CONFIGURATION INTERACTION SHELL MODEL STUDIES OF PHOTON STRENGTH FUNCTIONS OF LIGHT NUCLEI*

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In this contribution, we discuss selected results of calculations of E1 dipole response of *sd*-shell nuclei within the Configuration Interaction Shell Model framework. Systematic calculations within this approach were performed to provide results of interest for the PANDORA Collaboration and to deepen our understanding of the low-lying dipole strength in neutron-rich nuclei.

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1. Introduction

Photo-nuclear reaction rates provide key inputs to various applications of nuclear physics and consist of fundamental probes of nuclear structure, from single-particle to collective excitations, revealing the nature of complicated nucleonic correlations. Among the excitations of nuclei due to external electromagnetic field, the E1 dipole response is of particular interest. It is dominated by isovector Giant Dipole Resonance (GDR) understood as a relative oscillation of protons against the neutrons. Already in the 1960s, an enhancement of low-lying gamma-ray strength was measured in many isotopes by Bartholomew *et al.* [1]. This was shortly after referred to as Pygmy Dipole Resonances (PDR). Theoretical predictions in neutron-rich nuclei suggest that an oscillatory movement of the excess neutrons relative to the proton–neutron core can generate this low-energy E1 strength [2]. An excess of E1 strength at low energies has been noted in several nuclei, as

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discussed in references *i.e.* [3]. However, the theoretical explanation of this phenomenon remains a topic of debate [4–7]. The knowledge of the PDR serves to probe the neutron-skin thickness of medium to heavy nuclei [8, 9], constrain the nuclear symmetry energy [10] and the properties of neutron stars [11].

Recently, the PANDORA (Photo-Absorption of Nuclei and Decay Observation for Reactions in Astrophysics) project has been proposed to explore the photoresponse of light and mid-mass nuclei comprehensively [12]. Given its focus on lighter nuclei, Configuration Interaction Shell Model (CI-SM) calculations are a suitable approach to provide the necessary theoretical predictions. Systematic studies of the dipole response of *sd*-shell nuclei were thus performed within this approach and are partially reported in this work, see [13] for more details. We start with a brief overview of the theoretical methods in Section 2 and then present selected results in Section 3. Conclusions and perspectives are given in Section 4.

2. Theoretical framework

The CI-SM, known as well as the Large-Scale Shell Model approach, permits a diagonalization of the (generally) one- plus two-body nuclear Hamiltonian within the configuration space that can be formed by placing n nucleons within a given set of single-particle orbits, called the model space. In our case, a full $1\hbar\omega$ p–sd–pf model space is used to study the spectroscopy and E1 transitions of the *sd*-shell nuclei. The shell-model Hamiltonian reads

$$H = \sum_i \epsilon_i c_i^\dagger c_i + \sum_{ijkl} V_{ijkl} c_i^\dagger c_j^\dagger c_l c_k + \beta H_{\mathrm{COM}}\,, \tag{1}$$

where the center-of-mass (COM) Hamiltonian with a multiplication coefficient $\beta = 10$ is added to decouple the COM excitations from the intrinsic ones. The isovector E1 transition operator is considered

$$\hat{O}_{1\mu} = -e\frac{Z}{A}\sum_{i=1}^{N} r_i Y_{1\mu}(\hat{r}_i) + e\frac{N}{A}\sum_{i=1}^{Z} r_i Y_{1\mu}(\hat{r}_i) \tag{2}$$

substracting the COM motion. The effective interaction used in this work, dubbed PSDPF, is the semi-empirical one developed in [14] to describe intruder states in the *sd*-shell and employed later for a systematic study of the E3 transitions in *sd*-shell nuclei [15]. We employ the ANTOINE shell-model code [16] to compute distributions of the E1 strength with the Lanczos strength function method with 300 iterations [17].

In the following, we discuss the computed centroids and widths that characterize the E1 strength distributions, obtained following standard definitions (see *e.g.* [18, 19]):

$$\bar{S} = \frac{S_1}{S_0}\,, \qquad \Delta S = \sqrt{\frac{S_2}{S_0} - \bar{S}^2}\,, \tag{3}$$

where

$$S_k = \sum_{\nu} (E_\nu - E_0)^k \left| \langle \nu | \hat{O} | 0 \rangle \right|^2 \tag{4}$$

is the sum rule of the order of k. In the analysis of pygmy resonances, we also use transition densities between final and initial states defined as

$$\delta\rho(\vec{r}) = \langle J_\mathrm{f} | \sum_k \delta(\vec{r} - \vec{r}_k) | J_\mathrm{i} \rangle \tag{5}$$

(see Ref. [20] for details of calculations in the shell-model context).

3. Results

3.1. Systematic study of the sd-shell nuclei

In this section, we discuss systematic photoabsorption strength distributions computed for the 36 long-lived sd-shell nuclei in the $1\hbar\omega$ model space (from ^{17}O to ^{40}Ca). We show in Figs. 1 and 2 the deviations of CI-SM predictions from available photoabsorption data for centroids and widths, respectively. To this end, we compare our calculations with data from the IAEA PSF database [21], calculating the necessary quantities in the same energy range for theoretical predictions and experiment. As can be seen from the figure, the centroid position and distribution width are rather well reproduced within the CI-SM framework: the root-mean-square (r.m.s.) deviation for 25 nuclei is of 0.84 MeV for the centroid and of 0.56 MeV for the width. When excluding nuclei at the extremes of the p–sd–pf valence space, specifically O, F, and Ca, the r.m.s. values improve further, reducing to 0.72 MeV for the centroid and 0.17 MeV for the width. This last number suggests that CI-SM effectively captures the essential correlations needed to model the strength distribution within the experimentally observed region, as can be expected from this type of calculation.

It can be however noted from Fig. 1 that except for the 3 lightest nuclei, CI-SM has a tendency to underestimate the centroid position of the $B(\mathrm{E1})$ distribution. This systematic shift of the centroid is cumbersome and would require a revision of the effective interaction: one should remind, the PSDPF interaction was only adjusted to reproduce the low-energy negative parity states of sd-shell nuclei, while here we use it to study excitations at much higher energies. In spite of that, the CI-SM still outperforms the QRPA predictions available in the IAEA PSF database [22]: The QRPA also underestimates systematically the position of the centroid, leading to a much

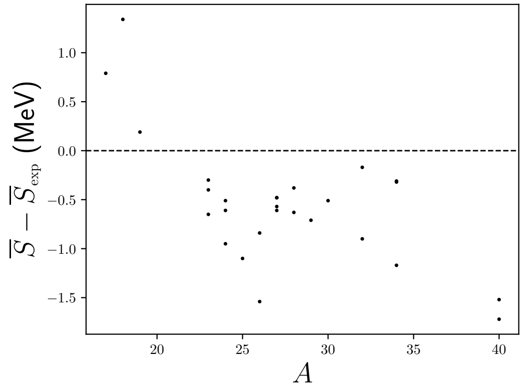

Fig. 1. Difference of theoretical centroids and centroids calculated from photoabsorption data (IAEA PSF database [21]).

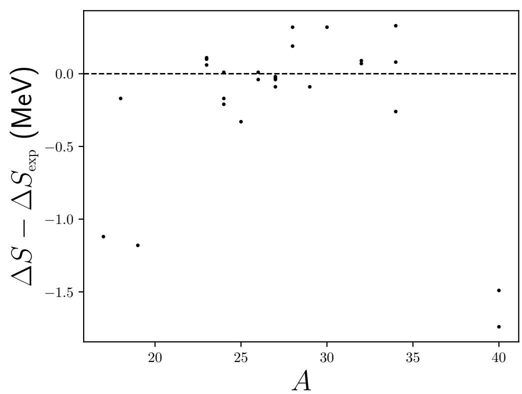

Fig. 2. Difference of predicted widths and widths calculated from photoabsorption data (IAEA PSF database [21]).

larger discrepancy (r.m.s. = 1.3 MeV), and misses additionally the details of the E1 distributions, in spite of a similar average error on the widths (r.m.s. = 0.5 MeV). This is not surprising as the truncation of many-body space of QRPA omits physical effects that are fully accounted for in a complete CI-SM diagonalization and cannot be captured by simple empirical centroids shift. More advanced many-body approaches aim at decreasing such errors by including higher-order excitations ($2p$–$2h$, $3p$–$3h$, phonon-coupling), which enhances the fragmentation of the spectrum, while shifting the centroid of the resonance [23–27].

3.2. Analysis of the PDR mode in ^{26}Ne

In this section, we discuss the PDR in ^{26}Ne based on our CI-SM calculation. Let us remind first what is usually meant by the "pygmy" dipole resonance: nowadays this term is frequently used for the concentration of the low-lying E1 strength, without implying any particular structure. Note that different theoretical approaches predict systematically low-energy E1 strength but its collectivity and resonant nature are still debated and some authors prefer to use the term Pygmy Dipole Strength (PDS) rather than PDR [4, 5] (see as well Paar's contribution to this volume [28]).

^{26}Ne has been extensively studied both theoretically [29–32] and experimentally [33] in this context. Experimental work suggested the presence of the PDR mode, with the B(E1) strength below 10 MeV, accounting for approximately 4% of the TRK sum rule. The dipole response of Ne isotopes was previously addressed in the present framework in Ref. [29], in order to study the validity of the Brink–Axel hypothesis. It was shown that enhancement of the E1 strength below 10 MeV appears in $^{26-28}$Ne, compatible with Refs. [30, 32, 33]. Here, we investigate in more detail the nature of the low-lying E1 mode in ^{26}Ne, computing for the first time in the CI-SM the transition densities in the neutron-rich nucleus with the PDR.

Precisely, the present calculation in ^{26}Ne predicts 14 1^- states with sizable B(E1) transitions to the ground state below 10 MeV. Among these states, two of them are located around 5 MeV, while the remaining 12, above 7 MeV, may constitute a PDR. In Fig. 3, we plot the average proton

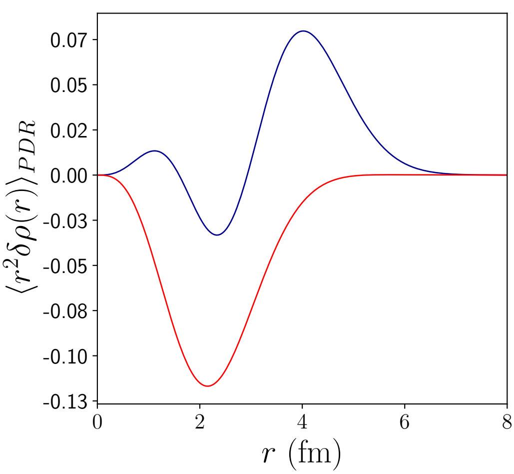

Fig. 3. (Colour on-line) Non-weighted average transition density in the PDR energy region. Red/gray curve: proton transition density. Blue/black curve: neutron transition density.

and neutron transition densities in the PDR energy region (from 7 MeV to 10 MeV). Note that this energy interval is not an *ad hoc* prescription but is inferred from the analysis of the structure of each of the individual low-lying states (*i.e.* their $B(\mathrm{E1})$ value, wave-function composition, and transition density), permitting us to exclude the first two predicted 1^- states from the PDR region as well as higher-lying 1^- states, which belong to the tail of the GDR. In Fig. 3 the average is made over the remaining 12 states which have similar properties, evidencing a possible resonant nature of this mode. We observe an isoscalar bulk response, indicating that on average, the proton and neutron fluids in the nucleus' core oscillate in-phase. Simultaneously, we notice a distinctive neutron-skin response at the nucleus' boundary. Hence, our understanding of the PDR in this case goes beyond a simple neutron excess oscillation. We propose rather a neutron skin oscillation on top of an in-phase core response. The question of the collectivity of this oscillation will be addressed in the forthcoming publication [13].

4. Conclusions

We have studied systematically the E1 photo-response of light nuclei that can be described in the *p–sd–pf* shell-model framework. We found a satisfactory agreement with available experimental data as far as centroids and widths of the distributions are considered. Our analysis of transition densities in the low-energy region in ^{26}Ne shows that the PDR can be interpreted as neutron skin oscillation on top of an isoscalar core response. The complete set of our results will be presented in a forthcoming publication [13].

It can be concluded from the current study that CI-SM is a suitable method to provide predictions of dipole response of light-mass systems and gives a valuable insight into the fine structure of resonances. The study shall continue to provide predictions for $f_{7/2}$-shell nuclei and analyse the PDR strength in Ca isotopes within the recently developed *sd–pf–gds* shell-model framework [34].

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REFERENCES

[1] G.A. Bartholomew, *Annu. Rev. Nucl. Part. Sci.* **11**, 259 (1961).
[2] R. Mohan, M. Danos, L. Biedenharn, *Phys. Rev. C* **3**, 1740 (1971).
[3] D. Savran, T. Aumann, A. Zilges, *Prog. Part. Nucl. Phys.* **70**, 210 (2013).
[4] N. Paar, D. Vretenar, P. Ring, *Phys. Rev. Lett.* **94**, 182501 (2005).
[5] D. Vretenar, Y. Niu, N. Paar, J. Meng, *Phys. Rev. C* **85**, 044317 (2012).
[6] P.-G. Reinhard, W. Nazarewicz, *Phys. Rev. C* **87**, 014324 (2013).
[7] E. Litvinova, P. Ring, V. Tselyaev, K. Langanke, *Phys. Rev. C* **79**, 054312 (2009).
[8] A. Tamii *et al.*, *Phys. Rev. Lett.* **107**, 062502 (2011).
[9] J. Piekarewicz, *Phys. Rev. C* **83**, 034319 (2011).
[10] X. Roca-Maza *et al.*, *Phys. Rev. C* **92**, 064304 (2015).
[11] C. Horowitz, J. Piekarewicz, *Phys. Rev. Lett.* **86**, 5647 (2001).
[12] PANDORA Collaboration (A. Tamii *et al.*), *Eur. Phys. J. A* **59**, 208 (2023).
[13] O. Le Noan, K. Sieja, `arXiv:2501.17646 [nucl-th]`.
[14] M. Bouhelal *et al.*, *Nucl. Phys. A* **864**, 113 (2011).
[15] M. Bouhelal, M. Labidi, F. Haas, E. Caurier, *Phys. Rev. C* **96**, 044304 (2017).
[16] E. Caurier, F. Nowacki, *Acta Phys. Pol. B* **30**, 705 (1999).
[17] E. Caurier *et al.*, *Rev. Mod. Phys.* **77**, 427 (2005).
[18] P. Ring, P. Schuck, «The Nuclear Many-body Problem», *Springer*, Berlin, Heidelberg 1980.
[19] I. Stetcu, C.W. Johnson, *Phys. Rev. C* **67**, 044315 (2003).
[20] H.-L. Ma *et al.*, *Phys. Rev. C* **85**, 044307 (2012).
[21] S. Goriely *et al.*, *Eur. Phys. J. A* **55**, 172 (2019), `arXiv:1910.06966 [nucl-ex]`.
[22] S. Goriely, S. Hilaire, S. Péru, K. Sieja, *Phys. Rev. C* **98**, 014327 (2018).
[23] D. Gambacurta *et al.*, *Phys. Rev. C* **86**, 021304 (2012).
[24] D. Gambacurta, M. Grasso, J. Engel, *Phys. Rev. C* **92**, 034303 (2015).
[25] F. Knapp *et al.*, *Phys. Rev. C* **107**, 014305 (2023).
[26] R. Trippel, Ph.D. Thesis, TU Darmstadt, 2016.
[27] V. Tselyaev, N. Lyutorovich, J. Speth, P.-G. Reinhard, *Phys. Rev. C* **102**, 064319 (2020).
[28] N. Paar, A. Kaur, *Acta Phys. Pol. B Proc. Suppl.* **18**, 2-A31 (2025), this issue.
[29] K. Sieja, *Eur. Phys. J. A* **59**, 147 (2023).
[30] M. Kimura, *Phys. Rev. C* **95**, 034331 (2017).
[31] M. Martini, S. Péru, M. Dupuis, *Phys. Rev. C* **83**, 034309 (2011).
[32] L.-G. Cao, Z.-Y. Ma, *Phys. Rev. C* **71**, 034305 (2005).
[33] J. Gibelin *et al.*, *Phys. Rev. Lett.* **101**, 212503 (2008).
[34] K. Sieja, *Phys. Rev. Lett.* **119**, 052502 (2017).