Entanglement study of atomic nuclei using shell model

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Introduction

Atomic nuclei are self-bound quantum many-body systems consisting of protons and neutrons, collectively known as nucleons, that interact via nucleon-nucleon forces. Among various approaches to study the structure of atomic nuclei, the nuclear shell model is one of the widely successful approaches for different mass regions across the nuclear chart. Shell model formalism has recently been explored using quantum computation [1–3]. Like any other quantum many-body system, the entanglement structure can reveal the underlying properties of atomic nuclei. This work aims to investigate the entanglement properties of a few atomic nuclei in the *sd*-shell within the shell model formalism.

Formalism

Quantum entanglement characterizes correlations between different partitions within a system that can not be described independently of one another. Two systems A and B, characterized by states $|\psi_A\rangle$ and $|\psi_B\rangle$, are said to be entangled if the complete state of the system $|\psi\rangle$ can not be written as $|\psi\rangle = |\psi_A\rangle \otimes |\psi_B\rangle$. The entanglement between two systems or two partitions within the same system can be measured using different entanglement measures such as single-orbital entanglement, von Neumann entropies, and mutual information. In this work, we have explored single-orbital entanglement of a few selected *sd*-shell nuclei with microscopic DJ16 [4] interaction and the monopole-corrected (DJ16A) and charge-dependent (DJ16-CD) versions of this interaction. In calculating the single-orbital entanglement, a bipartition of a single orbital and the rest of the system is considered, and it is written as:

$$S_i = -\gamma_i \log_2 \gamma_i - (1-\gamma_i)\log_2(1-\gamma_i)$$

where, $\gamma_i = \langle\psi|a_i^\dagger a_i|\psi\rangle$ is the occupation number of the i^{th} single-orbital in the state $|\psi\rangle$ [5]. Another quantity relevant to this work is total single-orbital entanglement $S_{tot} = \sum_i S_i$.

Results and Discussions

In this work, firstly, we have calculated the S_i for even-even Ne isotopes from $N = 8$ to 16, corresponding to DJ16 and DJ16A interactions. We are mainly concentrating on the entanglement pattern of 0_1^+-2_1^+-4_1^+ states and how it is changing as we go from ^{18}Ne towards neutron-rich ^{26}Ne. The S_{tot} for ^{18}Ne 0_1^+, 2_1^+, and 4_1^+ states are 1.626 (1.636), 1.678, (1.621), and 1.033 (1.027), respectively corresponding to DJ16 (DJ16A) interaction and all contributions are coming from proton orbitals only. As we go toward the neutron-rich side, the S_{tot} becomes maximum at ^{22}Ne for all three low-lying states, then it starts decreasing for ^{24,26}Ne. The major contribution toward maximum S_{tot} for ^{22}Ne low-lying states comes from the maximally entangled neutron $0d_{5/2}$ orbital. On the other hand, the S_{tot}^p, which is the sum of proton S_i, becomes maximum at $N = Z$, ^{20}Ne and then decreases along the isotopic chain. Also, $S_{tot}(0^+)$ is less than both $S_{tot}(2^+)$ and $S_{tot}(4^+)$ for $N > Z$ Ne-isotopes. The S_{tot} for monopole-corrected DJ16A interaction is slightly less than the original DJ16 interaction for all $N \geq Z$ cases considered in this work except for the case of ^{24}Ne. For the case of ^{24}Ne, the S_{tot} for 0_1^+, 2_1^+, and 4_1^+ are decreased by 12.16, 7.67, and 14.37 % corresponding to DJ16A interaction in comparison to DJ16 results. All these results are shown in Fig. 1(a).

Secondly, we calculated the S_i for 2^+-3^+-4^+ isobaric analog states of $|T_z| = 1$ triplet (^{20}F,

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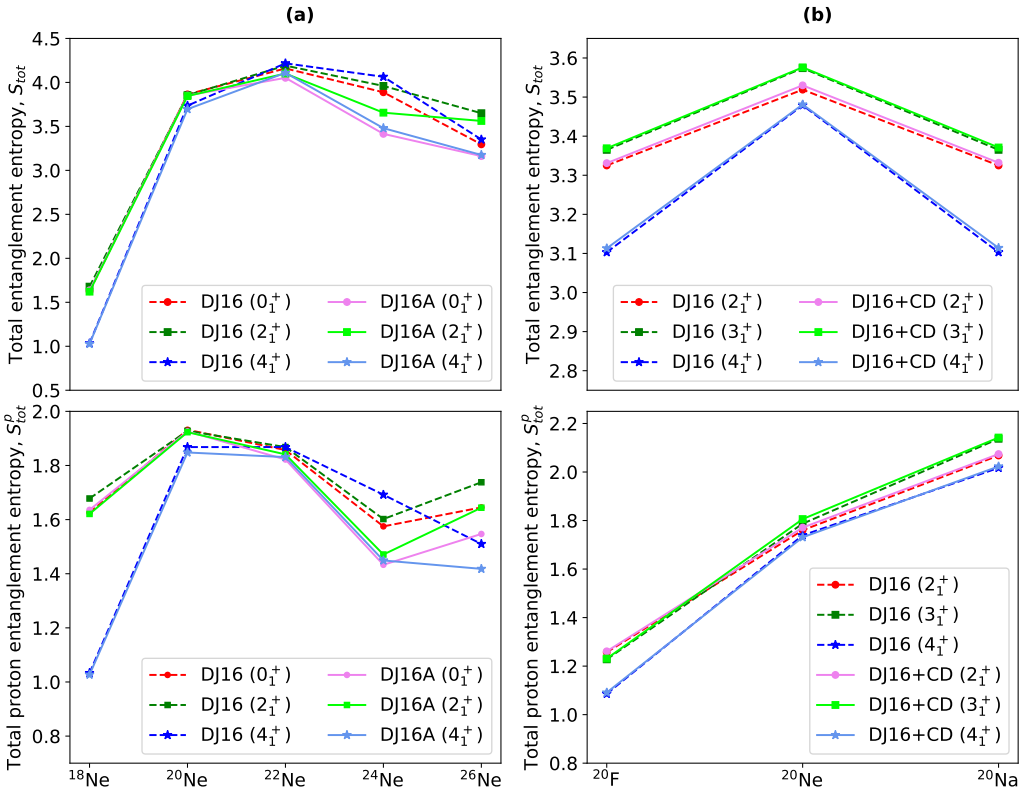

FIG. 1: (a) The S_{tot} and S^p_{tot} corresponding to DJ16 and DJ16A interactions for even-even Ne isotopes, (b) S_{tot} and S^p_{tot} corresponding to DJ16 and DJ16-CD interactions for $A = 20$ triplet.

^{20}Ne, ^{20}Na) using DJ16 and DJ16-CD interactions. The DJ16-CD interaction is obtained by combining the original DJ16 interaction and Coulomb CD from [6]. It is found that the S_{tot} increases slightly for all three cases considered in this work for DJ16-CD interaction compared to the original DJ16 interaction, as shown in Fig. 1(b).

Entanglement measures can provide valuable information about the nuclear system as well as the nuclear interaction used to describe such a system.

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