Dipole excitations in nuclei: recent Configuration Interaction studies

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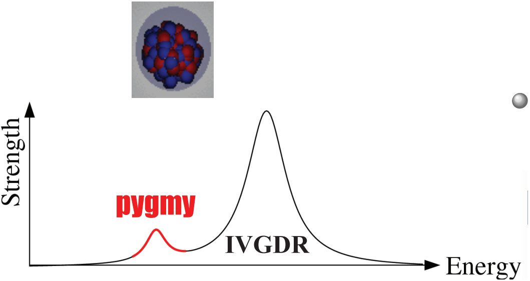
ECT*, 24-28.10.2022

Outline

- Motivation: Brink-Axel hypothesis
- Calculations of E1/M1 photoabsorption and photoemission SF in CI framework
- Low-energy strength in neon isotopes
- Influence on neutron-capture rates

Pygmy-dipole resonance: motivation



- the pygmy part impacts astrophysical reaction rates and resulting abundances in the r-process

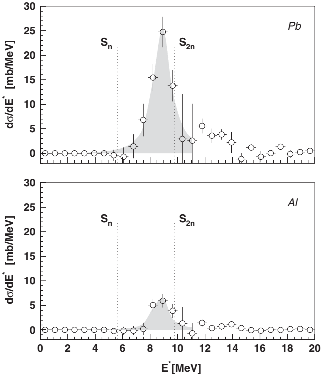
  S. Goriely, E. Khan and M. Samyn, Nucl. Phys. A739 (2004) 331

  E. Litvinova et al., Nucl. Phys. A823 (2009) 26

- in stellar environements finite temperatures
  (1) reactions on excited states
  (2) Brink-Axel hypothesis becomes crucial
- Brink-Axel hypothesis
  (1) the photoabsorption cross section is independent on the initial state
  (2) photoabsorption SF = photoemission SF

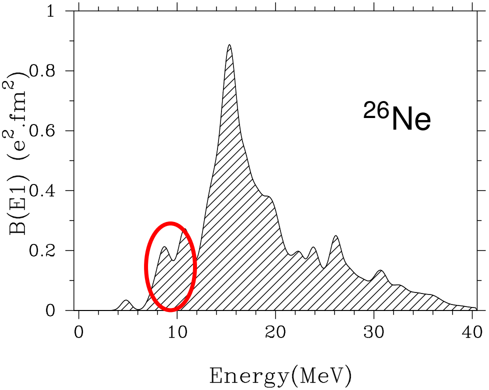
E1 in ^{26}Ne: experimental evidence of pygmy

EXP: $\sum B(E1)=0.49\pm0.16$ e^2fm^2 (6-10MeV)
5% of TRK sum rule



J. Gibelin et al., Phys. Rev. Lett. 101 (2008) 212503

THEO: $\sum$ B(E1)=0.485 e^2fm^2 (0-10MeV)



SM from Strasbourg (unpublished)
QRPA study *M. Martini, S. Péru, and M. Dupuis, Phys. Rev. C 83, 034309 (2011)*

Low peaks structure: $\nu s_{1/2}^{-1} p_{3/2}^{1}$, $\nu s_{1/2}^{-1} p_{1/2}^{1}$
SM: Complex wave functions
(major contributions $\leq 10\%$)
QRPA main contribution: 70% of $\nu s_{1/2}^{-1} p_{3/2}^{1}$

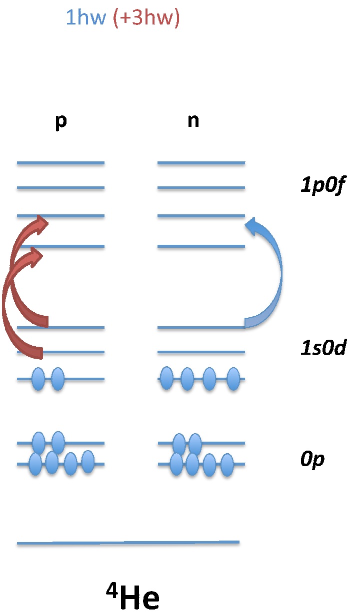
☞Evolution of photoabsorption strength with energy (spin)

CI calculations in psdpf space

$$Q_\mu^{\lambda=1} = \frac{Z}{A} e \sum_{k=1}^{N} r_k Y_{1\mu}(r_k) - \frac{N}{A} e \sum_{k=1}^{Z} r_k Y_{1\mu}(r_k)$$

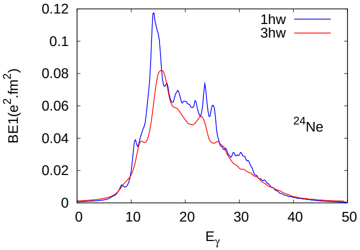
- full *sd* diagonalization + full $1\hbar\omega(+3\hbar\omega)$ excitations
- Exact removal of COM components
- Interaction: PSDPF

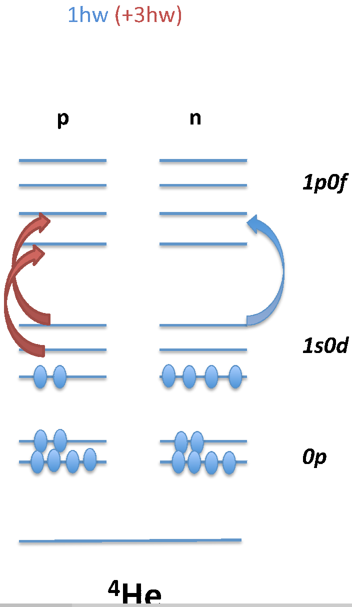
  M. Bouhelal, F. Haas, E. Caurier, F. Nowacki and A. Bouldjedri, Nucl. Phys. A864 (2011) 113.
- 300 Lanczos iterations to get distributions
- Lorentzian smoothing with $\Gamma/2 = 500 keV$



CI calculations in psdpf space

- $1\hbar\omega$ calculations
  $0\hbar\omega$ for positive parity states
  $1\hbar\omega$ for negative parity states
- $3\hbar\omega$ calculations
  $0+2\hbar\omega$ for positive parity states
  $1+3\hbar\omega$ for negative parity states





$1\hbar\omega$: sufficient for low-energy strength
$3\hbar\omega$: correlations suppress $E1$ strength

Lanczos strength function method

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

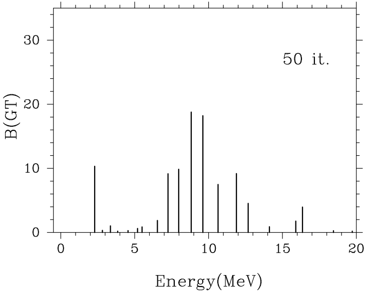
The operator $\hat{O}$ does not commute with H and $\hat{O}|\psi_i\rangle$ is not necessarily the eigenstate of the Hamiltonian. But it can be developed in the basis of energy eigenstates:

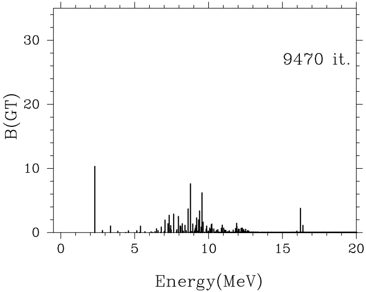
$$\hat{O}|\psi_i\rangle = \sum_f S(E_f)|E_f\rangle,$$

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?





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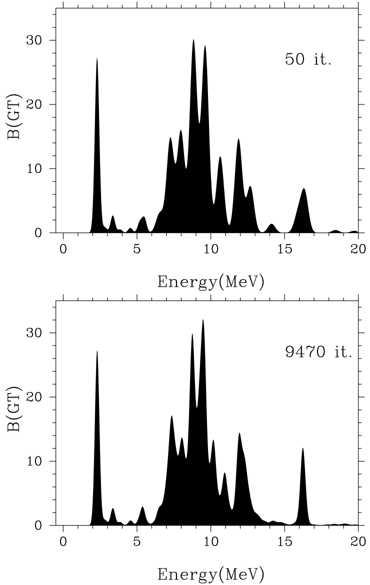


CI calculations in psdpf space: COM treatment

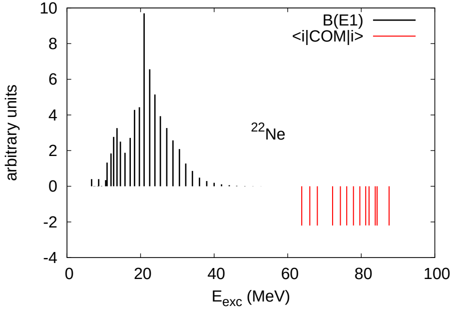
$$H = \sum_i \varepsilon_i c_i^\dagger c_i + \sum_{i,j,k,l} V_{ijkl} c_i^\dagger c_j^\dagger c_l c_k + \beta_{c.m.} H_{c.m.}$$

- SF are obtained with LSF method with 300 iterations
- keep states with the largest overlap with the SR state
- compute $\langle \Phi_i | H_{c.m.} | \Phi_i \rangle$ for the states kept

Example: ^{22}Ne
$\langle \Phi_i | H_{c.m.} | \Phi_i \rangle \leq 5 \cdot 10^{-4} MeV$ for all i

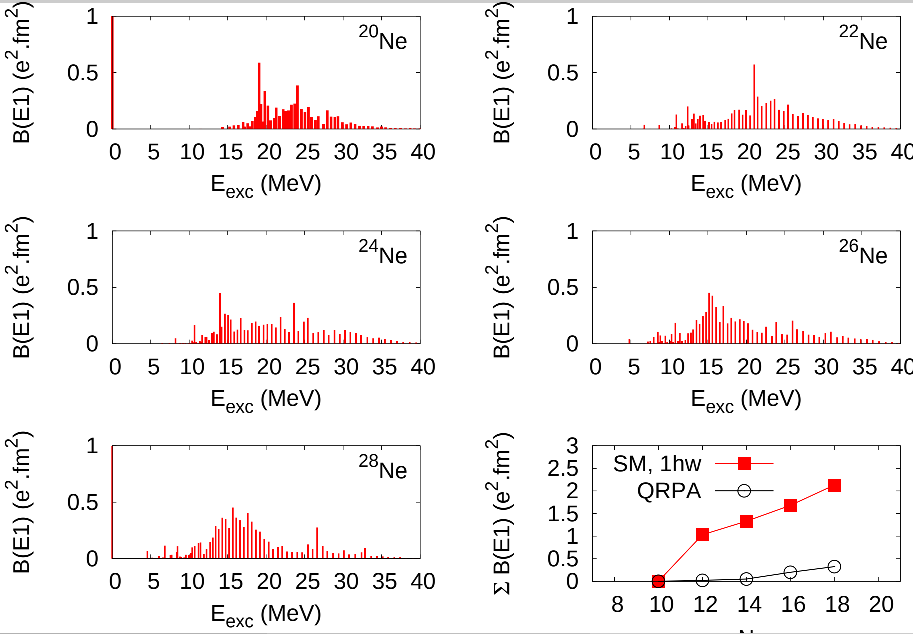
Spuriosity $\leq$ 0.002% for the largest peaks

- 100 Lanczos iterations
- keep all states and compute $\langle \Phi_i | H_{c.m.} | \Phi_i \rangle$



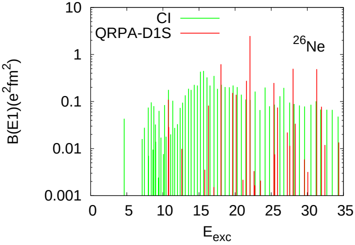
No spuriosity below $E_{exc} = 50$MeV

E1 strength in even neon isotopes



E1 strength at low energy: example of ^{26}Ne

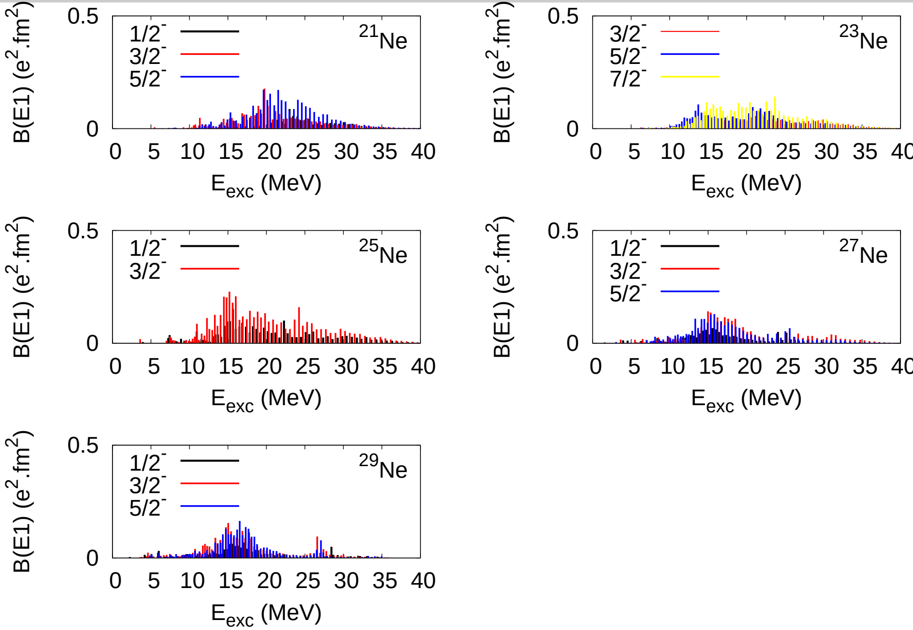
E_{exc} (MeV)	N	$B(E1; 0^+_{g.s.} \rightarrow 1^-)(e^2 fm^2)$	% of ν 1p1h	% of π 1p1h	component
4.64	1	0.041	94	6	$27\% \nu 2s^1_{1/2} p^1_{3/2}$
7.13	3	0.015	63	37	$\leq 10\%$
7.43	4	0.026	63	37	$\leq 10\%$
7.97	5	0.07	44	56	$10\% \pi 1p^{-1}_{1/2} 1d^1_{3/2}$
8.38	7	0.09	90	10	$\leq 10\%$
8.74	9	0.075	82	18	$\leq 10\%$
9.46	13	0.06	68	32	$\leq 10\%$
10.76	21	0.16	61	39	$\leq 10\%$



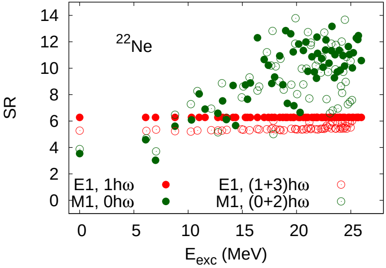
QRPA first peak:
10.7MeV $67.6\% \nu 2s^1_{1/2} p^1_{3/2}$

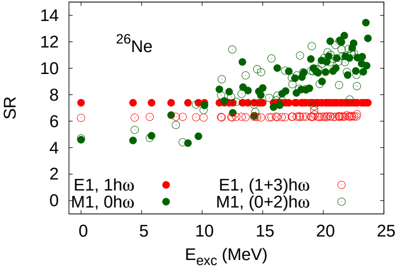
QRPA-D1M SR = $5.7 e^2 fm^2$
CI SR = $7.4 e^2 fm^2$

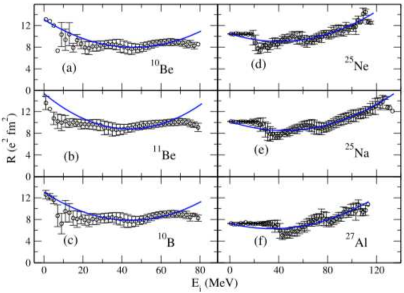
E1 strength in odd neon isotopes



E1 and M1 sum rules dependence on initial state



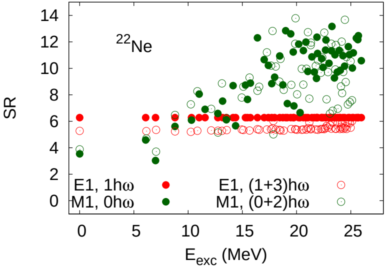


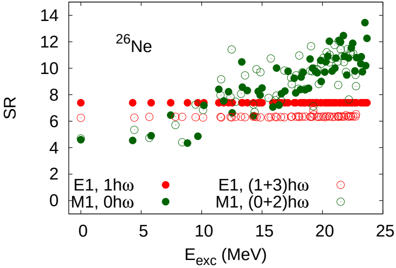


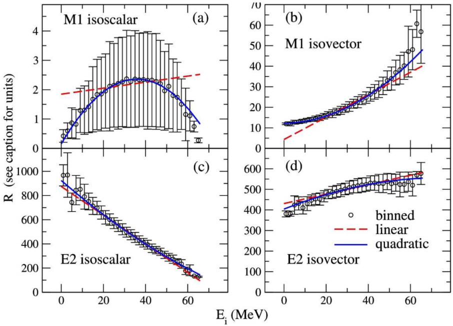
C. Johnson, Phys. Lett. 750 (2015) 72

- $3\hbar\omega$ correlations reduce $E1$ sum rule up to 15%
- $E1$ sum rule stays constant within energy/spin range
- good agreement with previous SM studies

E1 and M1 sum rules dependence on initial state





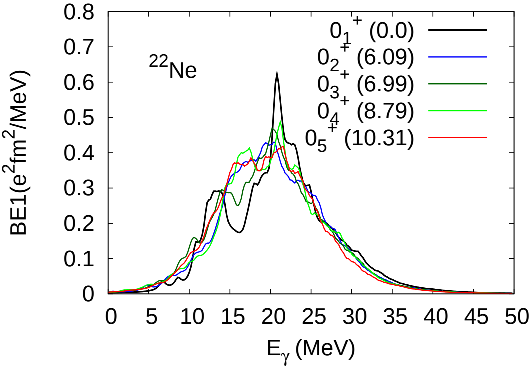


C. Johnson, Phys. Lett. 750 (2015) 72

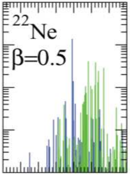
- no distinct trend with correlations
- good agreement with previous SM studies

E1 strength functions on excited states

J_i^π	first peak (MeV)	centroid (MeV)	width (MeV)	$\sum B(E1)$ ($e^2 fm^2$)	$\sum(E_\gamma \cdot B(E1))$ (MeV$e^2 fm^2$)
^{22}Ne					
0_1^+	6.55	21.04	6.20	0.08	0.65
0_2^+	0.46	20.42	6.07	0.22	1.67
0_3^+	0.35	20.11	6.25	0.26	2.07
0_4^+	0.34	20.32	6.06	0.28	2.08
0_5^+	0.23	19.89	5.95	0.24	1.82

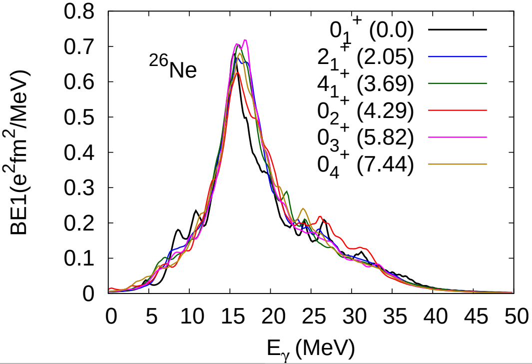


HF minimum with USDB:
$\beta = 0.49$
QRPA prediction in ^{22}Ne:



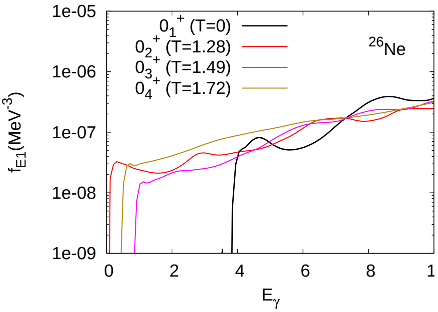
E1 strength functions on excited states

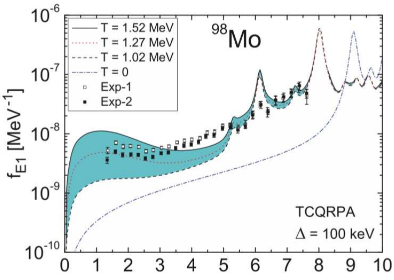
J_i^π ^{26}Ne	first peak (MeV)	centroid (MeV)	width (MeV)	$\sum B(E1)$ ($e^2 fm^2$)	$\sum(E_\gamma \cdot B(E1))$ ($MeV e^2 fm^2$)
0_1^+	4.64	18.96	7.13	0.48	3.96
2_1^+	2.59	18.82	6.71	0.45	3.12
4_1^+	1.67	18.83	6.72	0.48	3.71
0_2^+	0.35	19.17	6.79	0.42	3.06
0_3^+	1.61	18.66	6.48	0.43	3.35
0_4^+	0.53	18.64	6.55	0.42	2.96



BA hypothesis holds for GDR

E1 strength functions on excited states





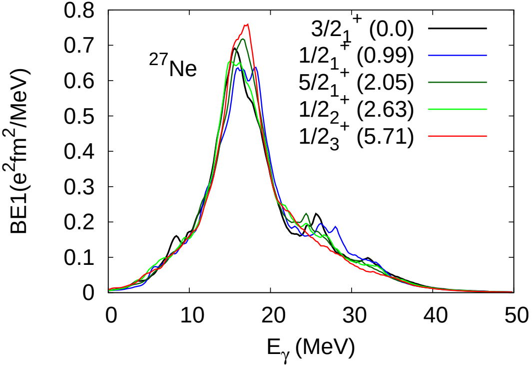
E. Litvinova and N. Belov, Phys. Rev. C88 (2013) 031302

J^π	first peak (MeV)	EWSR (0-10MeV)
0_1^+	4.64	3.96
0_2^+	0.35	3.06
0_3^+	1.61	3.35
0_4^+	0.53	2.96

- Different behavior at low energy in SM and TCQRPA
- Benchmark of many-body theories needed
- Larger deviations for g.s. strength function

E1 strength functions on excited states

J_i^π ^{27}Ne	first peak (MeV)	centroid (MeV)	width (MeV)	$\sum B(E1)$ ($e^2 fm^2$)	$\sum(E_\gamma \cdot B(E1))$ (MeV$e^2 fm^2$)
$3/2_1^+$	1.26	18.32	6.80	0.55	4.28
$1/2_1^+$	0.27	18.68	6.60	0.41	3.15
$5/2_1^+$	0.74	18.30	6.40	0.52	3.95
$1/2_2^+$	1.04	18.22	6.64	0.56	4.26
$1/2_3^+$	0.49	17.97	6.27	0.54	3.88



Same behavior as in even-even

E1 strength functions on excited states

J_i^π	first peak (MeV)	centroid (MeV)	width (MeV)	$\sum B(E1)$ $(e^2 fm^2)$	$\sum(E_\gamma \cdot B(E1))$ $(\mathrm{MeV} e^2 fm^2)$
^{27}Ne					
$3/2_1^+$	1.26	18.32	6.80	0.55	4.28
$1/2_1^+$	0.27	18.68	6.60	0.41	3.15
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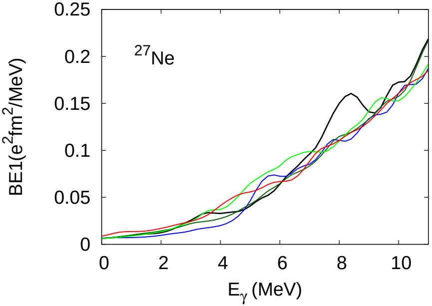
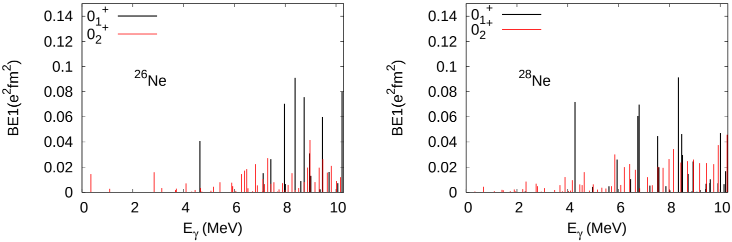


Pygmy peak clearly visible for the g.s. distribution only

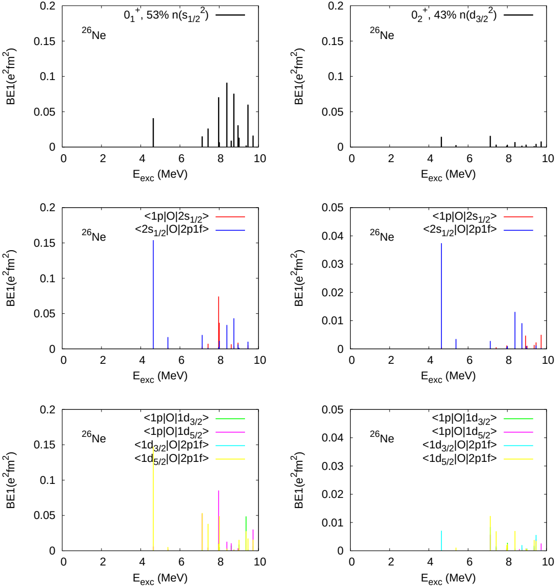
E1 strength at low-energy



Nucleus	$B(E1;0_1^+\uparrow)_{max}(e^2fm^2)$	$B(E1;0_2^+\uparrow)_{max}(e^2fm^2)$
^{26}Ne	0.09	0.04
^{28}Ne	0.09	0.037

Redistribution of the low-energy photoabsorption strength dependent on initial state structure

E1 strength at low energy: ground vs excited state

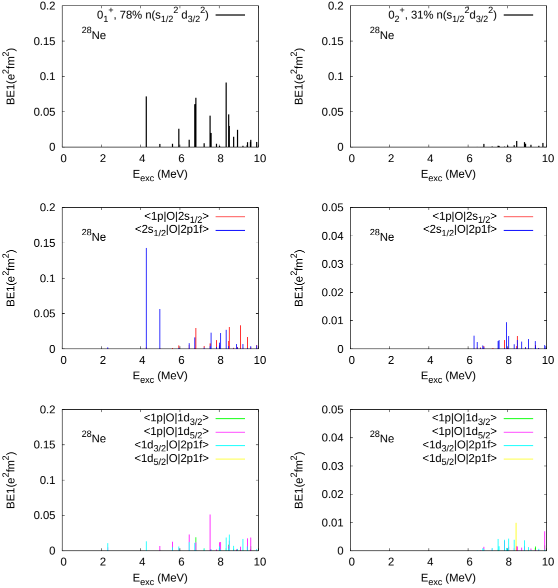


$E_{exc}(0_2^+)$=4.29MeV
$E_{exc}(1_1^-)$=4.64MeV

Many interfering contributions

$1d_{3/2} \rightarrow 1fp$ only in excited state

E1 strength at low energy: ground vs excited state



$E_{exc}(0_2^+)$=6.12MeV
$E_{exc}(1_1^-)$=4.28MeV

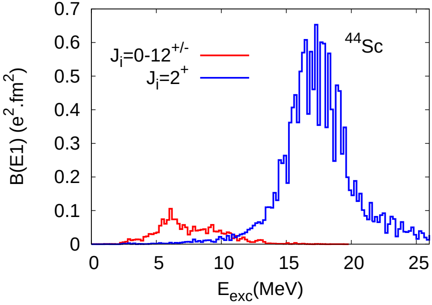
Enhanced mixing in the initial state
=> less transition strength to lowest states

Should be observed in any region of the nuclear chart (?)

Impact on neutron capture

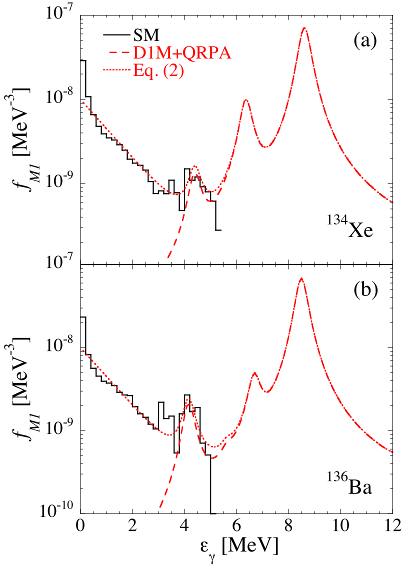
Calculating neutron-capture cross sections with microscopic (QRPA) photoabsorption strength functions requires that

photoemission SF = photoabsorption SF



$$f_{M1/E1}(E_\gamma) = 16\pi/9(\hbar c)^3 S_{M1/E1}(E_\gamma)$$
$$S_{M1/E1} = \langle B(M1/E1)\rangle \rho_i(E_i)$$

K. Sieja, PRL119 (2017) 052502



S. Goriely, S. Hilaire, S. Péru and K. Sieja, PRC98 (2018) 014327

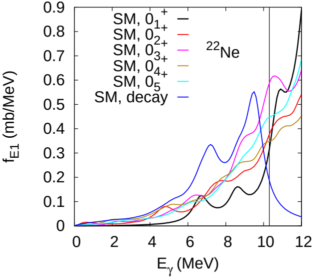
To describe radiative decay, phenomenological low-energy corrections fitted to reproduce SM trends and data are added to microscopic QRPA-Gogny $M1$ and $E1$ PSF:

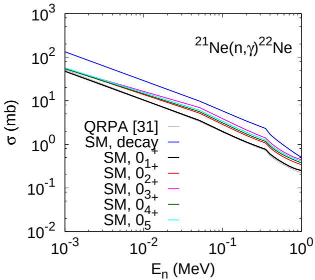
$$f_{E1}(\varepsilon_\gamma) = f_{E1}^{QRPA}(\varepsilon_\gamma) + f_0 U/[1+e^{(\varepsilon_\gamma-\varepsilon_0)}] \quad (1)$$

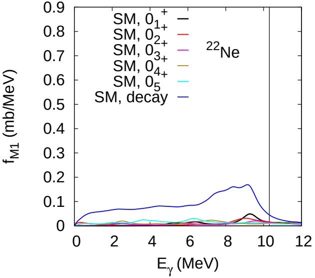
$$f_{M1}(\varepsilon_\gamma) = f_{M1}^{QRPA}(\varepsilon_\gamma) + Ce^{-\eta\varepsilon_\gamma} \quad (2)$$

- upper limit (0lim^+)
  $f_0 = 5\cdot 10^{-10}\text{MeV}^{-4}$, ε_0=5MeV,
  C=$3\cdot 10^{-8}\text{MeV}^{-3}$, $\eta = 0.8\text{MeV}^{-1}$
- lower limit (0lim^-)
  $f_0 = 10^{-10}\text{MeV}^{-4}$, ε_0=3MeV,
  C=10^{-8}MeV^{-3}, $\eta = 0.8\text{MeV}^{-1}$

Impact on radiative neutron capture



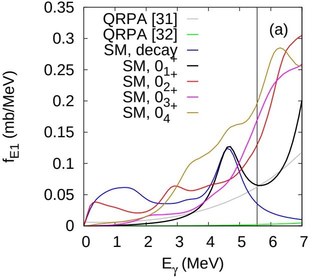


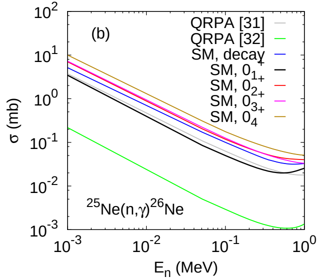


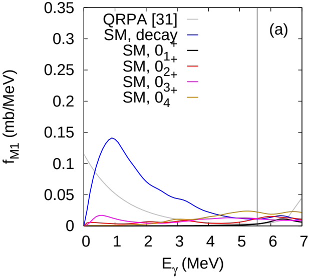
QRPA[31]: QRPA+empirical corrections+low-energy limits (TALYS)

- Radiative decay SF larger than photoabsorption SF
- Effect of higher level density around neutron threshold
- Empirically-corrected QRPA too small in this nucleus

Impact on radiative neutron capture







QRPA[31]: QRPA+empirical corrections+low-energy limits (TALYS)
QRPA[32]: “raw” QRPA from Martini et al.

- PDR has no influence on neutron-capture cross section
- Photoabsorption SF on excited state is a good approximation to radiative decay SF
- Reasonable agreement between CI and empirically-corrected QRPA

Summary

- The Brink-Axel hypothesis holds for E1 sum rules, giant resonances but not in the low-energy region
- Deviation from BA hypothesis for M1 transitions observed for sum rules and PSF
- The PDR seems to be a property of the ground state distribution only (?!)
- Photoabsorption$\neq$phoetoemission : the low-energy effects are reasonably taken into account by empirical treatment (TALYS) but better theory still needed
- The impact on neutron-capture cross section is sizeable

SM studies are continued to benchmark QRPA models of decay strength functions

Thanks to:
IN2P3/CNRS IEA project "Radiative Neutron Capture"

My special gratitude goes to the late Etienne Caurier, the author of the ANTOINE code and many other tools used in this study.