Ab initio investigations of $A=8$ nuclei: $\alpha-\alpha$ scattering, deformation in $^8$He, radiative capture of protons on $^7$Be and $^7$Li and the X17 boson

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Abstract. We apply the No-Core Shell Model with Continuum (NCSMC) that is capable of describing both bound and unbound states in light nuclei in a unified way with chiral two- and three-nucleon interactions as the only input. The NCSMC can predict structure and dynamics of light nuclei and, by comparing to available experimental data, test the quality of chiral nuclear forces. We discuss applications of NCSMC to the $\alpha-\alpha$ scattering and the structure of $^8$Be, the $p+^7$Be and $p+^7$Li radiative capture and the production of the hypothetical X17 boson claimed in ATOMKI experiments. The $^7$Be($p,\gamma$)$^8$B reaction plays a role in Solar nucleosynthesis and Solar neutrino physics and has been subject of numerous experimental investigations. We also highlight our investigation of the neutron rich exotic $^8$He that has been recently studied experimentally at TRIUMF with an unexpected deformation reported.
1. Introduction
The no-core shell model with continuum (NCSMC), first introduced in Refs. [1, 2], is a first-principles technique that has been successful in delivering predictive calculations of nuclear properties of light nuclei by combining bound and dynamic descriptions of an A-nucleon system (see Ref. [3] for a review). In the NCSMC, the A-body Schrödinger equation is solved for both bound and scattering boundary conditions with a trial wave function consisting of two parts: one describing the aggregate system when all nucleons are close together and the other considering explicitly sub-clusters that can completely separate. The input for these calculations are chiral Effective Field Theory (EFT) nucleon-nucleon (NN) and three-nucleon (3N) interactions.

2. Many-body calculation of α−α scattering
A major milestone in our ab initio reaction theory has been achieved recently by the development of a new formalism that takes full advantage of powerful second-quantization techniques, enabling the description of α−α scattering and an exploration of clustering in exotic nuclei such as 12Be [4]. Unlike in the original NCSMC formulation [2, 3], the cluster-cluster part now treats both the target and the composite projectile on the same footing, utilizing the second quantization for the construction of the reaction channels and evaluating their full matrix elements. The calculations are facilitated by the technique of boosting the center-of-mass quanta as described in Refs. [5, 6]. In Fig. 1, we compare the α−α differential cross sections obtained with the NN interaction only and with NN+3N interactions contrasting two different 3N models. The best agreement with experimental data, in the region impacted by the 2^+_1 resonance in 8Be in particular, is achieved with the NN+3N_{lnl} model [7, 8].

3. The 2^+ resonance of the exotic 8He
The 8He is an exotic nucleus with an extreme neutron to proton ratio N/Z=3. It is the drip line nucleus of the helium isotopic chain and its stronger binding suggests a possible closed subshell at N=6 which would make 8He a doubly closed shell nucleus. Properties of this exotic

![Figure 1](image1.png)

**Figure 1.** The α−α scattering differential cross section at c.m. angle θ=40°, 90°, 70°. The NN+3N_{lnl} Hamiltonian yields the overall best agreement with the data (symbols) from (a) Ref. [9] and (b) Ref. [10]. Further details are given in Ref. [4].

![Figure 2](image2.png)

**Figure 2.** 8He 2^+_1 excitation energy dependence on the NCSM and NCSMC basis size. Extrapolated values and the experimental result [11] are shown on the right. The vertical bars represent resonance widths. Further details are given in Ref. [11].
A resonance at 3.54(6) MeV was found. A coupled-channel and DWBA analysis identifies the resonance as a $2^+$ state in $^8\text{He}$. 

Ab initio NCSM and NCSMC calculations describe successfully the observed resonance [11]. We employed the same Hamiltonian as in our recent investigation of $^9\text{He}$ [12]. The NN interaction, denoted here as NN-$N^4\text{LO}$ [13], was renormalized by the SRG approach [14] with an evolution parameter $\lambda_{\text{SRG}}=2.4$ fm$^{-1}$. The NCSM and NCSMC convergence of the $^8\text{He}$ $2^+$ excitation energy with respect to the basis size characterized by $N_{\text{max}}$ is shown in Fig. 2. The NCSM calculations yield a large quadrupole neutron moment $Q_n = 6.15$ e fm$^2$ and a small proton quadrupole moment, $Q_p = 0.60$ e fm$^2$ for the $2^+_1$ state. For $^{12}\text{C}$ we predict $Q_n=Q_p$~6 e fm$^2$. Thus, the neutron deformation in $^8\text{He}$ is similar to that in $^{12}\text{C}$ and qualitatively consistent with the experimental observations.

As the $^7\text{He}$ $3/2^-$ ground state resonance is experimentally rather narrow (150 keV [15]), it is reasonable to use the $^7\text{He} (\text{gs})+n$ cluster to perform NCSMC calculations that extend the $^8\text{He}$ NCSM basis. The resonance position and width were determined by analyzing the $2^+$ eigenphase shifts. The $2^+$ resonance appears in the $^5P_2$ partial wave. In the eigenphase shift, there is also a significant admixture of the $^3P_2$ partial wave. The calculated $2^+_1$ excitation energy of 3.58(6) MeV and the width to be 750(50) keV is in an excellent agreement with the present experimental measurement.

### 4. Radiative proton capture on $^7\text{Be}$

Occurring at the tail end of the proton-proton chain, the radiative capture of a proton by a $^7\text{Be}$ nucleus to produce an $^8\text{B}$ nucleus (i.e., the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction) is key in determining the solar neutrino flux measured in terrestrial observatories. Given its importance, it has been measured multiple times over the years with various techniques. However, due to Coulomb repulsion between the proton and the $^7\text{Be}$ nucleus, a direct measurement at the astrophysically relevant energies is still missing, and theory calculations are used to extrapolate from higher energy experimental data. As a result of this extrapolation process, the uncertainty in the currently recommended [16] value of the zero-energy S-factor, $S_{1\gamma}(0) = 20.8 \pm 0.7(~\text{expt}) \pm 1.4(~\text{theory})$ eV-barn, is dominated by theoretical contributions.

In Ref. [17], we presented first-principles calculations of the $^7\text{Be}+p$ system, including the $^7\text{Be}(p,\gamma)^8\text{B}$ reaction, using NN and 3N interactions derived from chiral EFT. We used the NN interactions at 4th order of the chiral expansion defined in Ref. [7], denoted $N^4\text{LO}$, and those at 3rd, 4th and 5th ($N^5\text{LO}$) order of Ref. [13]. These NN interactions were supplemented by the 3N interaction of Ref. [18] with both local (3N_{loc}) [19, 20] and local plus non-local (3N_{nl}) regulators [8, 21]. Finally, a 3N interaction with an added sub-leading contact term enhancing the strength of the spin-orbit interaction [22] was also employed (3N_{nl}^*).

As an example of the obtained results, the $^7\text{Be}+p$ phase shifts are presented in Fig. 3 together with the astrophysical S factor obtained using the chiral NN $N^3LO^*$ and NN $N^3LO+3N_{nl}$ interactions. The positive parity eigenphase shifts show the well-established $1^+_1$ and $3^+_1$ resonances as well as predictions of several other broader resonances. The calculated astrophysical S-factor reproduces well the resonance contributions due to the M1 and, to a smaller extent, the E2 transitions from the $1^+$ resonance (the sharp peak at $\sim 0.6$ MeV) and $3^+$ resonance (the bump at $\sim 2.2$ MeV) to the weakly bound $2^+$ ground state of $^8\text{B}$. The calculated S-factor is in a reasonable agreement with the Junghans direct measurement data [23]. Overall, the new NCSMC calculations with the above discussed set of chiral interactions (six in total) [17] suggest a value for the $^7\text{Be}(p,\gamma)^8\text{B}$ S-factor at zero energy of $19.8\pm0.3$ eV-b, which is consistent with the latest recommended value [16], with the theoretical uncertainty significantly reduced.
5. Proton capture on $^7\text{Li}$ and the X17 boson

Anomalies in $^8\text{Be}$ and $^4\text{He}$ decay, in particular in the electron-positron pair production from the proton capture on $^7\text{Li}$ and $^3\text{H}$ were reported by the ATOMKI collaboration and interpreted as the decay of a new boson called X17 with the mass $\sim 17$ MeV [24, 25, 26, 27].

We embarked on an in-depth approach to the $p+^7\text{Li}$ capture reaction within the ab initio
NCSMC approach that allows us to describe simultaneously the structure of $^8$Be, the elastic and inelastic $^7$Li$(p,p)$ scattering, the charge exchange reaction $^7$Li$(p,n)^7$Be, the $\gamma$ capture $^7$Li$(p,\gamma)^8$Be, the internal pair conversion $^7$Li$(p,e^+e^-)^8$Be, as well as the X17 boson production $^7$Li$(p,X)^8$Be and decay for a variety of candidates for the hypothetical boson [29]. Preliminary NCSMC $^7$Li$(p,e^+e^-)^8$Be internal pair conversion correlation and integrated cross section results are shown in Fig. 4. Summing up the $E1$, $M1$, and $E2$ electromagnetic (EM) contributions using the formalism of Ref. [30] we obtain the dotted line shown in left panel. Including interference of the partial waves following the formalism of Ref. [31] we obtain a slight shift towards the ATOMKI EM background data although we still underpredict at low angles. The calculated integrated $^7$Li$(p,\gamma)^8$Be radiative capture cross section compares well with the data from Ref. [28].

The $E1$ and $M1$ contributions are shown separately. The two peaks dominated by the $M1$ contributions are due to the two $1^+$ resonances in $^8$Be with the lower one predominantly isospin $T=1$ while the higher one predominantly $T=0$ with a suppressed $M1$ decay to the $^8$Be $0^+$ ground state. Cross sections for the emission of the X17 boson, lower by several orders of magnitude, are also shown. Three X17 candidates were considered, a pseudo scalar (axion), axial vector, and $E1$ vector using operators from Refs. [32, 33, 34, 35]. The electron-positron pair production cross section (not shown) has a shape basically identical to the $\gamma$ capture cross section with its magnitude scaled by a factor of $\sim \alpha/\pi \sim 10^{-3}$. One could understand then that an anomaly would be hardly observed in the first resonance with the very high electromagnetic $M1$ rate. An effect from the hypothetical boson can be expected in the second $1^+$ resonance where both the pseudoscalar and the axial vector boson candidate cross sections peak. An anomaly between the $1^+$ resonances and at the second resonance would be consistent with the $E1$ vector. The latter is the preferred candidate according to the latest ATOMKI publications [26, 27].

6. Conclusions

We presented several recent results in $A=8$ nuclei that demonstrate capabilities of the ab initio NCSMC. With high-precision chiral NN+3N interactions as the input, one is able to predict with confidence properties of light nuclei even with a large neutron or proton excess. The method is capable to address issues of interest such as the evaluation of cross sections of reactions important for astrophysics or the X17 anomaly.

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