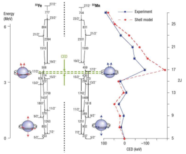
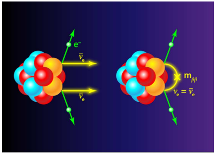
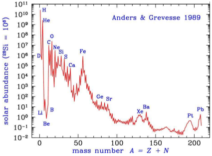
Nuclear Shell Model: structure of exotic nuclei, weak processes and astrophysical issues

F. Nowacki, K. Sieja (IPHC), N. Smirnova (CENBG), P. Van Isacker (GANIL)





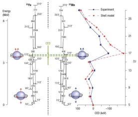


Prospectives nationales 2020-2030
Physique Nucléaire et Astrophysique nucléaire

New Frontiers for Shell Model calculations

Fundamental interactions and collectives excitations

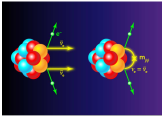
- Deformation, Superdeformation, Dipole/M1 resonances
- Superfluidity, Symmetries
- Isospin symmetry breaking

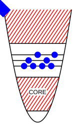


Weak processes

- β decay $\Longleftrightarrow$ fundamental interactions
- $\beta\beta$ decay $\Longleftrightarrow$ nature of neutrinos

$$[T^{0\nu}_{1/2}(0^+ \rightarrow 0^+)]^{-1} = G_{0\nu}|M^{0\nu}|^2\langle m_\nu\rangle^2$$

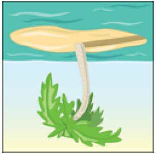




- define effective interaction
- $\mathcal{H}_{\text{eff}}\Psi_{\text{eff}} = E\Psi_{\text{eff}}$
- build and diagonalize energy matrix

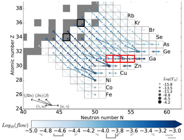
Nuclear structure far from stability

- New magic numbers
- Vanishing of shell closures



Astrophysics and nucleosynthesis

- rp process
- r process



Shell Model: Giant Computations

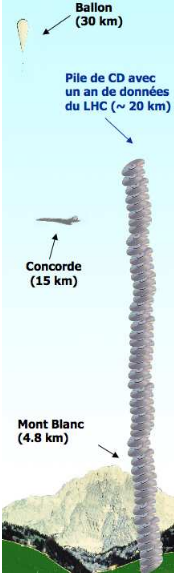
- exponential growth of basis dimensions:

$$|\Phi_\alpha\rangle = \prod_{i=nljm\tau} a_i^\dagger |0\rangle = a_{i1}^\dagger ... a_{iA}^\dagger |0\rangle$$

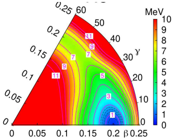
$$D \sim \begin{pmatrix} d_\pi \\ p \end{pmatrix} \cdot \begin{pmatrix} d_\nu \\ n \end{pmatrix}$$

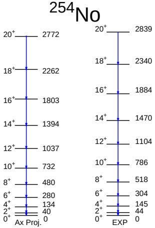
In *pf* shell :
^{56}Ni **1,087,455,228**
In *pf-sdg* space :
^{78}Ni **210,046,691,518**

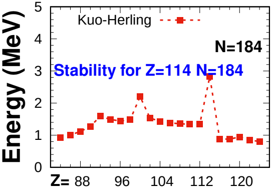
- Actual limits in giant diagonalizations: **$0.2\ 10^{12}$** for ^{114}Sn core excitations
- Largest matrices up to now contain up to **$\sim 10^{14}$** non-zero matrix elements.
- This would require more than 1,000,000 CD-ROM's to store the information for a single matrix !
- They cannot be stored on hard disk and are computed on the fly.



New opportunities:BMF-SM







B. Bounthong, PhD Thesis, IPHC(2016)

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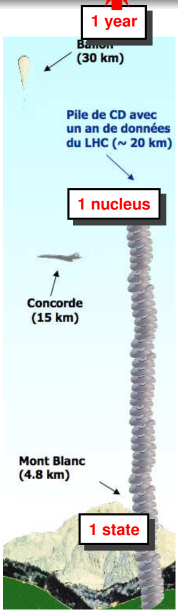

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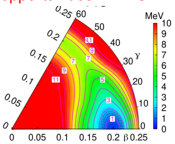

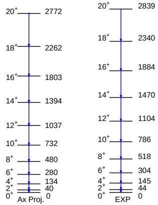

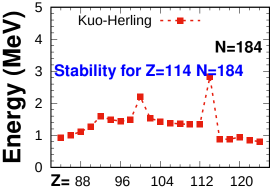

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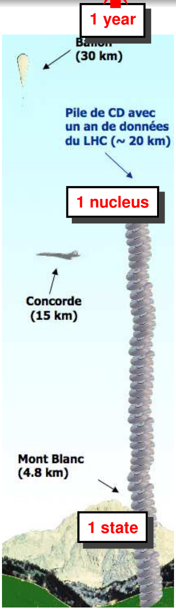

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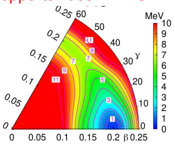
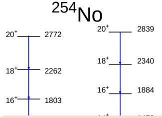
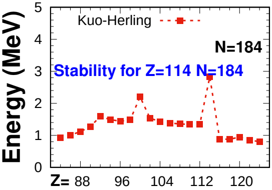




D. Dao post-doc (2020-2021)

IN2P3/IPHC



B. Bounthong, PhD Thesis, IPHC(2016)

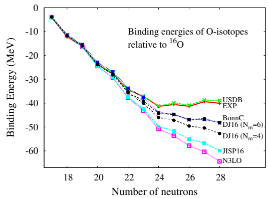
Structure and decay of exotic nuclei

- Nowadays, LSSM calculations in extended model spaces comprising a few oscillator shells to deal with the changing shell structure and the onset of deformation in very neutron-rich nuclei
- Development of accurate description of isospin-symmetry breaking using charge-dependent hamiltonians
- Construction of fully microscopic interactions for valence-space calculations as a path towards regions where no experimental data are available
- Development of numerical techniques and state-of-the-art computations
- Search for additionnal guidelines and short-cuts using symmetry based approaches

PHYSICAL REVIEW C **100**, 054329 (2019)

Effective interactions in the *sd* shell

N. A. Smirnova*
CENBG (CNRS/IN2P3 - Université de Bordeaux), 33175 Gradignan cedex, France



ARTICLE

https://doi.org/10.1038/s41586-019-1155-x

^{78}Ni revealed as a doubly magic stronghold against nuclear deformation

R. Taniuchi et al., NATURE **569**, 53-58 (2019)

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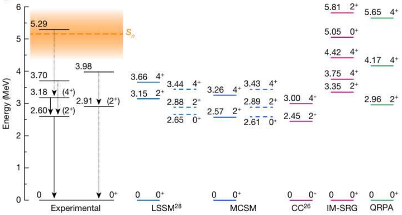
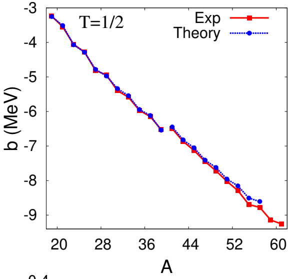
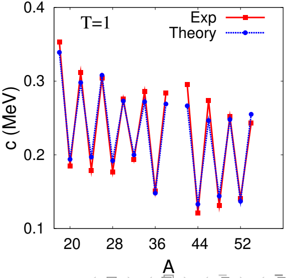


Weak-interaction processes and physics beyond the Standard Model

Isospin symmetry breaking in the Shell-Model context

- Accurate description of Isospin violation and associated phenomena through development of Isospin Non Conserving Shell Model hamiltonians in extended valence spaces: $((sd), (pf), (s_{1/2}d_{3/2}f_{7/2}p_{3/2})$ and beyond
- $\beta - p$ and $\beta - p\gamma$ decay studies and extraction of Isospin mixing in the IAS
- Development of Isospin Non Conserving Shell Model hamiltonian in the $(sd - pf)$ valence space and numerous applications
- Improvement of MED and TED description within a band
- Interpretation for b and c coefficients staggering
- support to forthcoming experimental studies





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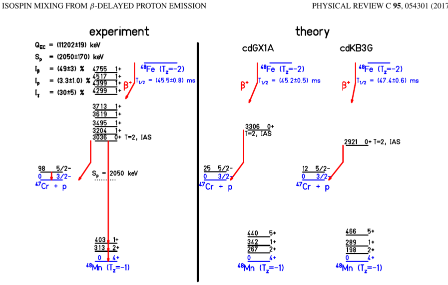


^{48}Mn: $S_{exp} = 2.7(9).10^{-3}$, $\alpha_{exp} = 1.4(5)\%$

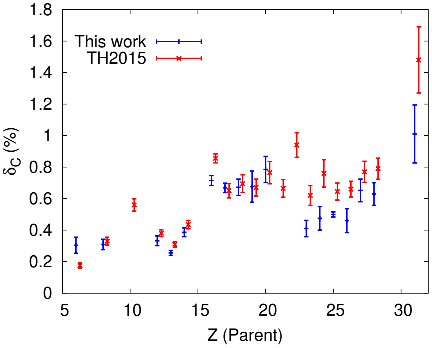
Weak-interaction processes and physics beyond the Standard Model

Superallowed β $0^+ \to 0^+$ as a test of fundamental interactions

$$\mathcal{F}t = (1+\delta_R)(1+\delta_{NS}-\delta_C)ft = \frac{K}{M_{F0}^2 G_F^2 |V_{ud}|^2 (1+\Delta_R)}$$

- Large scale calculations for all emitters below A $\leq$ 40 including nuclei in the vicinity of ^{40}Ca
- Use of Isospin Non Conserving hamiltonians and Woods-Saxon wave functions for untruncated *sd* and *pf* calculations
- New approach of radii determination without closure approximation
- Use of new effective interactions developped in Strasbourg

- Lanczos Structure Function Method for δ_C
- New $(sd-pf)$ interaction
- Effective Fermi Operator
- HF wave functions
- New emitters such as ^{58}Zn



Weak-interaction processes and physics beyond the Standard Model

Superallowed β $0^+ \to 0^+$ as a test of fundamental interactions

Nadezda Smirnova
Isospin-symmetry breaking: exotic nuclei, fundamental interactions and astrophysics (2017-2022)

IN2P3/CENBG/IPHC/GANIL

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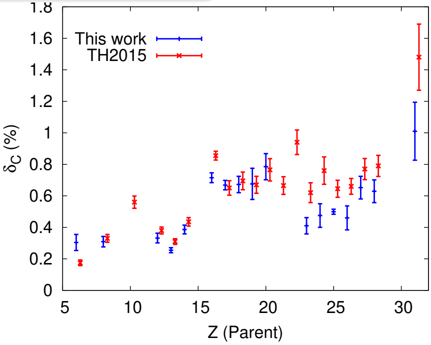


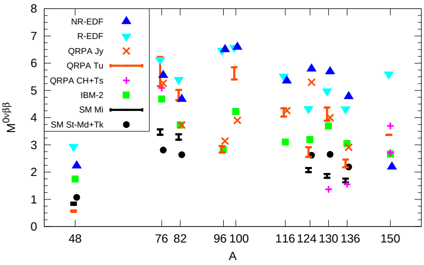
Weak-interaction processes and physics beyond the Standard Model

Reliable nuclear matrix elements needed to plan and fully exploit impressive experiments looking for neutrinoless $\beta\beta$ decay

• Matrix elements differences
between present calculations, factor 2-3
besides additionnal “quenching” ?

$$[T^{0\nu}_{1/2}(0^+ \rightarrow 0^+)]^{-1} = G_{0\nu}|M^{0\nu}|^2|f(m_i, U_{ei}|^2$$

• ^{48}Ca and ^{76}Ge matrix elements
in larger configuration space increase $\lessapprox$ 30% ,
missing correlations introduced in IBM, EDF



• First Ab-initio calculations of β decays do not need additionnal “quenching”,
Ab-initio ^{48}Ca matrix elements in progress

• $2\nu\beta\beta$ decay, μ-capture/ν-nucleus scattering and double Gamow-Teller transitions can give insight on $0\nu\beta\beta$ matrix elements

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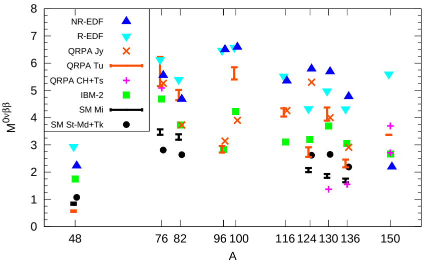

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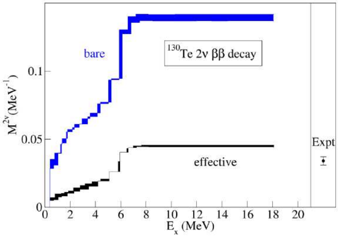
PHYSICAL REVIEW C **100**, 014316 (2019)

Renormalization of the Gamow-Teller operator within the realistic shell model

L. Coraggio,[1] L. De Angelis,[1] T. Fukui,[1] A. Gargano,[1] N. Itaco,[2,1] and F. Nowacki[3,4,2]



Renormalisation of the $(\beta\beta)_{2\nu}$ operator by MBPT

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The calculation of the neutrinoless double-β decay matrix element within the realistic shell model

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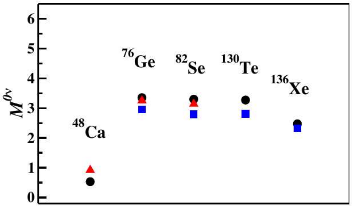


Renormalisation of the $(\beta\beta)_{0\nu}$ operator by MBPT

Collaboration IPHC - INFN/Université de Naples

Stellar rp and r-processes and nucleosynthesis

Proton capture reaction rates calculations for rp process (X-ray bursts) or novae

$$N_A\langle\sigma v\rangle = 1.54 * 10^{15}(\mu T_9)^{-3/2}\omega\gamma exp(\frac{-11.605E_r}{T_9})cm^3.s^{-1}.mol^{-1}$$

- Strong impact reactions (Cybert et al. AAJ, 2016):

$^{56}Ni(\alpha,p)^{59}Cu, ^{59}Cu(p,\gamma)^{60}Zn, ^{61}Ga(p,\gamma)^{62}Zn$

- Theoretical determination of unknown quantities:

Resonance energies (with Isospin breaking)

Widths with respect to proton and gamma emission

- Several reactions in *sd* shell

pf shell nuclei around ^{40}Ca

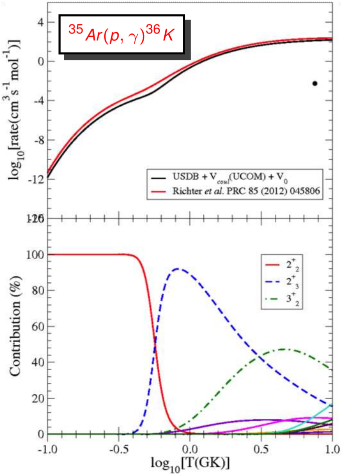
Thomas-Ehrman shift in *sd* shell

$(\alpha,\gamma), (\alpha,p), (p,\alpha)$ capture/emission modeling

$^{22}Mg(\alpha,p)^{25}Al$ and other reactions

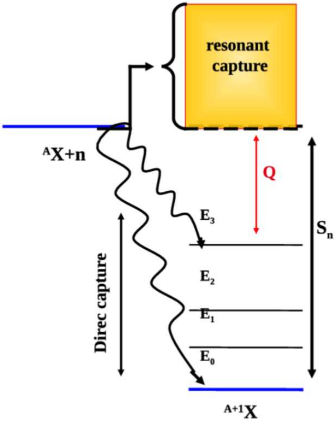
- $p - sd - pf$ valence space for non-natural parity states

Electron capture rates around ^{40}Ca



Radiative Neutron Capture: Theoretical Models and Applications

- SM can provide reliable spectroscopic factors and help testing usual theoretical assumptions in cases no experimental data is known $\longrightarrow$ 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 : $X10$
- develop/constraint/improve global microscopic models (HFB, QRPA) on a SM basis for all kind of applications (astrophysics, nuclear data, reactors etc ...)



Radiative Neutron Capture: Theoretical Models and Applications

Kamila Sieja
Gamma Strength (2017-2019)
Radiative Neutron Capture (2020-2022)

IN2P3/IPHC

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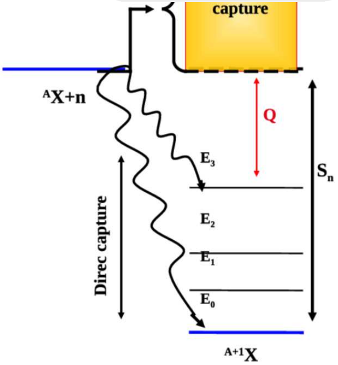

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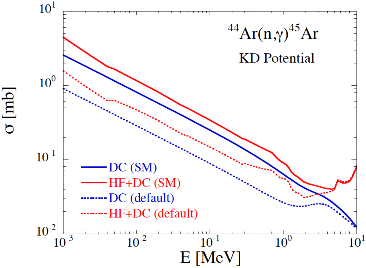


K. Sieja, work in progress

SM Studies

• High predictive power, accurate and detailed information (structure near and far from stability, nuclear and electroweak processes)

• success and robustness of the approach encourage further developments and applications

• Potential powerful description of simultaneous low-lying phenonema but need of precise dedicated local studies

• Intense support for future experimental programs and developments (but manpower insufficient ...)

• Existing cross fertilizing collaborations in several domains: ab-initio studies, isospin symmetry breaking, astrophysics, $\beta\beta$ decay ... and others to develop !

Ab-initio challenge

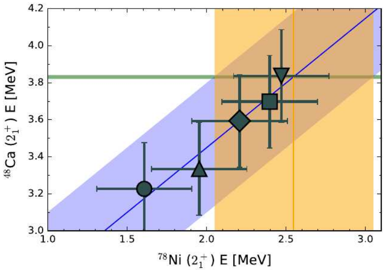


FIG. 2. Correlation between the energies of the 2_1^+ excited state in ^{48}Ca and ^{78}Ni, obtained from the interactions NNLO$_{\text{sat}}$ (circle), "2.0/2.0 (PWA)" (square), "2.0/2.0 (EM)" (diamond), "2.2/2.0 (EM)" (triangle up), and "1.8/2.0 (EM)" (triangle down). The error bars estimate uncertainties from enlarging the model space from $N = 12$ to $N = 14$. The thin horizontal line marks the known energy of the 2_1^+ state in ^{48}Ca.

Phys. Rev. Lett. 117, 172501 (2016)

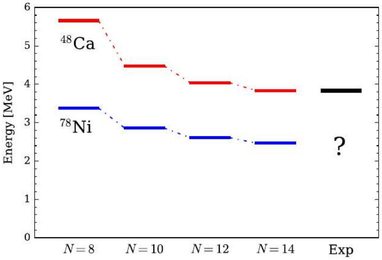
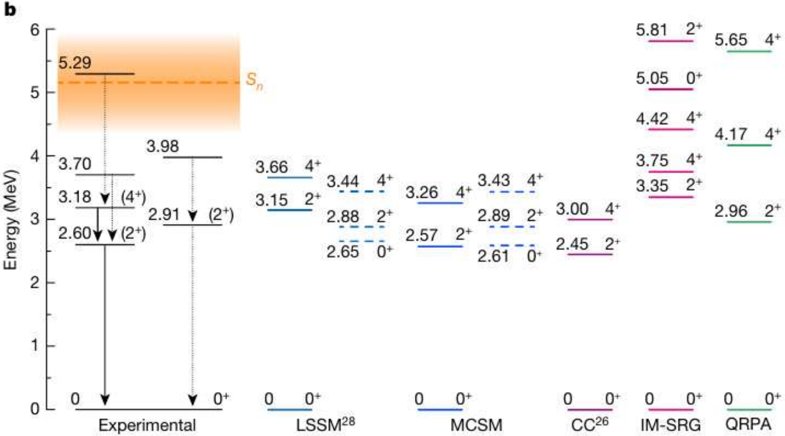


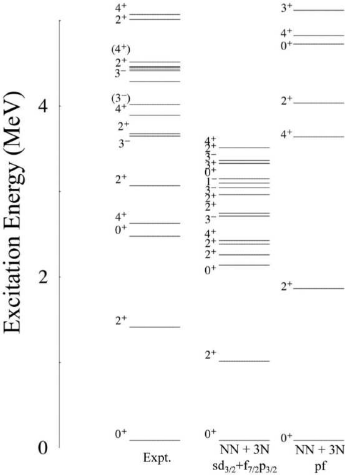
FIG. 3. Convergence of the first 2_1^+ excited state of ^{48}Ca and ^{78}Ni with increasing model-space size and compared to the data for the interaction 1.8/2.0 (EM) of Ref. [33].

Ab-initio challenge



R. Taniuchi et al., NATURE **569**, 53-58 (2019)

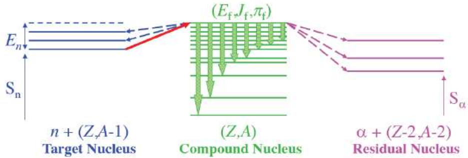
Ab-initio challenge



Phys. Rev. C100, 054327 (2019)

Stellar rp and r-processes and nucleosynthesis

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 ~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

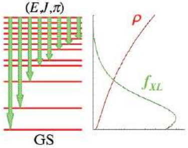
$T_n^{\mu} = T_n(E,J,\pi;E_i^{\mu},J_i^{\mu},\pi_i^{\mu})$ $T_\gamma^{\nu} = T_\gamma(E,J,\pi;E_m^{\nu},J_m^{\nu},\pi_m^{\nu})$- transmission coefficients

For a given multipolarity

$T_{XL}(E,J,\pi,E^{\nu},J^{\nu},\pi^{\nu}) = 2\pi E_\gamma^{2L+1} f_{XL}(E,E_\gamma)$

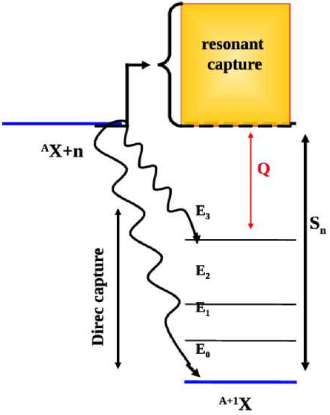
☞Test, using SM, the key ingredients of Hauser-Feshbach calculations:

- description of γ emission spectra
- Brink-Axel hypothesis



Stellar rp and r-processes and nucleosynthesis

Direct Capture



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

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

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

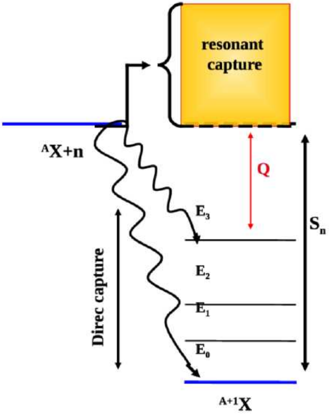
If no experimental data available:

- 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

Direct Capture



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