

## No core shell model results for oxygen chain

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### Introduction

No core shell model (NCSM) is a successful *ab initio* approach for explaining the properties like charge radii and electromagnetic moments of lighter nuclei accurately [1]. An *ab initio* calculation has been done for oxygen chain with coupled cluster effective interaction (CCEI) method in Ref. [2], which was focused only on the binding energies and *ab initio* no core full configuration (NCFC) approach has been used for  $^{14}\text{F}$  nucleus for finding g.s. energy [3]. The NCSM is useful to understand the nuclear structure and reaction physics precisely. Now, the calculations are also possible with the continuum effects in NCSM for explaining unbound states, scattering and nuclear reactions. Recently, the NCSM calculations with continuum (NCSMC) effects have been done in the case of  $^{11}\text{Be}$  in which the parity inversion problem is also solved with  $N^2\text{LO}_{\text{sat}}$  interaction only [4] because the spectrum is highly sensitive with respect to  $NN + NNN$  nuclear interactions. The essence of *ab initio* calculations is to minimize the model dependency of calculated results. In the present work, our focus is on oxygen isotopes. We show the energy spectra of  $^{18}\text{O}$  and evolution of occupancies of proton and neutron orbitals in the oxygen chain. We have used inside non local outside Yukawa potential (INOY) [6] for NCSM calculations.

The electromagnetic moments of *sd* shell nuclei with *ab initio* shell model calculations using effective interactions: in-medium similarity renormalization group (IM-SRG) and CCEI have been recently reported in Ref. [5].

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### No Core shell model formalism

In NCSM, we start with the completely intrinsic Hamiltonian

$$H_A = T_{\text{rel}} + V = \frac{1}{A} \sum_{i<j}^A \frac{(\vec{p}_i - \vec{p}_j)^2}{2m} + \sum_{i<j}^A V_{NN,ij}, \quad (1)$$

where  $m$  is the nucleon mass,  $V_{NN,ij}$  is the  $NN$  interaction having nuclear and coulomb part both. We add the center-of-mass (c.m.) Hamiltonian  $H_{c.m}^\Omega = T_{c.m} + U_{c.m}^\Omega$  to starting Eq. 1, where  $U_{c.m}^\Omega = \frac{1}{2}Am\Omega^2 \vec{R}^2$ ,  $\vec{R} = \sum_{i<j}^A \vec{r}/A$ .

$$H_A^\Omega = H_A + H_{c.m}^\Omega = \sum_{i=1}^A h_i + \sum_{i<j}^A V_{ij}^{\Omega,A} = \sum_{i=1}^A \left[ \frac{\vec{p}_i^2}{2m} + \frac{1}{2}m\Omega^2 \vec{r}_i^2 \right] + \sum_{i<j}^A \left[ V_{NN,ij} - \frac{1}{2A}m\Omega^2(\vec{r}_i - \vec{r}_j)^2 \right]. \quad (2)$$

We subtract again c.m. HO Hamiltonian in the final many-body calculation so there is no net effect on intrinsic properties of the many-body Hamiltonian. We have used INOY  $NN$  interaction for the calculations. This interaction have nonlocality in certain partial waves for describing the B.E. of  $^3\text{H}$  and  $^3\text{He}$  nuclei correctly and it is also useful in getting faster convergence at lower basis space size in compared to other interactions. The final Hamiltonian have dependency of frequency  $\Omega$  and model space size.

### Results and Discussions

In this work, we present the NCSM calculations for oxygen chain  $^{18,20,22,24}\text{O}$  using the

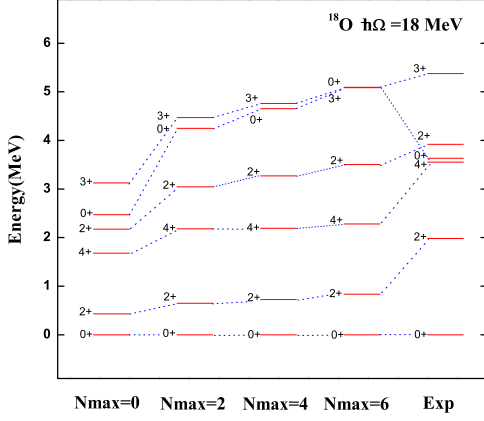


FIG. 1: Calculated and experimental excitation energies of  $^{18}\text{O}$  with  $\hbar\Omega=18\text{MeV}$  and increasing basis space size.

phenomenological INOY  $NN$  interaction. In the present calculations, we have taken the harmonic oscillator frequency  $\hbar\Omega=18\text{ MeV}$  for  $^{18}\text{O}$ ,  $^{20}\text{O}$ ,  $^{22}\text{O}$  and  $\hbar\Omega=14\text{ MeV}$  for  $^{24}\text{O}$ . In Fig. 1, we show the energy spectra for  $^{18}\text{O}$  with increasing basis space size up to energy  $\sim 6\text{ MeV}$ . We can see from this figure as basis space size increases the energy of the calculated  $2_1^+$  state approaches to the experimental data. We expect that as model space size will increase we will get better results. So, we will see the results at  $N_{max}=6$ . The order of states up to energy  $\sim 4\text{ MeV}$  is similar with the experiment. The states  $2_1^+$  and  $4_1^+$  are at much lower energy with respect to the experiment but the  $3_1^+$  and  $2_2^+$  states are near to the experiment.

In the present calculations, we have used 45 orbitals for both the protons and neutrons corresponding to  $N_{max}=6$  basis space size and 29 orbitals corresponding to  $N_{max}=4$  basis space size. Fig. 2 shows the occupancies for the ground state and first excited state in oxygen chain. We have shown the occupation numbers up to  $fp$  shell. Above the  $fp$  shell the occupation numbers are very small and very hard to visualize (in the present figure). So, we have not shown the orbitals beyond  $fp$  shell. The NCSM calculations give  $Q_{2_1^+}$  value

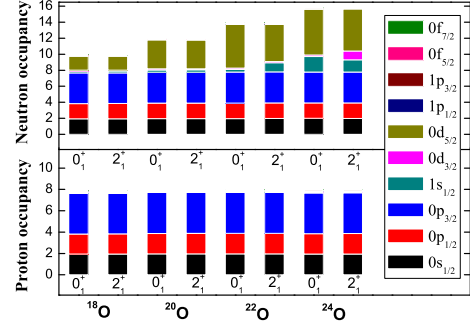


FIG. 2: Occupation numbers for ground state and  $2_1^+$  state in oxygen isotopes  $^{18}\text{O}$ ,  $^{20}\text{O}$ ,  $^{22}\text{O}$  and  $^{24}\text{O}$  using INOY  $NN$  interaction.

$-0.3895\text{eb}$  and  $BE(2_1^+ \rightarrow 0_1^+)$  value  $0.1868\text{ e}^2\text{fm}^4$  for  $^{18}\text{O}$ . For  $^{18}\text{O}$ , we have shown the calculations for basis space size  $N_{max}=6$  while for the other oxygen isotopes at  $N_{max}=4$  due to computational limitations. It is possible to get correct electromagnetic properties at higher  $N_{max}$ . The calculations for  $N_{max} > 6$  are still under progress.

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## References

- [1] C. Forssén, E. Caurier and P. Navrátil, Phys. Rev. C **79**, 021303(R) (2009).
- [2] G. Hagen *et al.*, Phys. Rev. C **80**, 021306(R) (2009).
- [3] P. Maris *et al.*, Phys. Rev. C **81**, 021301(R) (2010).
- [4] A. Calci *et al.*, Phys. Rev. Lett. **117**, 242501 (2016).
- [5] A. Saxena and P.C. Srivastava, Phys. Rev. C **96**, 024316 (2017).
- [6] P. Doleschall, Phys. Rev. C **69**, 054001 (2004).