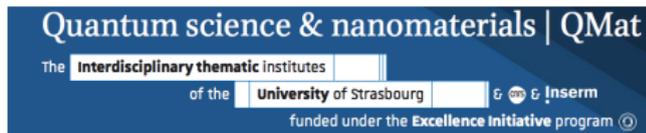


Configuration Interaction Shell Model: Recent Developments and Applications

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P(ND)²-3, 12/03/2026

- ① Configuration Interaction Shell Model: theory elements and details of calculations
- ② Photoabsorption strength in light mass nuclei:
-systematic studies of p and sd -shell nuclei with applications
- ③ Photoabsorption strength of mid-mass nuclei: perspectives

Configuration Interaction Shell Model

- We start with a reference state - Slater determinant - which we believe may be a dominant configuration of the ground state:

$$\Phi_0 = \frac{1}{\sqrt{N!}} \begin{pmatrix} \phi_1(\vec{x}_1) & \phi_1(\vec{x}_2) & \cdots & \phi_1(\vec{x}_N) \\ \phi_2(\vec{x}_1) & \phi_2(\vec{x}_2) & \cdots & \phi_2(\vec{x}_N) \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ \phi_N(\vec{x}_1) & \phi_N(\vec{x}_2) & \cdots & \phi_N(\vec{x}_N) \end{pmatrix}, \quad (1)$$

$\phi_i(\vec{x}_i)$ are single-particle basis states.

- The wave-function of the ground state can be thus expressed as a sum of the vacuum Φ_0 and particle-hole excitations build on this vacuum state

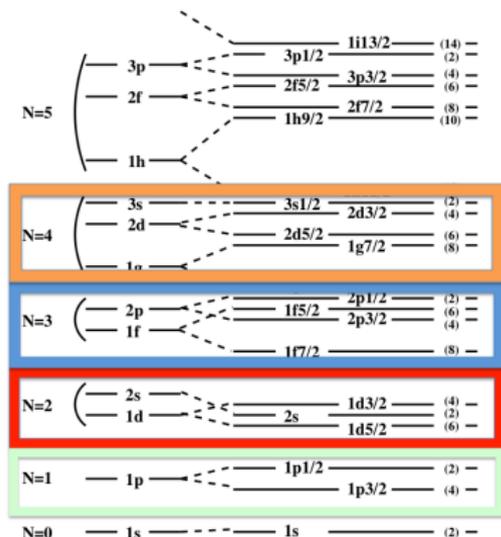
$$|\Psi_0\rangle = C_0|\Phi_0\rangle + \sum_{i\alpha} C_{i\alpha}|\Phi_{i\alpha}\rangle + C_{ij\alpha\beta}|\Phi_{ij\alpha\beta}\rangle + \cdots = \sum_{ph} C_{ph}|\Phi_{ph}\rangle \quad (2)$$

- The equation for the energy reads

$$E = \langle \Psi_0 | \hat{H} | \Psi_0 \rangle = \sum_{pp'h'h'} C_{p'h'}^* \langle \Phi_{p'h'} | \hat{H} | \Phi_{ph} \rangle C_{ph} \quad (3)$$

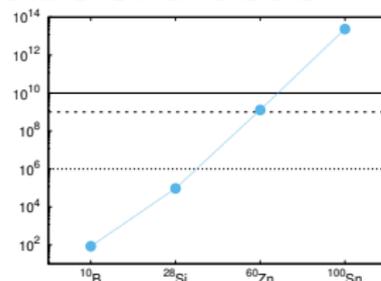
and it is solved by diagonalization (Lanczos method). For a given H, the diagonalization provides us with EXACT results for ground state and all excited states.

Configuration Interaction Shell Model



- To describe low-energy spectroscopy, $0\hbar\omega$ model spaces are often sufficient

- $0\hbar\omega$ CI-SM dimensions:



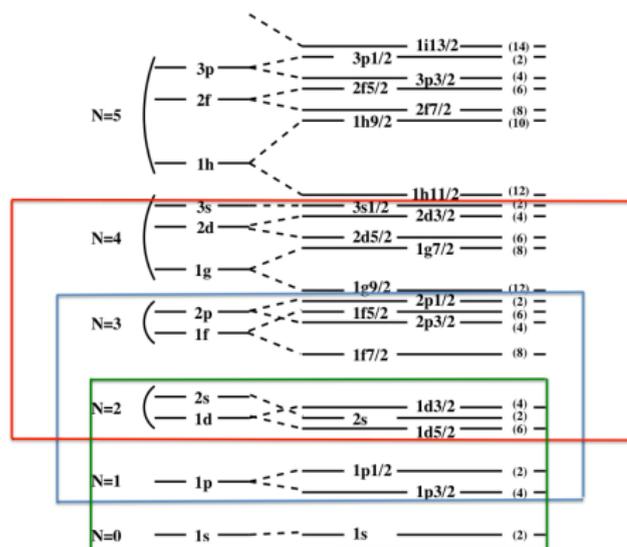
10^6 : feasible on a laptop

10^9 : standard for M-scheme SM codes

10^{10} : current limit

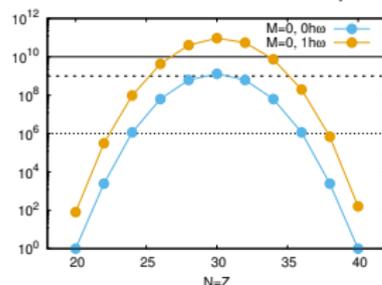
- Many empirically-adjusted SM interactions of good quality publicly available in classical model-spaces, i.e. p , sd , pf , gds shells

Configuration Interaction Shell Model



- To describe $E1$ transitions, $1\hbar\omega$ model spaces needed

- CI-SM dimensions in the pf -shell:



10^6 : feasible on a laptop

10^9 : standard for M-scheme SM codes

10^{10} : current limit

- SM interactions of good quality rare in multi-shell valence spaces

Lanczos strength function method

$$S = |\hat{O}|\psi_i\rangle| = \sqrt{\langle\psi_i|\hat{O}^2|\psi_i\rangle}$$

The operator \hat{O} does not commute with H and $\hat{O}|\psi_i\rangle$ is not necessarily the eigenstate of the Hamiltonian. But it can be developed in the basis of energy eigenstates:

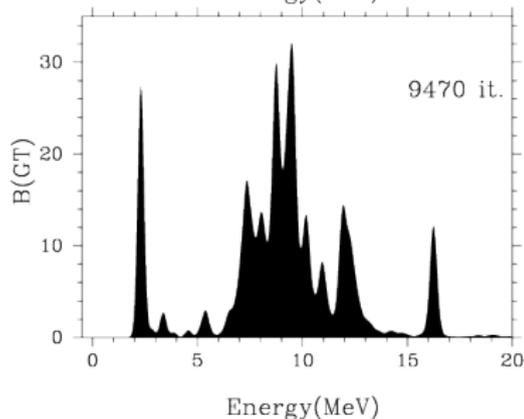
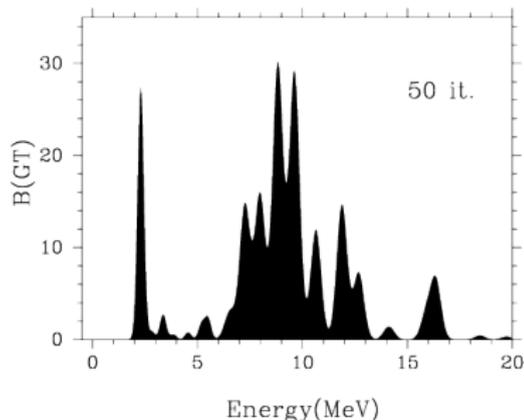
$$\hat{O}|\psi_i\rangle = \sum_f S(E_f)|E_f\rangle,$$

where $S(E_f) = \langle E_f|\hat{O}|\psi_i\rangle$ is called **strength function**.

If we carry Lanczos procedure using $|O\rangle = \hat{O}|\psi_i\rangle$ as initial vector then H is diagonalized to obtain eigenvalues $|E_f\rangle$ and after N iterations we have the also the strength function:

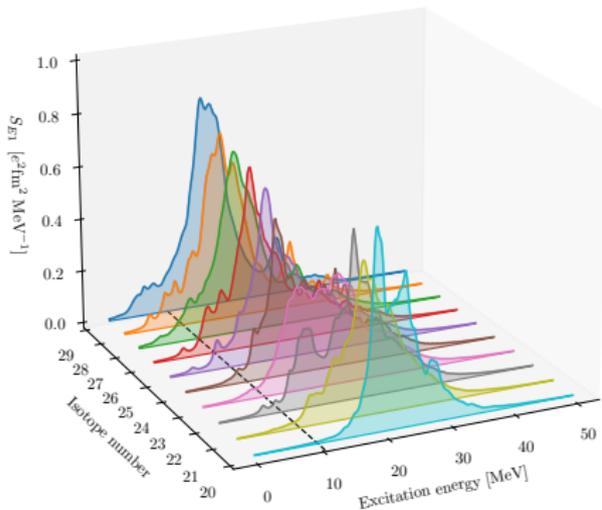
$$\tilde{S}(E_f) = \langle E_f|O\rangle = \langle E_f|\hat{O}|\psi_i\rangle.$$

How good is the strength function \tilde{S} after N iterations compared to the exact one S ?



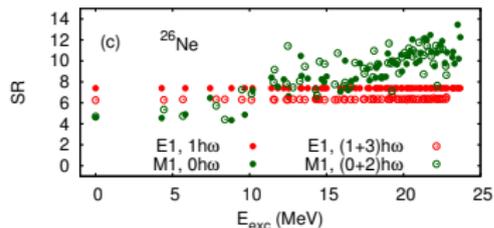
Dipole response of Ne nuclei and PDR modes

Dipole response in Ne isotopic chain

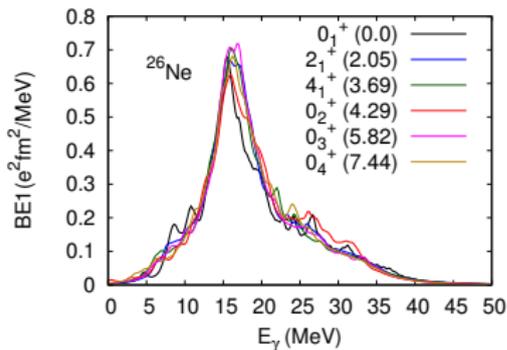


O. Le Noan and K. Sieja, Phys. Rev. C111, 064308 (2025)

E1/M1 sum rule dependence on initial state



E1 dipole response on excited states



K. Sieja, Eur. Phys. JA59, 147 (2023)

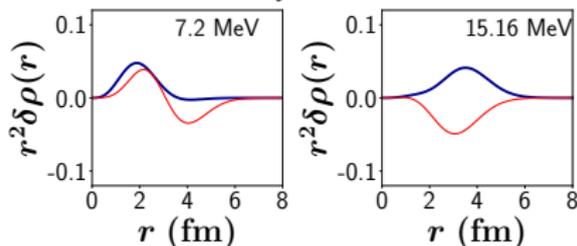
Dipole response: isospin mixing in PDR states

$$\delta\rho_{v0}(\vec{r}) = \langle v | \sum_k \delta(\vec{r} - \vec{r}_k) | 0 \rangle$$

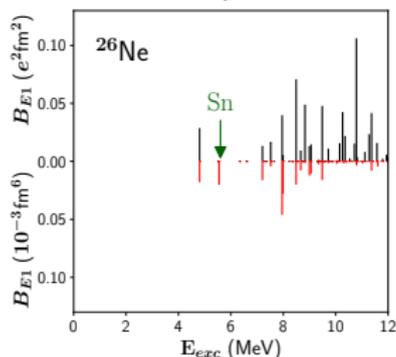
$$\hat{O}_{1\mu}^{IV} = -e \frac{Z}{A} \sum_{i=1}^N r_i Y_{1\mu}(\hat{r}_i) + e \frac{N}{A} \sum_{i=1}^Z r_i Y_{1\mu}(\hat{r}_i)$$

$$\hat{O}_{1\mu}^{IS} = \sum_{i=1}^A r_i^3 Y_{1\mu}(\hat{r}_i)$$

Transition density in ^{26}Ne : PDR vs GDR

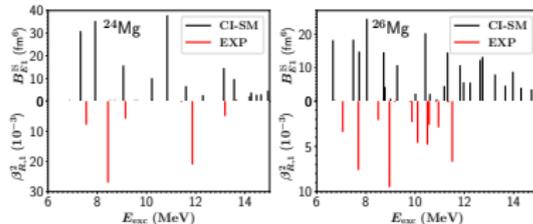


IV and IS response in ^{26}Ne



CI-SM and QRPA isoscalar strength (in fm^6) summed up to 16MeV

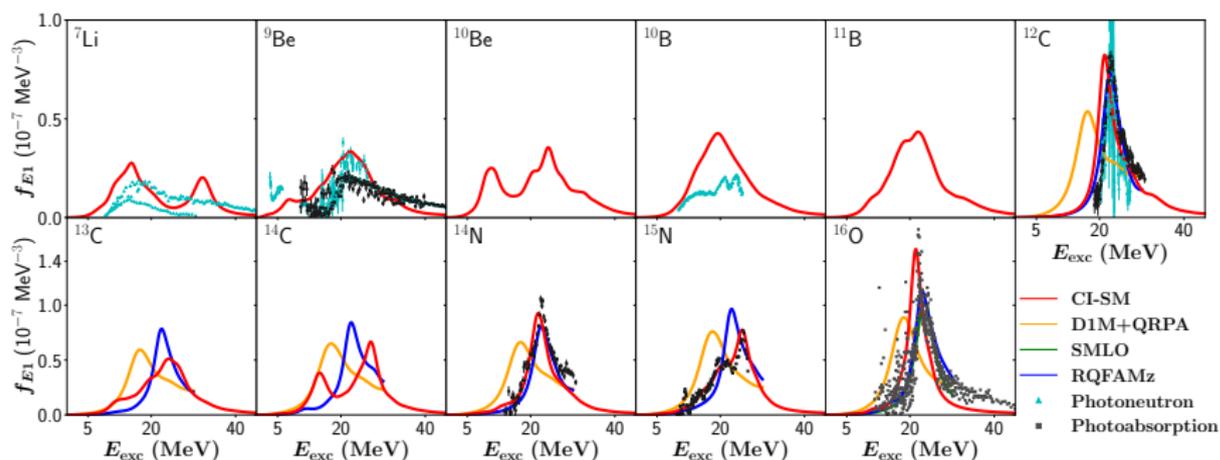
Nucleus	QRPA	CI-SM
^{24}Mg	162	176
^{26}Mg	230	223
^{28}Si	189	251



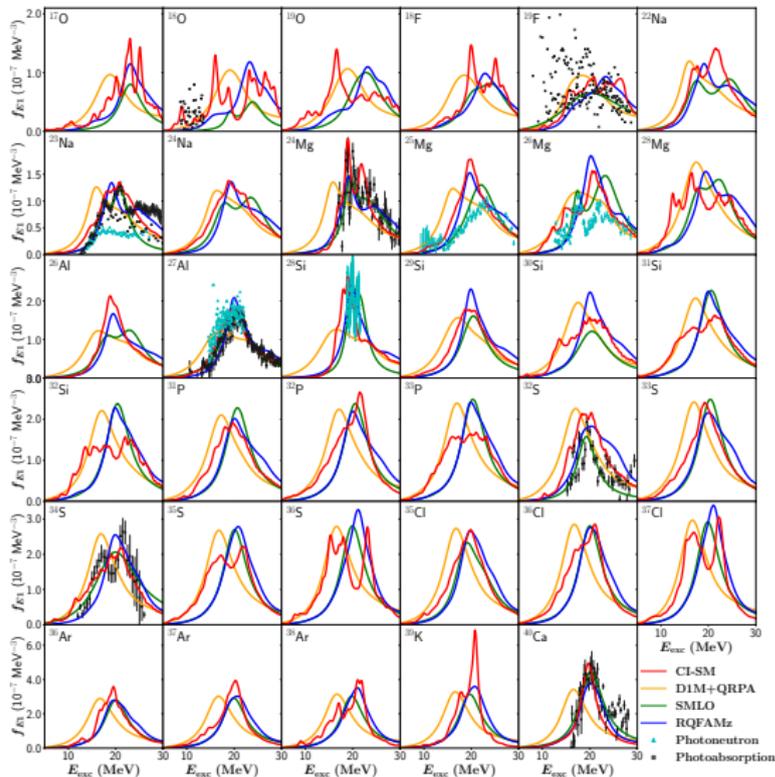
P. Adsley et al., Phys. Rev. C103, 044315 (2021)

Systematics of $E1$ strength in p and sd -shell nuclei

- CI-SM study of $E1$ strength of 137 nuclei from ${}^7\text{Li}$ to ${}^{40}\text{Ca}$
- use of well-established empirical interactions WBP and PSDPF
E. K. Warburton and B. A. Brown, *Phys. Rev. C* 46, 923 (1992)
M. Bouhelal et al., *Nuc. Phys. A* 864, 113 (2011)
- PSF available (TALYS database)
- Comparison to available experimental data and QRPA models:
D1M+QRPA: S. Goriely, S. Hilaire, S. Péru, and K. Sieja, *PRC* 98, 014327 (2018)
RQFAMz: L. Gonzalez-Miret Zaragoza, J.-P. Ebran, S. Goriely, S. Hilaire, E. Khan, and S. Péru, *PRC* 112, 044303 (2025)

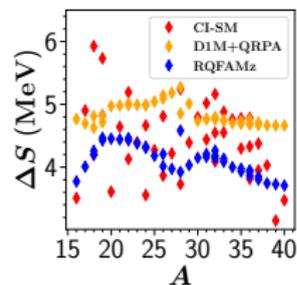
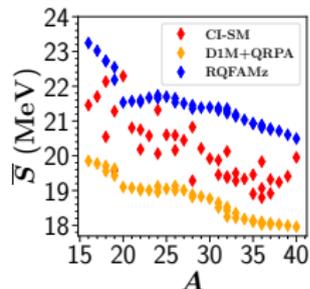


Systematics of $E1$ strength in p and sd -shell nuclei



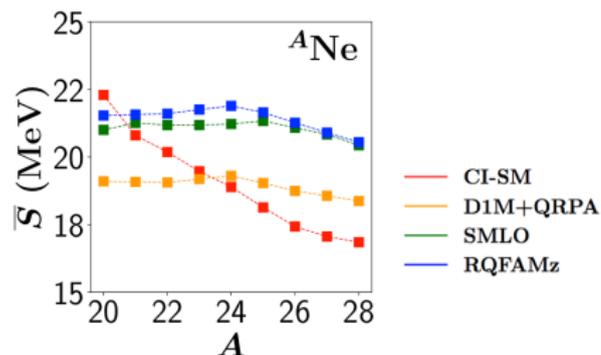
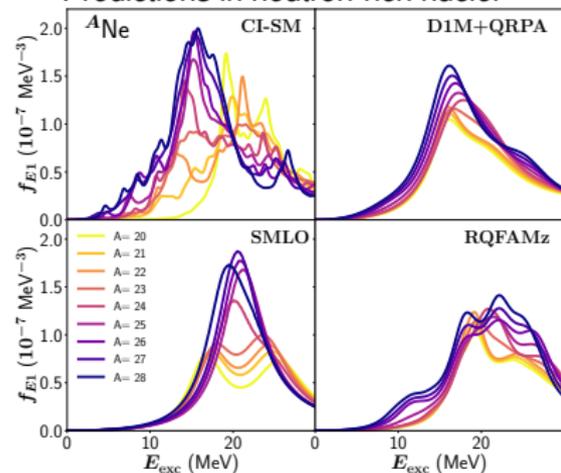
RMS for 26 nuclei

Model	$\sigma_{\bar{S}}$	$\sigma_{\Delta S}$
CI-SM	0.85	0.51
D1M + QRPA	1.71	0.49
RQFAMz	0.89	0.48

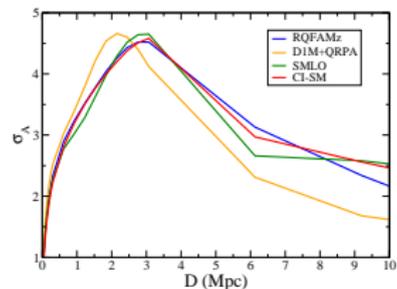
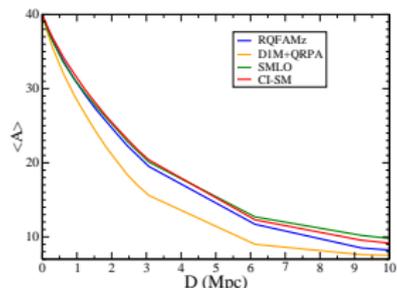


Systematics of $E1$ strength in p and sd -shell nuclei

Predictions in neutron-rich nuclei

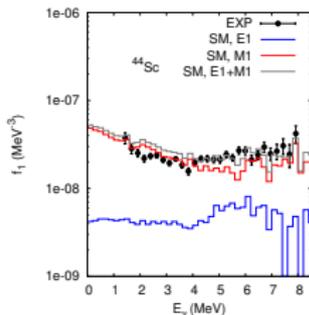
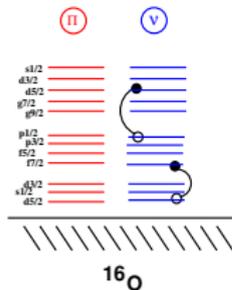


Application to UHECR propagation



O. Le Noan, E. Khan, S. Goriely and K. Sieja,
arXiv:2512.16329

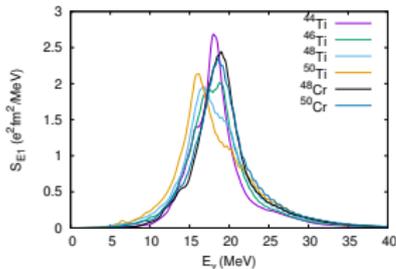
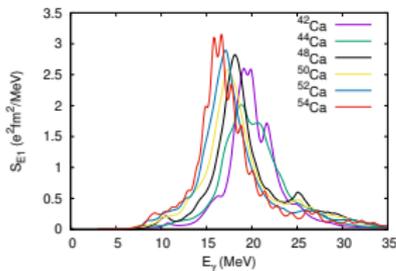
$E1$ strength in pf -shell nuclei: work in progress



K. Sieja, PRL119 (2017) 052502

- fp -calculations for positive parity states
- $1\hbar\omega$ calculations for negative parity states
- Interaction: v_{lowk} + empirical corrections

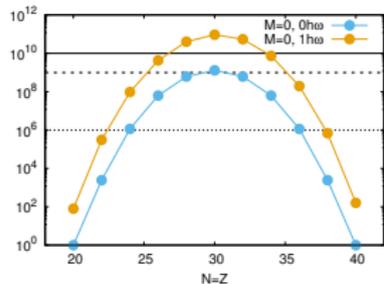
Preliminary results



- Systematics of low-energy, abnormal-parity excitations in the mass region $A=40-80$ (improvement of effective Hamiltonian)
- Systematics of PSF for nuclei up to $A \sim 50$ (renormalization of the effective operator)
- Analysis of PDR modes in the Ca chain

E1 strength in pf -shell nuclei: future work

CI-SM dimensions in the pf -shell:



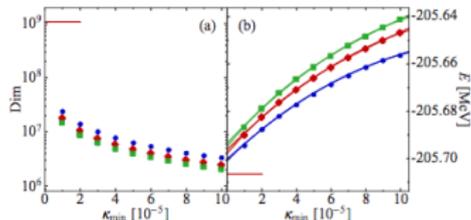
10^6 : feasible on a laptop

10^9 : standard for M-scheme SM codes

10^{10} : current limit

^{56}Ni	M=0	$6.5 \cdot 10^8$
	0.01	$3 \cdot 10^2$
	0.001	$1.1 \cdot 10^4$
	0.0001	$2.8 \cdot 10^5$
^{48}Cr	M=0	$1.1 \cdot 10^6$
	0.01	$1.1 \cdot 10^3$
	0.001	$5.1 \cdot 10^4$
	0.0001	$5 \cdot 10^5$

- Importance-truncated CI-SM methods
 - no-core CI-SM: R. Roth, PRC79 (2009) 064324
 - valence-space CI-SM: C. Stumpf, J. Braun and R. Roth, PRC93 (2016) 021301R



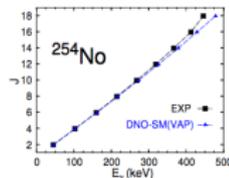
- PGCM (in valence spaces)

B. Bally et al., Eur.Phys.J.A 57 (2021) 2, 69

MCSM: T. Otsuka et al., Prog. Part. Nuc. Phys. 47 (2001) 319

QVSM: N. Shimizu et al., PRC 103 (2021) 014312

DNO-SM: D. Dao and F. Nowacki, PRC 105 (2022)



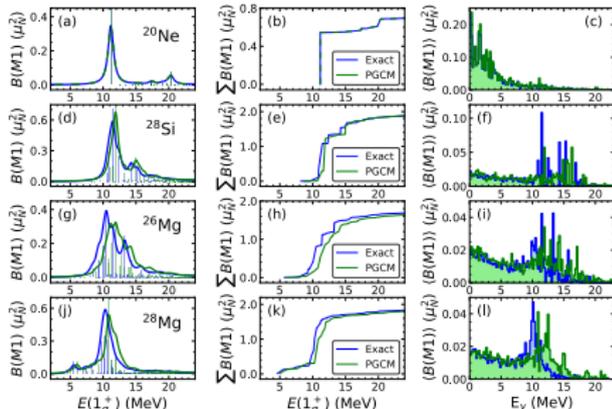
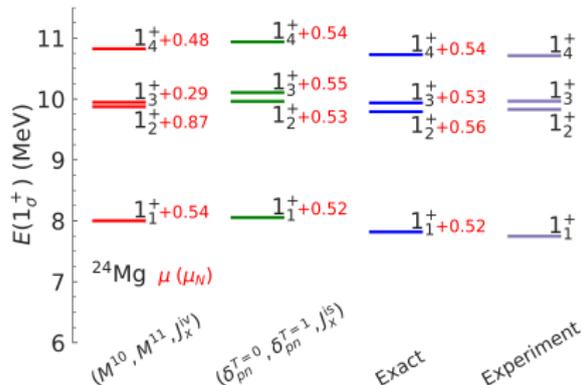
054314

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M1 strength in valence-spaces: PGCM vs CI-SM

- sd-shell model space with USDb interaction
- two different sets of generating coordinates
- codes TAURUS & PAN@CEA

^{24}Mg	$J = 0^+$	$J = 1^+$
M=0	$2.8 \cdot 10^4$	$2.8 \cdot 10^4$
J-coupled	1161	3096
PGCM	320	890



S. Bofos, J. Martinez-Larraz, B. Bally, T. Duguet, M. Frosini, T. Rodriguez and K. Sieja, PRC112 (2025) 064312

Conclusions & Perspectives

- CI-SM provides a good quality dipole PSF in addition to its “traditional” applications in low-energy spectroscopy:
 - ① Systematics of PSF in light nuclei (up to ^{40}Ca) available
 - ② Short-term perspective: $E1$ in low-mass pf -shell nuclei and study of PDR in Ca isotopes
 - ③ Mid-term perspective: remaining pf -shell nuclei using IT-CI-SM methods
- Additionally, CI-SM can be used as benchmark of other many-body methods (QRPA, PGCM) in valence spaces with CI-SM Hamiltonians:
 - ① Short-term perspective: predictions of $M1$ strength in heavier nuclei (PGCM in valence spaces)