Recent shell-model studies of nuclear structure and applications to radiative neutron capture

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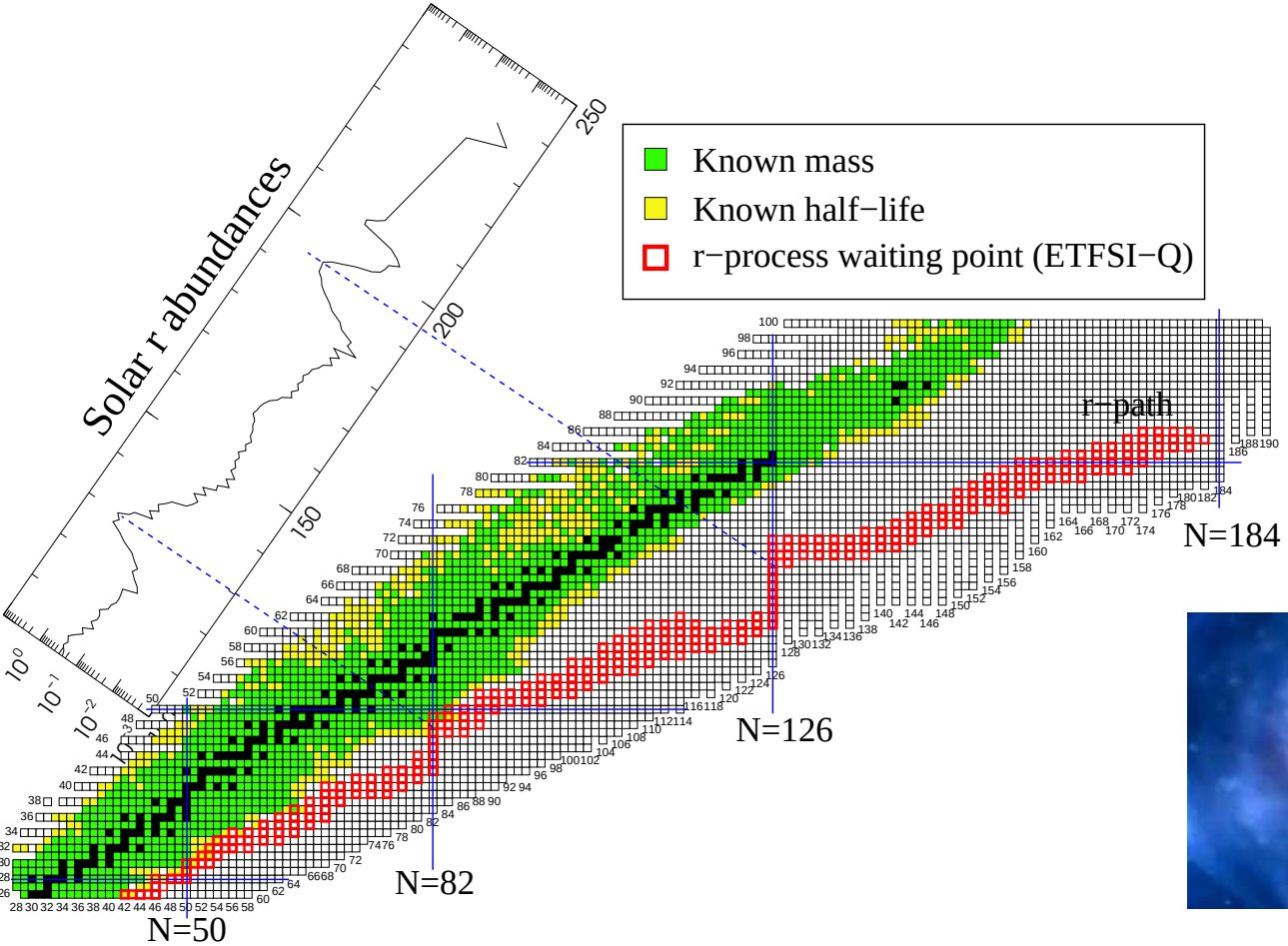
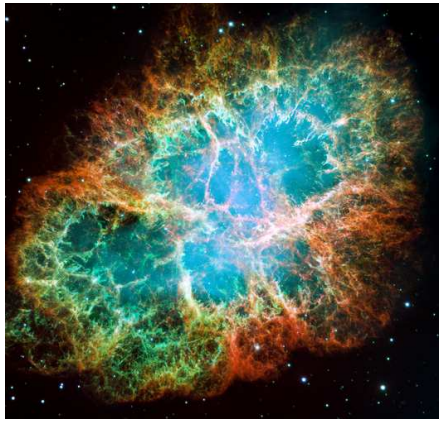
IN2P3 theory project: "Photoabsorption Strength Functions from CI method"

NUSPIN, 25.06.2019

R-process nucleosynthesis

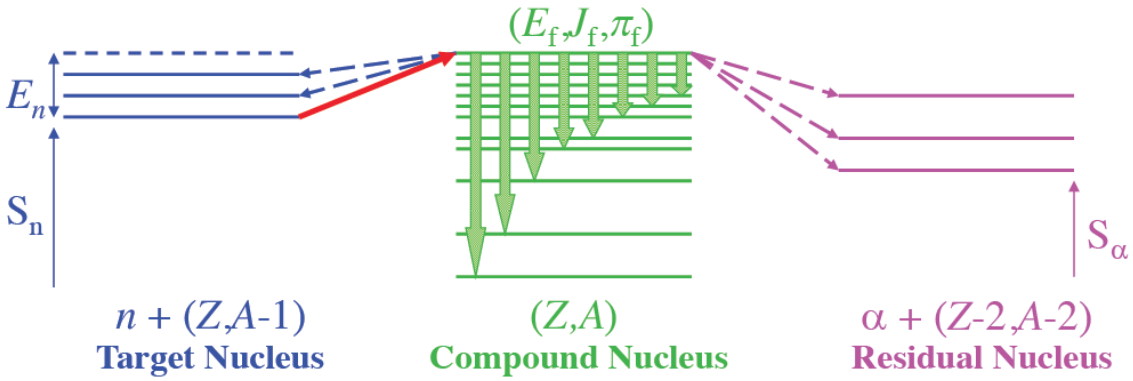
☞Nuclear models are needed to provide input for r-process simulations: *masses*, *level densities (ρ)*, *β half-lives*, *γ-Strength Functions (f_{XL})*, fission barriers...





B. Metzger, G. Martinez-Pinedo et al., Monthly Notices of the Royal Astronomical Society. 406, 2650 (2010)

Radiative neutron capture: resonant capture

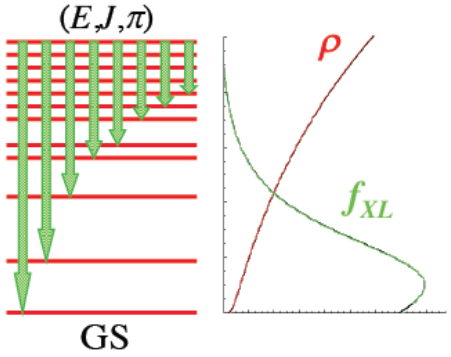


$$\sigma^{\mu\nu}_{(n,\gamma)}(E_i,n) = \frac{\pi\hbar^2}{2M_{i,n}E_{i,n}} \frac{1}{(2J_i^\mu+1)(2J_n+1)} \sum_{J,\pi}(2J+1)\frac{T_n^\mu T_\gamma^\nu}{T_n^\mu + T_\gamma^\nu}$$

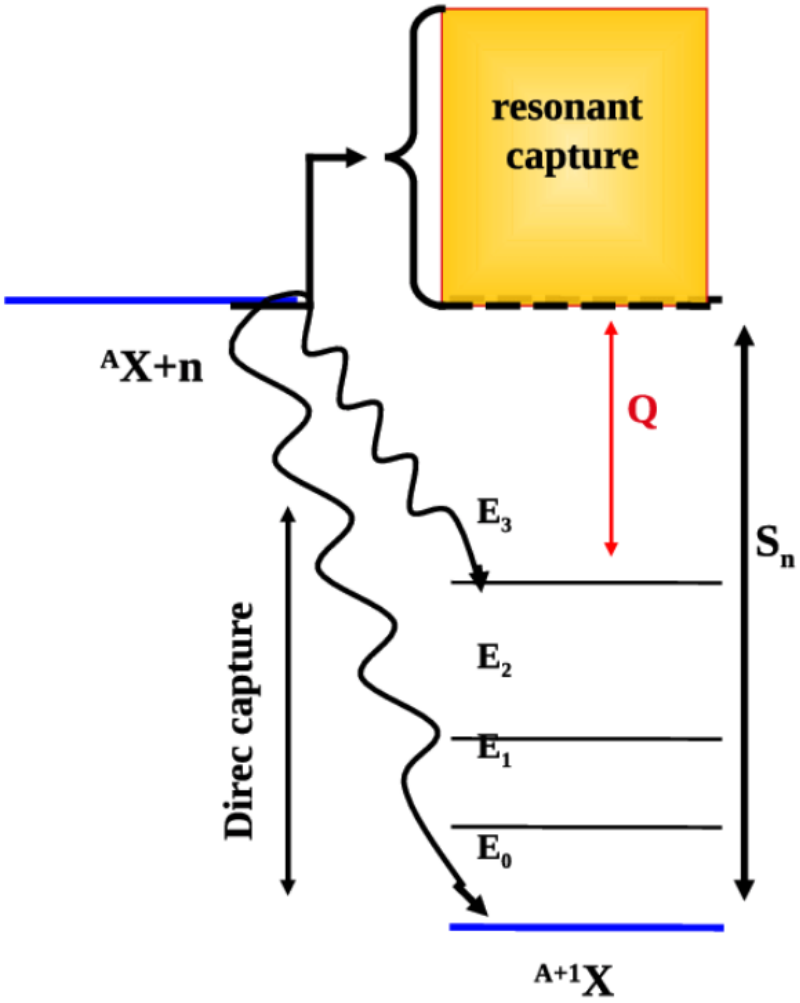
for $E_n \sim$keV $\quad T_n^\mu \gg T_\gamma^\nu \longrightarrow \boldsymbol{\sigma^{\mu\nu} \sim T_\gamma^\nu}$
$E_{i,n}, M_{i,n}$- center-of-mass energy, reduced mass of the system
$J_n = 1/2$-neutron spin
$T_n^\mu = T_n(E,J,\pi;E_i^\mu,J_i^\mu,\pi_i^\mu)$ $T_\gamma^\nu = T_\gamma(E,J,\pi;E_m^\nu,J_m^\nu,\pi_m^\nu)$- transmission coefficients

For a given multipolarity
$T_{XL}(E,J,\pi,E^\nu,J^\nu,\pi^\nu) = 2\pi E_\gamma^{2L+1} f_{XL}(E,E_\gamma)$
☞Test, using SM, the key ingredients of Hauser-Feshbach calculations:

- description of γ emission spectra
- Brink-Axel hypothesis



Radiative neutron capture: direct capture



Xi. Yu and S. Goriely, Phys. Rev. C86 (2012) 045801

$$\sigma^{DC}(E) = \sum_{f=0}^{x} S_f \sigma_{dis}(E)$$

$$+ \quad \langle S \rangle \int_{E_x}^{S_n} \sum_{J_f,\pi_f} \rho(E_f, J_f, \pi_f) \times \sigma_f^{cont} dE_f$$

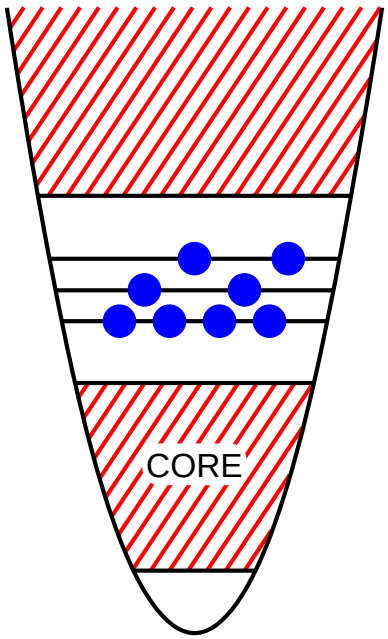
If no experimental data available:

- use combinatorial model for the level density with $\langle S \rangle$=0.5

☞The key ingredients: low-energy levels and spectroscopic factors
☞Validate theoretical approximations (HFB) in exotic nuclei using SM predictions

Shell model: generalities

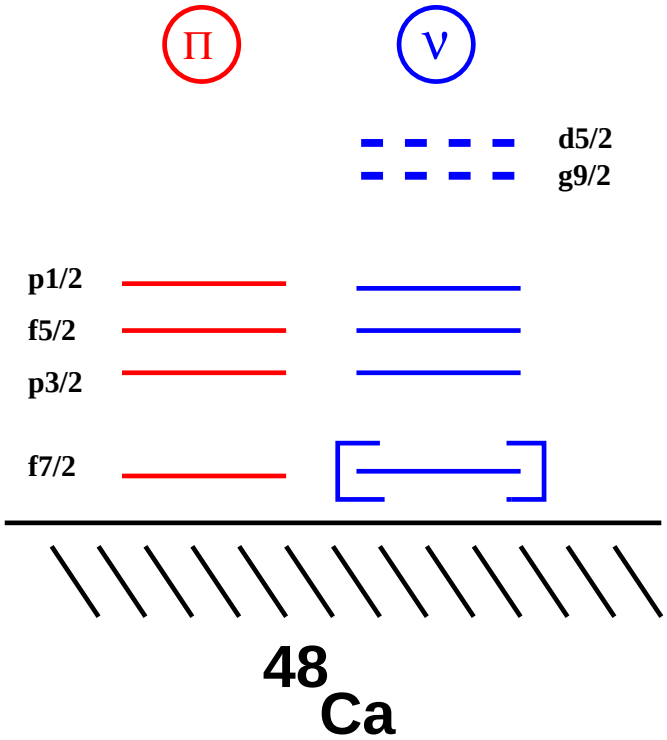
Shell model relies on the possibility of diagonalizing the Hamiltonian matrix and deriving (constraining empirically) a suitable effective interaction.



$$H_{eff}|\Psi_{eff}\rangle = E|\Psi_{eff}\rangle$$

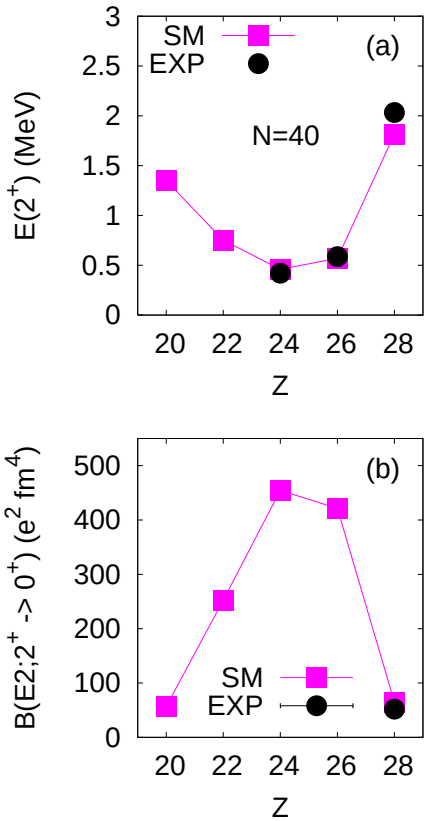
- **Direct capture:** knowledge of the lowest-lying levels (energies and spectroscopic factors)$\rightarrow$ quality of the effective Hamiltonian
- **Resonant capture:** knowledge of statistical properties (energies and transitions in nuclear continuum)$\rightarrow$ possibility of computing of hundreds of nuclear levels

Lenzi-Nowacki-Poves-Sieja interaction



LNPS interaction:

- based on realistic TBME
- new fit of the pf shell (KB3GR, E. Caurier)
- monopole corrections

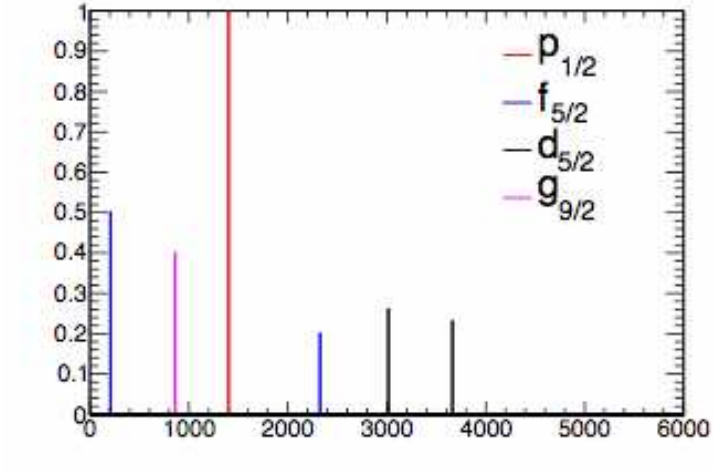


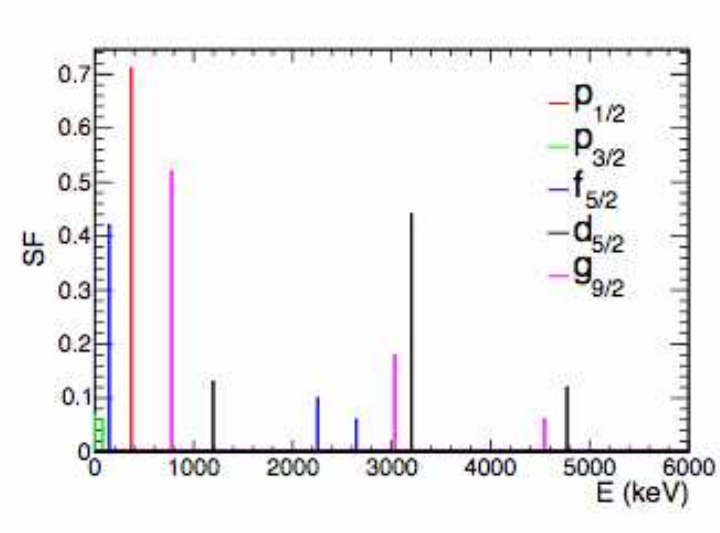
S. Lenzi et al, Phys. Rev. C82 (2010) 054301

Used succesfully in over 50 papers (masses, spectroscopy, transitions, spectroscopic factors...)

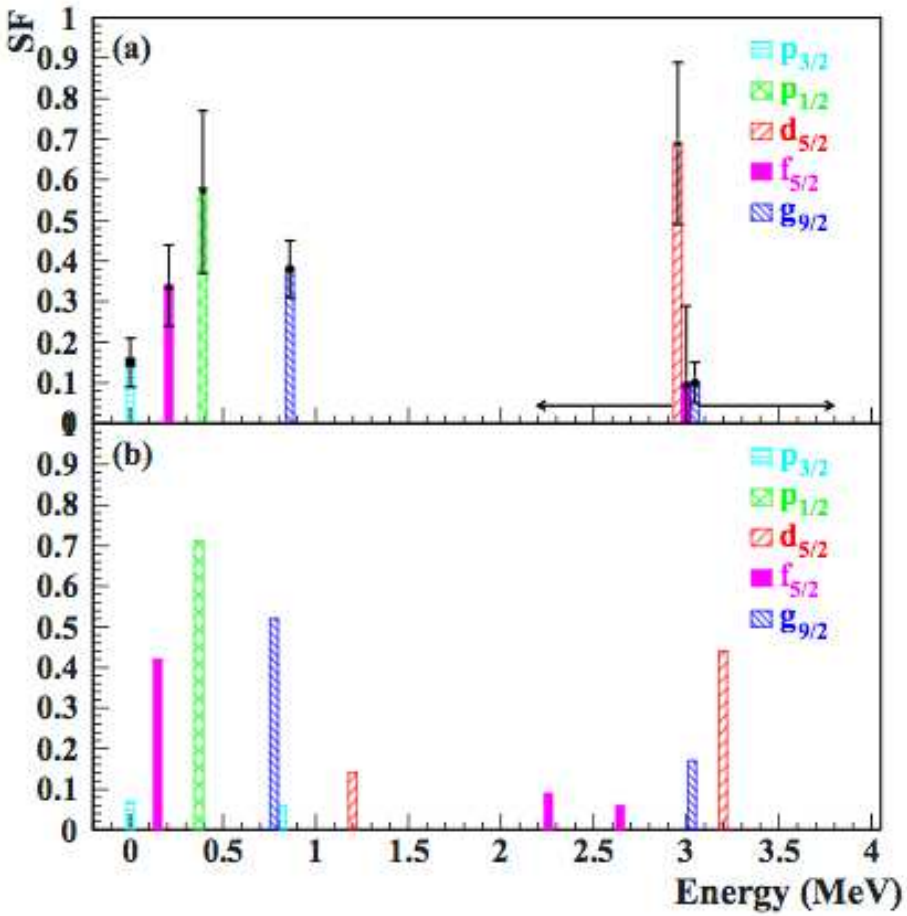
^{60}Fe spectroscopic factors

S. Giron, PhD Orsay, 2012

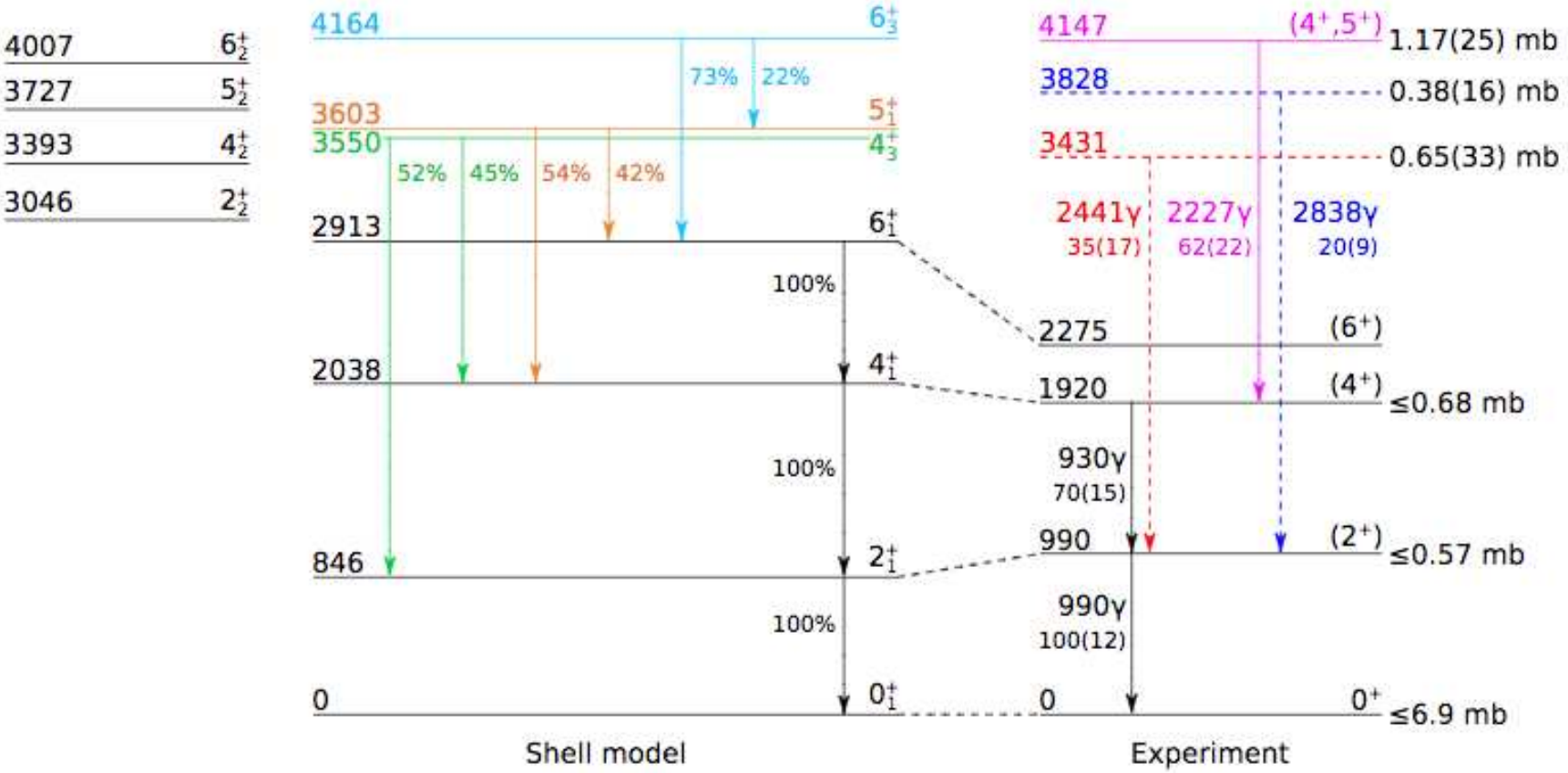




S. Giron et al.,Phys. Rev. C95 (2017) 035806

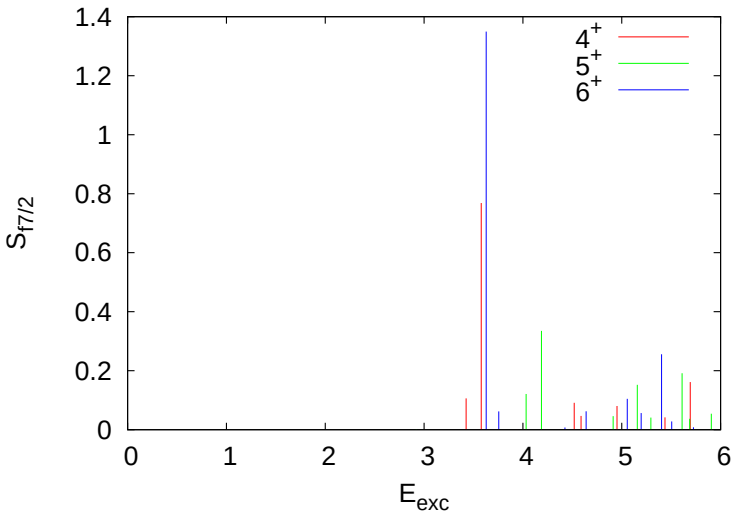


^{76}Ni from $(p,2p)$ reaction



Z. Elekes etal, Phys. Rev. C99 (2019) 014312

^{76}Ni from $(p,2p)$ reaction

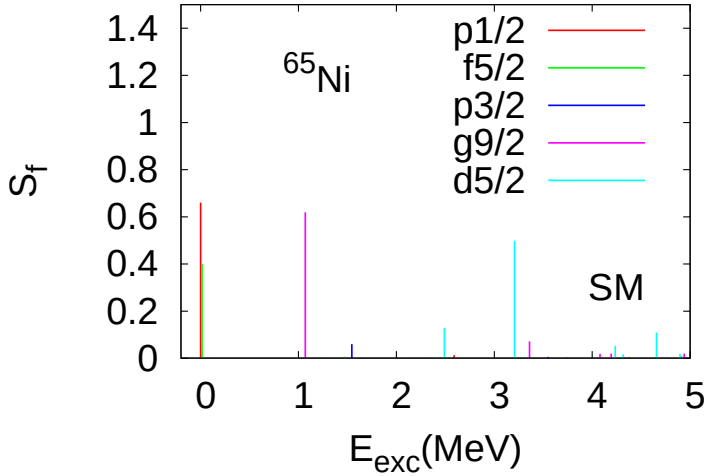


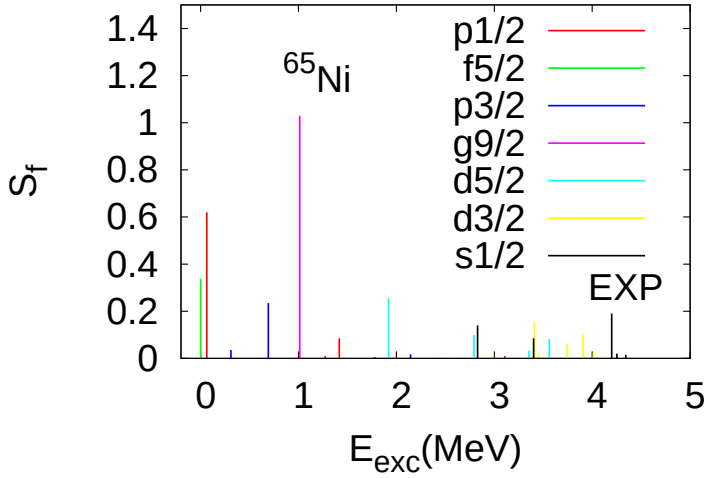
- Proton gap $Z = 28$ estimated to be 4.4MeV in ^{76}Ni and 5.2MeV in ^{78}Ni, compatible with other recent studies in the region.

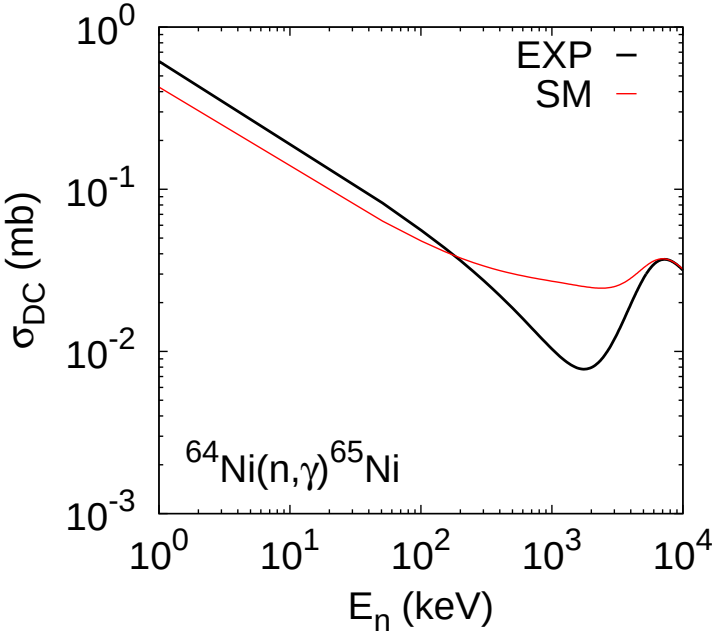
E_{theor} (MeV)	J^π	Spectroscopic factor		σ_{theor} (mb)	E_{expt} (MeV)	σ_{expt} (mb)
0	0_1^+	0.60	$f_{5/2}$	0.74	0	$\leqslant$6.9
0.846	2_1^+	<0.01	$f_{7/2}$	0.28	0.990	$\leqslant$0.57
		0.23	$f_{5/2}$			
2.038	4_1^+	<0.01	$f_{7/2}$	<0.10	1.920	$\leqslant$0.68
		<0.01	$f_{5/2}$			
2.913	6_1^+	<0.01	$f_{7/2}$	<0.10	2.275	
					3.431	0.65(33)
					3.828	0.38(16)
3.550	4_3^+	0.77	$f_{7/2}$	1.08	4.147	1.17(25)
		<0.01	$f_{5/2}$			
3.603	5_1^+	0.72	$f_{7/2}$	1.02		
		<0.01	$f_{5/2}$			
4.164	6_3^+	0.62	$f_{7/2}$	0.86		

Direct capture rates using SM results

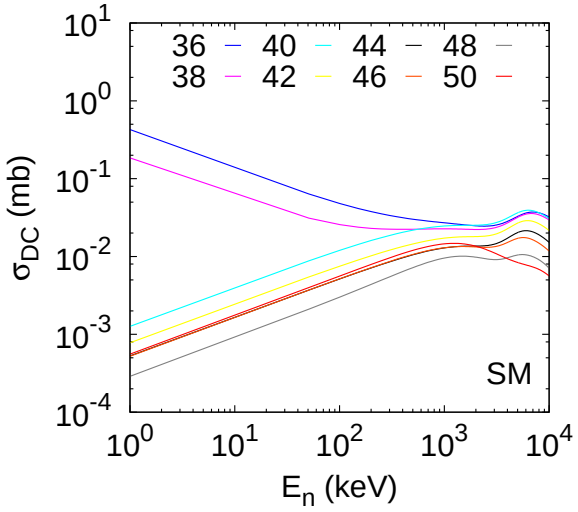
^{64}Ni$(n,\gamma)^{65}$Ni

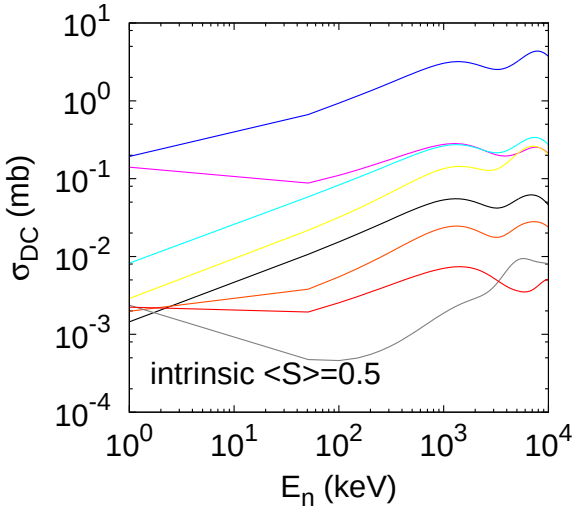


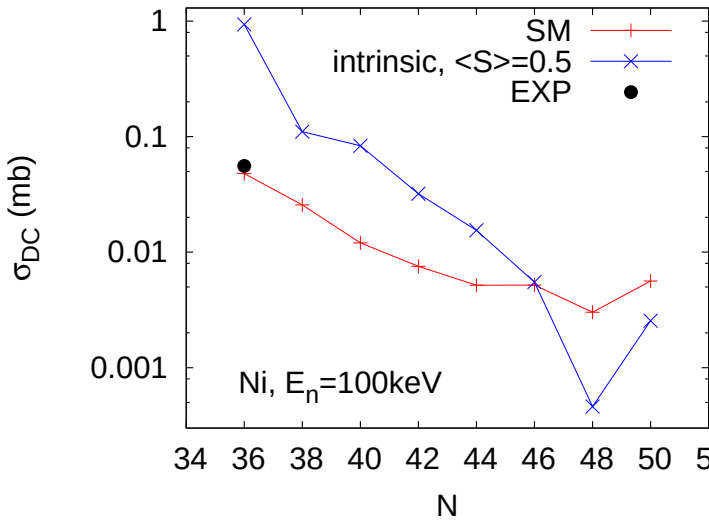


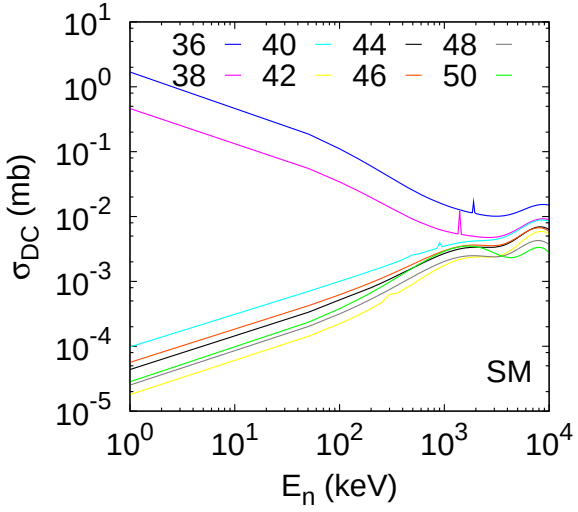


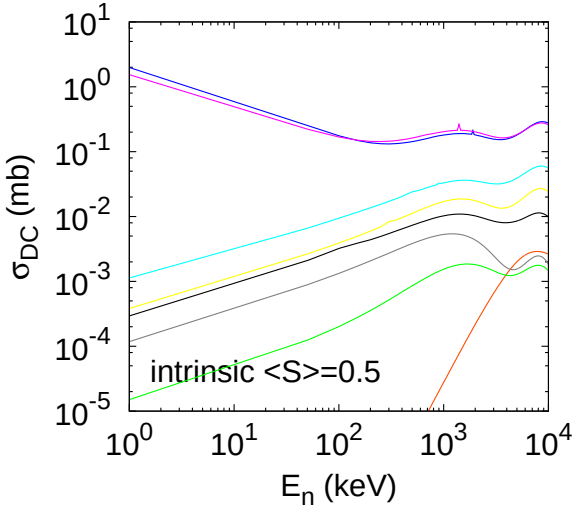
Direct capture rates using SM: Ni & Cr

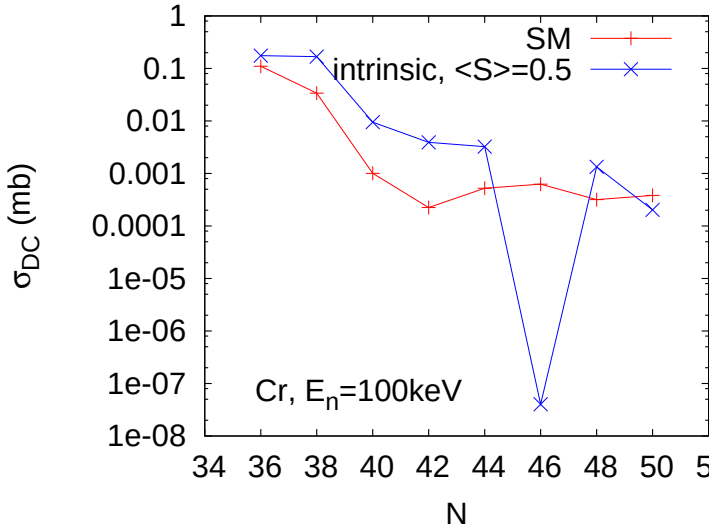




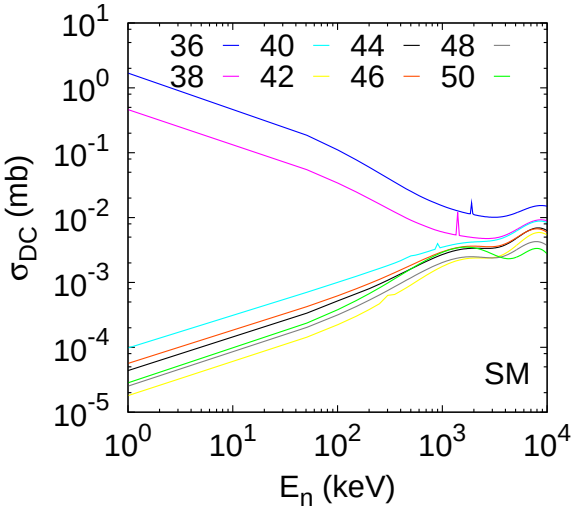


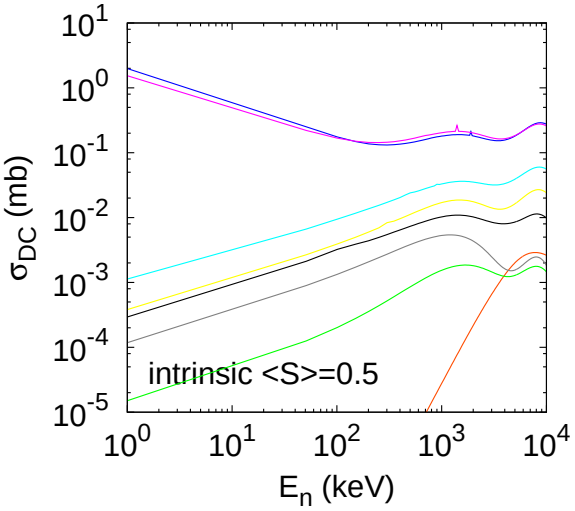




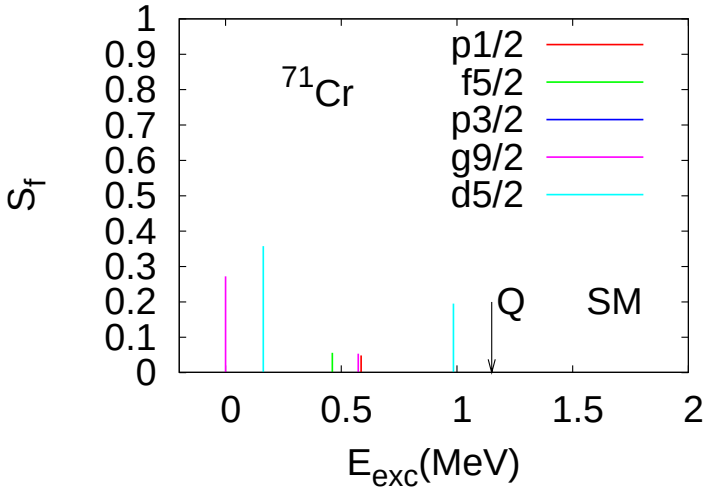


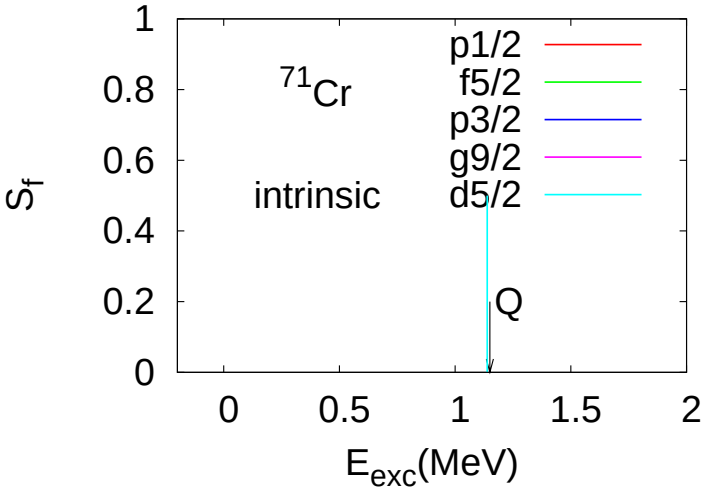
Direct capture rates using SM results: chromiums



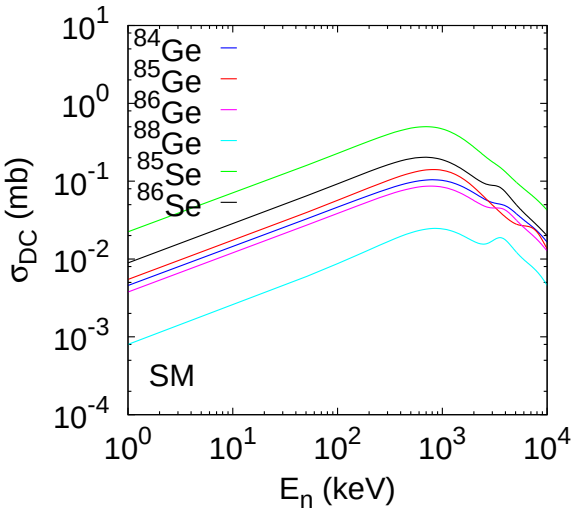


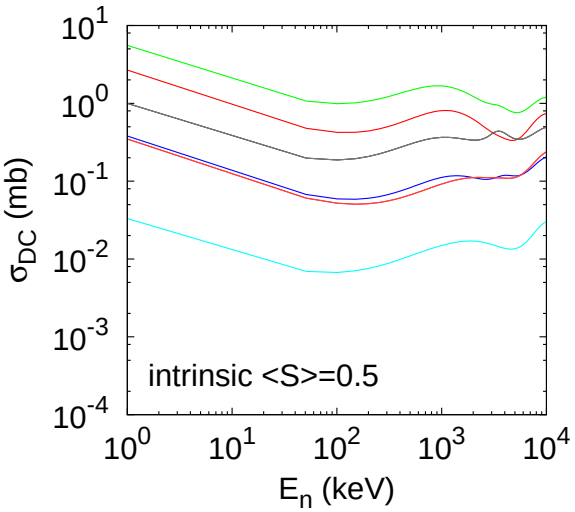
☞Great sensitivity to the structure details in very neutron-rich nuclei.





Direct capture using SM: triaxial nuclei above ^{78}Ni

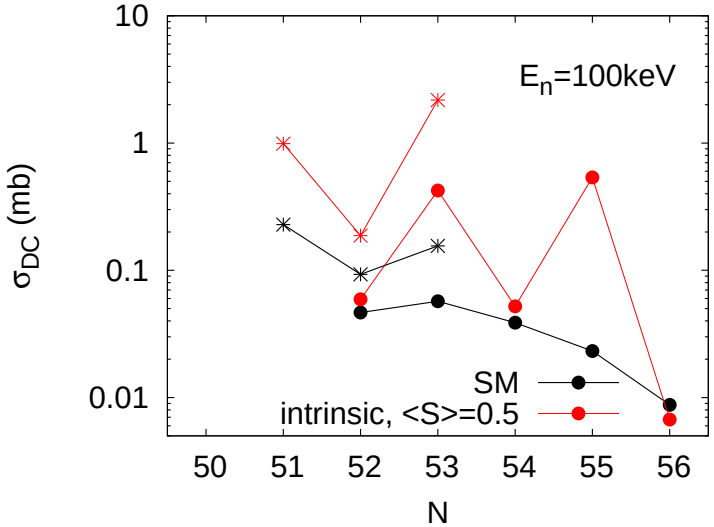


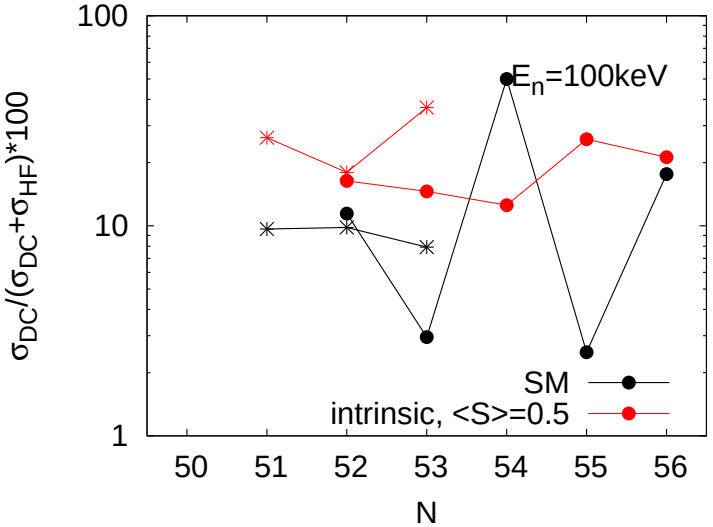


Calculations with NI78-II interaction
Prediction of triaxiality above ^{78}Ni

K. Sieja et al.,Phys. Rev. C88 (2013) 034327

M. Lettmann et al.,Phys. Rev. C96 (2017) 011301R





☞Spectroscopy of odd-N nuclei past $N = 50$ of interest for nuclear models

Going beyond usual SM applications: γ-decay

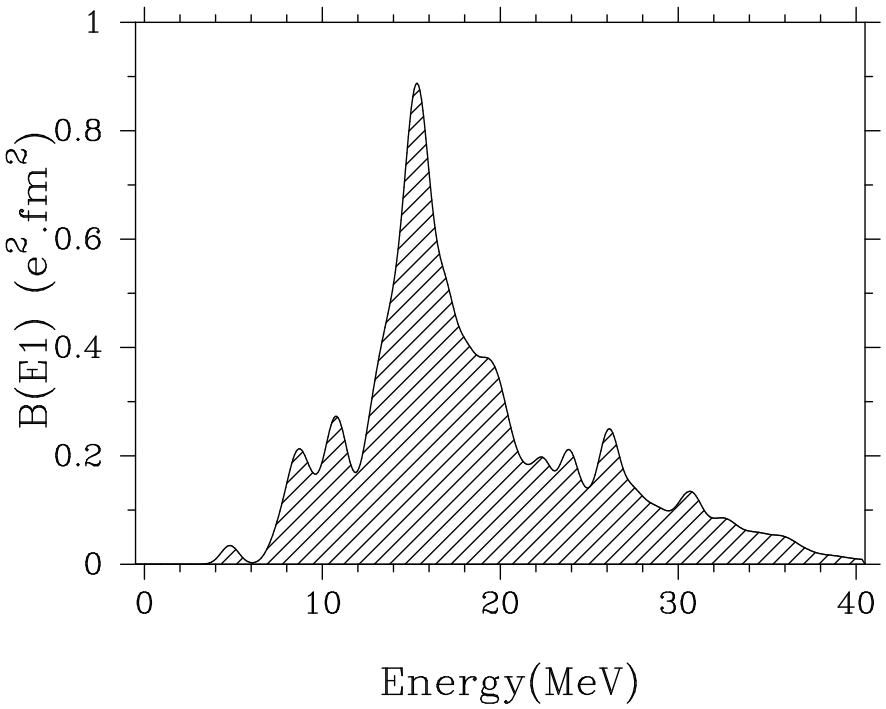
photoabsorption (PSF)

- use Lanczos Strength Function method with a large number of iterations

EXP: $\sum$B(E1)=0.49$\pm$0.16 e^{2}fm^2 (6-10MeV)

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

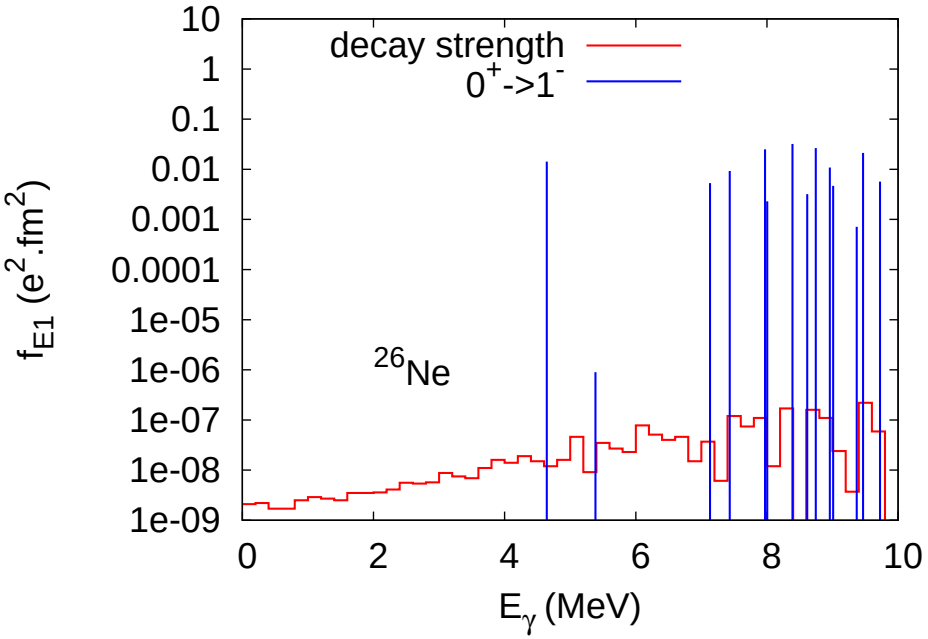
THEO: $\sum$ B(E1)=0.485 e^{2}fm^2 (0-10MeV)



γ-decay (RSF)

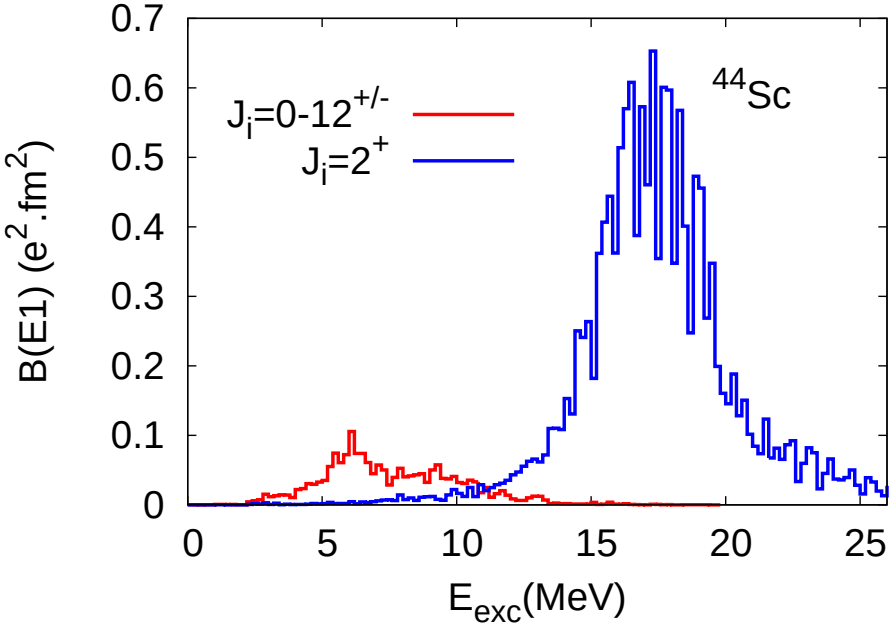
- calculate desired number of low lying states using standard SM diagonalization techniques
- obtain the averages and radiative strength functions from relations:

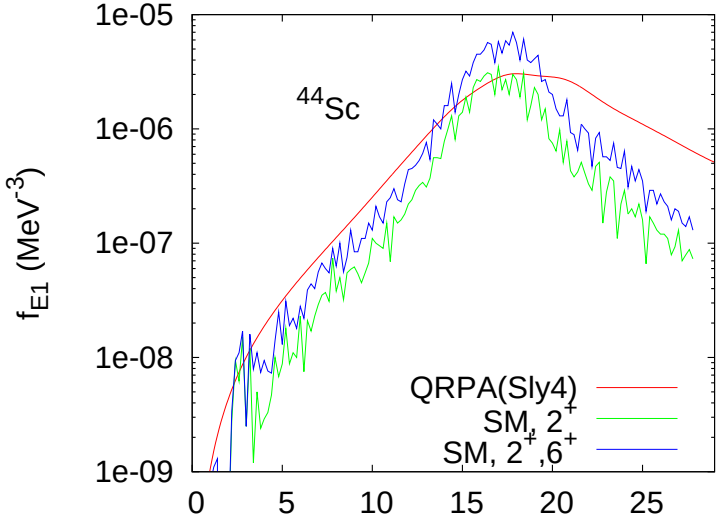
$$f_{M1/E1}(E_\gamma) = 16\pi/9(\hbar c)^3 S_{M1/E1}(E_\gamma)$$
$$S_{M1/E1} = \langle B(M1/E1)\rangle \rho_i(E_i)$$

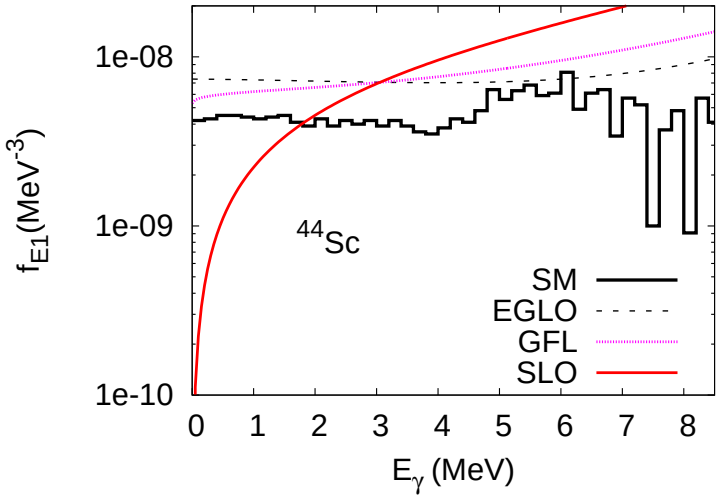


$E1$ strength: comparison to other models

K. Sieja, PRL119 (2017) 052502







- Description of the resonance and radiative decay in the same theoretical framework.
- Reasonable agreement between QRPA and SM PSF up to 15MeV.
- Microscopic SM strength has a non-zero limit for $E_\gamma = 0$. Consistent with the EGLO model.

Dipole strength in ^{44}Sc: theory vs exp

PRL 119, 052502 (2017) PHYSICAL REVIEW LETTERS week ending 4 AUGUST 2017

Electric and Magnetic Dipole Strength at Low Energy

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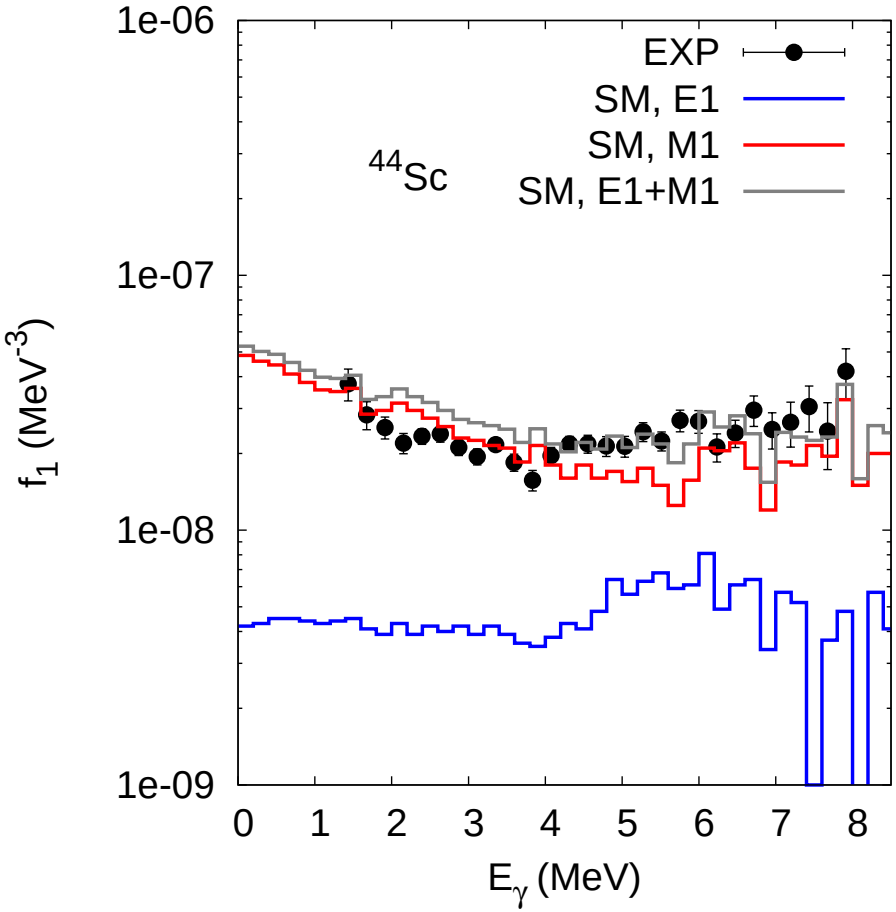
(Received 7 March 2017; revised manuscript received 6 May 2017; published 31 July 2017)



-all states below $S_n \sim$10MeV
-86642 $M1$matrix elements
-65670 $E1$ matrix elements

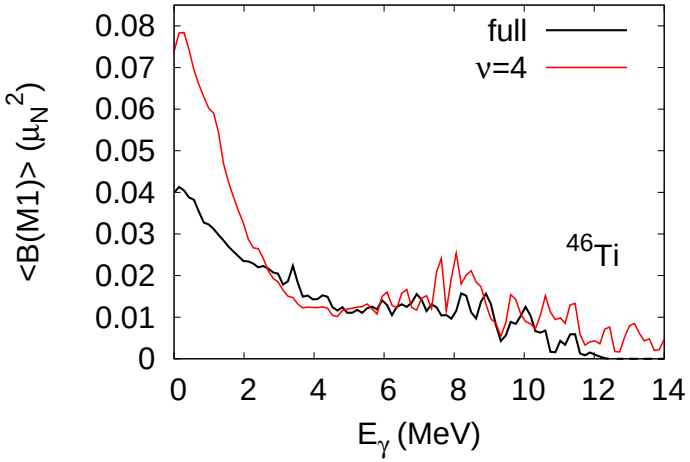
☞Overall good agreement with data:
-the upbend is due to $M1$ transitions
-the $E1$ pattern is flat with the non-zero $E_\gamma \to 0$ limit

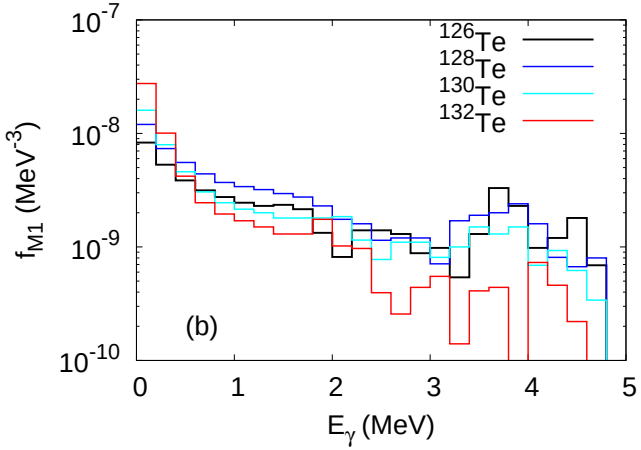
$M1$ upbend: general trends

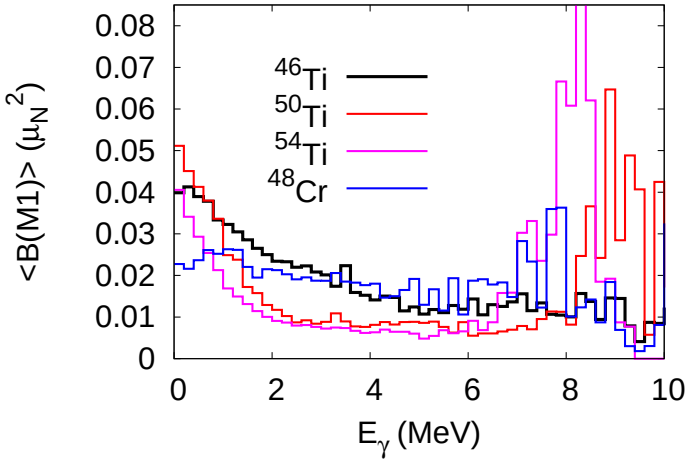
K. Sieja, Eur. Phys. J. Web of Conf.146 (2017) 05004 ND2016

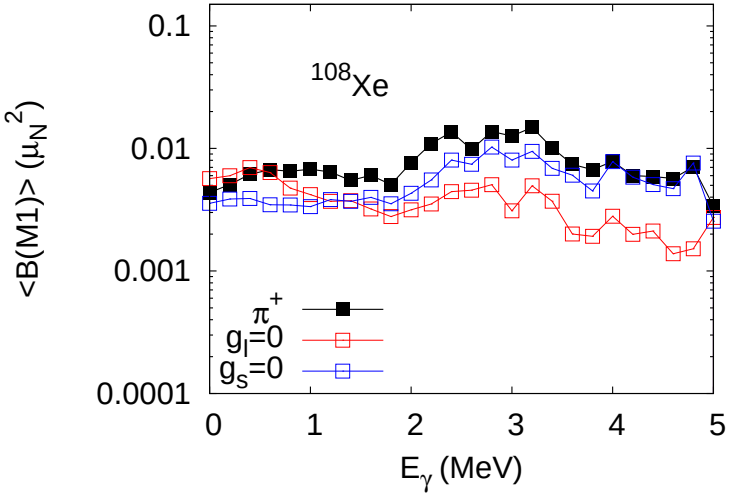
S. Karampagia et al., Phys. Rev. C95 (2017) 024322

K. Sieja, Phys. Rev. C98 (2018) 064312







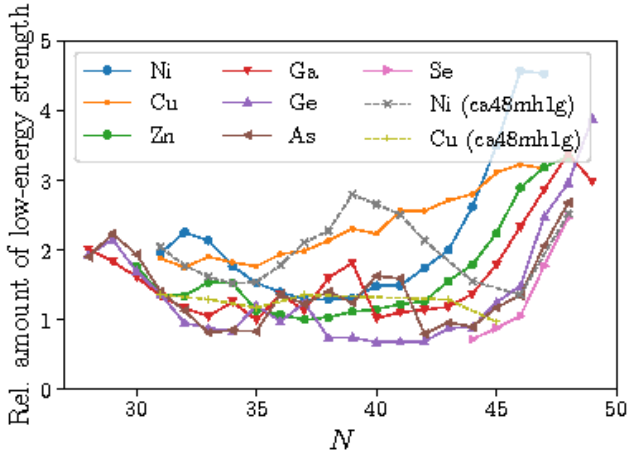


☞The strength at $E_\gamma = 0$ peaks around shell closures and is flat in deformed nuclei

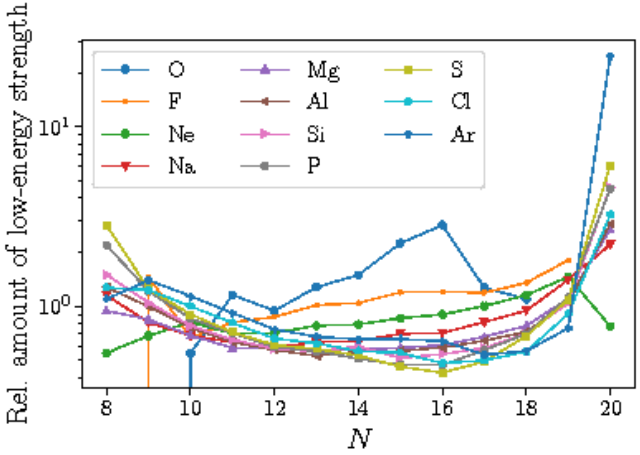
Shell structure in the nuclear quasi-continuum

Ratio of $B(M1)$ strength: $\frac{\langle B(M1)\rangle(0-2MeV)}{\langle B(M1)\rangle(2-6MeV)}$

mid-mass nuclei:

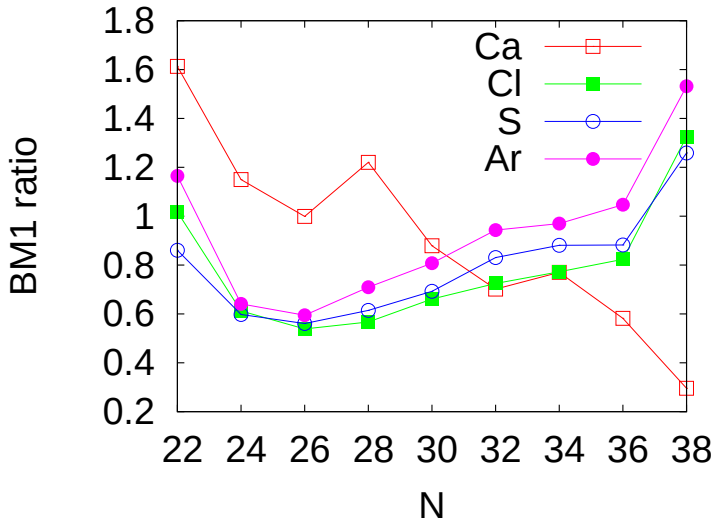


sd-shell nuclei:



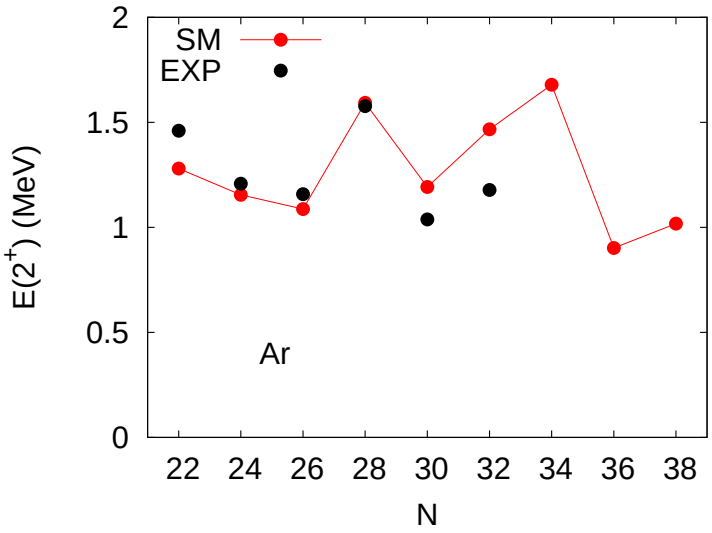
J. Midtbo et al., Phys. Rev. C98 (2018) 064321

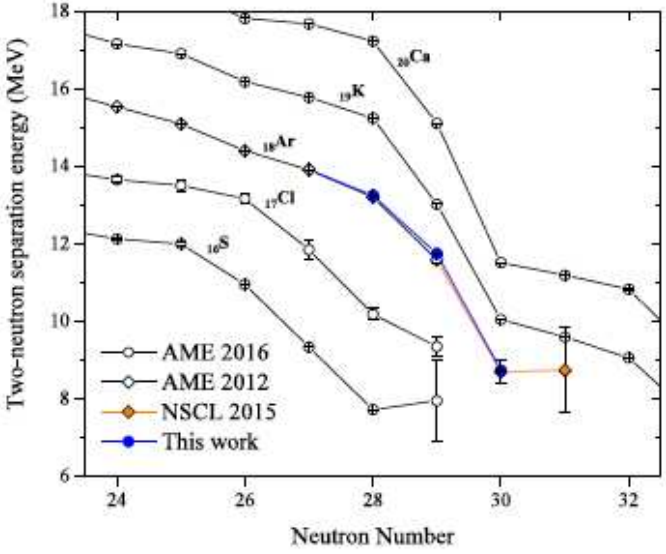
sd − *pf* nuclei:



- The ratio peaks towards the edges of the model spaces at $N = 8, 20, 40, 50$.
- Some extra shell effects are present in the Ni chain.
- In sd-pf nuclei the ratio peaks at $N = 28$ for Ca only.

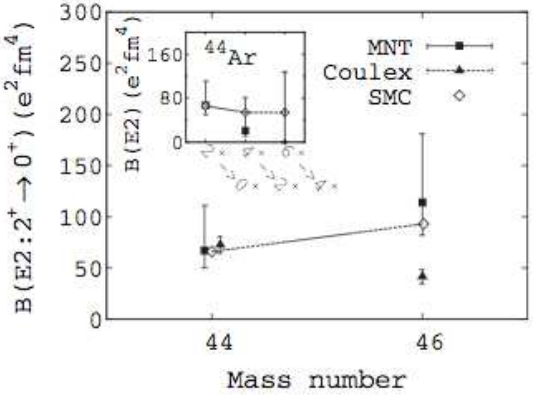
The puzzling case of ^{46}Ar



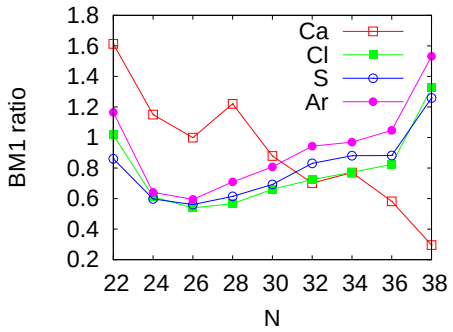


M. Mougeot, PhD thesis, Orsay 2018

D. Mengoni etal., Phys. Rev. C82 (2010) 024308

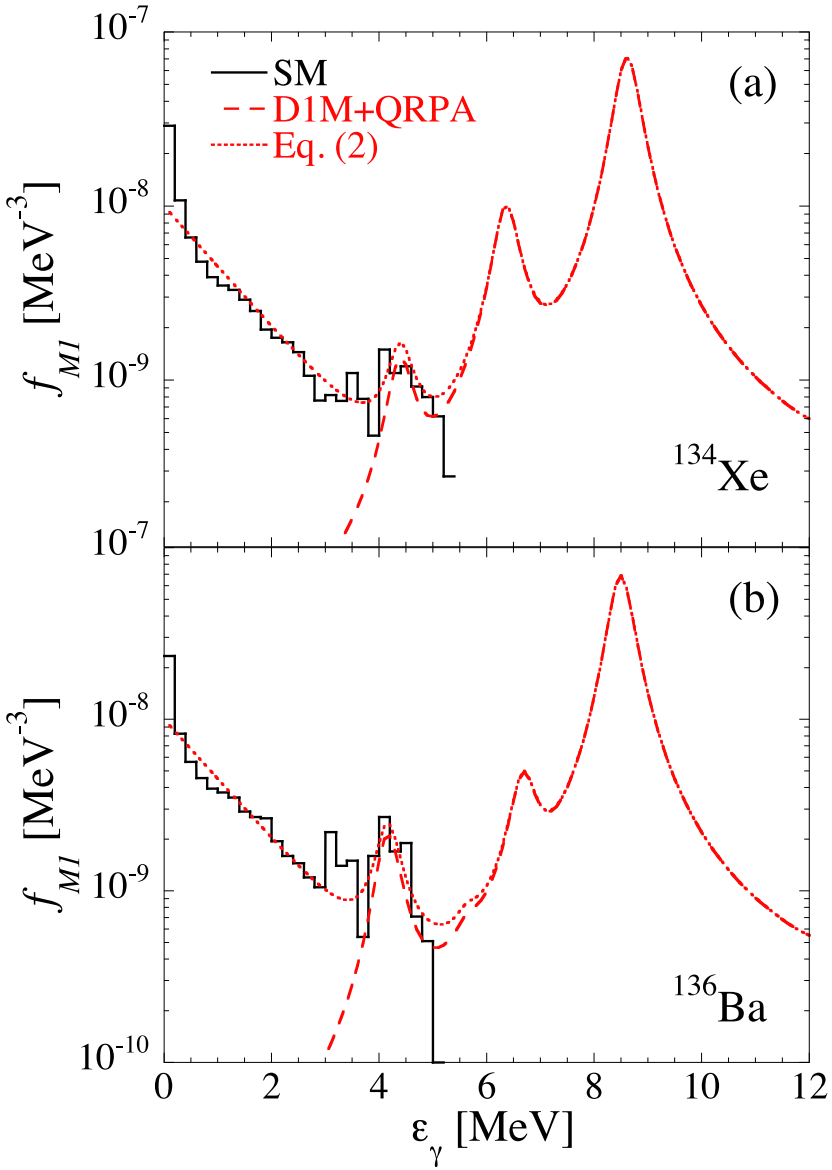


- Signs of shell closure in ^{46}Ar from 2^+ energies and two-neutron separation energies
- Confusing evidence from $B(E2)$ values
- No shell closure from the $B(M1)$ decay strength!



Application of the low-energy limit to the QRPA results

Collaboration with S. Goriely (ULB), S. Hilaire and S. Péru (CEA-DAM)



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

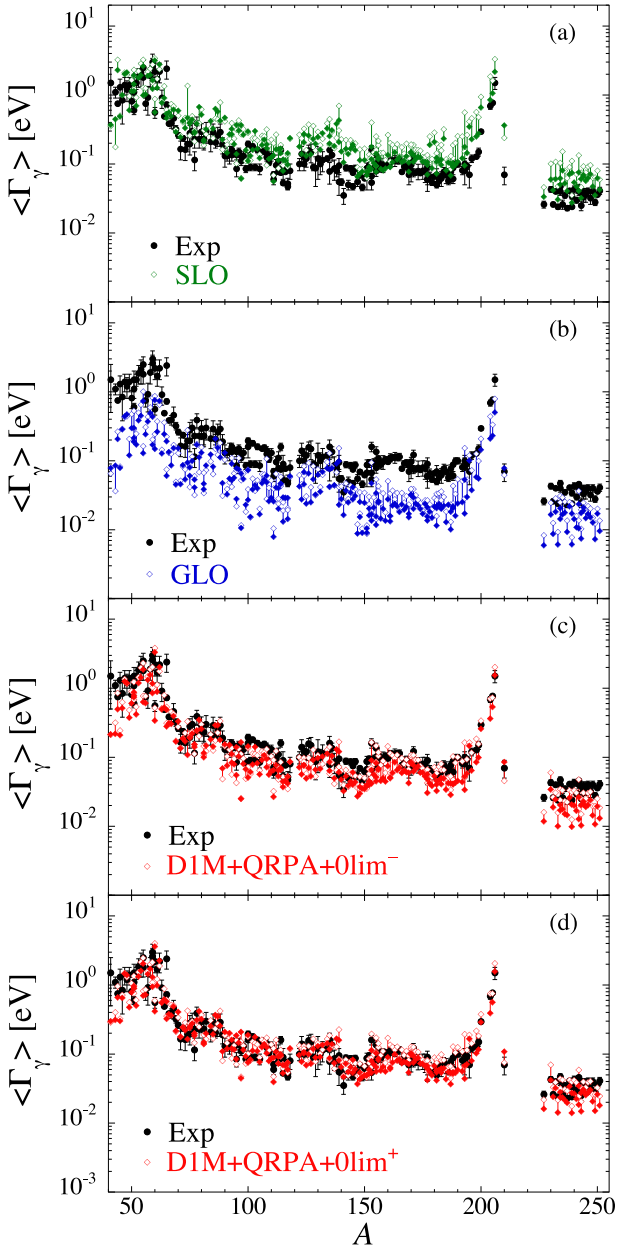
To describe radiative decay, phenomenological low-energy corrections fitted to reproduce SM trends and data are added to microscopic QRPA-Gogny $M1$ and $E1$ PSF:

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

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

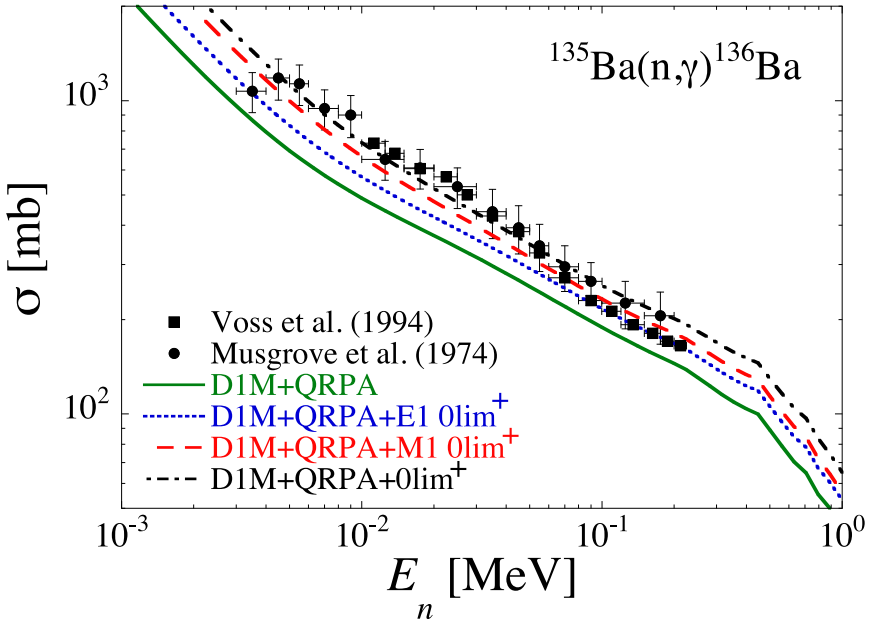
- upper limit (0lim$^+$)
  $f_0 = 5{\cdot}10^{-10}$MeV^{-4}, ε_0=5MeV,
  C=3·10^{-8}MeV^{-3},$\eta = 0.8$MeV^{-1}
- lower limit (0lim$^-$)
  $f_0 = 10^{-10}$MeV^{-4}, ε_0=3MeV,
  C=10^{-8}MeV^{-3},$\eta = 0.8$MeV^{-1}

Impact on radiative neutron capture



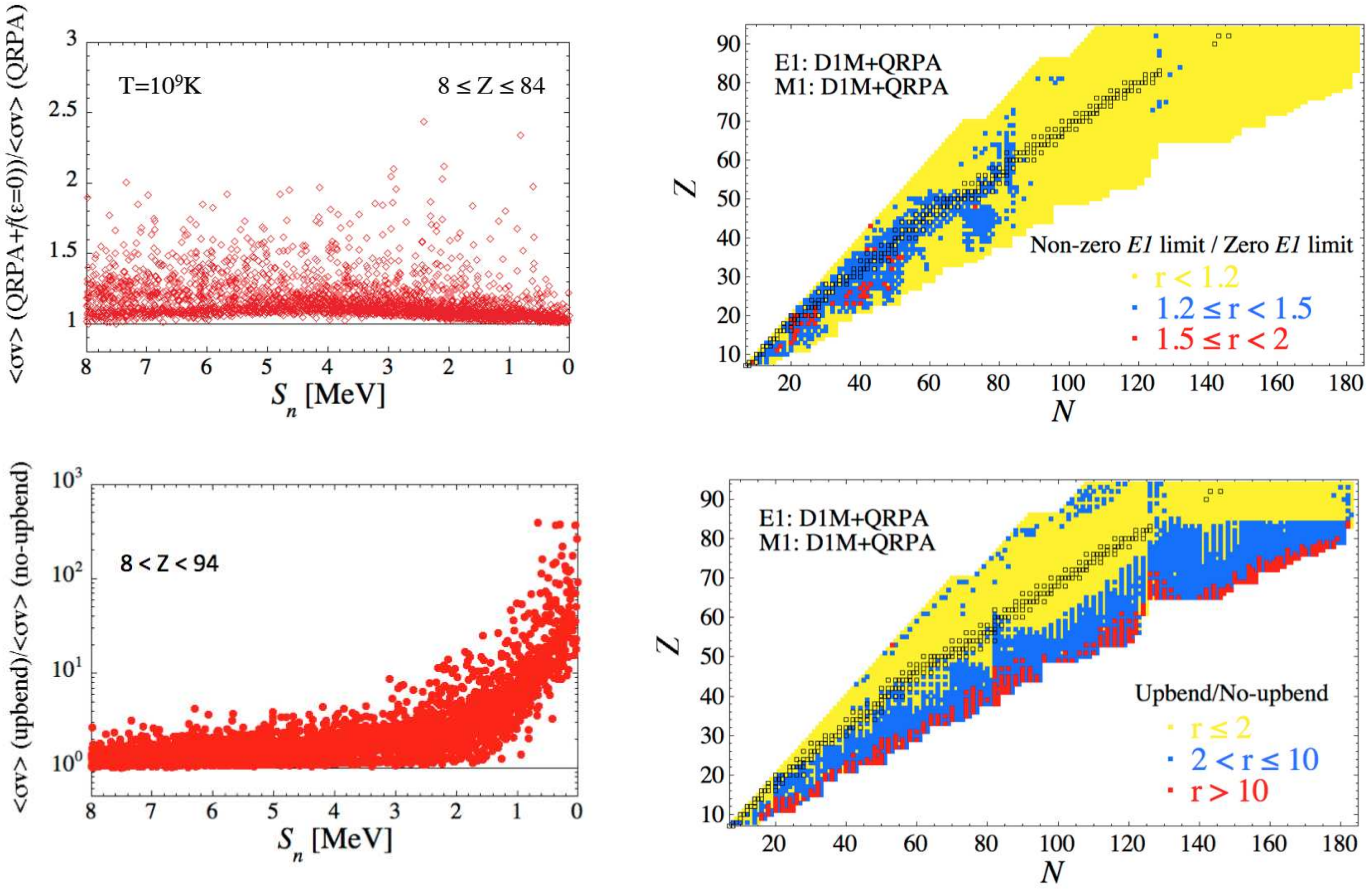
rms/datum

	$\langle\Gamma_\gamma\rangle$	$\langle\sigma\rangle$
$0\mathrm{lim}^-$(Comb)	0.88	1.07
$0\mathrm{lim}^-$(CT)	0.74	0.95
$0\mathrm{lim}^+$(Comb)	1.02	1.30
$0\mathrm{lim}^+$(CT)	0.90	1.15
GLO(Comb)	0.48	0.61
GLO(CT)	0.38	0.53



Impact on the radiative capture

MACS ratio at $T = 10^9$K



☞Non-zero limit of the $E1$ strength from SM has small impact on neutron capture: $20-50\%$
☞$M1$ upbend can alternate the cross-section by a factor >10 in exotic nuclei

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

Summary

- SM can provide reliable spectroscopic factors and help testing usual theoretical assumptions in cases no exprimental data is known $\rightarrow$ work in progress.
- Spectroscopy of neutron-rich nuclei around ^{78}Ni is still of interest for nuclear models.
- $E1/M1$ RSF and PSF can be microscopically obtained within the SM.
- Shell effects survive at higher excitation energies and are visible in $M1$ dipole strength functions.
- $M1$ upbend has a significant impact on neutron capture cross sections in exotic nuclei: $\times 10$.