^-$, which is observed in the case of Ar to Si isotopes. The appearance of $3/2^-$ as the ground state is a clear indication of the breakdown of the $N = 20$ shell gap in Ne and Mg. The ground states in these nuclei are formed by mixtures of normal and intruder or multi-particle-hole (*npnh*) configurations where the intruder configurations dominate. The probabilities of $2p2h$ excitations in Ne and Mg are 64% and 82%, respectively, while the ground state in Si is dominated by normal configuration or $0p0h$ excitations with a probability of 76%. In the $N = 21$ isotones, we have studied both positive and negative parity single-particle states, their systematics, and the probabilities of multi-particle hole configurations involved in them.

The deformed natures of the single-particle states are addressed by calculating the $E2$ transition strengths that connect them, along with their quadrupole moments. The VS-IMSRG results suggest deformed ground states in the Ne and Mg nuclei located in the "island of inversion" region, consistent with experimental observations [4]. Nuclear magnetic moments provide direct insights into the composition and single-particle structure of the wave functions. Additionally, we have analyzed the ground state magnetic moments and their evolution as we approach to the "island of inversion" region. It can be noted that the $E2$ strengths and magnetic moments are calculated from the $E2$ and $M1$ operators that are consistently evolved through the IMSRG framework. Hence, the $E2$ and $M1$ observables are calculated using bare charges and g-factors of protons and neutrons, unlike traditional shell model interactions where effective charges and g- factors are used. All the results will be presented and discussed in detail at the conference.

Acknowledgments

S.S would like to thank UGC (University Grant Commission), India, for providing financial support for his Ph.D. research work. We would like to thank the National Super computing Mission (NSM) for providing computing resources of 'PARAM Ganga' at IIT Roorkee. We also acknowledge a research grant from SERB (India), CRG/2022/005167.

References

[1] T. Otsuka *et al*, Rev. Mod. Phys. **92**, 015002 (2020).

[2] T. Miyagi *et al*, Phys. Rev. C **102**, 034320 (2020).

[3] S. R. Stroberg *et al*, Phys. Rev. Lett. **118**, 032502 (2017).

[4] D. Bazin *et al*, Phys. Rev. C **103**, 064318 (2021).