Level densities and gamma-ray strengths

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ICTP-IAEA Workshop on Simulation of Nuclear Reaction Data with the TALYS Code - TRIESTE - October 2023

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Content

MONDAY

- **Introduction**
- **General features about nuclear reactions**
  - Time scales and associated models
  - Types of data needed
  - Data format = f (users)
- **Nuclear Models**
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  - Optical model
  - Pre-equilibrium model
  - Compound Nucleus model
- **Model ingredients**
  - Level densities
  - Gamma-ray strengths
  - Fission transmission coefficients
- **Fission reactions**
  - Generalities about fission
  - Fission neutrons and gammas
  - Fission yields
  - Fission cross sections
- **Prospects**

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  - Basic structure properties
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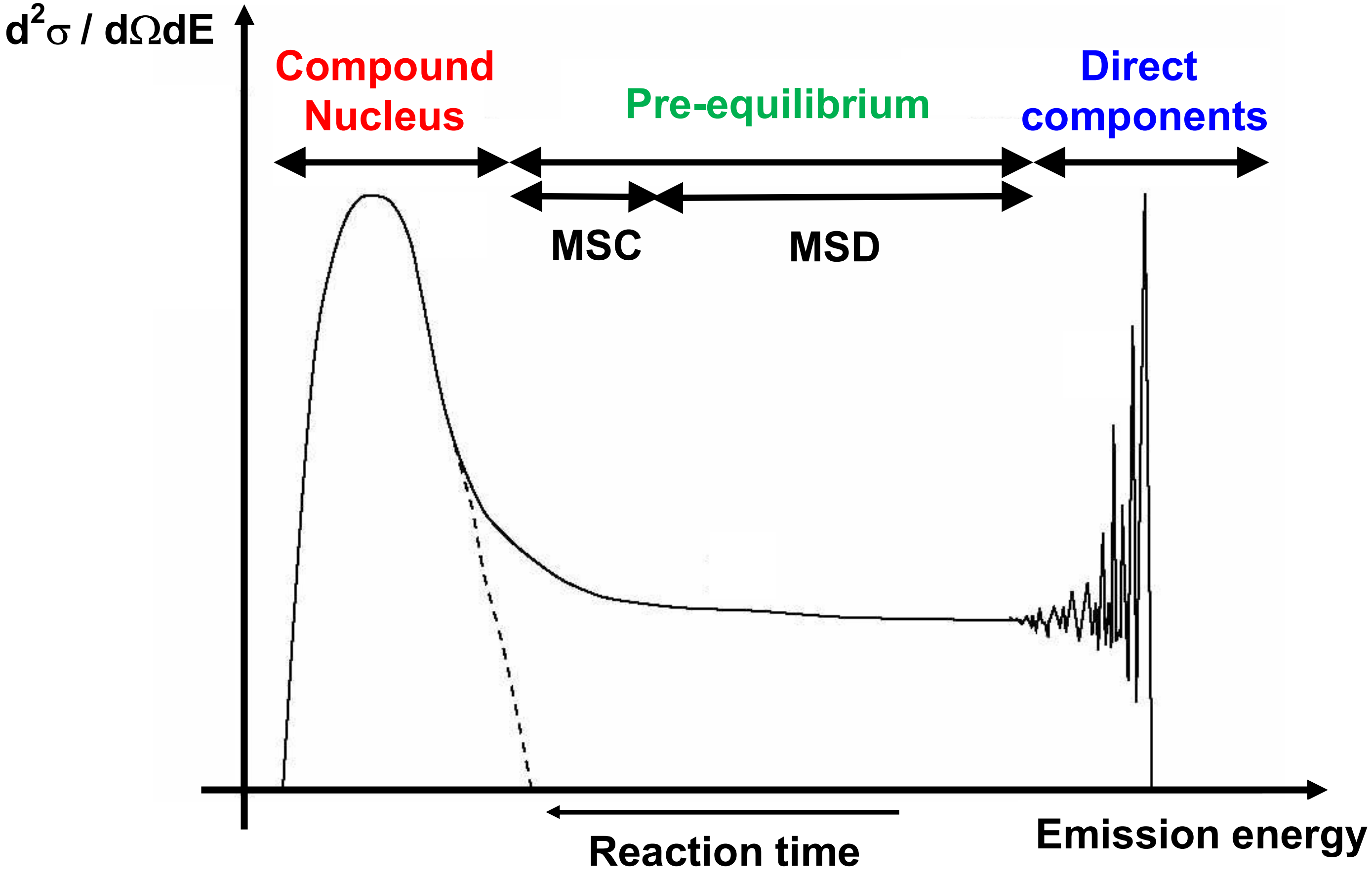
THURSDAY

- **Fission reactions**
  - Generalities about fission
  - Fission neutrons and gammas
  - Fission yields
  - Fission cross sections
- **Prospects**

Content

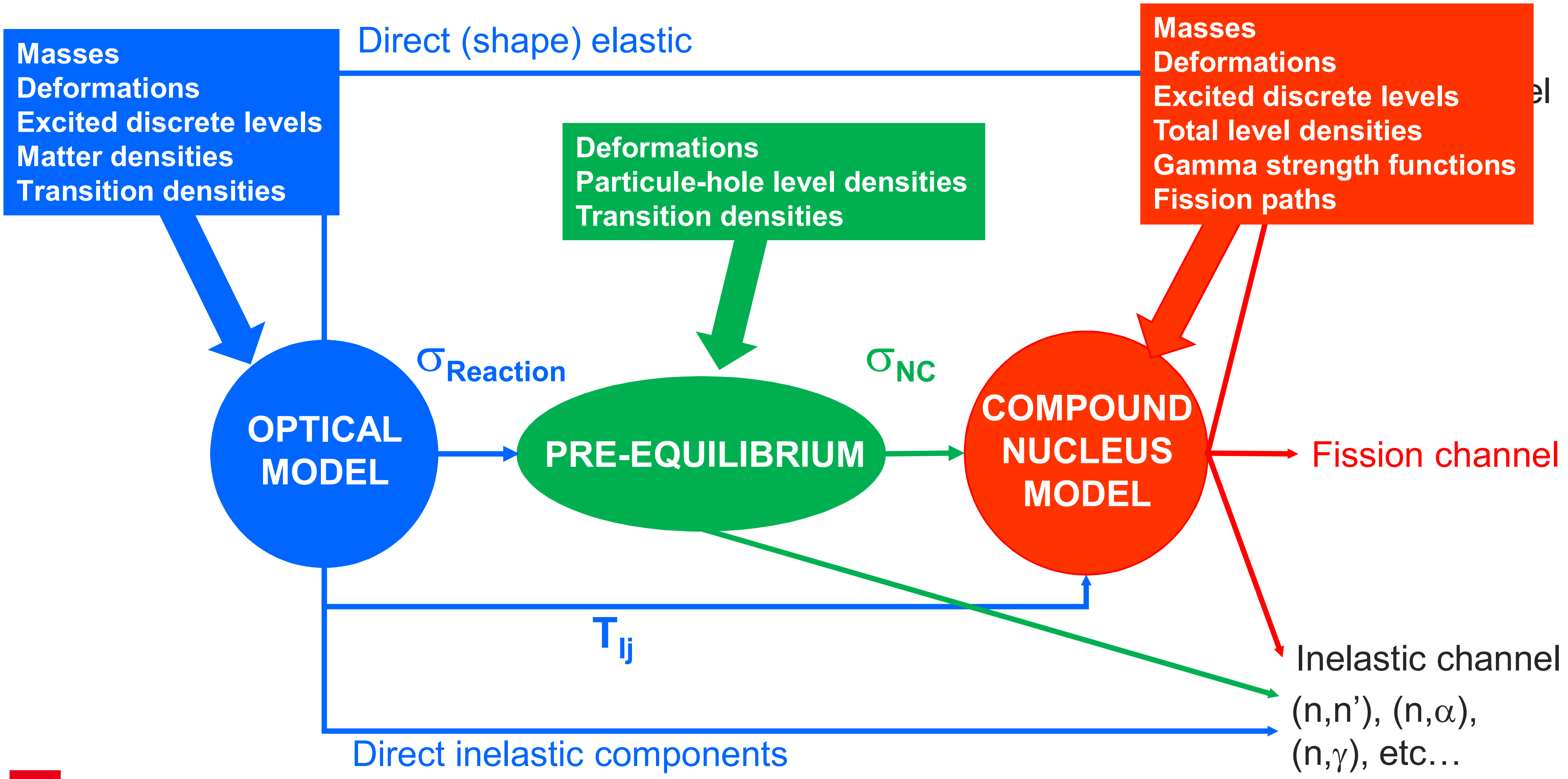
1. FEW REMINDERS

Time scales and associated models



Real scale	:	10^{-15} s	10^{-22} s
Human scale	:	year	s

Models sequence and required ingredients



Masses
Deformations
Excited discrete levels
Matter densities
Transition densities

Direct (shape) elastic

Deformations
Particule-hole level densities
Transition densities

Masses
Deformations
Excited discrete levels
Total level densities
Gamma strength functions
Fission paths

el

OPTICAL MODEL

σ_{Reaction}

PRE-EQUILIBRIUM

σ_{NC}

COMPOUND NUCLEUS MODEL

Fission channel

T_{lj}

Inelastic channel

(n,n'), (n,α), (n,γ), etc…

Direct inelastic components

2. LEVEL DENSITIES

Level densities

- Why and where do we need them ?

- Why ?
- Where ?

- Particle-hole level densities for pre-equilibrium

- The equidistant spacing model
- Beyond the ESM

- Total level densities

- Qualitative features
- Quantitative analysis with analytical approaches
- Shell Model Monte Carlo approach
- HFB+BCS Statistical approach
- Combinatorial approach

- Impacts on cross sections

- Parity non equipartition
- Non-Gaussian spin distribution
- Governing competition
- Tabulated data adjustment

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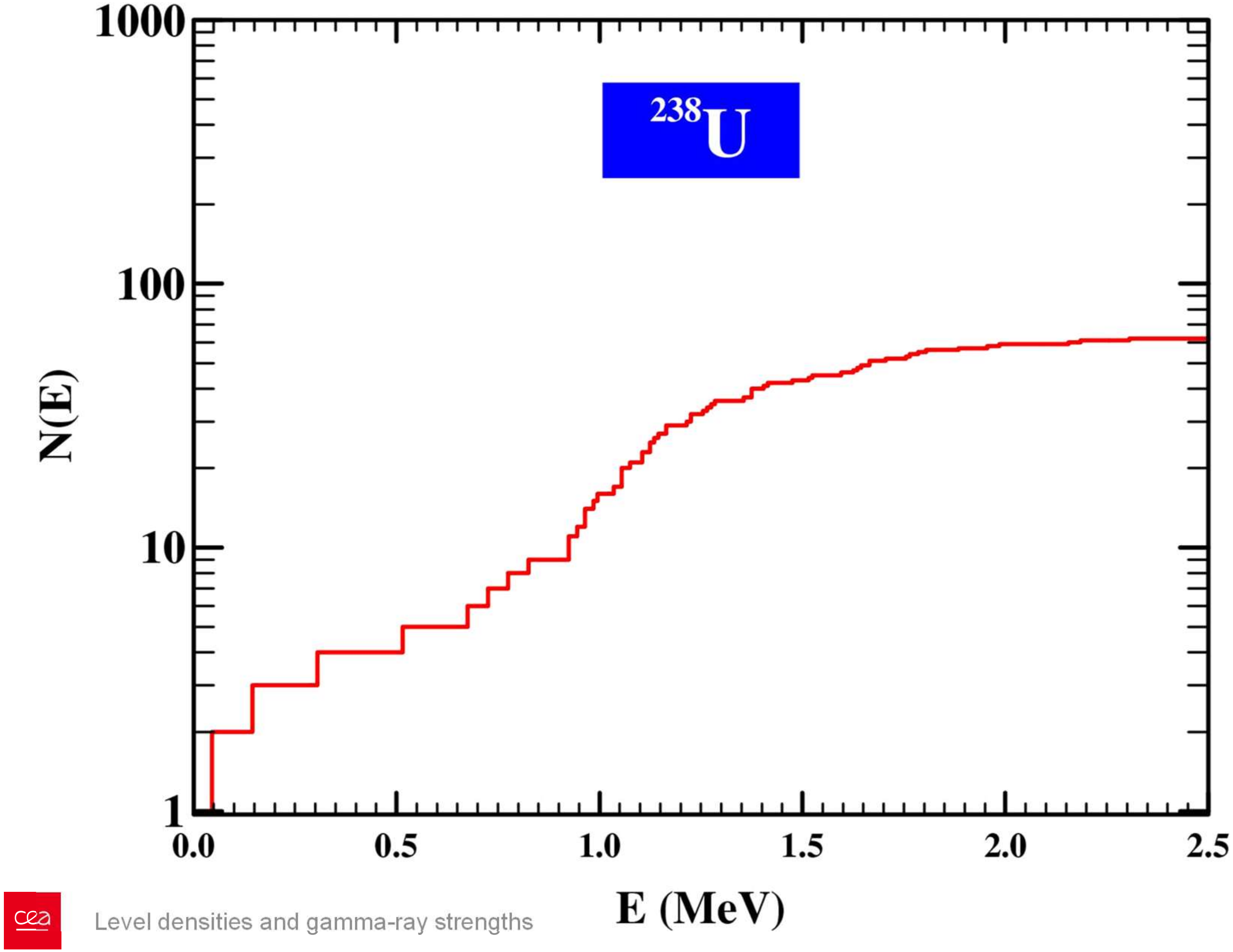
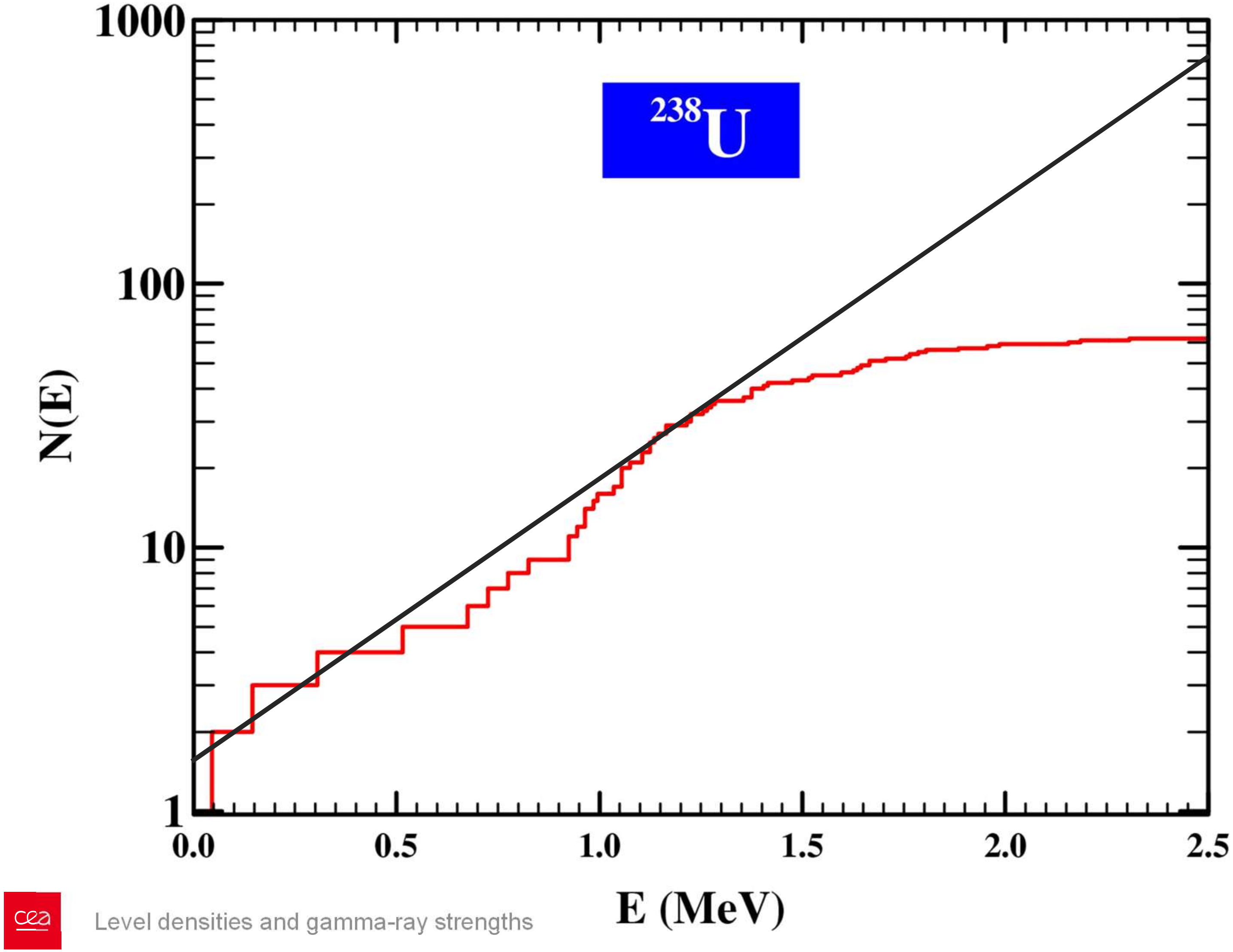
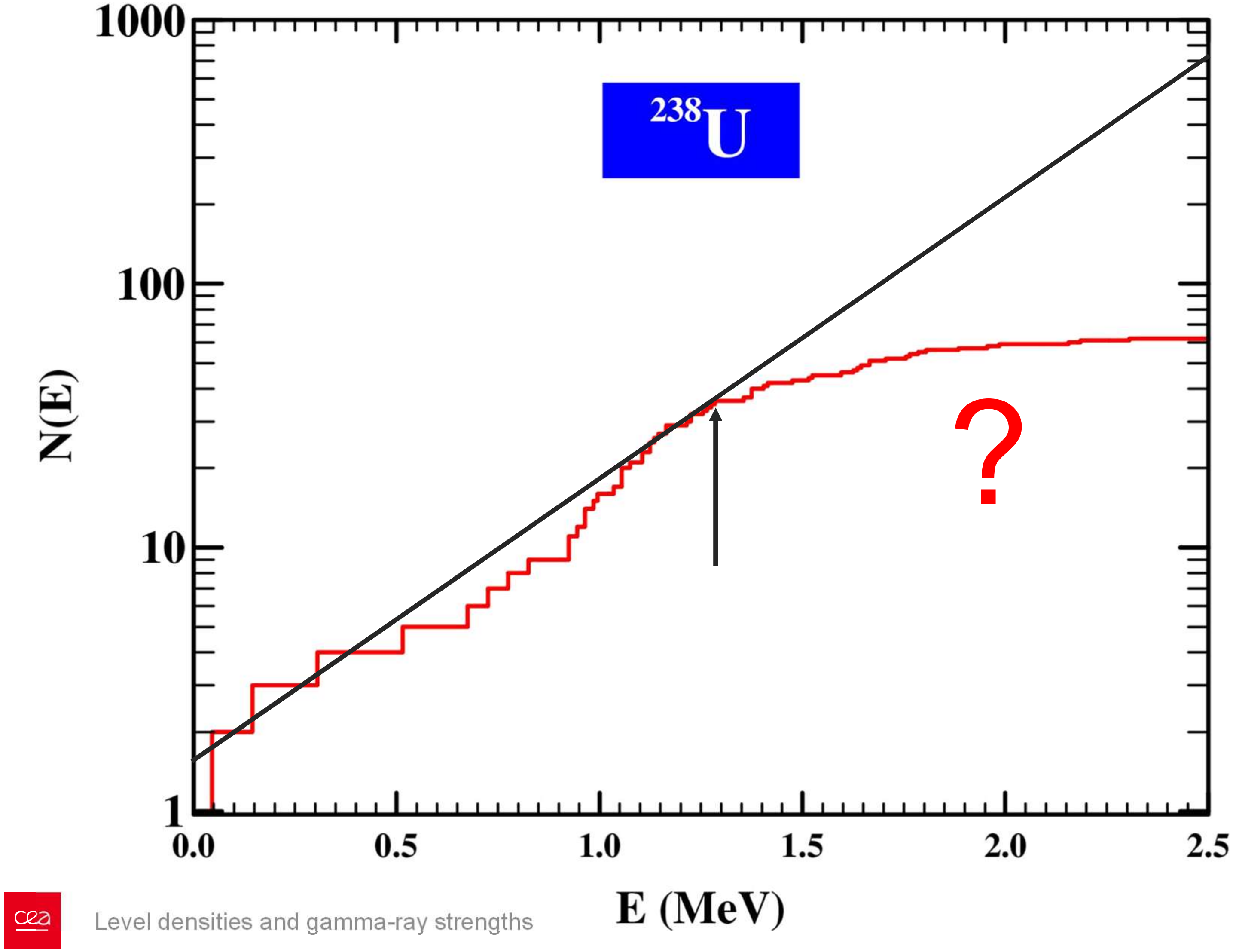
Level densities : why ?



Level densities : why ?



Level densities : why ?



Level densities : where do we need them ?

⇒ partial or p-h level densities for pre-equilibrium model

The pre-equilibrium model : master equation

P(n,E,t) = Probability to find for at time t the composite system with an energy E and an exciton number n.

$\lambda_{a,\,b}$ (E) = Transition rate from an initial state a towards a state b for a given energy E.

Evolution equation

$$\frac{dP(n,E,t)}{dt} = P(n-2, E, t)\,\lambda_{n-2,\,n}(E) + P(n+2, E, t)\,\lambda_{n+2,\,n}(E) - P(n, E, t)\left[\lambda_{n,\,n+2}(E) + \lambda_{n,\,n-2}(E) + \lambda_{n,\,emiss}(E)\right]$$

Emission cross section in channel c

$$d\sigma_c(E, \varepsilon_c) = \sigma_R \int_0^{\infty} \sum_{n,\,\Delta n=2} P(n, E, t)\,\lambda_{n,\,c}(E)\,dt\;\; d\varepsilon_c$$

The pre-equilibrium model : initialisation & transition rates

Initialisation

$P(n,E,0) = \delta_{n,n_0}$ with n_0=3 for nucleon induced reactions

Transition rates

$$\lambda_{n,\,n-2}(E) = \frac{2\pi}{\hbar}\langle M^2\rangle\ \omega(p,h,E) \text{ with } p+h=n-2$$

$$\lambda_{n,\,n+2}(E) = \frac{2\pi}{\hbar}\langle M^2\rangle\ \omega(p,h,E) \text{ with } p+h=n+2$$

$$\lambda_{n,\,c}(E) = \frac{2s_c+1}{\pi^2\hbar^3}\ \mu_c\ \varepsilon_c\ \sigma_{c,inv}(\varepsilon_c)\ \frac{\omega(p-p_b,h,E-\varepsilon_c-B_c)}{\omega(p,h,E)}\ Q_c(n)\ F_c$$

State densities

$\omega(p,h,E)$ = number of ways of distributing p particles and h holes among all accessible single particle levels with the available excitation energy E

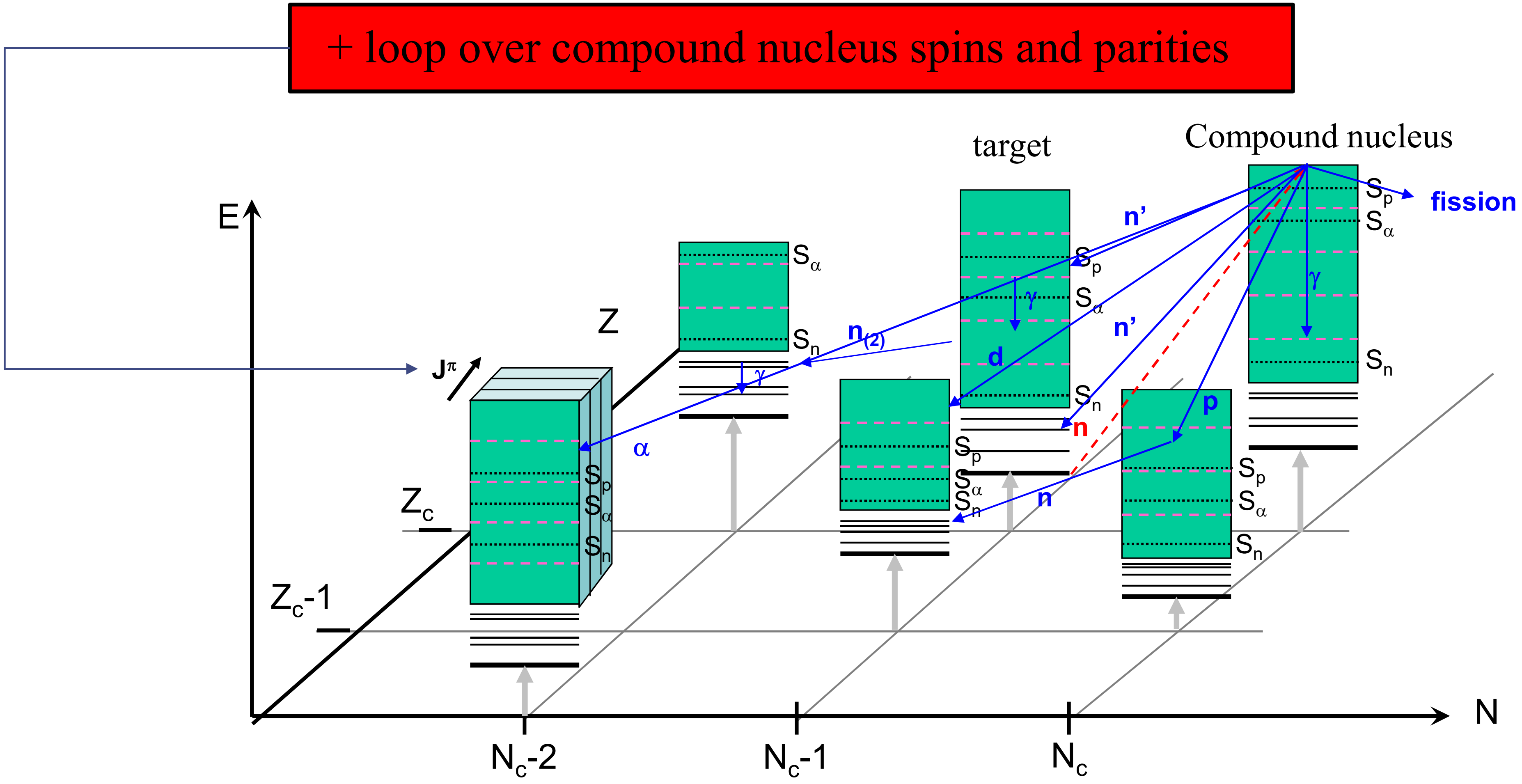
Level densities : where do we need them ?

⇒ partial or p-h level densities for pre-equilibrium model

⇒ total level densities for compound-nucleus model

- Light particle emission in continuum bins
- Gamma decay
- Fission cross section

The compound nucleus model : multiple emission



The compound nucleus model : compact expression

$$\sigma_{NC} = \sum_{b} \sigma_{ab}$$ where b = γ , n, p, d, t, …, fission

$$\sigma_{ab} = \frac{\pi}{k_a^2} \sum_{J,\pi} \sum_{\alpha,\beta} \frac{(2J+1)}{(2s+1)(2I+1)} T_{lj}^{J\pi}(\alpha) \frac{\left\langle T_b^{J\pi}(\beta) \right\rangle}{\sum_{\delta} \left\langle T_d^{J\pi}(\delta) \right\rangle} W_{\alpha\beta}$$

with $J = l_\alpha + s_\alpha + I_A = j_\alpha + I_A$ and $\pi = (-1)^{l_\alpha} \pi_A$

and $\left\langle T_b(\beta) \right\rangle$ = transmission coefficient for outgoing channel β associated with the outgoing particle b

The compound nucleus model : various decay channels

Possible decays

- Emission to a discrete level with energy E_d

$$\left\langle T_b(\beta) \right\rangle = T_{lj}^{J\pi}(\beta)$$

given by the O.M.P.

- Emission in the level continuum

$$\left\langle T_b(\beta) \right\rangle = \int_{E}^{E+\Delta E} T_{lj}^{J\pi}(\beta)\, \rho(E,J,\pi)\, dE$$

$\rho(E,J,\pi)$ density of residual nucleus' levels (J,π) with excitation energy E

- Emission of photons, fission

Specific treatment

The compound nucleus model : various decay channels

Possible decays

- Emission to a discrete level with energy E_d

$$\left\langle T_b(\beta) \right\rangle = T_{lj}^{J\pi}(\beta)$$ given by the O.M.P.

LDs needed

- Emission in the level continuum

$$\left\langle T_b(\beta) \right\rangle = \int_{E}^{E+\Delta E} T_{lj}^{J\pi}(\beta)\, \rho(E,J,\pi)\, dE$$

$\rho(E,J,\pi)$ density of residual nucleus' levels (J,π) with excitation energy E

- Emission of photons, fission

Specific treatment

The compound nucleus model : GOE triple integral

$$W_{a,l_a,j_a,b,l_b,j_b} = \int_0^{+\infty} d\lambda_1 \int_0^{+\infty} d\lambda_2 \int_0^{1} d\lambda \; \frac{\lambda(1-\lambda)|\lambda_1-\lambda_2|}{\sqrt{\lambda_1(1+\lambda_1)\lambda_2(1+\lambda_2)(\lambda+\lambda_1)^2(\lambda+\lambda_2)^2}}$$

T < 1

$$\prod_c \frac{(1-\lambda\, T^J_{c,l_c,j_c})}{\sqrt{(1+\lambda_1\, T^J_{c,l_c,j_c})(1+\lambda_2\, T^J_{c,l_c,j_c})}} \quad \Bigg\{ \delta_{ab}(1- \; T^J_{a,l_a,j_a})$$

$$\left[\frac{\lambda_1}{1+\lambda_1\, T^J_{a,l_a,j_a}} + \frac{\lambda_2}{1+\lambda_2\, T^J_{a,l_a,j_a}} + \frac{2\lambda}{1-\lambda\, T^J_{a,l_a,j_a}}\right]^2 + (1+\delta_{ab})$$

$$\Bigg[\frac{\lambda_1(1+\lambda_1)}{(1+\lambda_1\, T^J_{a,l_a,j_a})(1+\lambda_1\, T_{b,l_b,j_b})} + \frac{\lambda_2(1+\lambda_2)}{(1+\lambda_2\, T^J_{a,l_a,j_a})(1+\lambda_2\, T_{b,l_b,j_b})}$$

$$+ \frac{2\lambda(1-\lambda)}{(1-\lambda\, T^J_{a,l_a,j_a})(1-\lambda\, T_{b,l_b,j_b})}\Bigg]\Bigg\}$$

Level densities

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- Qualitative features
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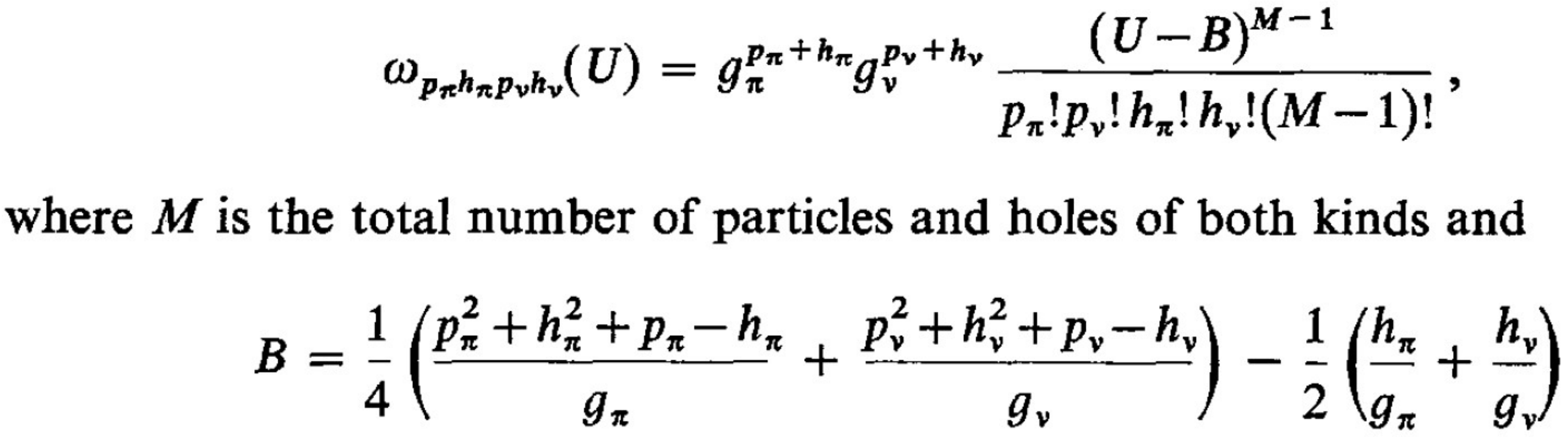
Level densities : particule-hole level densities

State densities in ESM

- **Ericson 1960 : no Pauli principle**
- **Griffin 1966 : no distinction between particles and holes**
- **Williams 1971 : distinction between particles and holes as well as between neutrons and protons but infinite number of accessible states for both particle and holes**



$$\omega_{p_\pi h_\pi p_\nu h_\nu}(U) = g_\pi^{p_\pi+h_\pi} g_\nu^{p_\nu+h_\nu} \frac{(U-B)^{M-1}}{p_\pi! p_\nu! h_\pi! h_\nu! (M-1)!},$$

where M is the total number of particles and holes of both kinds and

$$B = \frac{1}{4}\left(\frac{p_\pi^2+h_\pi^2+p_\pi-h_\pi}{g_\pi} + \frac{p_\nu^2+h_\nu^2+p_\nu-h_\nu}{g_\nu}\right) - \frac{1}{2}\left(\frac{h_\pi}{g_\pi}+\frac{h_\nu}{g_\nu}\right)$$

Level densities : particule-hole level densities

State densities in ESM

- Ericson 1960 : no Pauli principle
- Griffin 1966 : no distinction between particles and holes
- Williams 1971 : distinction between particles and holes as well as between neutrons and protons but infinite number of accessible states for both particle and holes
- Běták and Doběs 1976 : account for finite number of holes' states
- Obložinský 1986 : account for finite number of particles' states (MSC)
- Anzaldo-Meneses 1995 : first order corrections for increasing number of p-h
- Hilaire and Koning 1998 : generalized expression in ESM

Level densities : particule-hole level densities

Refinement to the ESM

- **Fu 1984 : advanced pairing correction**
- **Akkermans and Gruppelaar 1985 : ensure consistency between ph and total level densities**
- **Fu 1985 : advanced spin cut-off factor**
- **Kalbach 1995 : Inclusion and treatment of a gap in the ESM**
- **Harangozo 1998 : Energy dependent single particle state density g(ε)**

Level densities

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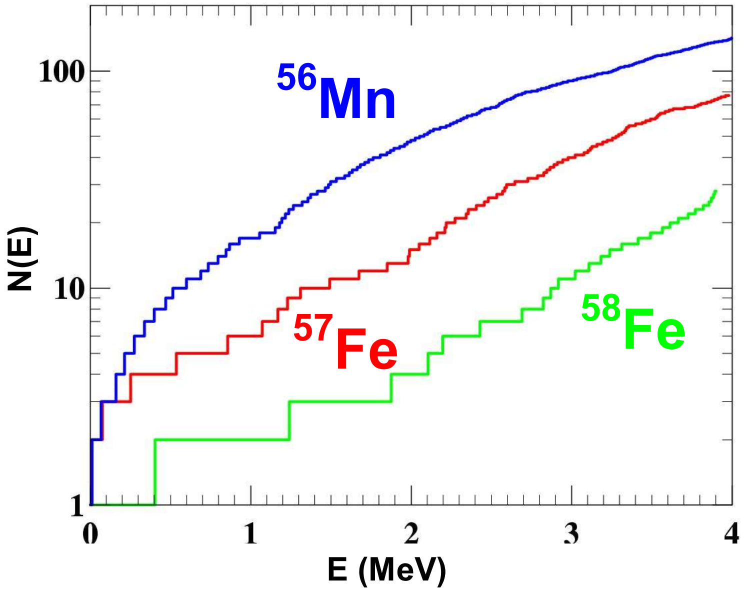
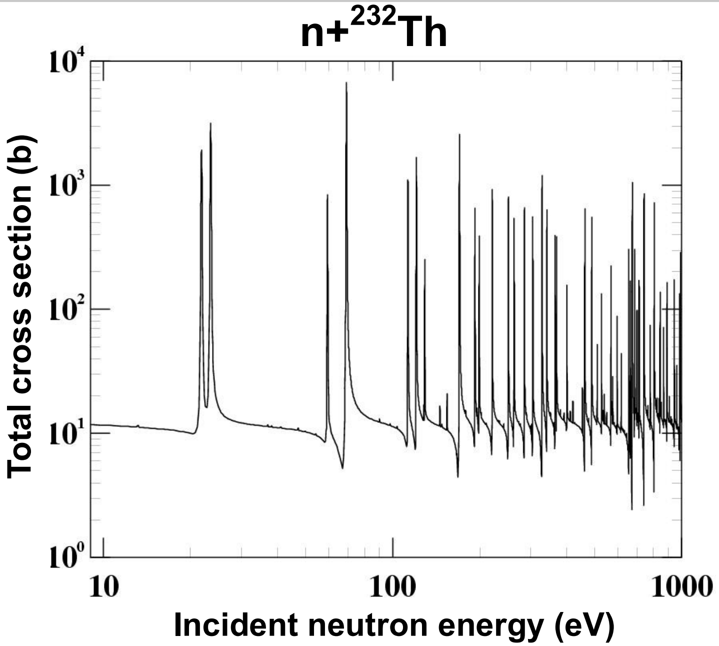
Level densities : qualitative aspects from experiment





- **Exponential increase of the cumulated number of discrete levels N(E) with energy**

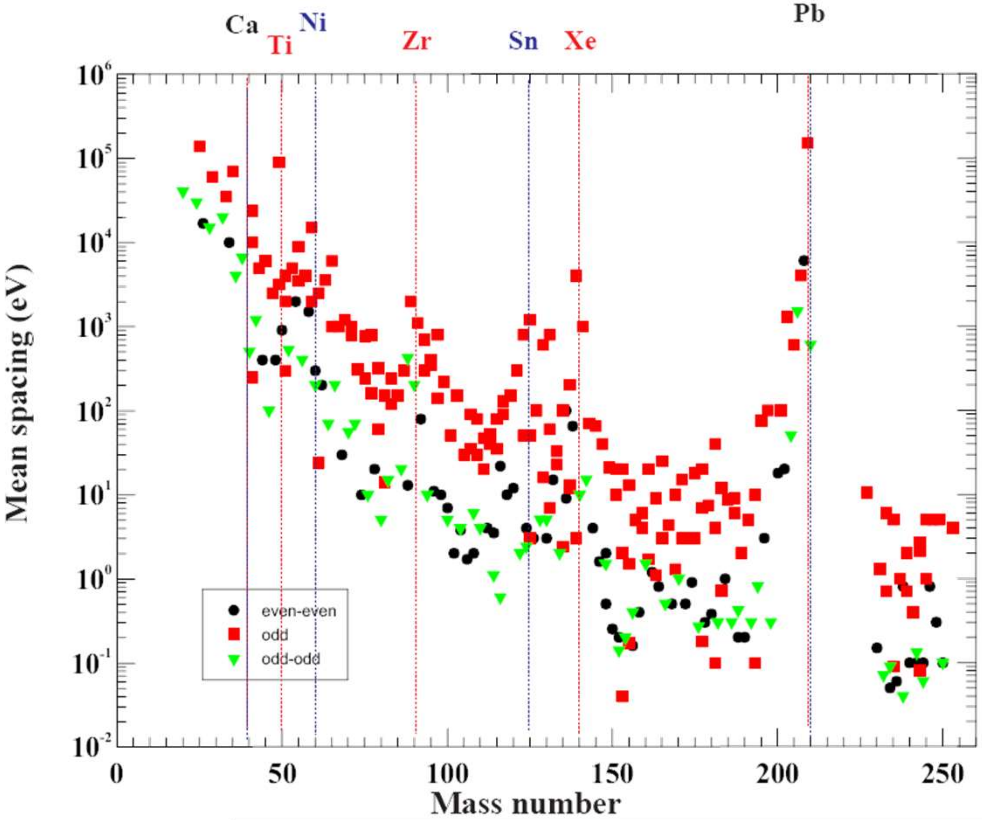
$\Rightarrow$ $\rho(E)= \frac{dN(E)}{dE}$ increases exponentially

$\Rightarrow$ odd-even effects

- **Mean spacings of s-wave neutron resonances at B_n of the order of few eV**

$\Rightarrow$ $\rho(B_n)$ of the order of $10^4 – 10^6$ levels / MeV

Level densities : qualitative aspects D_0 vs mass A

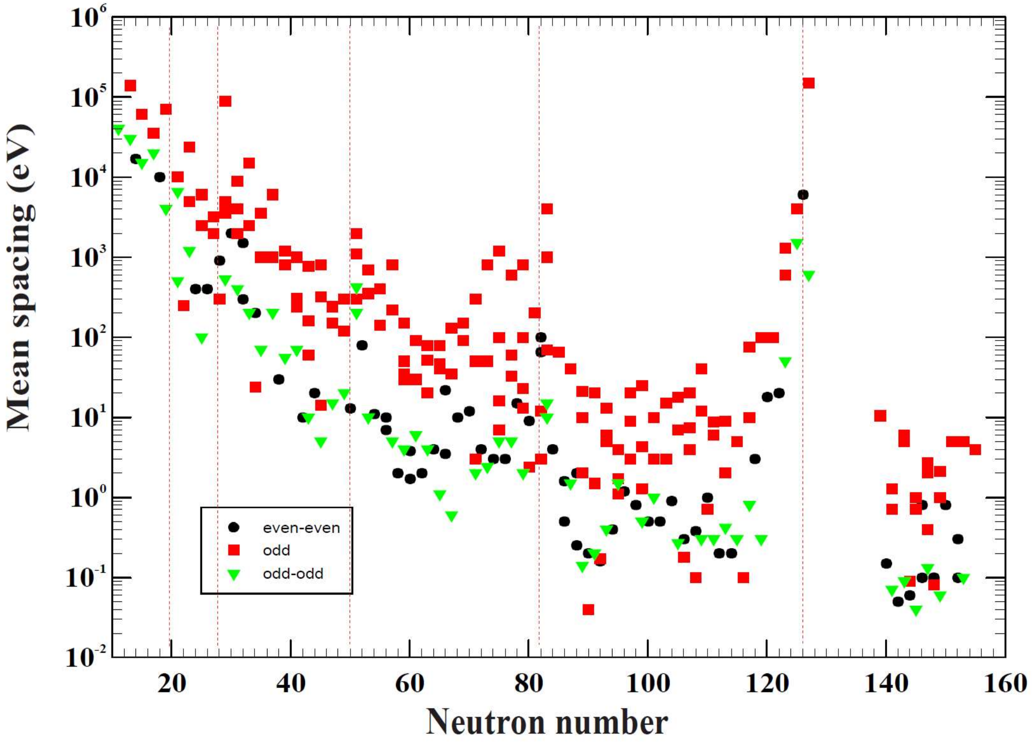


Iljinov et al., NPA 543 (1992) 517.

$\Rightarrow$ **Mass dependency**
Odd-even effects
Shell effects

$$\frac{1}{D_0} = \rho\,(B_n, 1/2, \pi_t) \text{ for an even-even target}$$
$$= \rho\,(B_n, I_t+1/2, \pi_t) + \rho\,(B_n, I_t-1/2, \pi_t) \text{ otherwise}$$

Level densities : qualitative aspects D_0 vs neutron number N



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⇒ **Mass dependency**
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Level densities : quantitative analysis of D_0

$$\rho\,(U, J, \pi) = \frac{1}{2}\;\frac{\sqrt{\pi}}{12}\;\frac{\exp\left(2\sqrt{aU}\right)}{a^{1/4}U^{5/4}}\;\frac{2J+1}{2\sqrt{2\pi}\;\sigma^{3}}\;\exp - \left[\frac{\left(J+\frac{1}{2}\right)^{2}}{2\sigma^{2}}\right]$$

$$+\;\;\sigma^{2} = I_{rig}\;\sqrt{\frac{U}{a}}$$

Level densities : quantitative analysis of D_0

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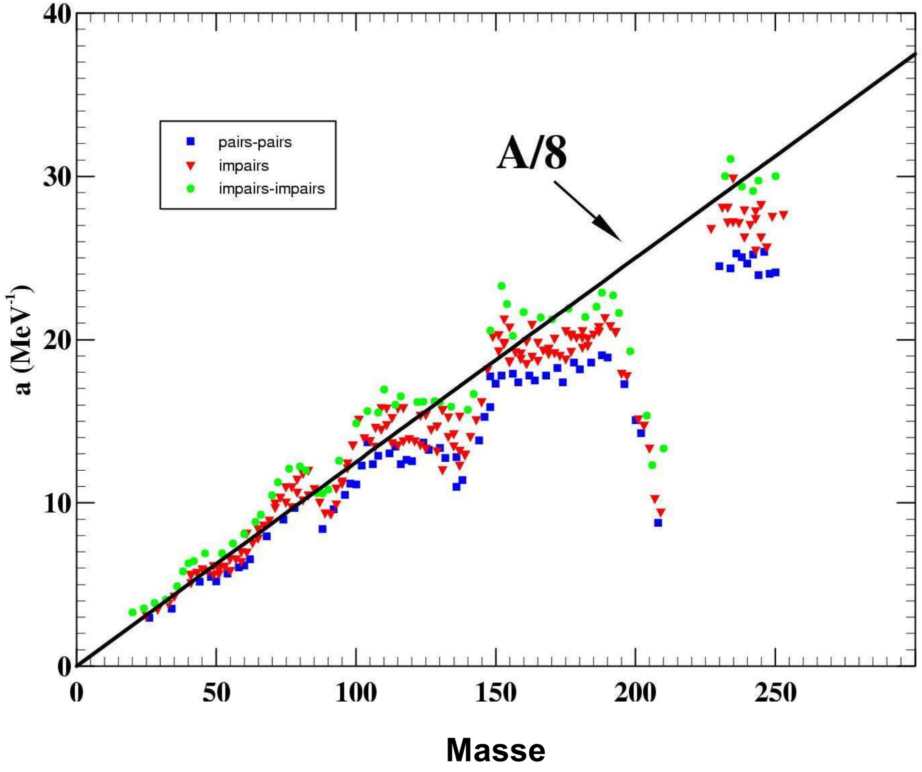

⇒ odd-even effects

Level densities : quantitative analysis of D_0

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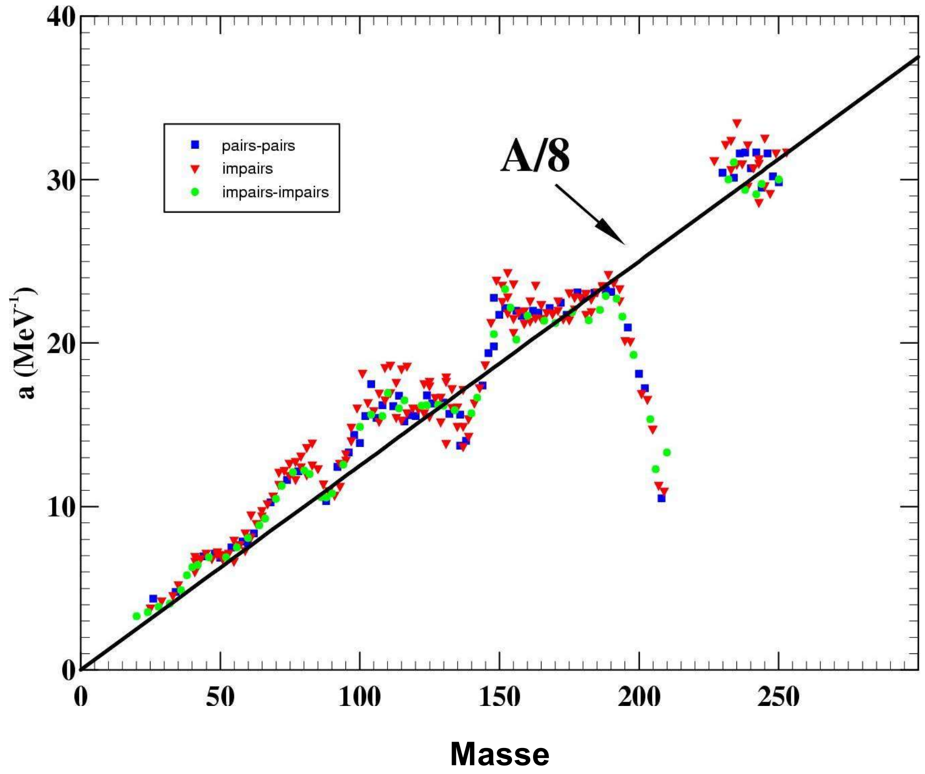


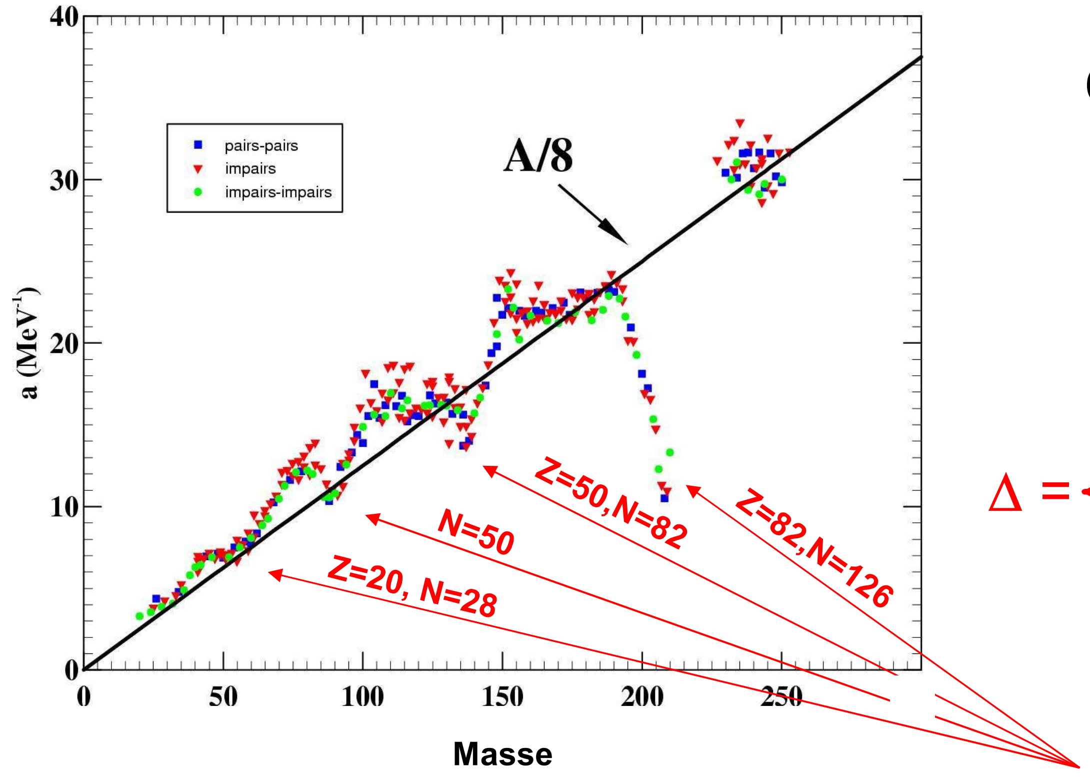
Odd-even effects accounted for

$$U \rightarrow U^{*}=U - \Delta$$

$$\Delta = \begin{cases} 0 & \text{odd-odd} \\ 12/\sqrt{A} & \text{odd-even} \\ 24/\sqrt{A} & \text{even-even} \end{cases}$$

Level densities : quantitative analysis of D_0

$$\rho\,(U, J, \pi) = \frac{1}{2}\;\frac{\sqrt{\pi}}{12}\;\frac{\exp\left(2\sqrt{aU}\right)}{a^{1/4}U^{5/4}}\;\frac{2J+1}{2\sqrt{2\pi}\,\sigma^3}\;\exp-\left[\frac{\left(J+½\right)^2}{2\sigma^2}\right]$$



Shell effects

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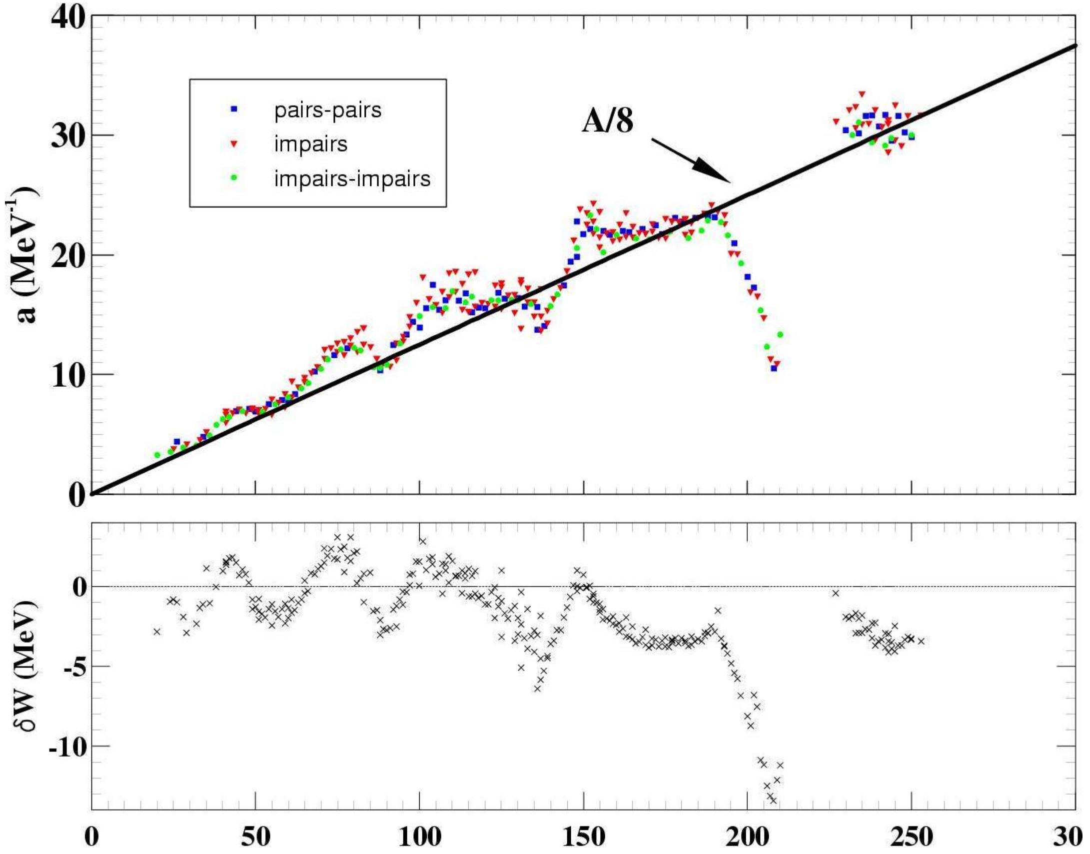
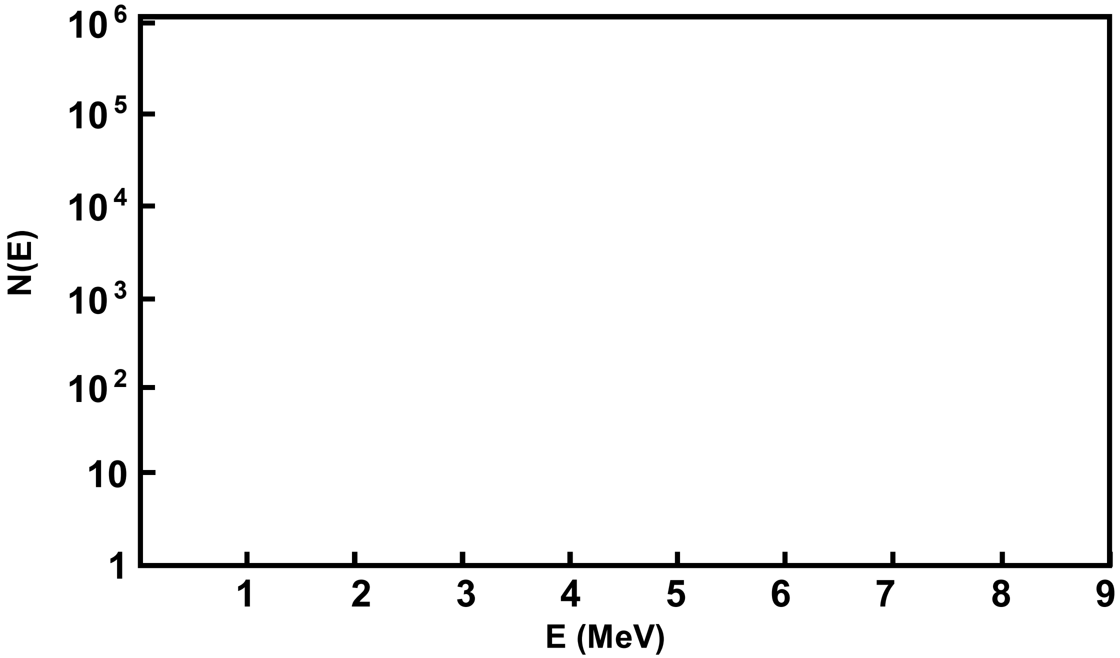
Level densities : Ignatyuk formula



$$a\,(N, Z, U^*) = \tilde{a}\,(A) \left[1 + \delta W(N,Z) \frac{1 - \exp(-\gamma U^*)}{U^*} \right]$$

Level densities : summary of analytical description

ldmodel 1 in TALYS



Level densities : summary of analytical description

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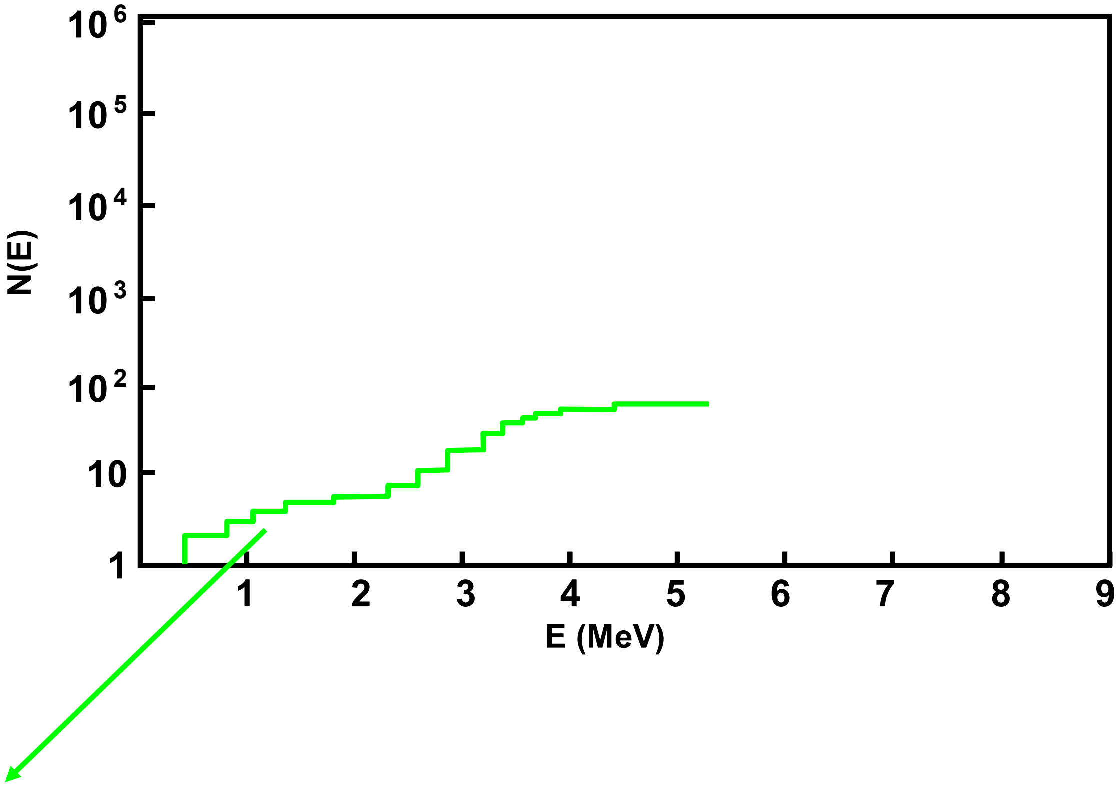
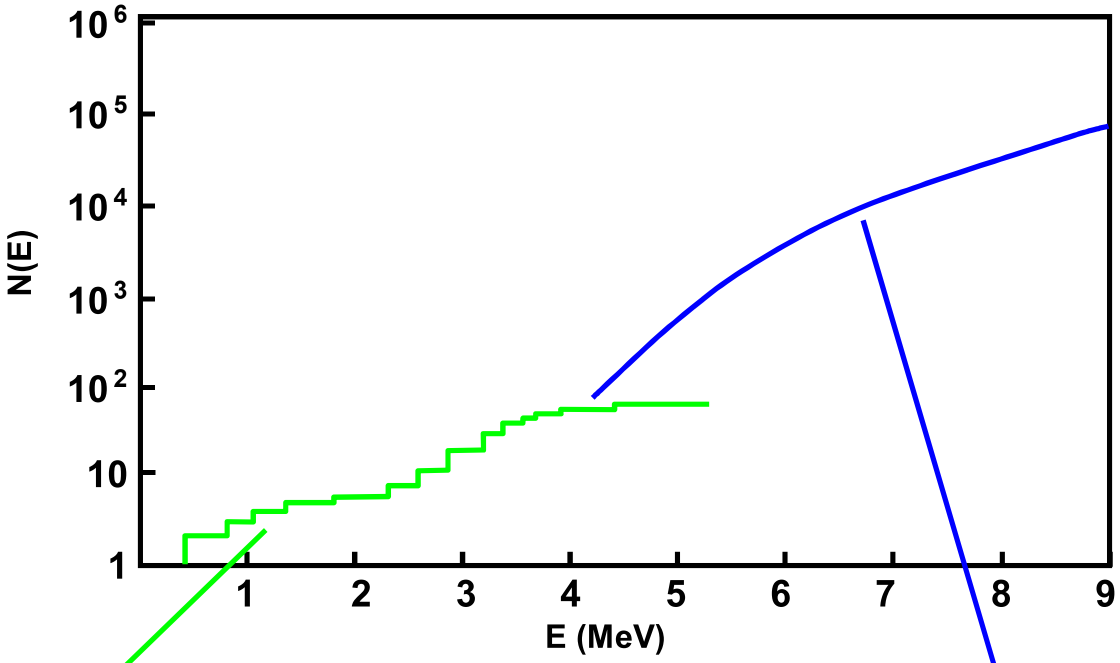


Discrete levels (spectroscopy)

Level densities : summary of analytical description

ldmodel 1 in TALYS



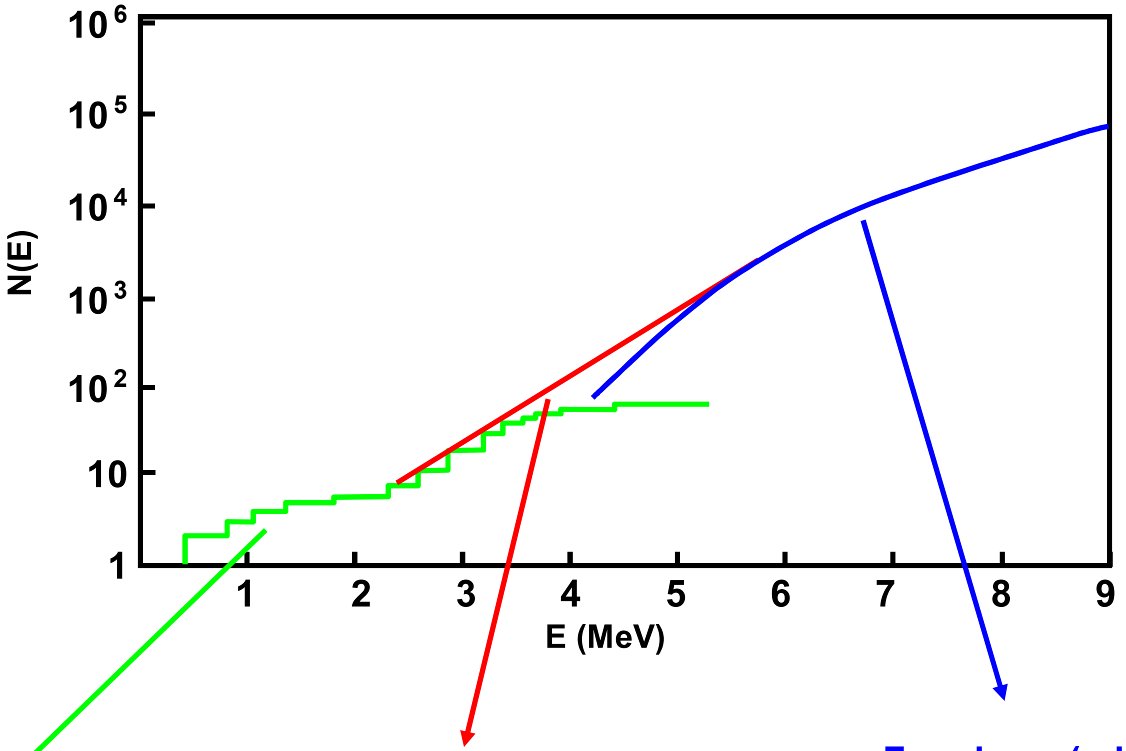
Discrete levels
(spectroscopy)

Fermi gaz (adjusted at B_n)

$$\rho\,(E) = \alpha \frac{\exp\left(2\sqrt{aU^*}\right)}{a^{1/4}U^{*5/4}}$$

Level densities : summary of analytical description

ldmodel 1 in TALYS



Discrete levels (spectroscopy)

Temperature law

$$N(E)=\exp\left(\frac{E-E_0}{T}\right)$$

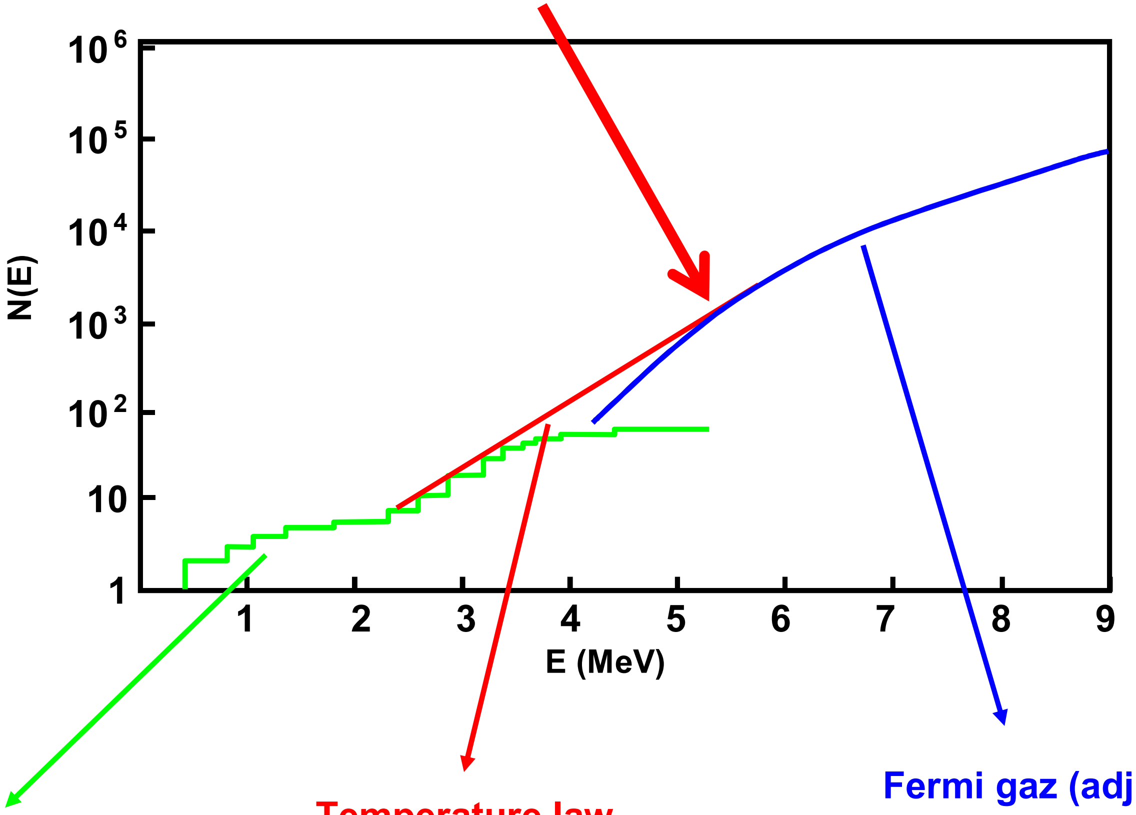
Fermi gaz (adjusted at B_n)

$$\rho\,(E)=\alpha\,\frac{\exp\left(2\sqrt{aU^*}\right)}{a^{1/4}U^{*5/4}}$$

Level densities : summary of analytical description

Matching conditions : continuity of ρ and of its derivative (sometimes difficult)

ldmodel 1 in TALYS



Discrete levels (spectroscopy)

Temperature law

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Fermi gaz (adjusted at B_n)

$$\rho(E)=\alpha\,\frac{\exp\left(2\sqrt{aU^*}\right)}{a^{1/4}U^{*5/4}}$$

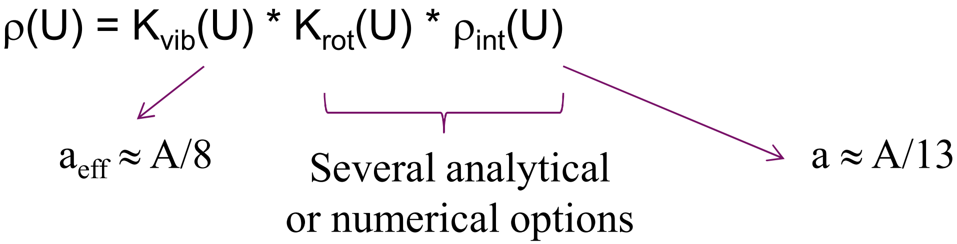
Level densities : More sophisticated analytical expression

Ldmodel 3 in TALYS

- **Superfluid model & Generalized superfluid model**

Ignatyuk et al., PRC 47 (1993) 1504 & RIPL3 paper (IAEA)

⇒ More correct treatment of pairing for low energies
⇒ Fermi Gas + Ignatyuk beyond critical energy
⇒ Explicit treatment of collective effects



$$\rho(U) = K_{vib}(U) * K_{rot}(U) * \rho_{int}(U)$$

$a_{eff} \approx A/8$

Several analytical
or numerical options

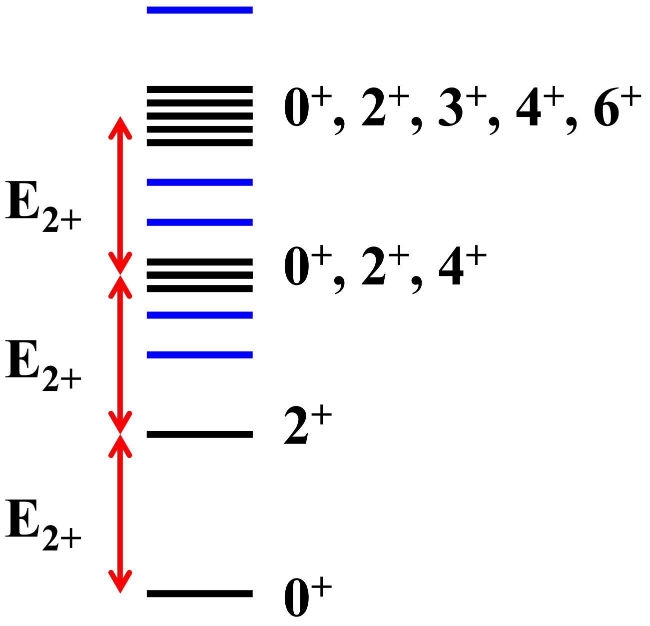
$a \approx A/13$

⇒ **Collective enhancement** only if $\rho_{int}(U) \neq 0$ not correct for vibrational states

⇒ yet not the most used one in pratice

Level densities : collective levels

⇒ vibrational level sequence for a spherical even-even nucleus



3 coupled phonons

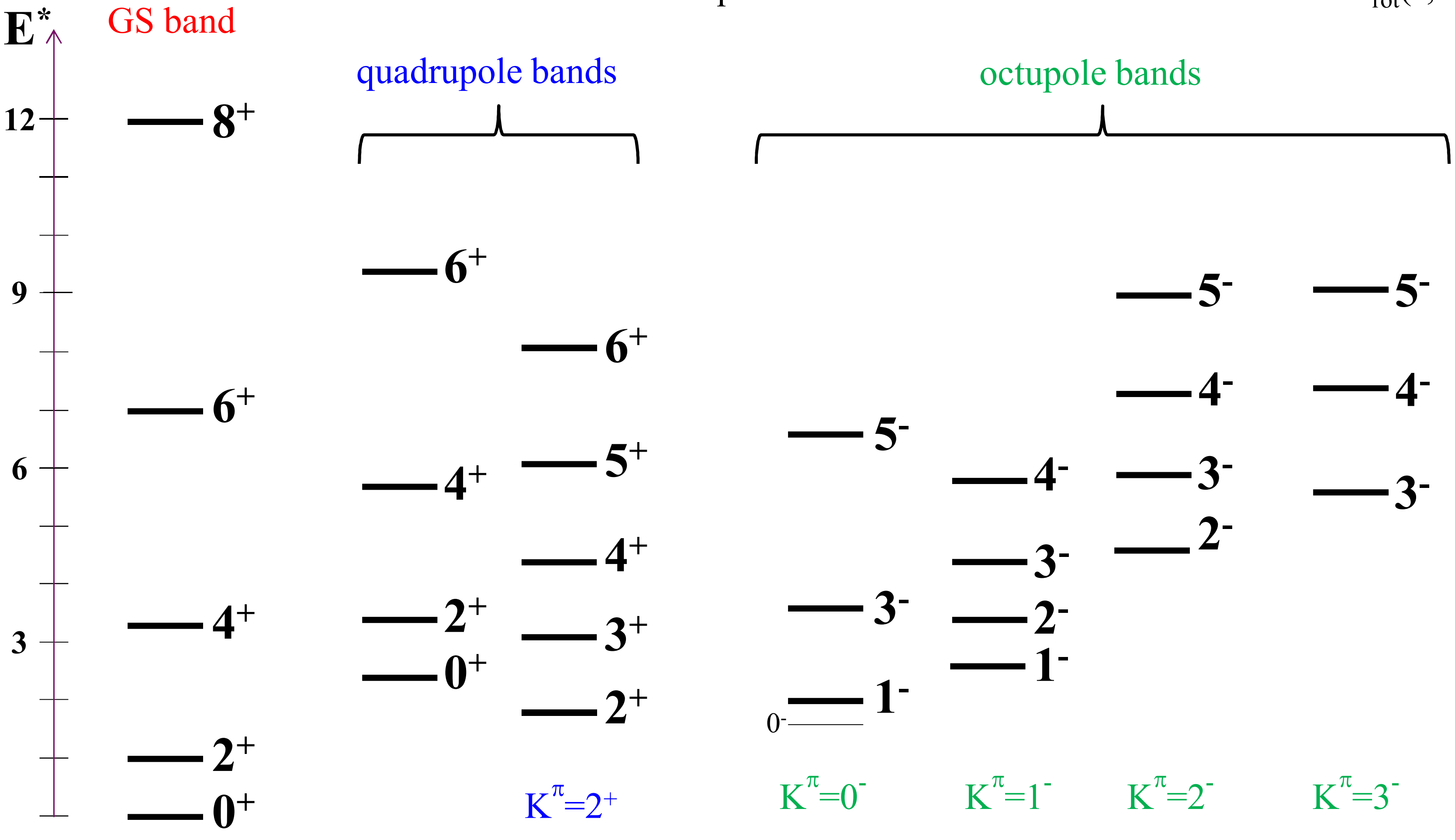
2 coupled phonons

1 phonon

other levels

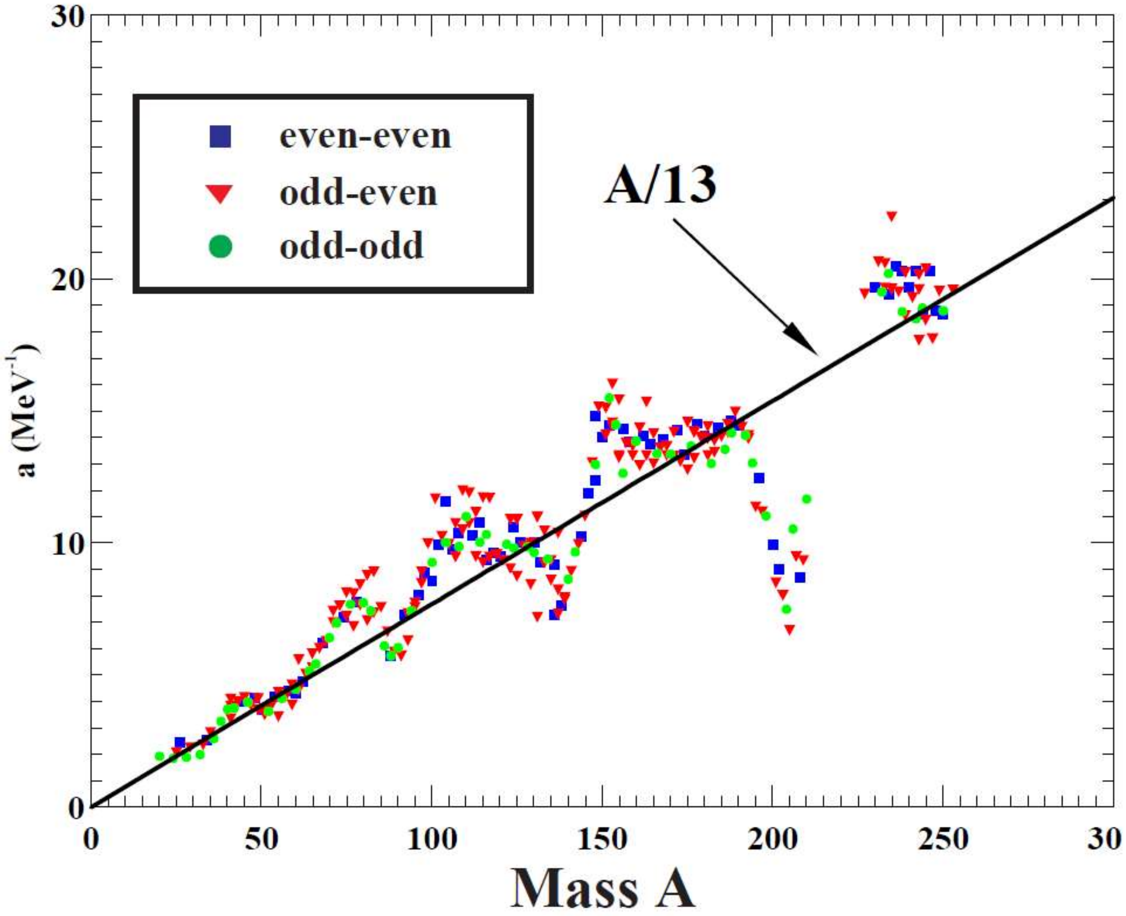
Level densities : collective levels

⇒ General level sequence for a deformed even-even nucleus : $E_{rot}(J,K) = \dfrac{J(J+1) - K^2}{2\,\mathcal{J}_\perp(U,\beta)}$



Level densities : explicit treatment of collective effect

$$\rho(U) = K_{vib}(U) \times K_{rot}(U,\beta) \times \rho_{int}(U)$$

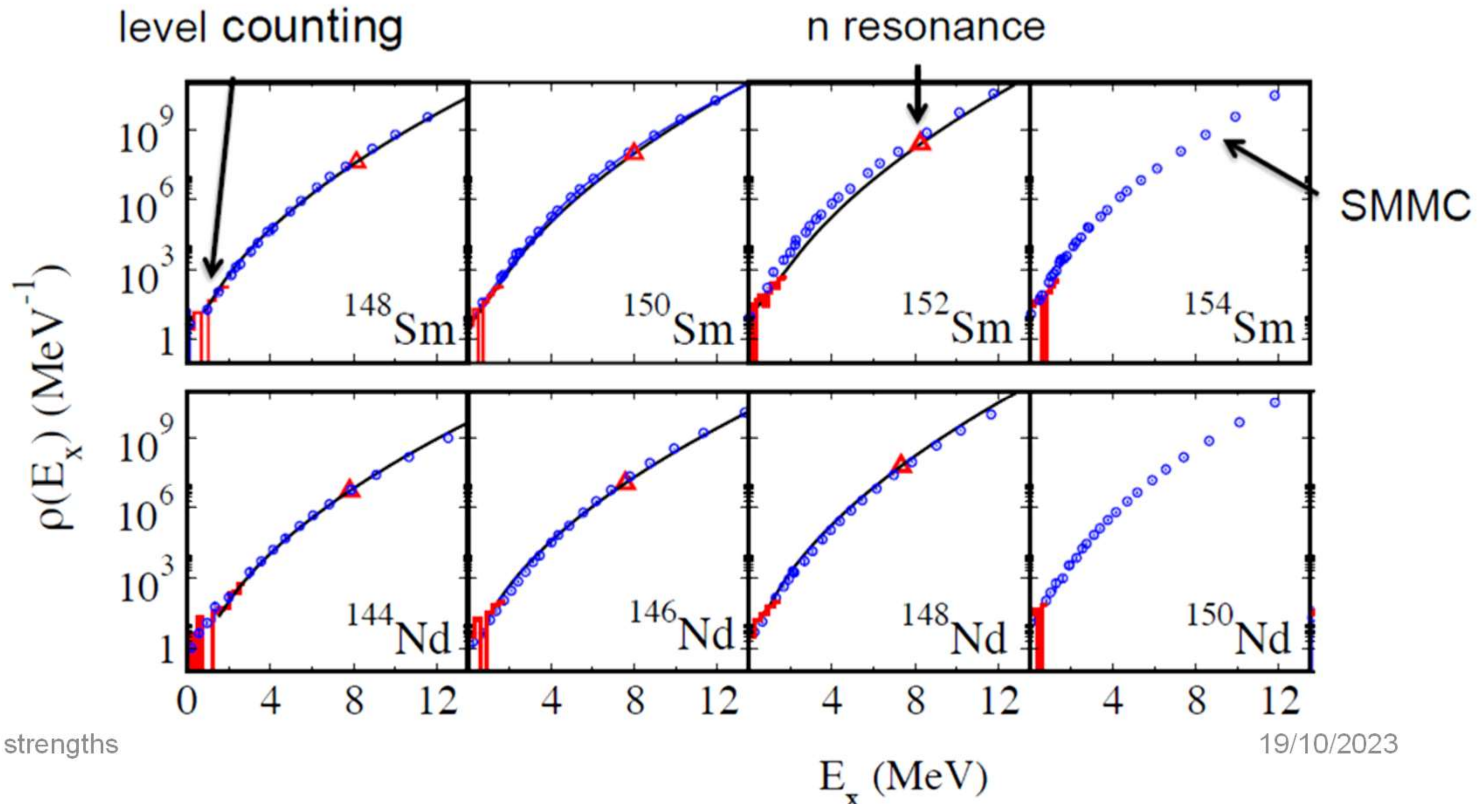


Shell Model Monte Carlo

- **Shell Model Monte Carlo approach**

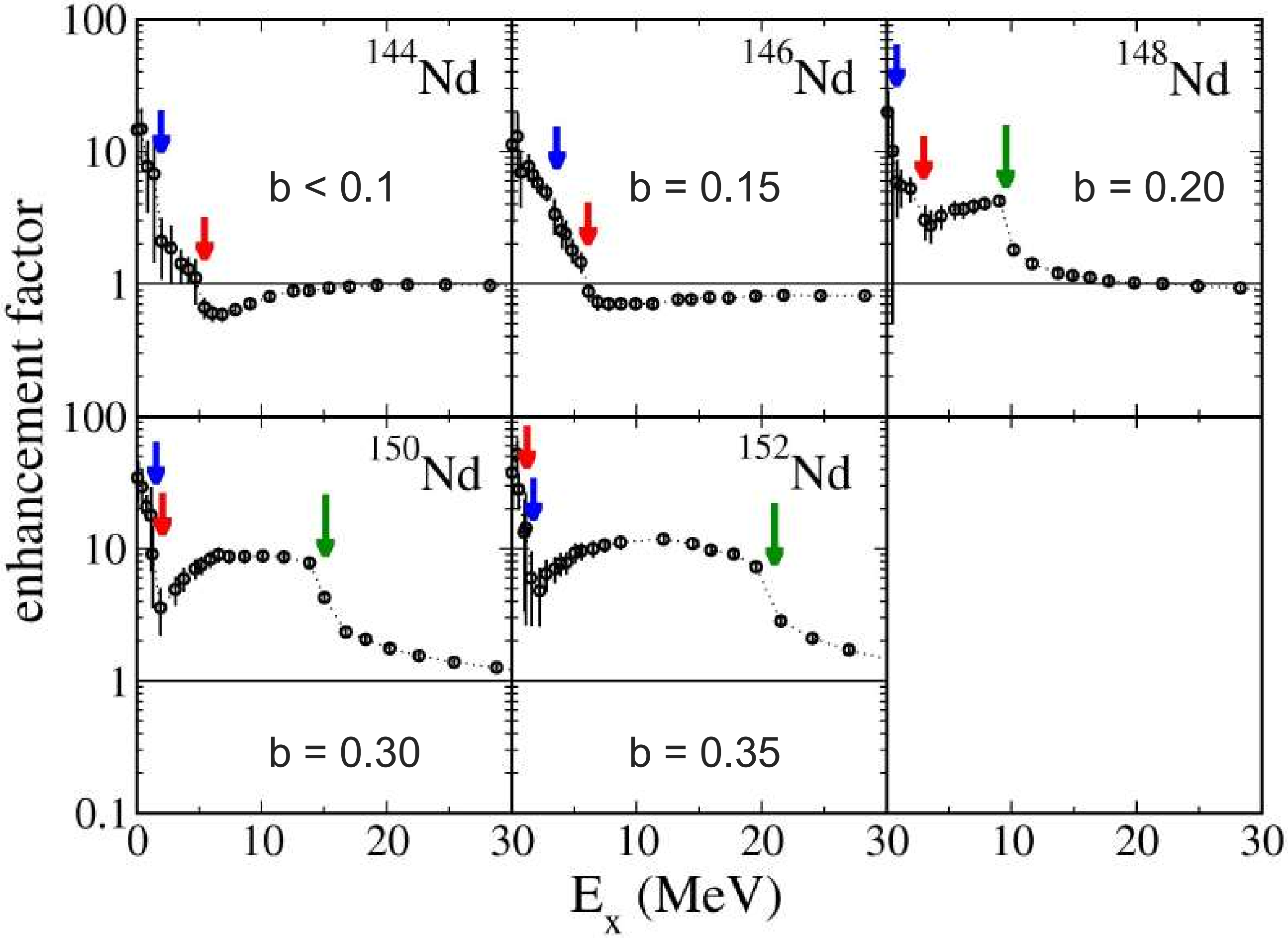
  Agrawal et al., PRC 59 (1999) 3109 + Koonin et al, Phys. Rep. 278 (1997) 1 + Alhassid et al, Phys. Rev. Lett 99 (2007) 162504.

  ⇒ Realistic Hamiltonians but not global
  ⇒ Coherent and incoherent excitations treated on the same footing
  ⇒ Time consuming and not systematically applied



Courtesy Y. Alhassid

Shell Model Monte Carlo (collective effects vanishing)



neutron pair breaking proton pair breaking shape transition

Courtesy Y. Alhassid

HFBCS Statistical approach

Mean Field + Statistical NLD formula

ldmodel 4 in TALYS

Partition function method applied to the discrete SPL scheme predicted by a MF model

Courtesy S. Goriely

$$\omega(U) = \frac{\mathrm{e}^{S(U)}}{(2\pi)^{3/2}\sqrt{D(U)}} \qquad U(T) = E(T) - E(T=0)$$

$$S(T) = 2\sum_{q=n,p}\sum_k \ln\left[1+\exp(-E_q^k/T)\right] + \frac{E_q^k/T}{1+\exp(-E_q^k/T)}$$

$$E(T) = \sum_{q=n,p}\sum_k \varepsilon_q^k\left[1-\frac{\varepsilon_q^k-\lambda_q}{E_q^k}\tanh(\frac{E_q^k}{2T})\right] - \frac{\Delta_q^2}{G}$$

$$N_q = \sum_k\left[1-\frac{\varepsilon_q^k-\lambda_q}{E_q^k}\tanh(\frac{E_q^k}{2T})\right]$$

$$\frac{2}{G_q} = \sum_k \frac{1}{E_q^k}\tanh(\frac{E_q^k}{2T})$$

$$\sigma^2(T) = \frac{1}{2}\sum_{q=n,p}\sum_k \omega_q^{k^2}\ \mathrm{sech}^2(\frac{E_q^k}{2T})$$

HFBCS Statistical approach

Mean Field + Statistical NLD formula

ldmodel 4 in TALYS

$$\rho_{sph}(U,J) = \frac{2J+1}{2\sqrt{2\pi}\sigma^3} e^{-\frac{J(J+1)}{2\sigma^2}} \omega(U)$$

$$\rho_{def}(U,J) = \frac{1}{2}\sum_{K=-J}^{J} \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\left[\frac{J(J+1)}{2\sigma_\perp^2} + \frac{K^2}{2}\left(\frac{1}{\sigma^2} - \frac{1}{\sigma_\perp^2}\right)\right]} \omega(U)$$

Courtesy S. Goriely

The inclusion of rotational bands may increase the NLD by a factor of 10-70

→ Strong impact and sensitivity to the GS deformation of the nucleus !

→ deformation is known to disappear with increasing excitation

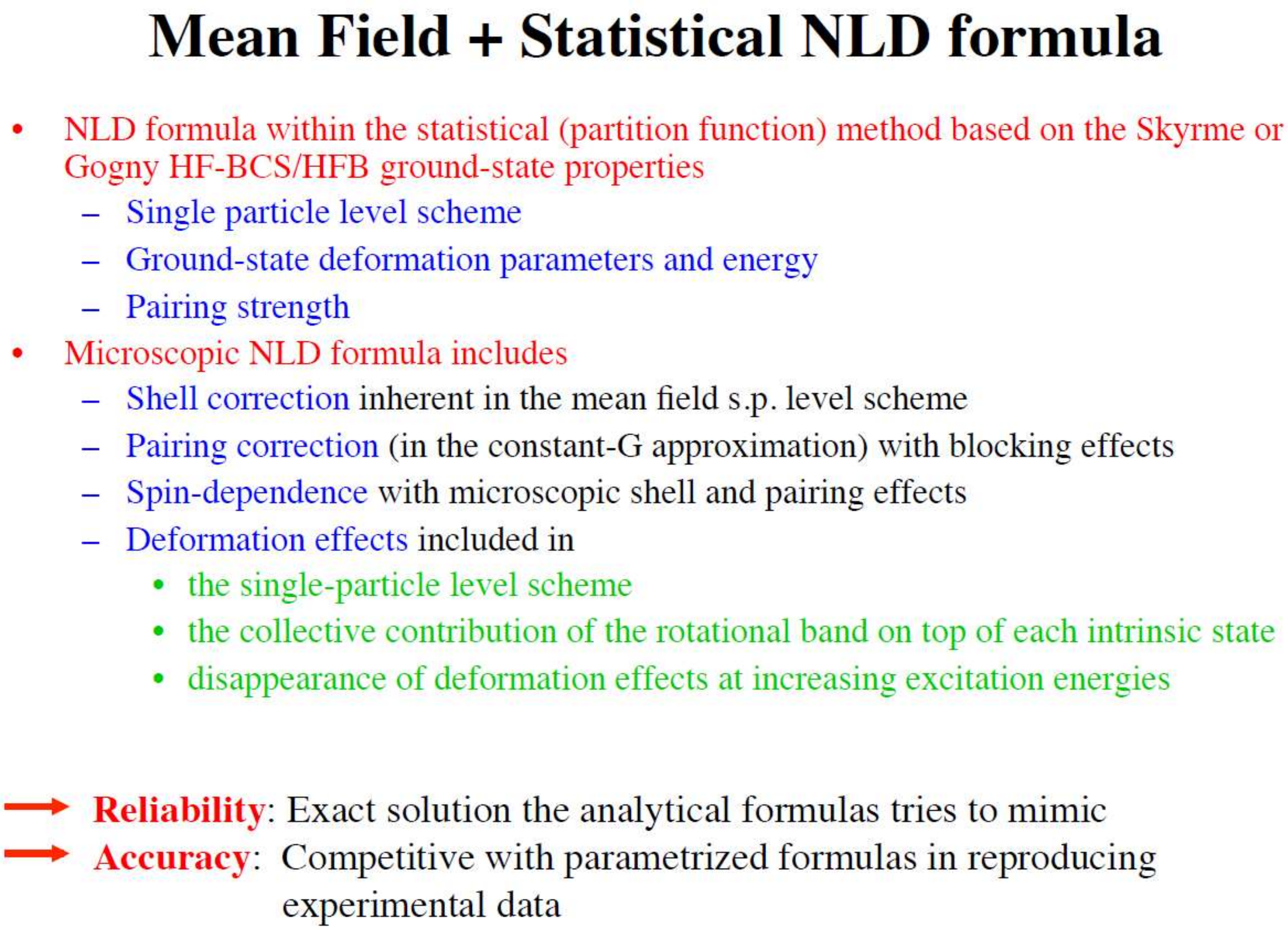
$$\rho(U,J) = \left[1 - f_{dam}(U)\right]\rho_{sph}(U,J) + f_{dam}(U)\ \rho_{def}(U,J)$$

providing a smooth deformed (f_{dam}=1) to spherical (f_{dam}=0) transition, e.g

$$f_{dam}(U) = \frac{1}{1+e^{(U-E_{def})/d_u}} \left[1 - \frac{1}{1+e^{(\beta_2-\beta^*)/d_\beta}}\right]$$

HFBCS Statistical approach

ldmodel 4 in TALYS



Mean Field + Statistical NLD formula

- NLD formula within the statistical (partition function) method based on the Skyrme or Gogny HF-BCS/HFB ground-state properties
  - Single particle level scheme
  - Ground-state deformation parameters and energy
  - Pairing strength
- Microscopic NLD formula includes
  - Shell correction inherent in the mean field s.p. level scheme
  - Pairing correction (in the constant-G approximation) with blocking effects
  - Spin-dependence with microscopic shell and pairing effects
  - Deformation effects included in
    - the single-particle level scheme
    - the collective contribution of the rotational band on top of each intrinsic state
    - disappearance of deformation effects at increasing excitation energies

→ **Reliability**: Exact solution the analytical formulas tries to mimic

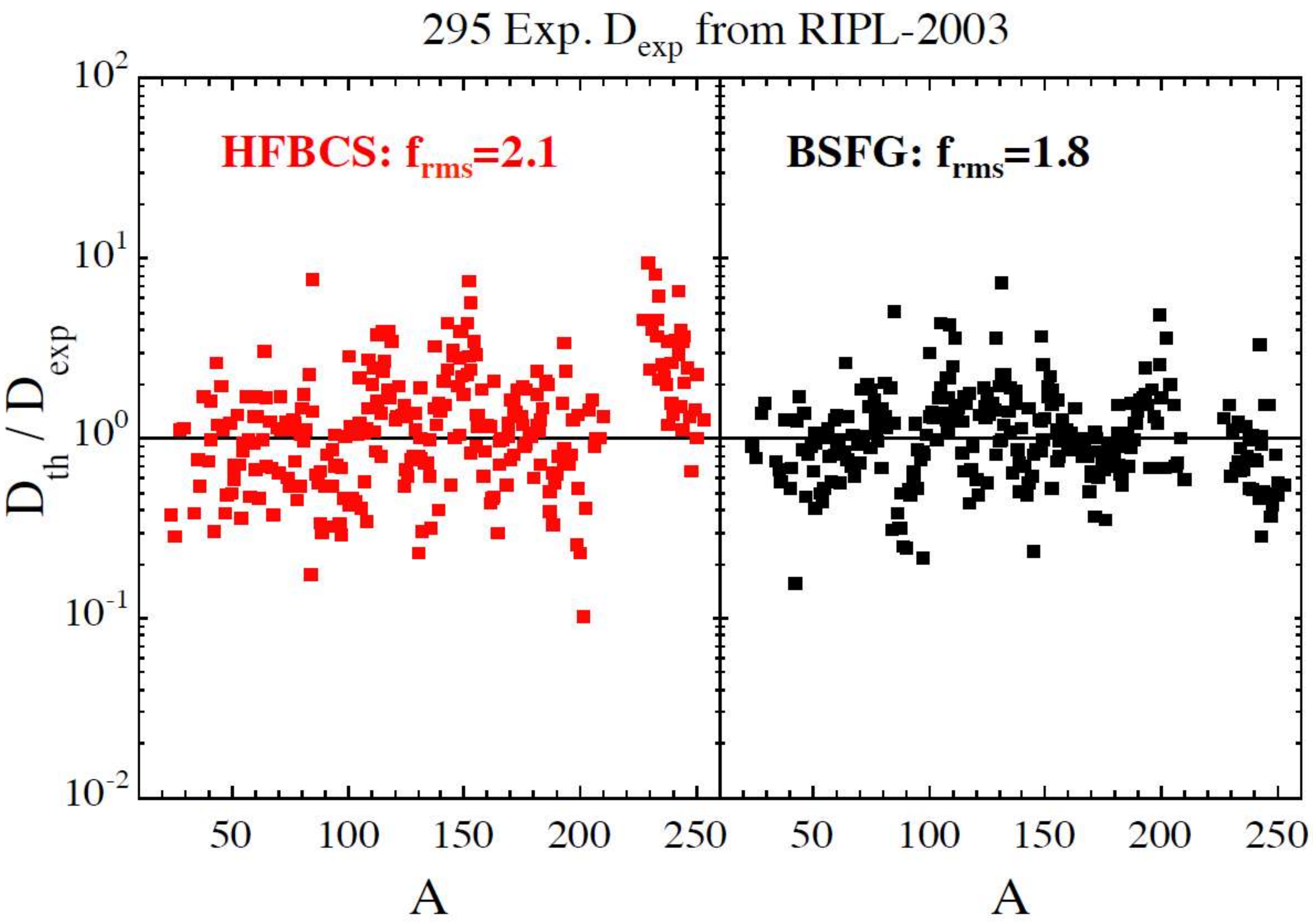
→ **Accuracy**: Competitive with parametrized formulas in reproducing experimental data

Courtesy S. Goriely

HFBCS Statistical approach

Comparison with experimental neutron resonance spacings

Idmodel 4 in TALYS

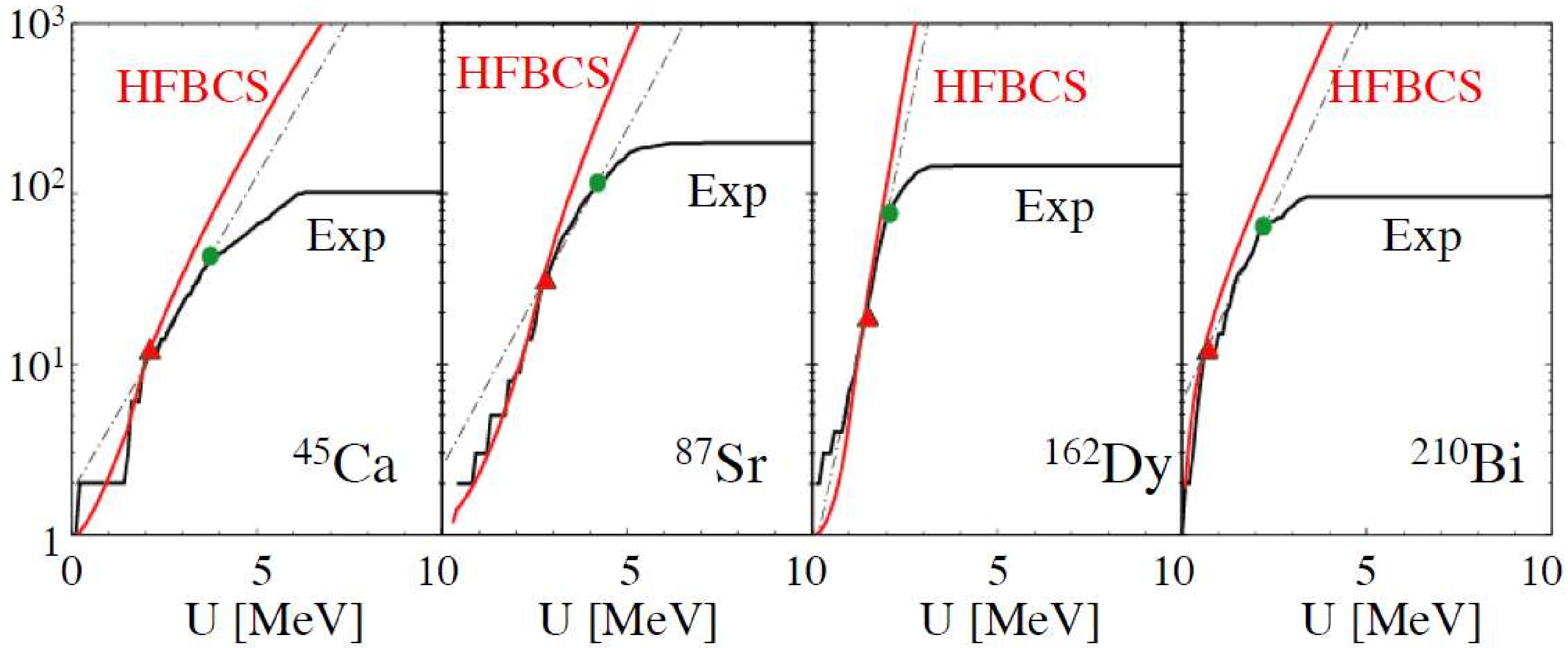


Courtesy S. Goriely

HFBCS Statistical approach

ldmodel 4 in TALYS

Comparison with experimental low-lying levels

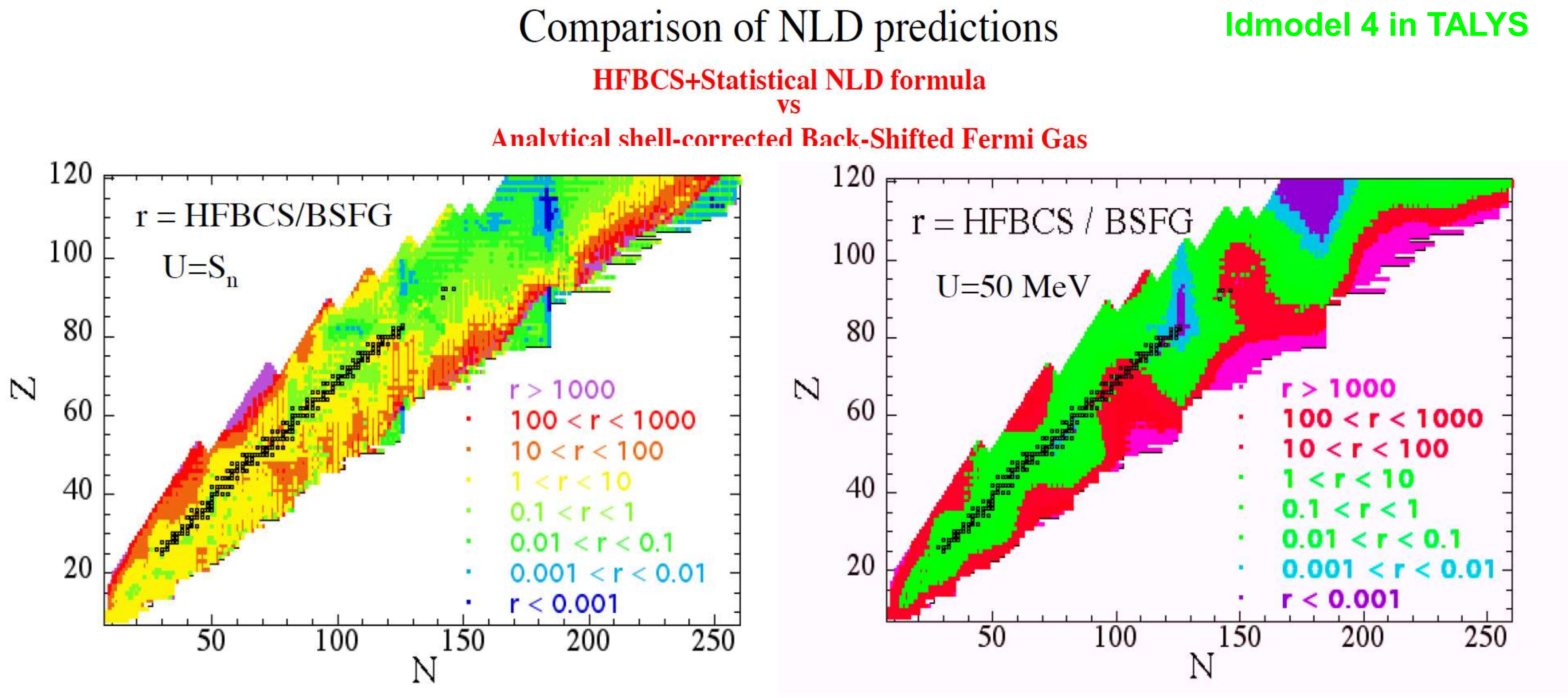


Courtesy S. Goriely

NLD provided for all ~8000 8 ≤ Z ≤ 110 nuclei in table format

HFBCS Statistical approach

ldmodel 4 in TALYS

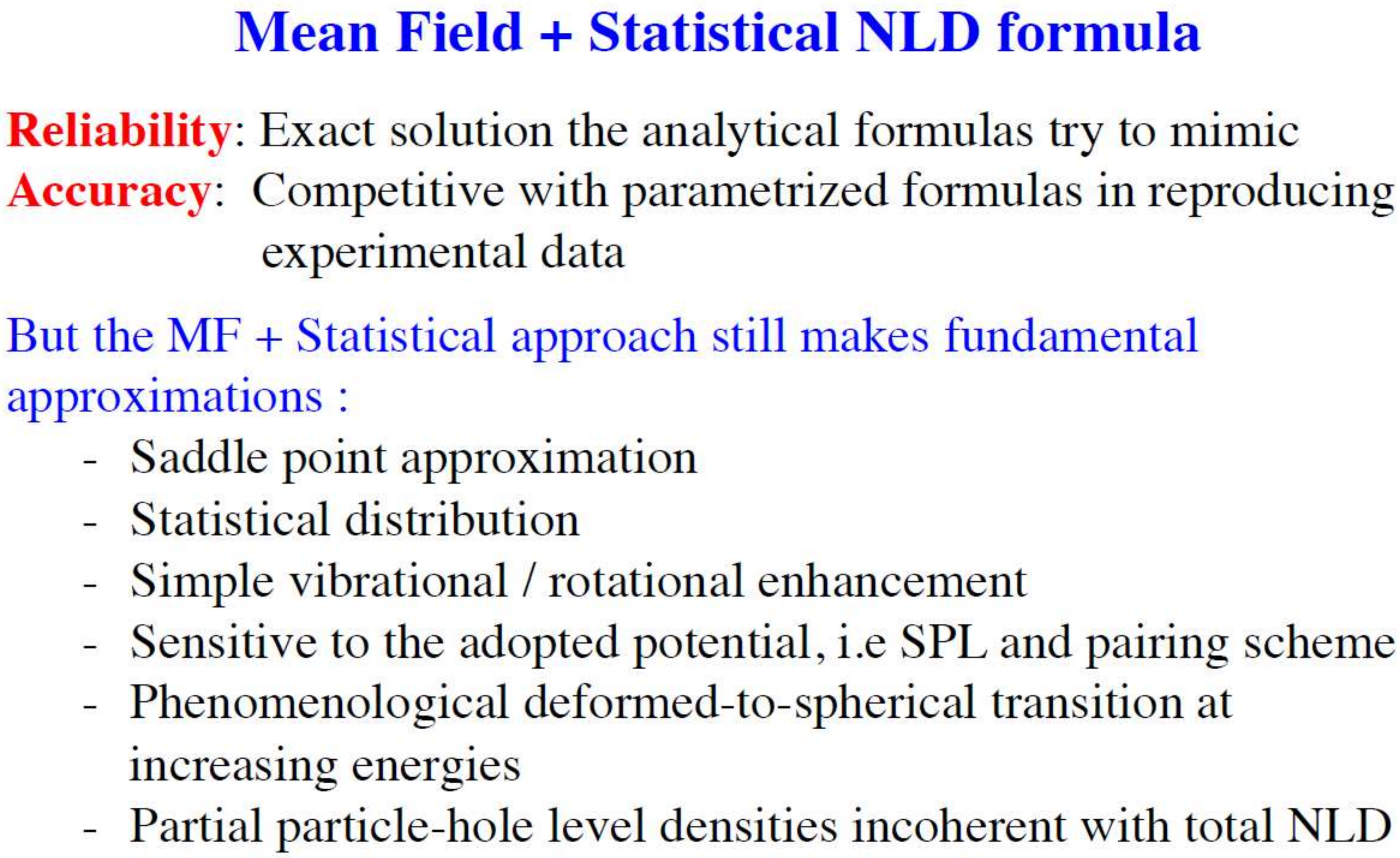

Comparison of NLD predictions

HFBCS+Statistical NLD formula
vs
Analytical shell-corrected Back-Shifted Fermi Gas

Courtesy S. Goriely

HFBCS Statistical approach : summary

Idmodel 4 in TALYS



Mean Field + Statistical NLD formula

Reliability: Exact solution the analytical formulas try to mimic
Accuracy: Competitive with parametrized formulas in reproducing experimental data

But the MF + Statistical approach still makes fundamental approximations :

- Saddle point approximation
- Statistical distribution
- Simple vibrational / rotational enhancement
- Sensitive to the adopted potential, i.e SPL and pairing scheme
- Phenomenological deformed-to-spherical transition at increasing energies
- Partial particle-hole level densities incoherent with total NLD

Courtesy S. Goriely

Level densities : combinatorial approach

- **Combinatorial approach**

  S. Hilaire & S. Goriely, NPA 779 (2006) 63 & PRC 78 (2008) 064307.

  ⇒ Direct level counting
  ⇒ Total (compound nucleus) and partial (pre-equilibrium) level densities
  ⇒ Non statistical effects (spin and parity in particular)
  ⇒ Global (tables)

Level densities : combinatorial approach

See PRC 78 (2008) 064307 for details

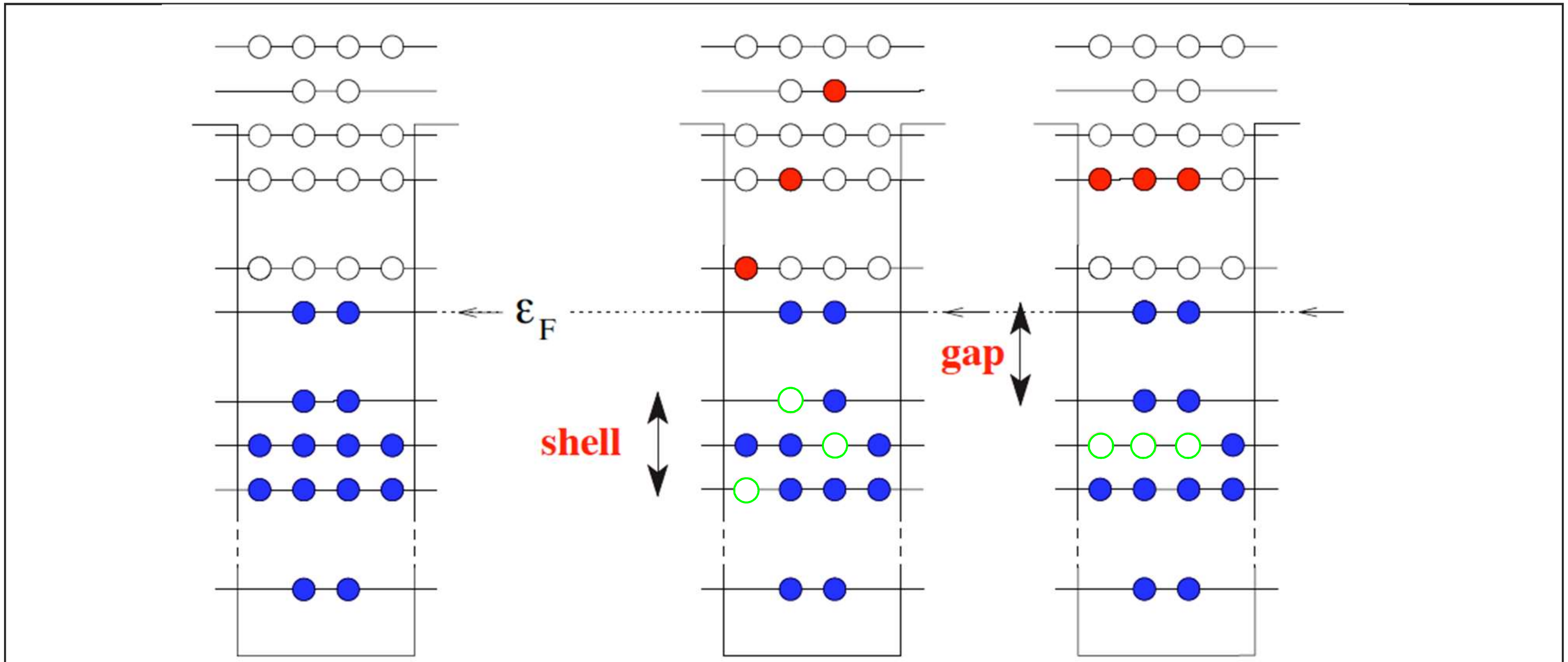
ldmodel 5 in TALYS

- **HFB + effective nucleon-nucleon interaction ⇒ single particle level schemes**
- **Combinatorial calculation ⇒ intrinsic p-h and total state densities ω_{ph} (U, K, π)**

Level densities : combinatorial approach

See PRC 78 (2008) 064307 for details

ldmodel 5 in TALYS



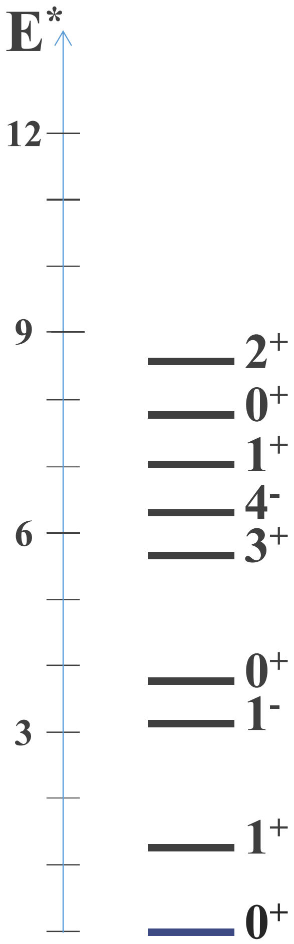
Ground state

Excited States

(3 particules - 3 trous)

Level densities : combinatorial approach

ldmodel 5 in TALYS



Level densities : combinatorial approach

See PRC 78 (2008) 064307 for details

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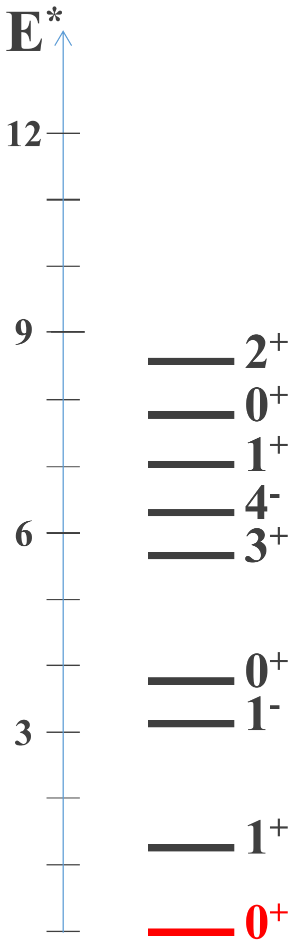
  1) folding of intrinsic states and vibrational states : $\omega = \omega_{ph} * \omega_{vib}$

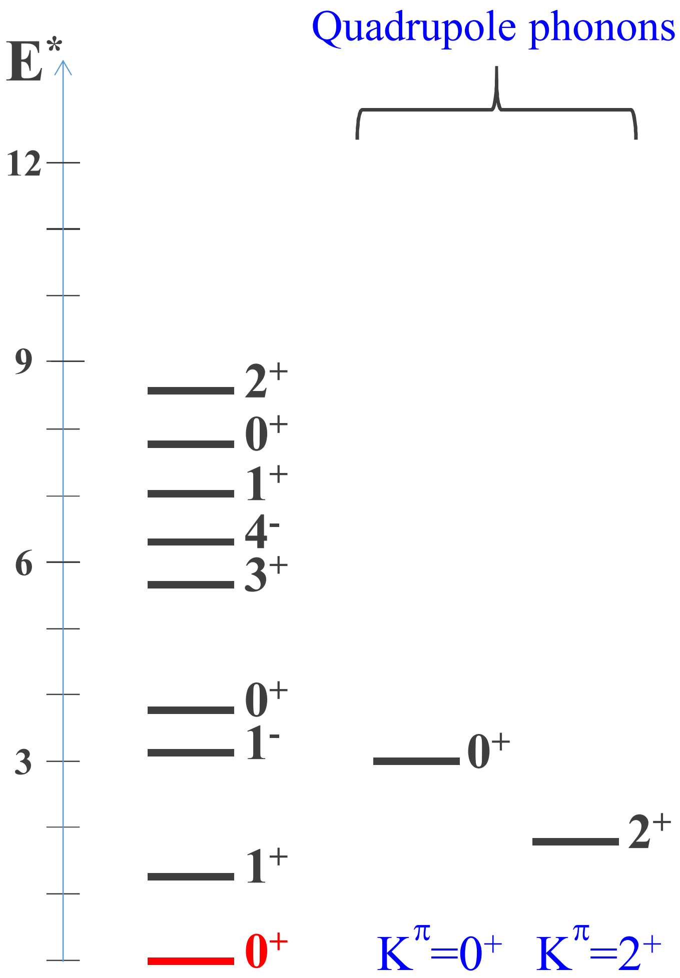
Level densities : combinatorial approach

ldmodel 5 in TALYS



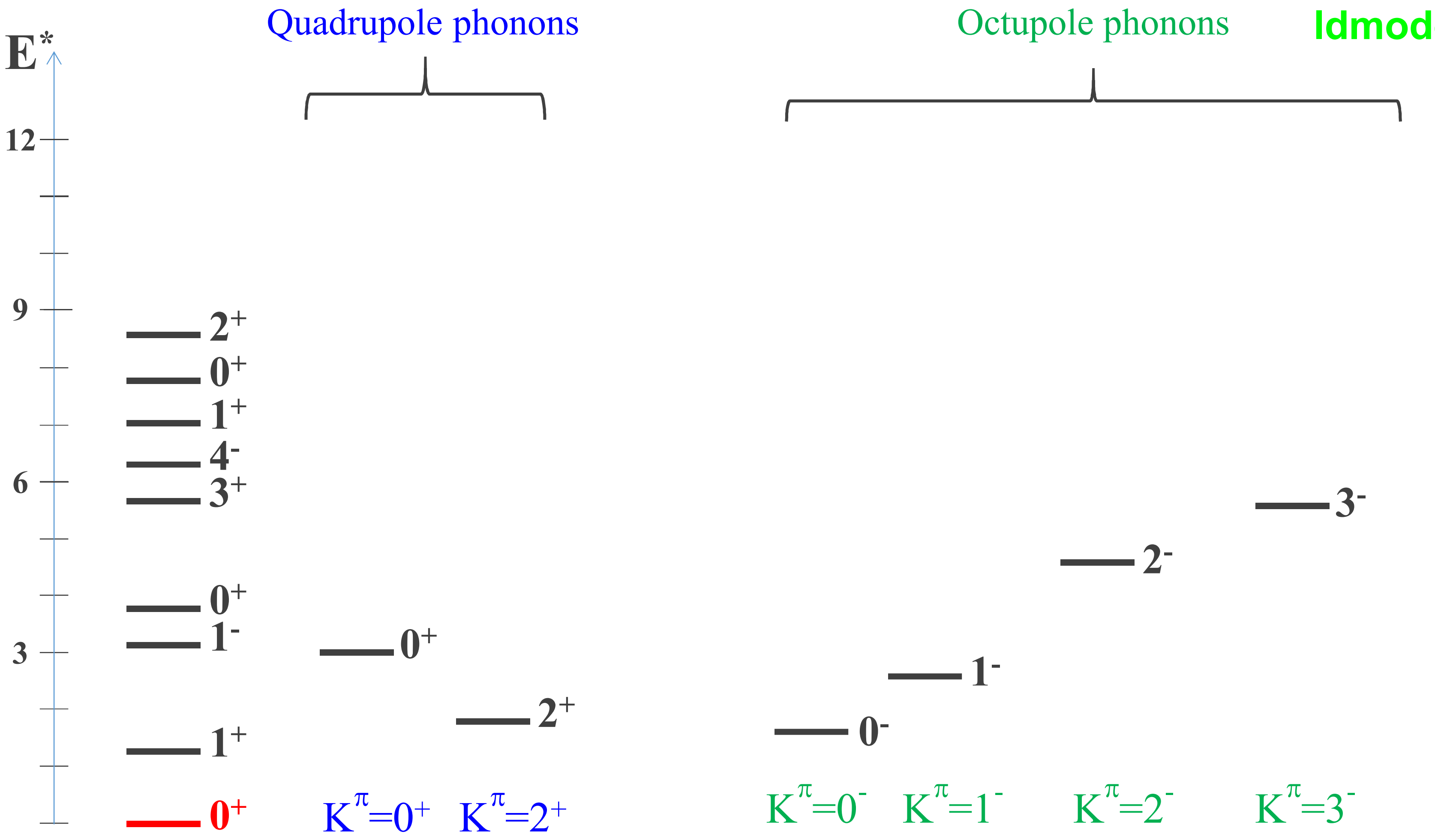
Level densities : combinatorial approach

Idmodel 5 in TALYS



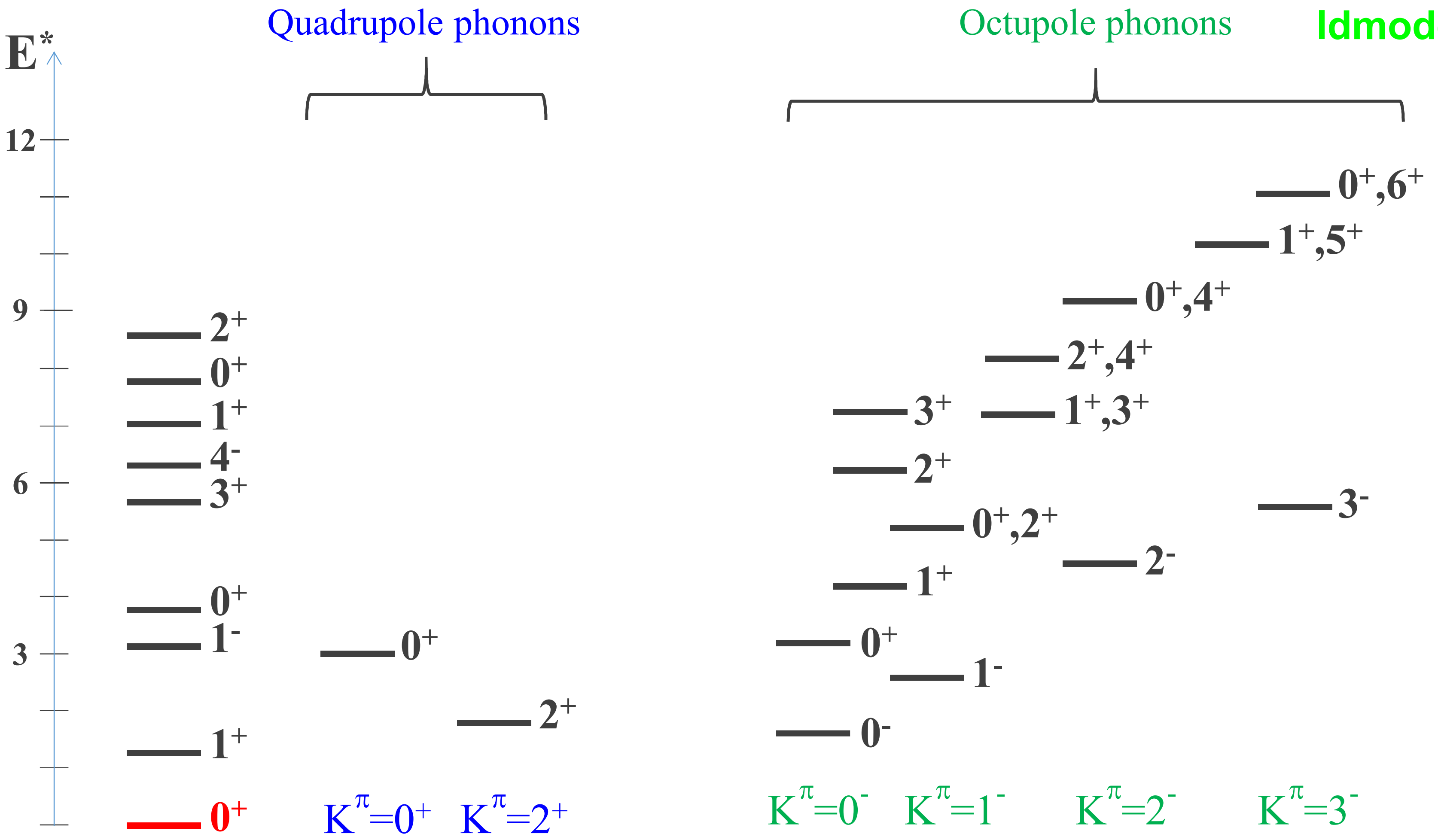
Level densities : combinatorial approach

ldmodel 5 in TALYS



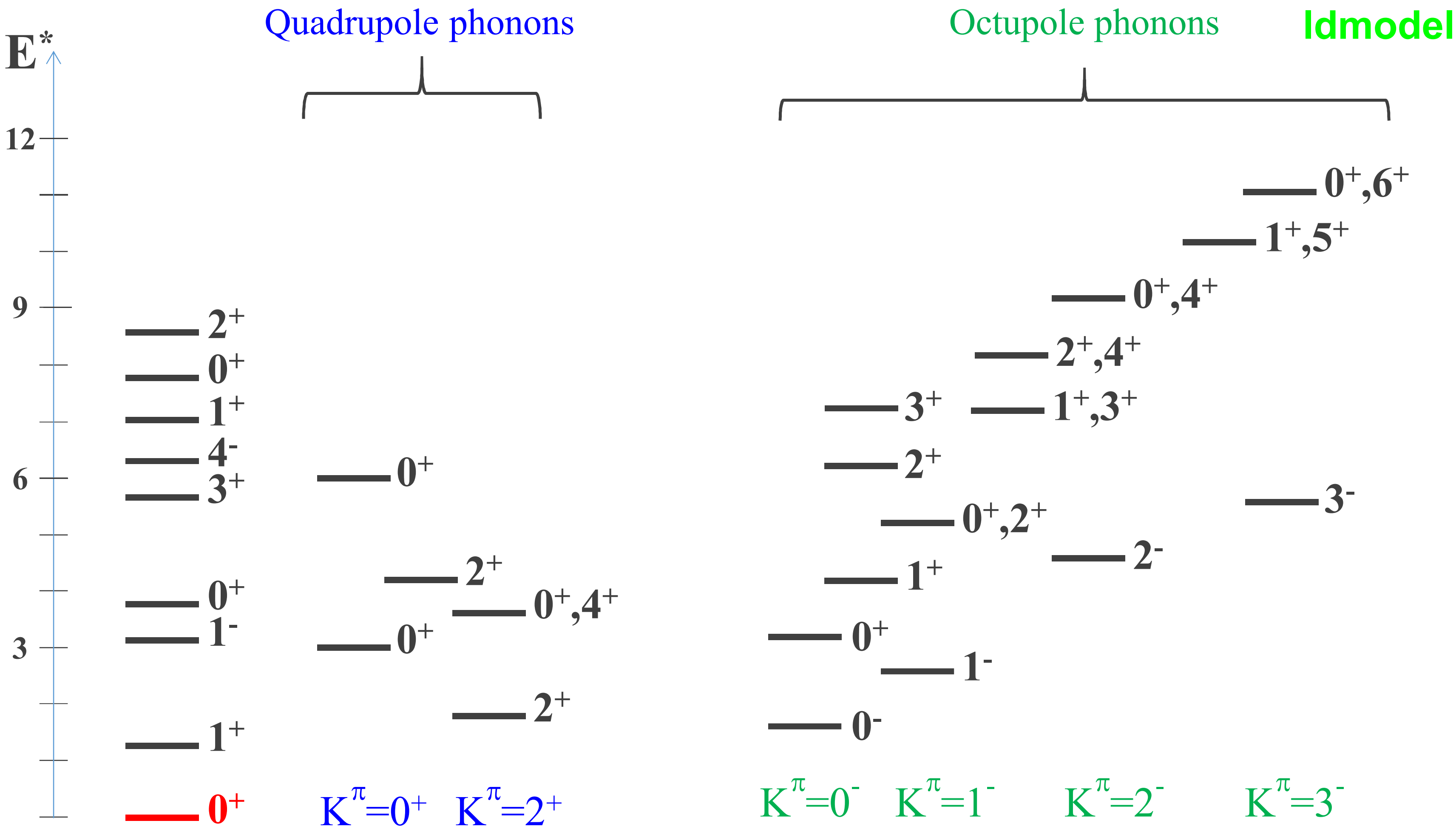
Level densities : combinatorial approach

ldmodel 5 in TALYS



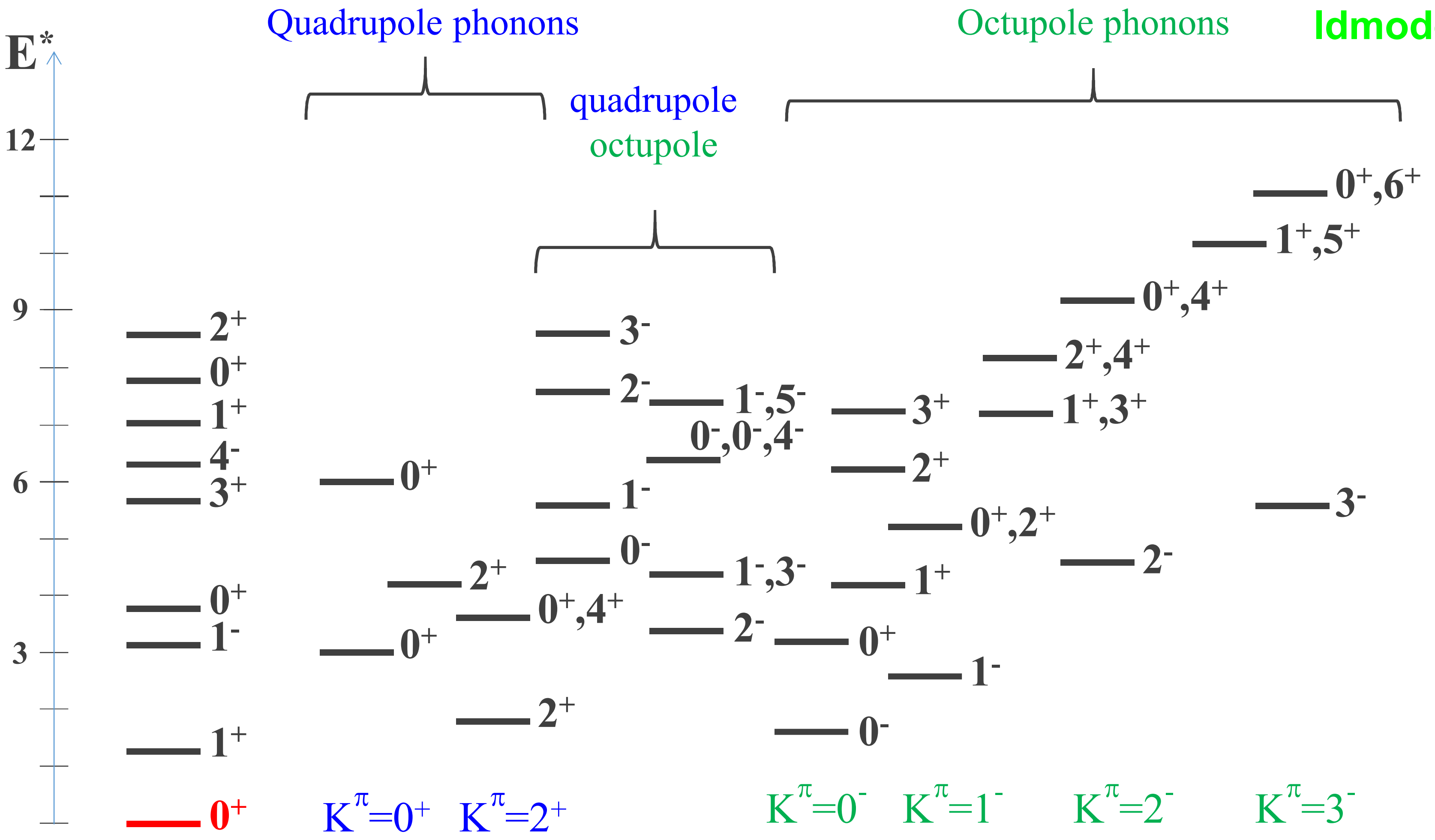
Level densities : combinatorial approach

ldmodel 5 in TALYS



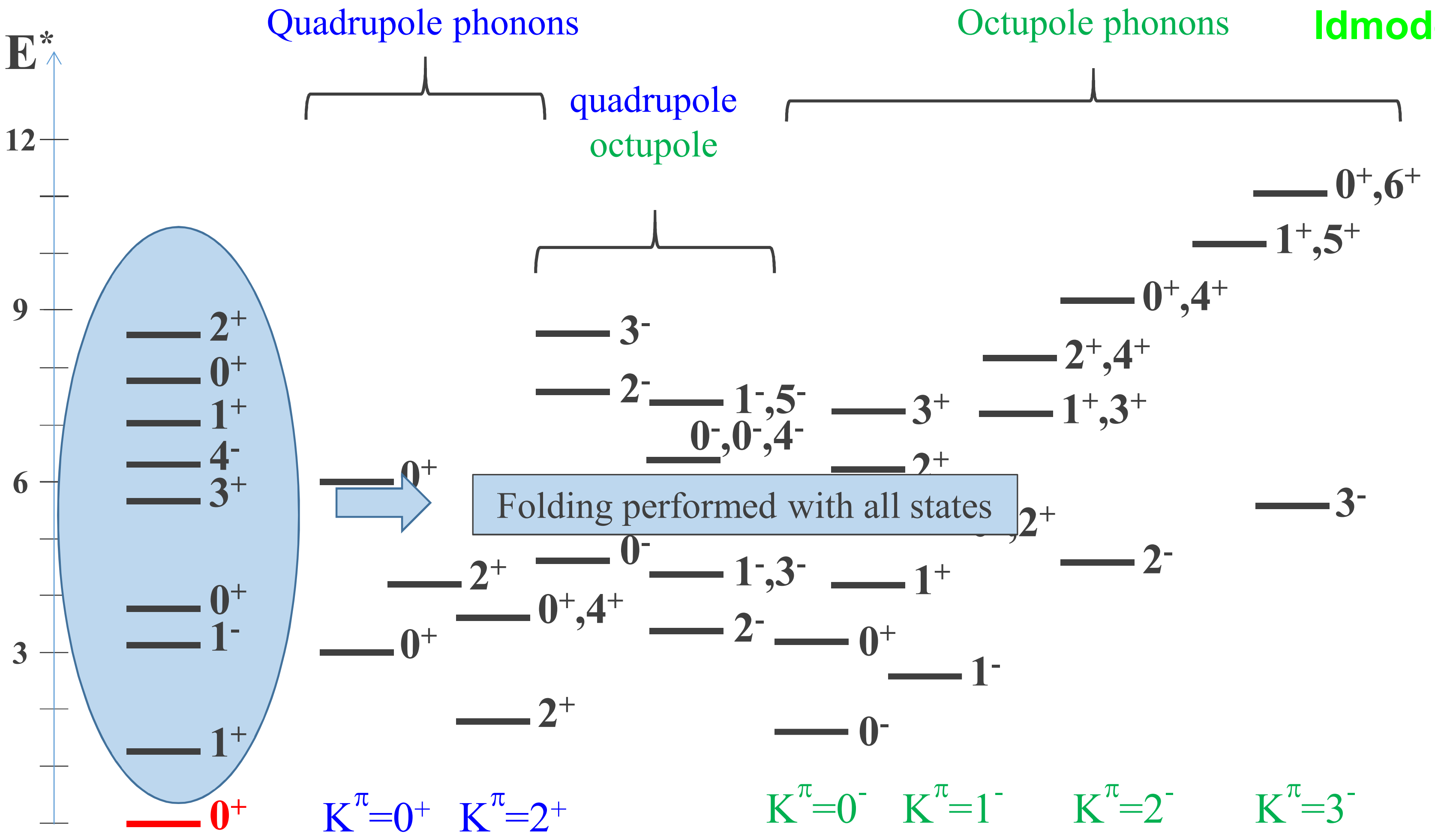
Level densities : combinatorial approach

Idmodel 5 in TALYS



Level densities : combinatorial approach

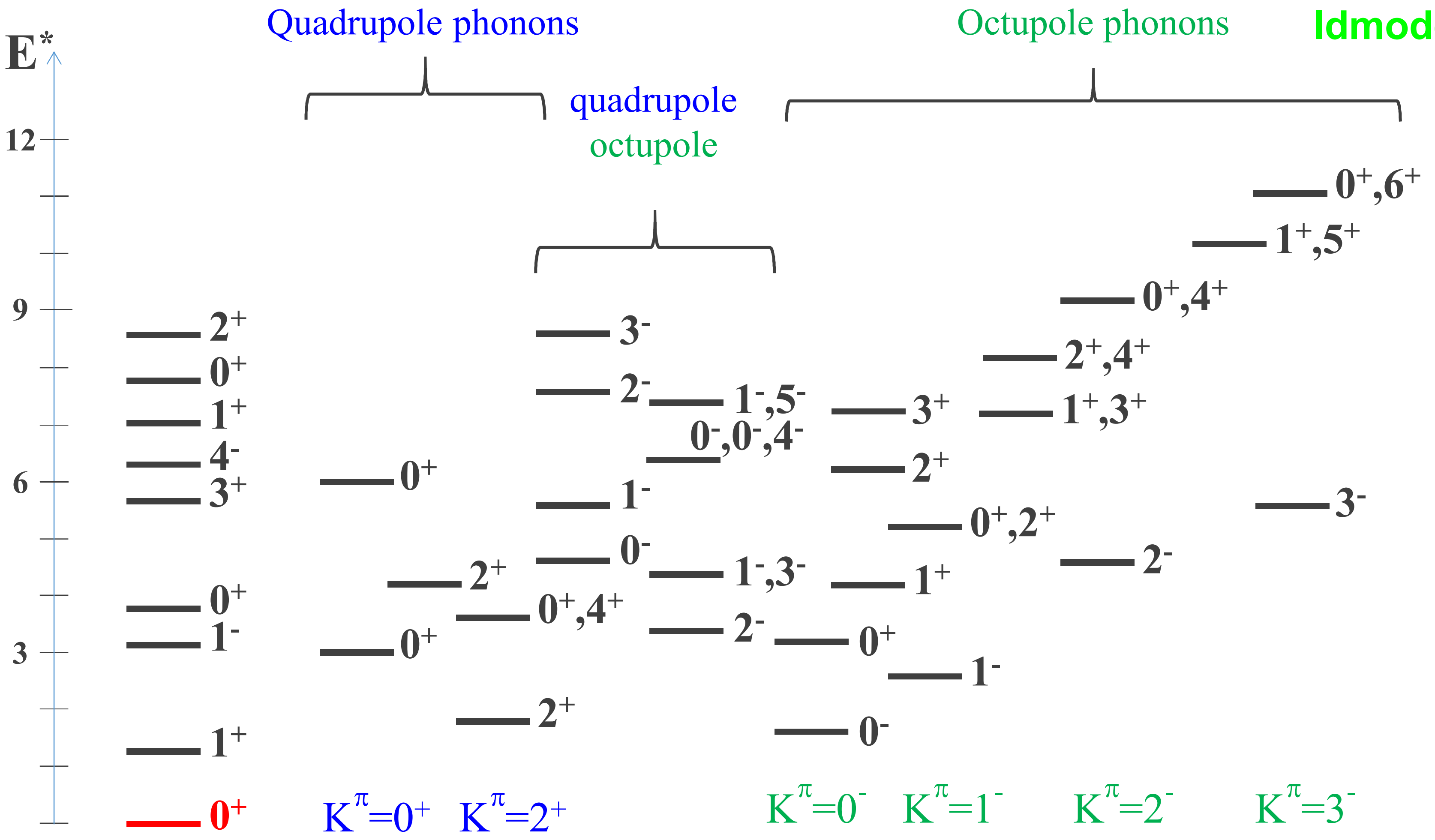
ldmodel 5 in TALYS



Folding performed with all states

Level densities : combinatorial approach

ldmodel 5 in TALYS



Level densities : combinatorial approach

See PRC 78 (2008) 064307 for details

ldmodel 5 in TALYS

- HFB + effective nucleon-nucleon interaction ⇒ single particle level schemes
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2) construction of rotational bands for deformed nuclei

$$\rho(U, J, \pi) = \sum_{K} \omega\ (U - E^{JK}_{rot}, K, \pi)$$

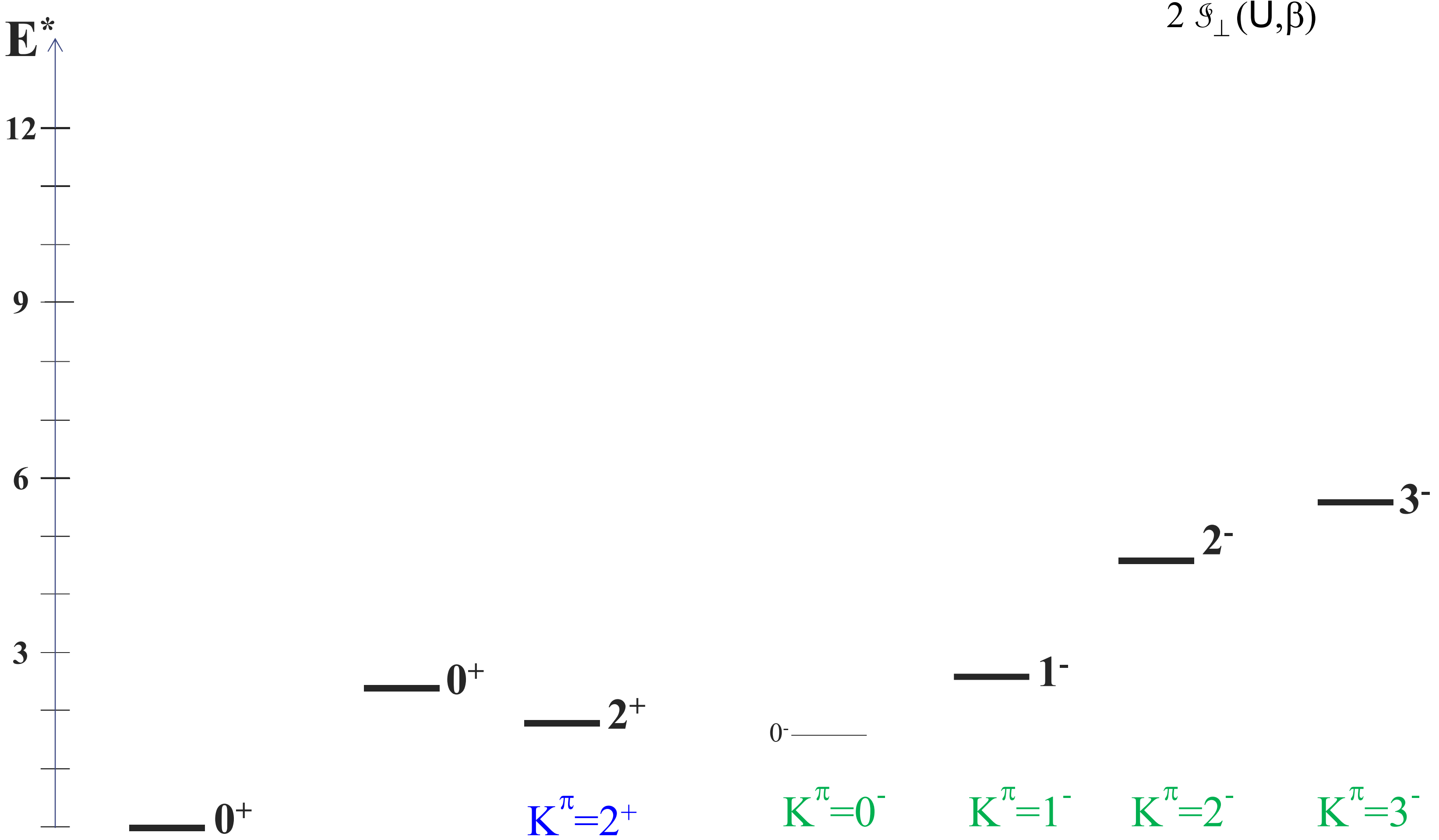
trivial relation for spherical nuclei

$$\rho(U, J, \pi) = \omega\ (U, K=J, \pi) - \omega\ (U, K=J+1, \pi)$$

Level densities : combinatorial approach

Ldmodel 5 in TALYS

⇒ General level sequence for a deformed even-even nucleus : $E_{rot}(J,K) = \dfrac{J(J+1) - K^2}{2\,\mathcal{J}_\perp(U,\beta)}$



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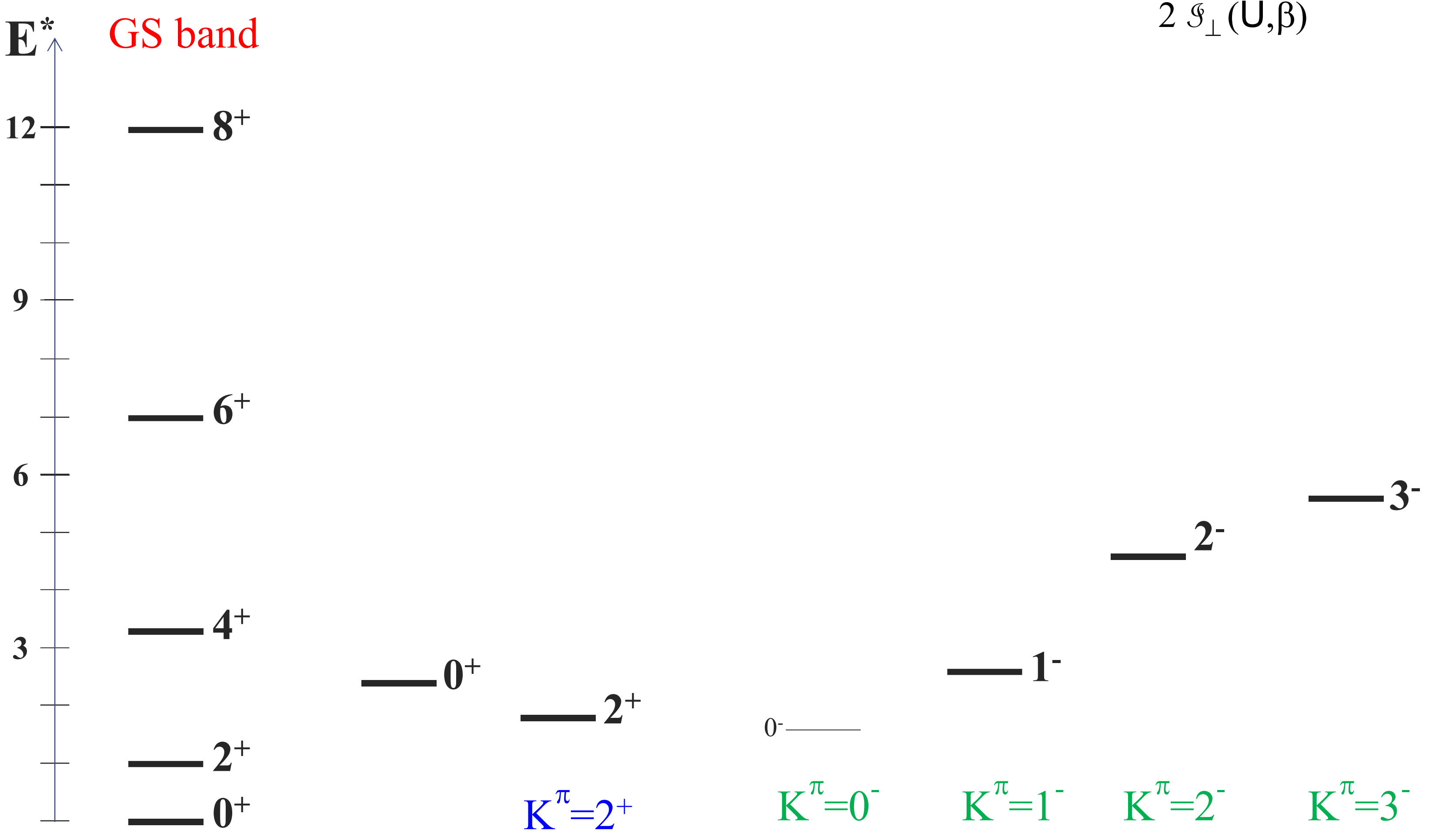
ldmodel 5 in TALYS



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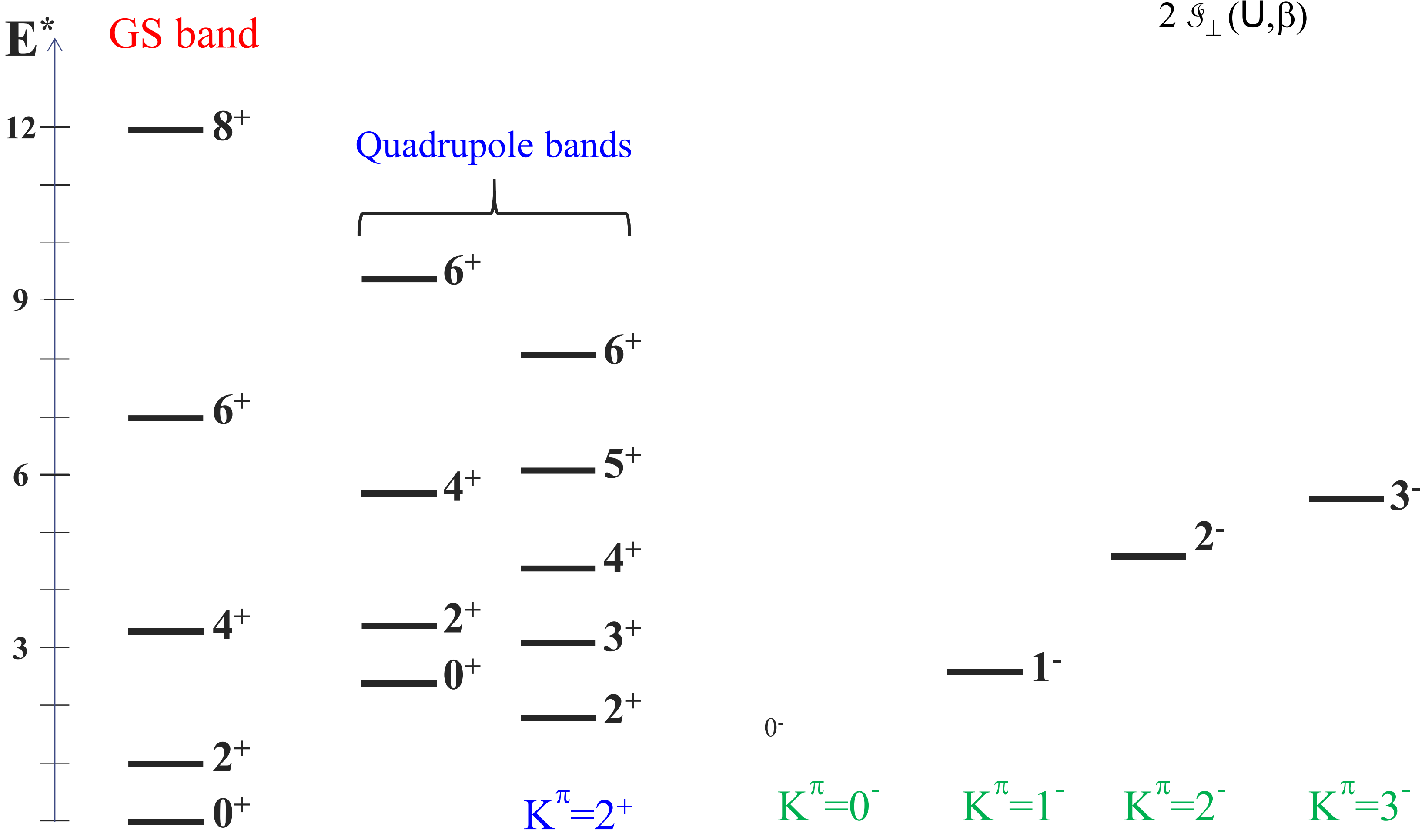
ldmodel 5 in TALYS



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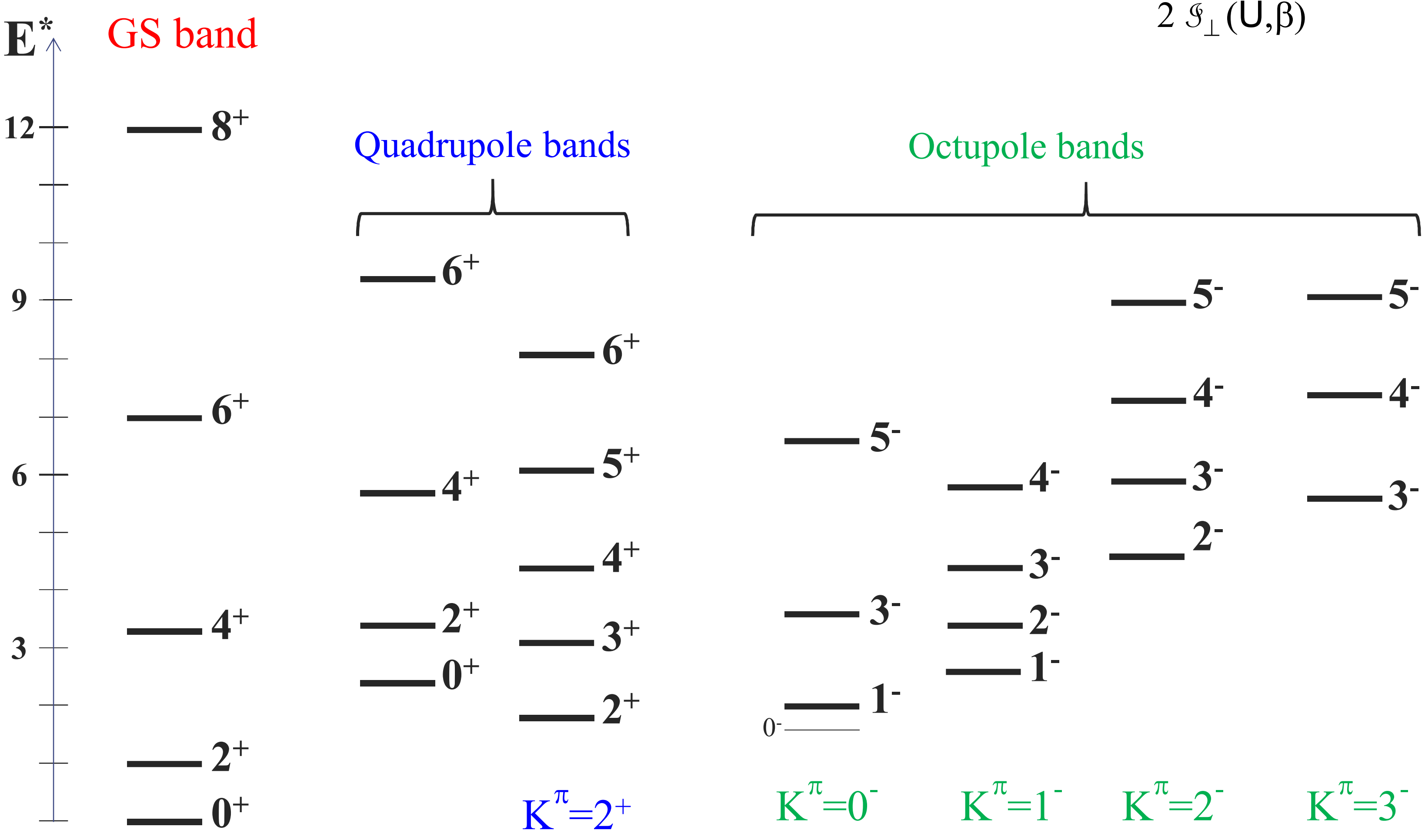
ldmodel 5 in TALYS



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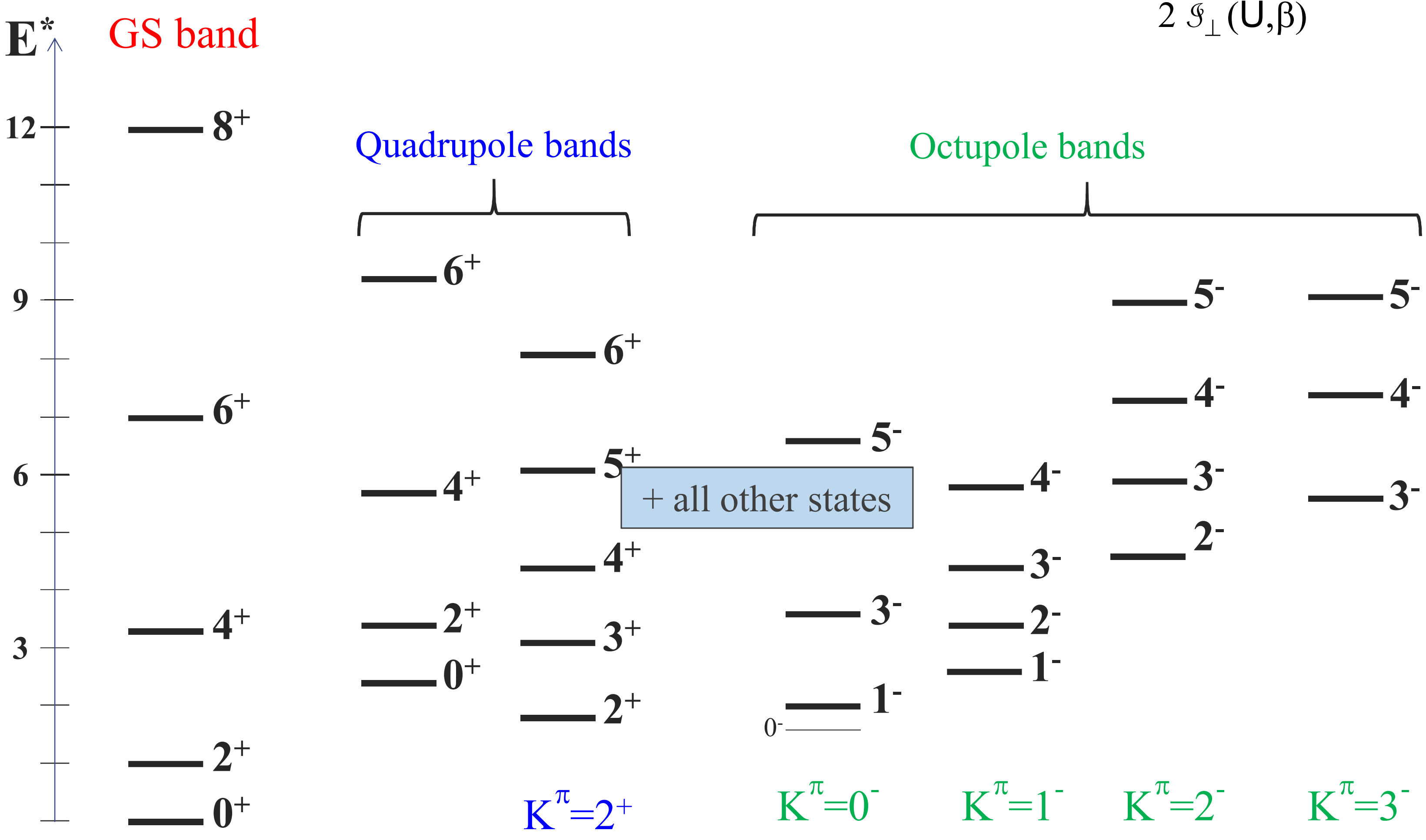
ldmodel 5 in TALYS



Level densities : combinatorial approach

See PRC 78 (2008) 064307 for details

ldmodel 5 in TALYS

- **HFB + effective nucleon-nucleon interaction ⇒ single particle level schemes**
- **Combinatorial calculation ⇒ intrinsic p-h and total state densities ω_{ph} (U, K, π)**
- **Collective effects ⇒ from state to level densities ρ(U, J, π)**

1) folding of intrinsic states and vibrational states : $\omega = \omega_{ph} * \omega_{vib}$

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$$\rho(U, J, \pi) = \sum_{K} \omega\,(U - E^{JK}_{rot}, K, \pi)$$

trivial relation for spherical nuclei

$$\rho(U, J, \pi) = \omega\,(U, K{=}J, \pi) - \omega\,(U, K{=}J{+}1, \pi)$$

- **Phenomenological mixing of spherical and deformed level densities for small deformations**

Level densities : combinatorial approach + temperature

See PRC 78 (2008) 064307 and PRC 86 (2012) 064317 for details

ldmodel 6 in TALYS

- **TDHFB + effective nucleon-nucleon interaction**

  ⇒ temperature (energy) dependent single particle level schemes

- Combinatorial calculation ⇒ intrinsic p-h and total state densities ω_{ph} (U, K, π)

- Collective effects ⇒ from state to level densities ρ(U, J, π)

1) folding of intrinsic states and vibrational states : $\omega = \omega_{ph} * \omega_{vib}$

2) construction of rotational bands for deformed nuclei

$$\rho(U, J, \pi) = \sum_{K} \omega\left(U - \boxed{E_{rot}^{JK}}, K, \pi\right)$$

Predicted within the same theoretical framework (coherence)

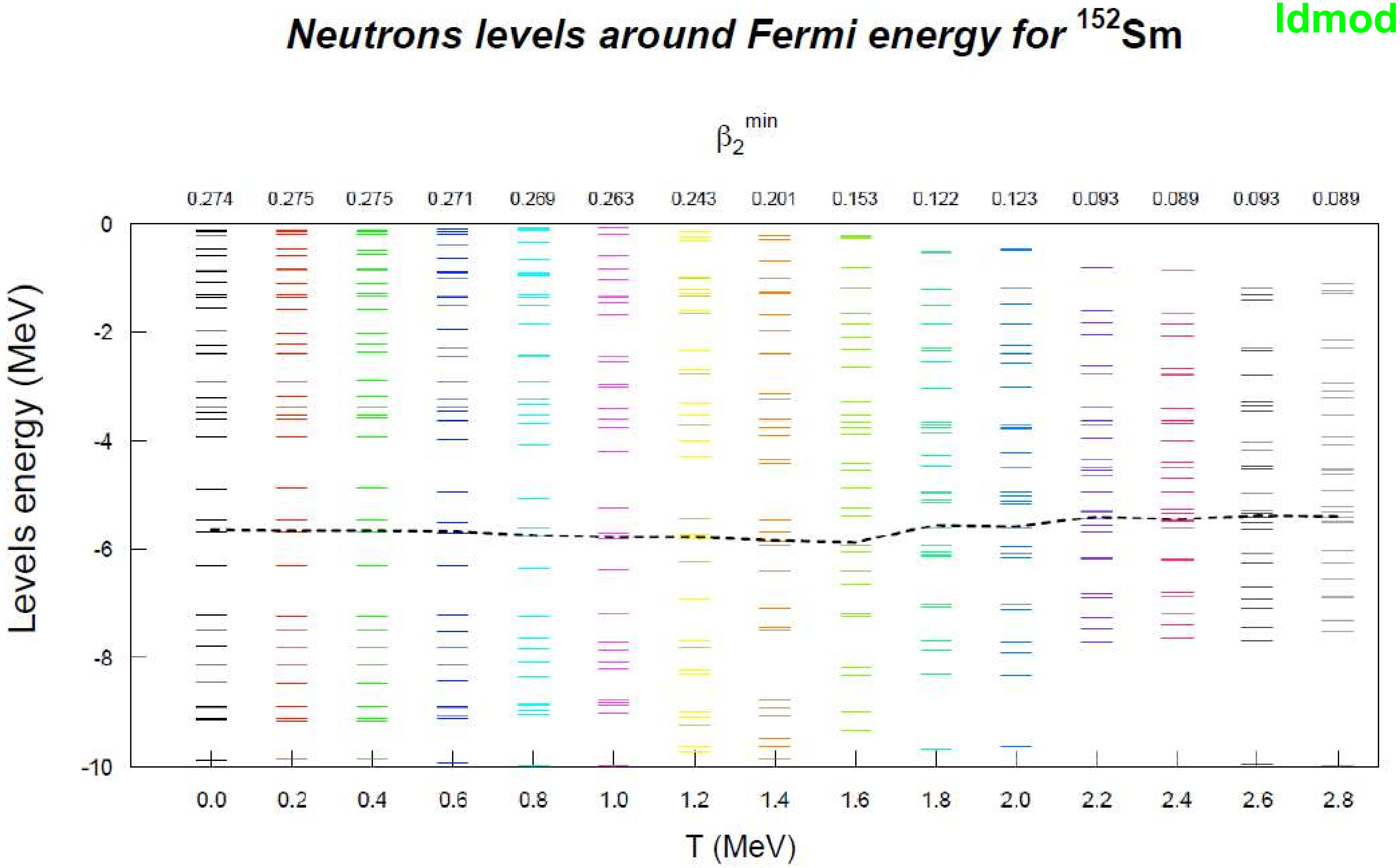
trivial relation for spherical nuclei

$$\rho(U, J, \pi) = \omega\,(U, K{=}J, \pi) - \omega\,(U, K{=}J{+}1, \pi)$$

- Phenomenological mixing of spherical and deformed level densities for small deformations

Level densities : combinatorial approach + temperature

ldmodel 6 in TALYS



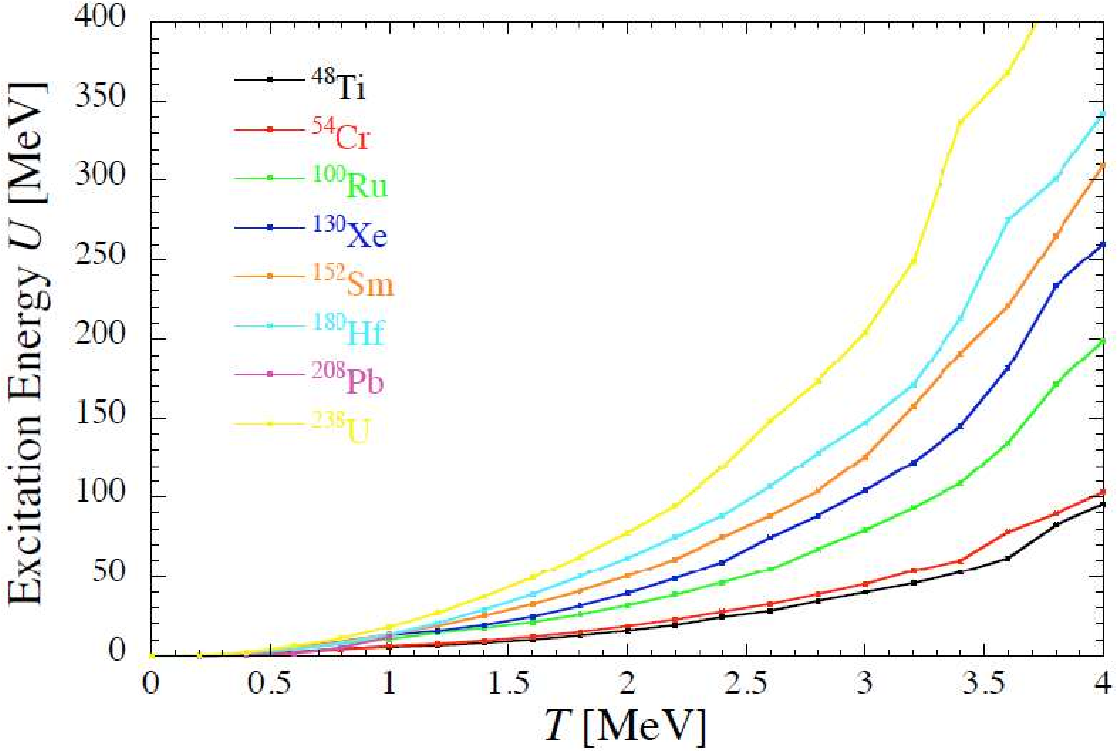
Level densities : combinatorial approach +temperature

ldmodel 6 in TALYS

For each temperature, the excitation energy is determined.

→ expected parabolic shape ($U \propto T^2$) is observed.

Excitation energy as a function of the temperature

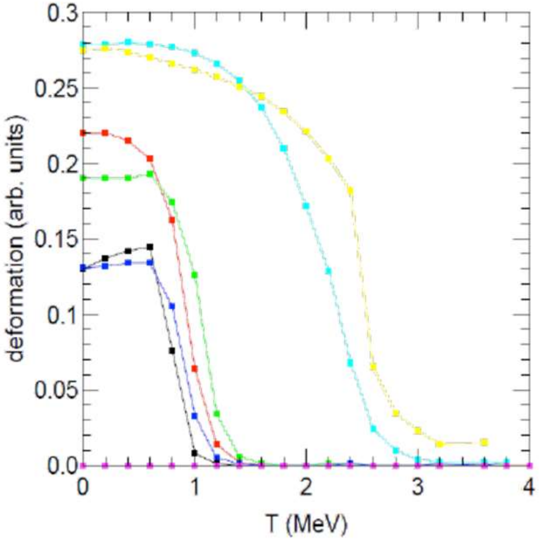


Level densities : combinatorial approach +temperature

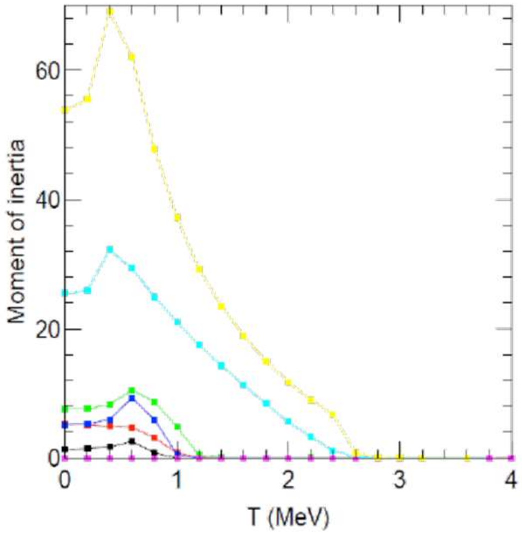
Temperature evolution of nuclear structure properties relevant for level density calculations within the combinatorial model

ldmodel 6 in TALYS

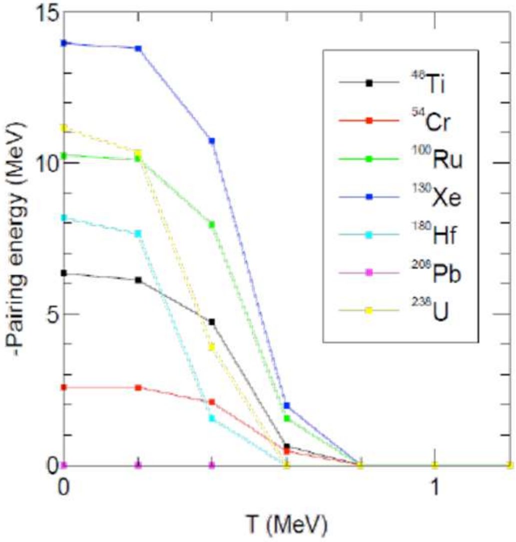
Quadrupole deformation



Cranking moment of Inertia



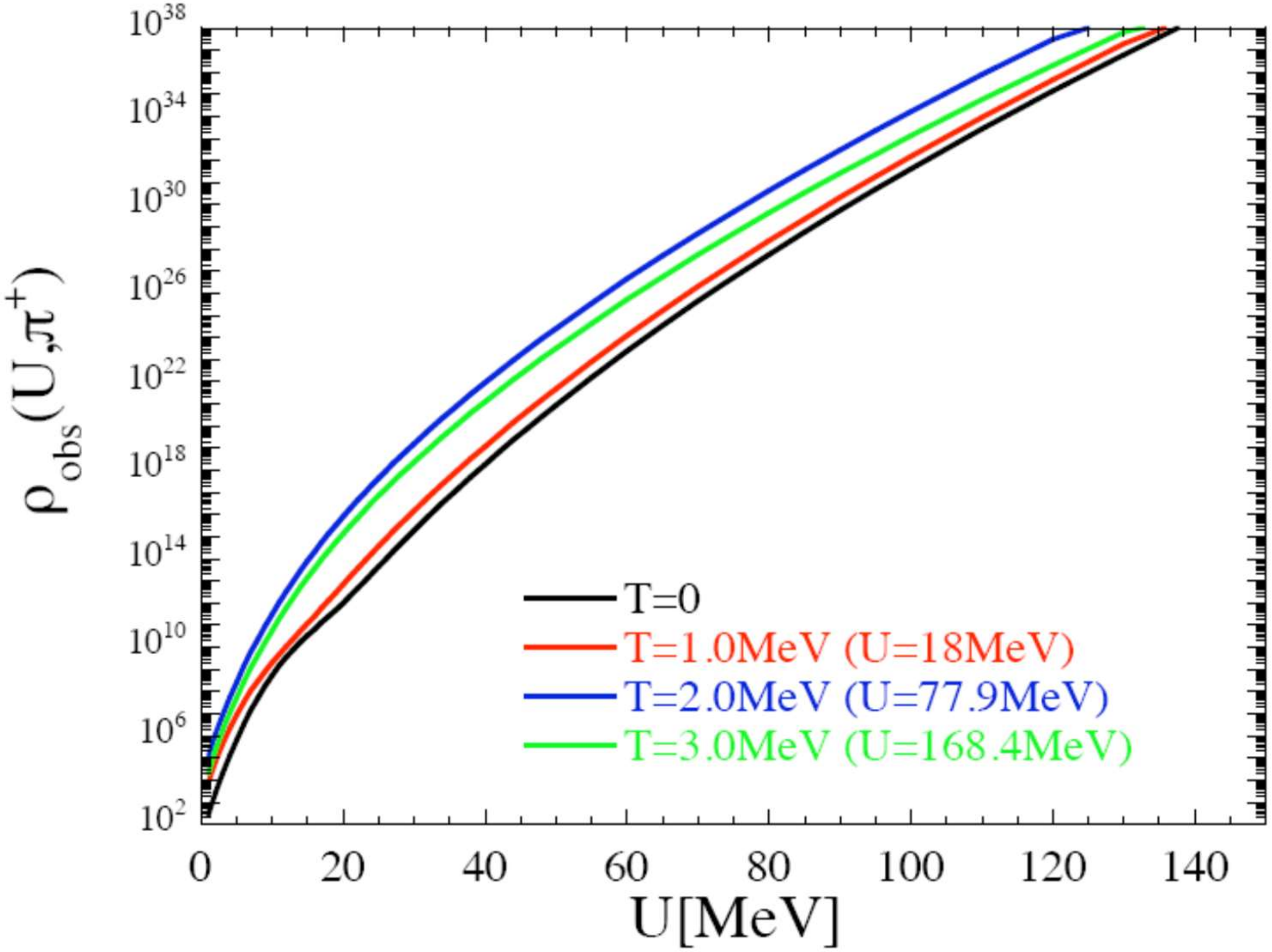
Total pairing energy



Level densities : combinatorial approach +temperature

Level density for ^{238}U

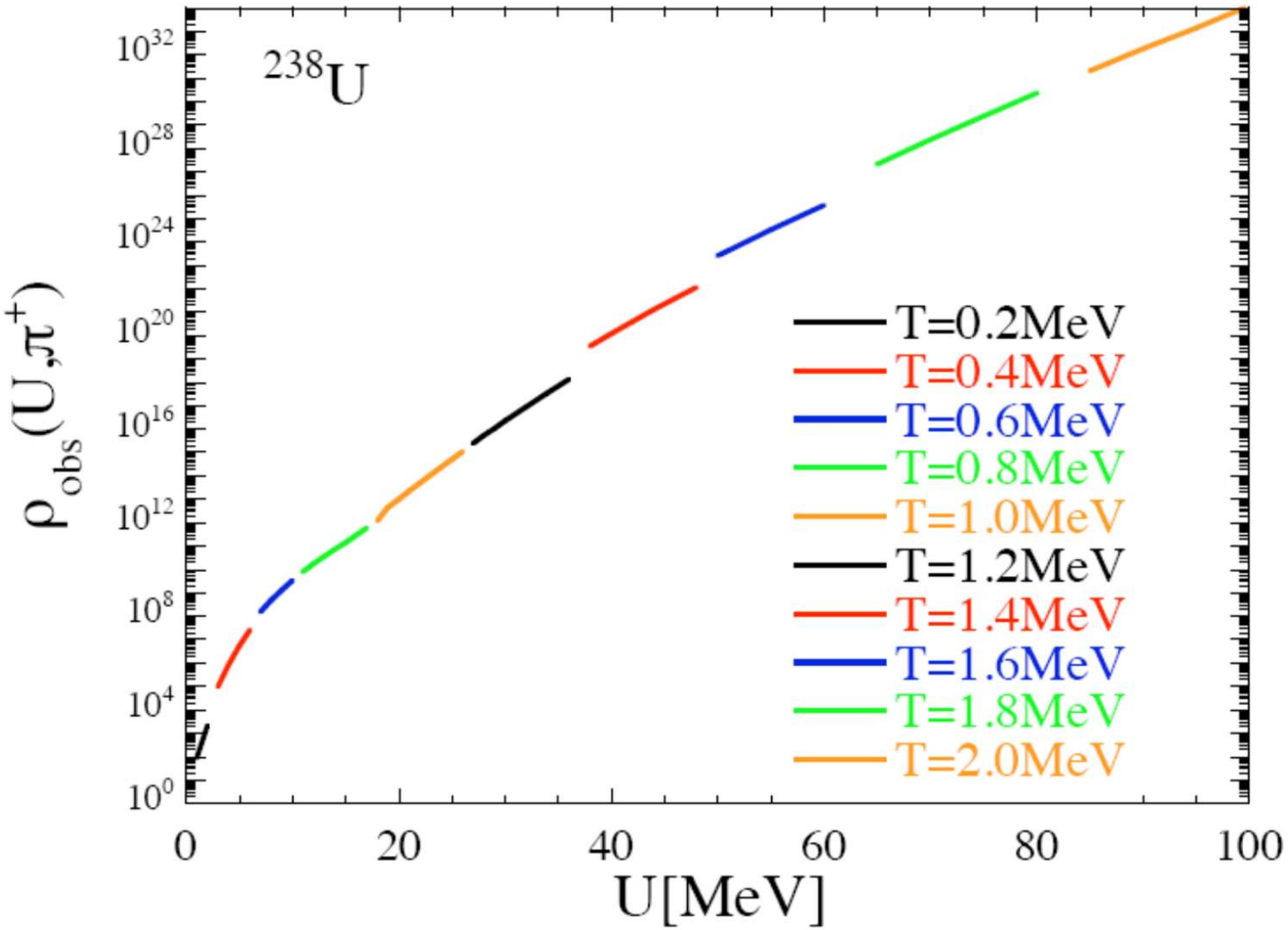
ldmodel 6 in TALYS



Level densities : combinatorial approach +temperature

Level density for ^{238}U

ldmodel 6 in TALYS



Level densities : combinatorial approach +temperature

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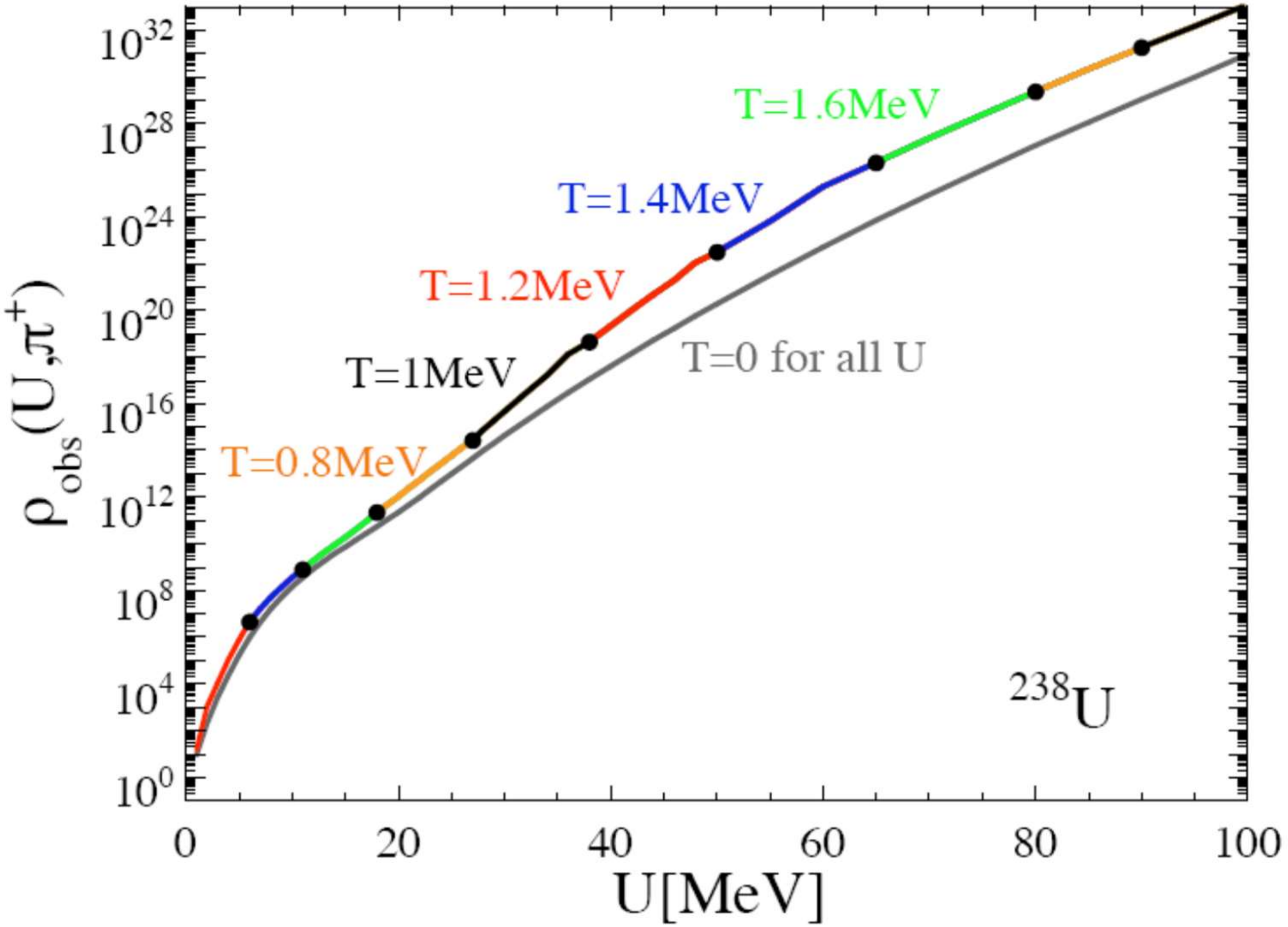
ldmodel 6 in TALYS



Level densities : combinatorial approach +temperature

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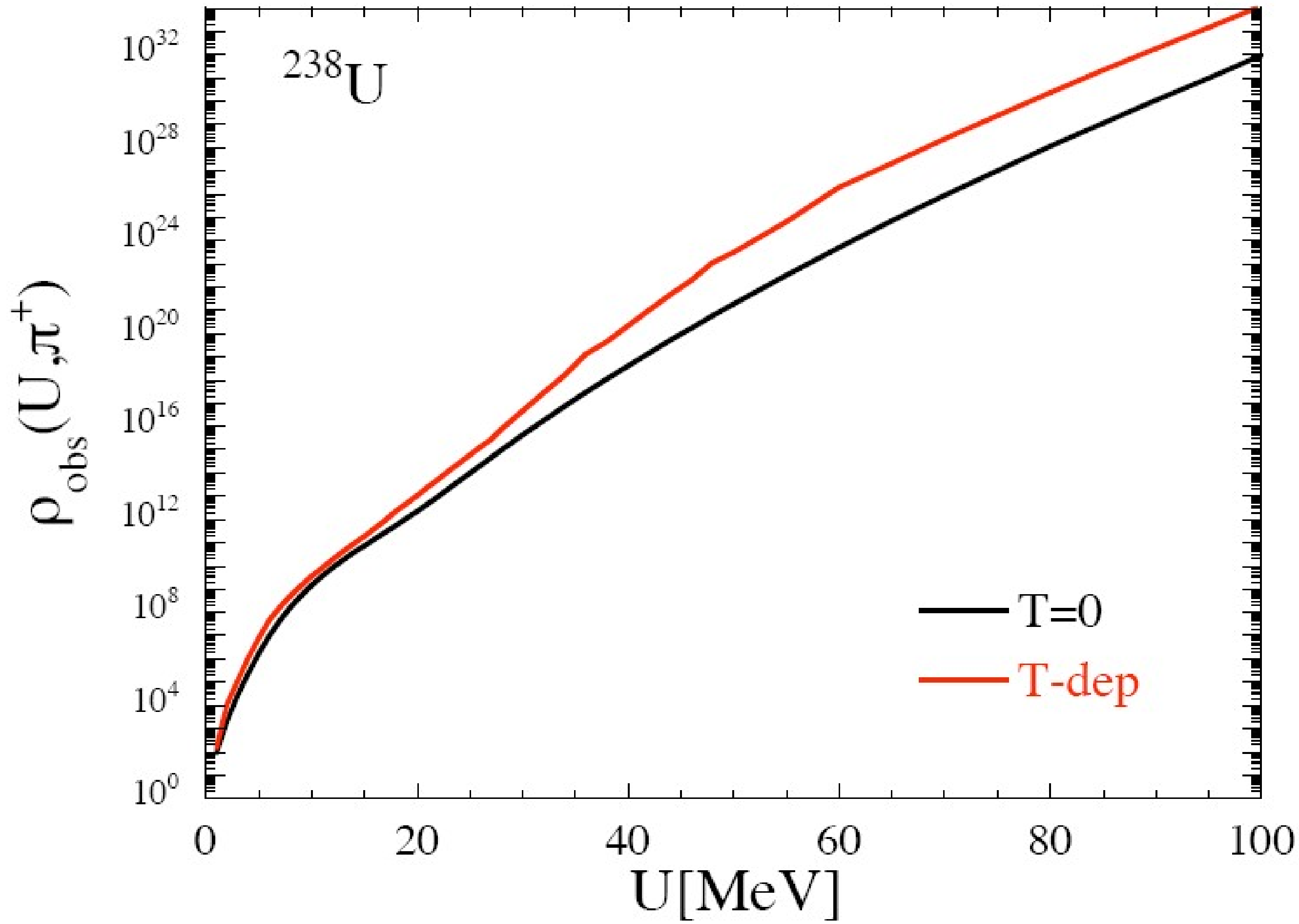
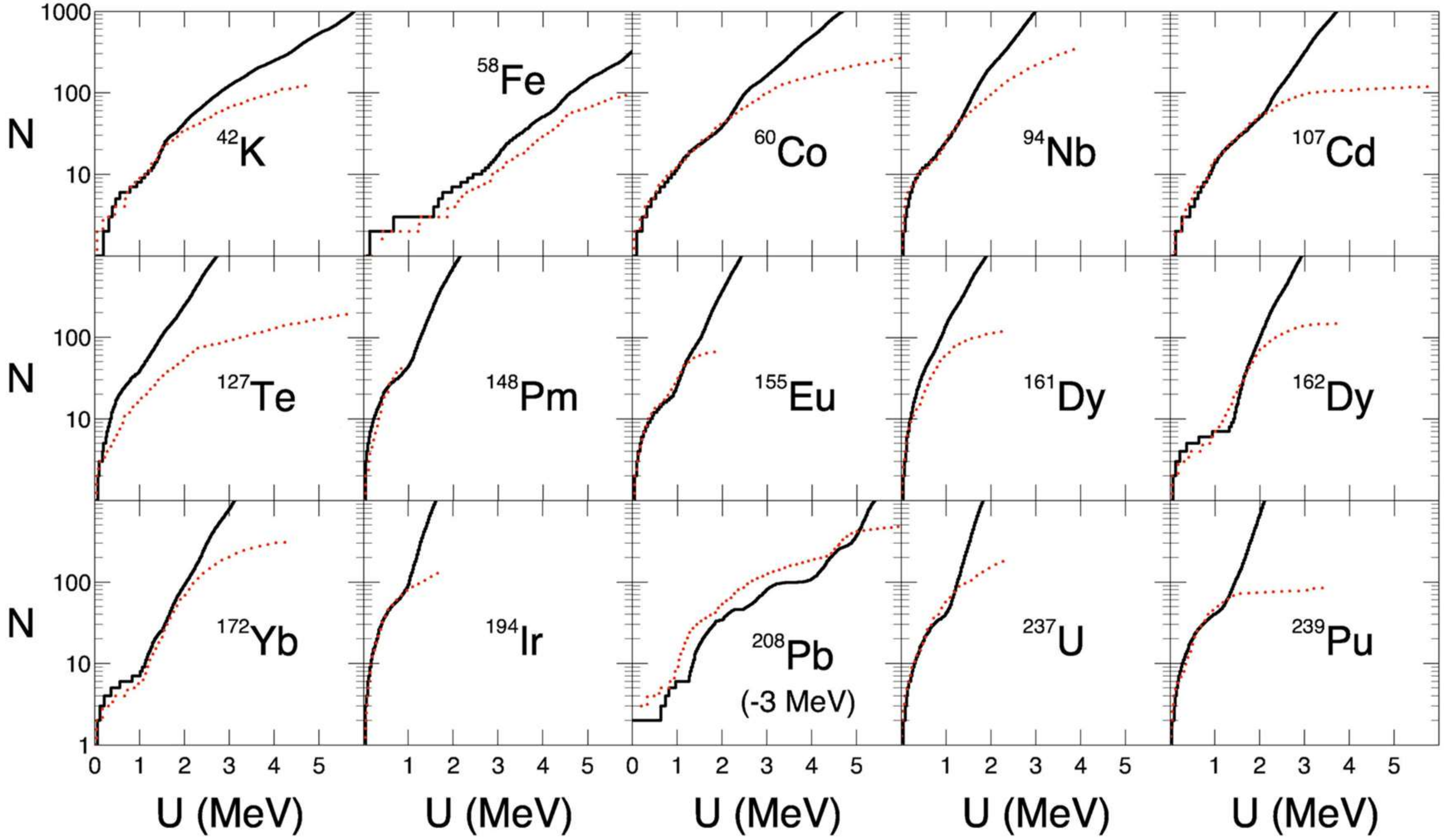
ldmodel 6 in TALYS



Level densities : combinatorial approach +temperature

Ldmodel 6 in TALYS

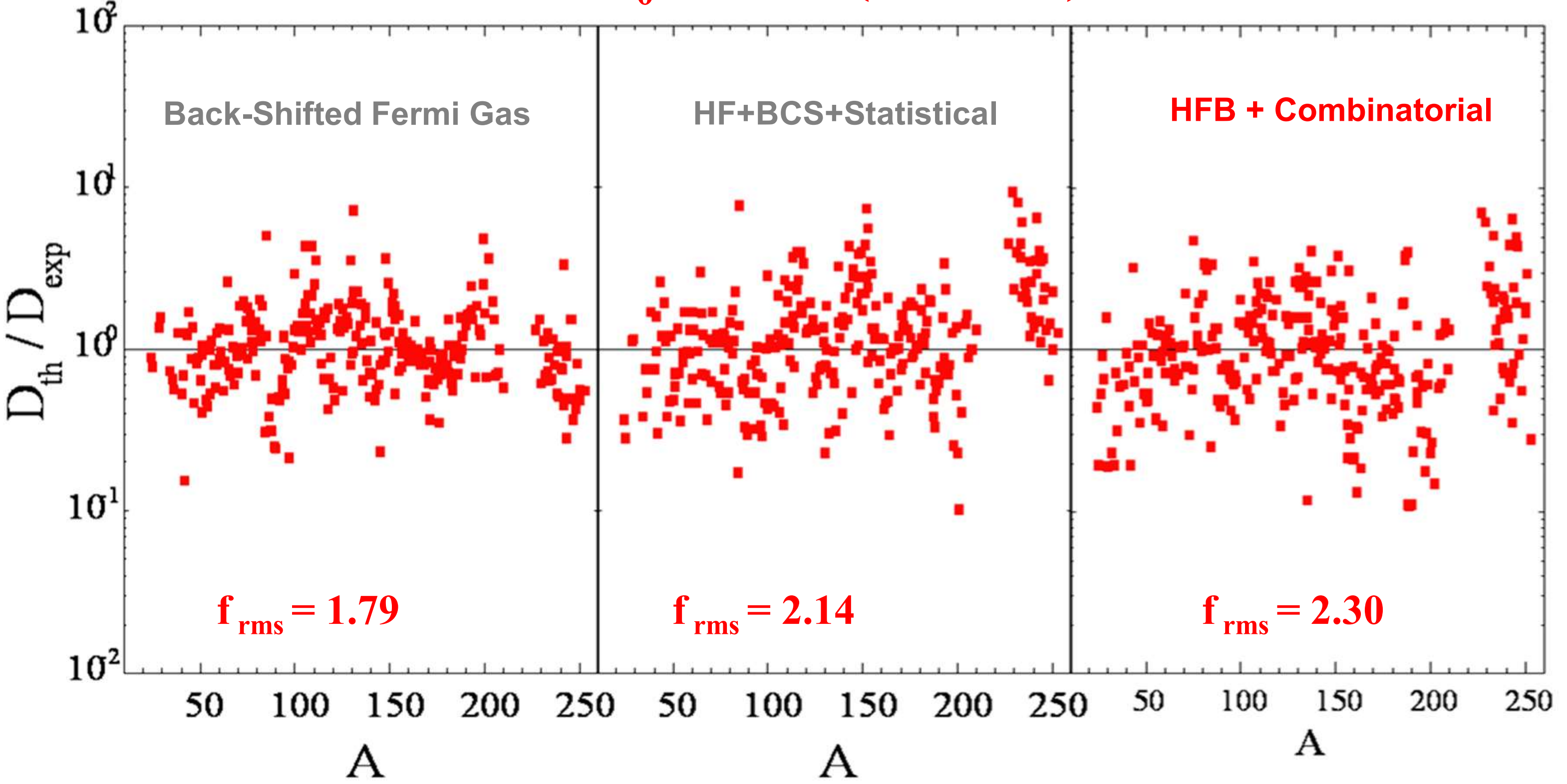


➡ **Structures typical of non-statistical feature**

Level densities : combinatorial approach +temperature

ldmodel 6 in TALYS

D_0 values (s-waves)

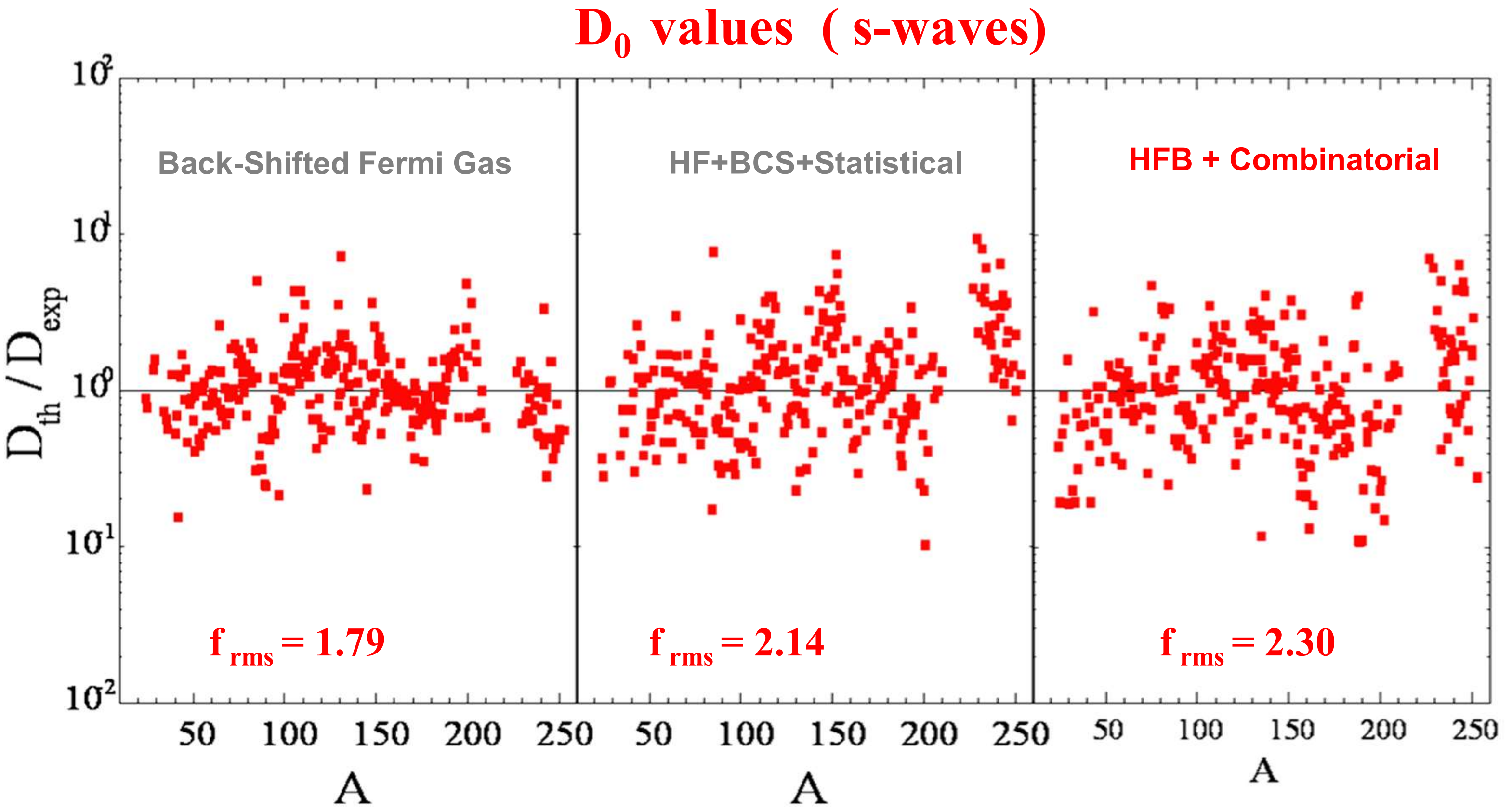


$$f_{\text{rms}} = \exp\left[\frac{1}{N_e}\sum_{i=1}^{N_e}\ln^2\frac{D^i_{\text{th}}}{D^i_{\text{exp}}}\right]^{1/2}$$

Level densities : combinatorial approach +temperature

D_0 values (s-waves)

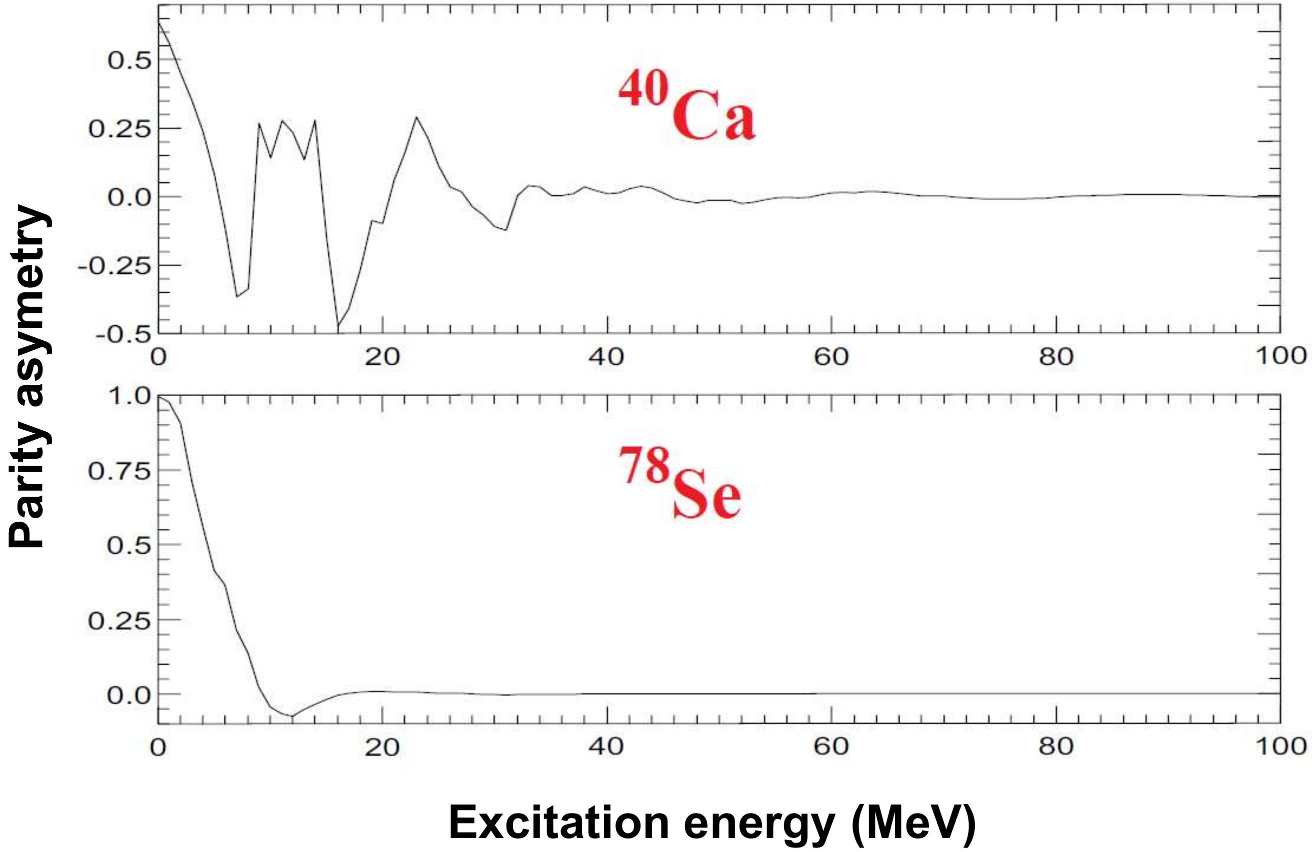
Idmodel 6 in TALYS



➡ **Description similar to that obtained with other global approaches**

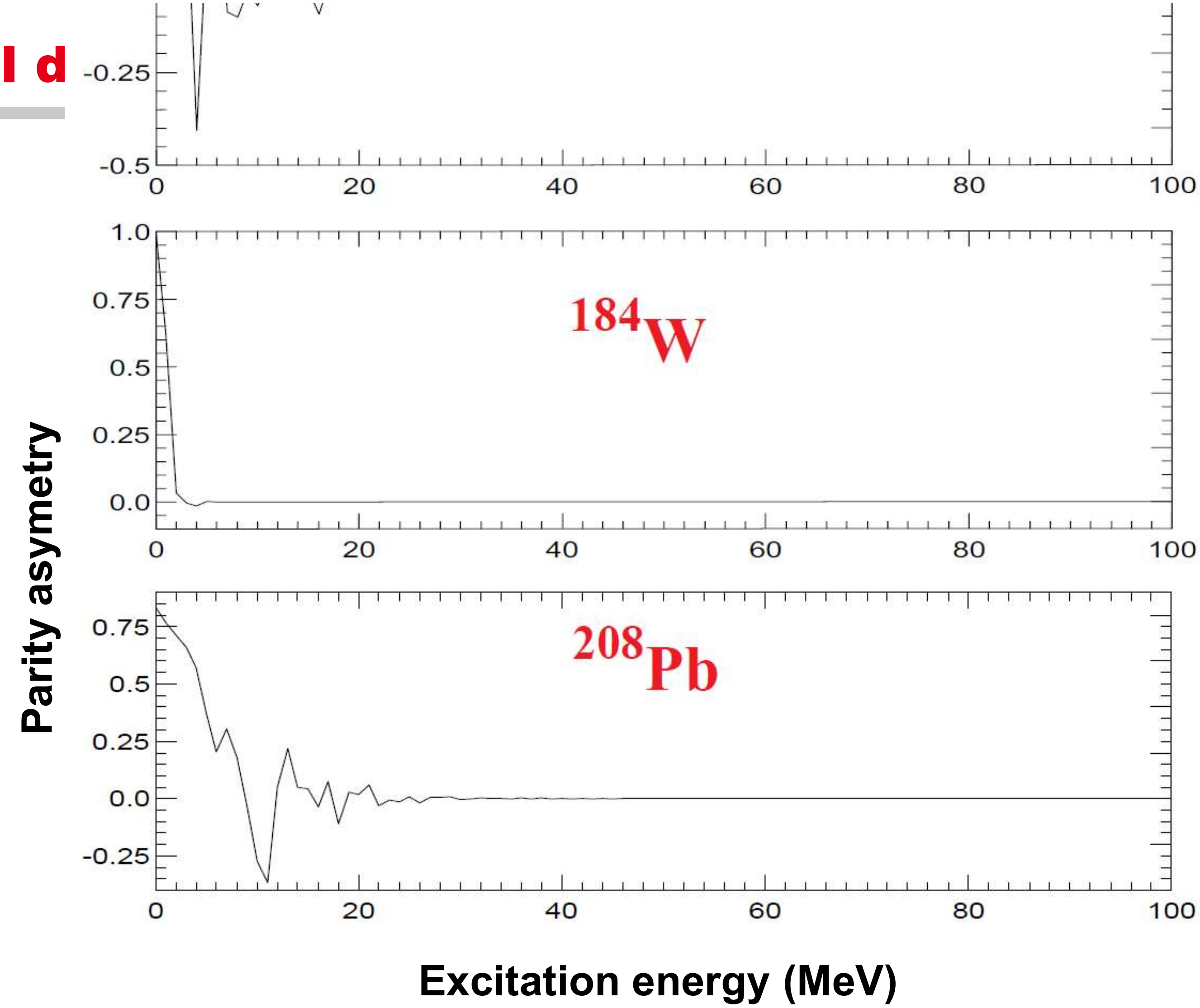
Level densities : combinatorial approach +temperature

ldmodel 6 in TALYS



Level d rature

ldmodel 6 in TALYS



Level densities

- Why and where do we need them ?

- Why ?
- Where ?

- Particle-hole level densities for pre-equilibrium

- The equidistant spacing model
- Beyond the ESM

- Total level densities

- Qualitative features
- Quantitative analysis with analytical approaches
- Shell Model Monte Carlo approach
- HFB+BCS Statistical approach
- Combinatorial approach

- Impacts on cross sections

- Parity non equipartition
- Non-Gaussian spin distribution
- Governing competition
- Tabulated data adjustment

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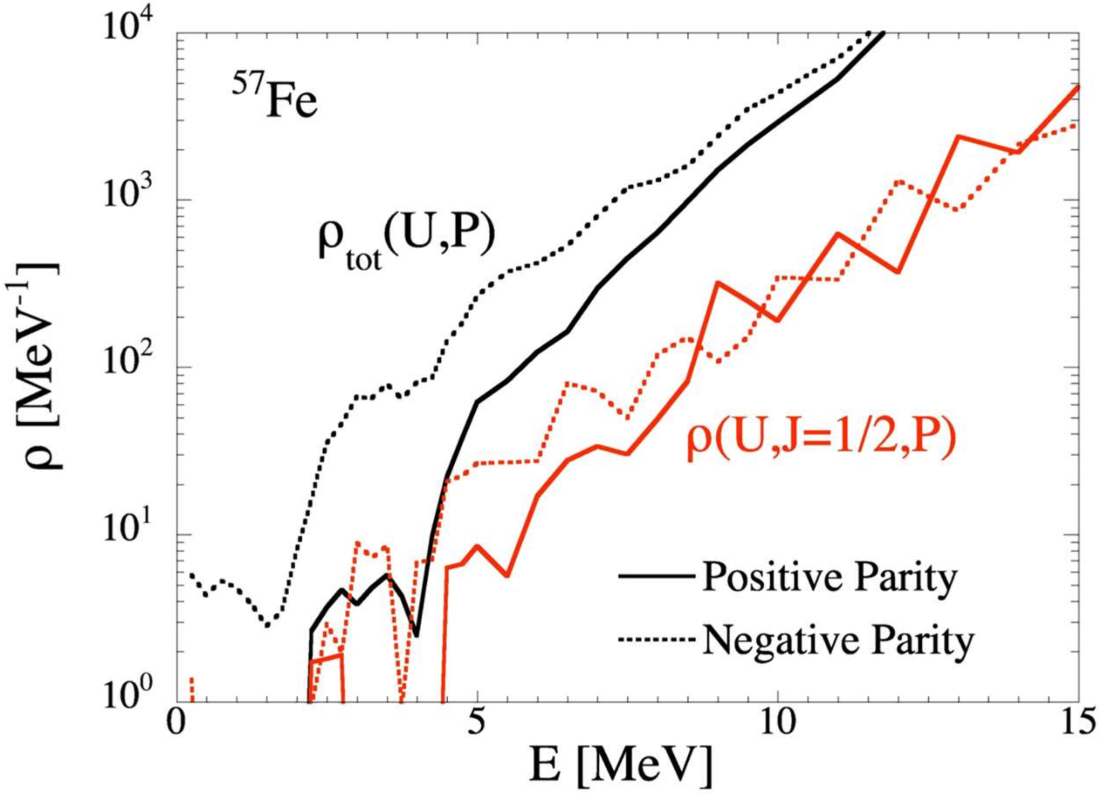
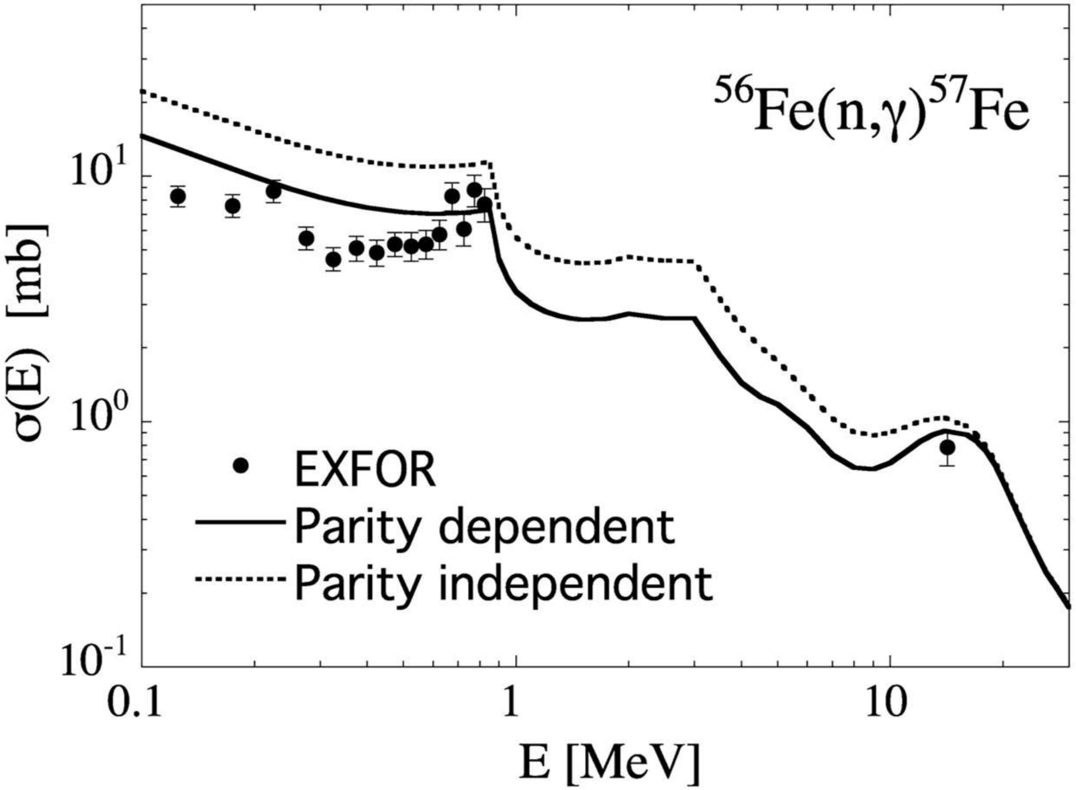
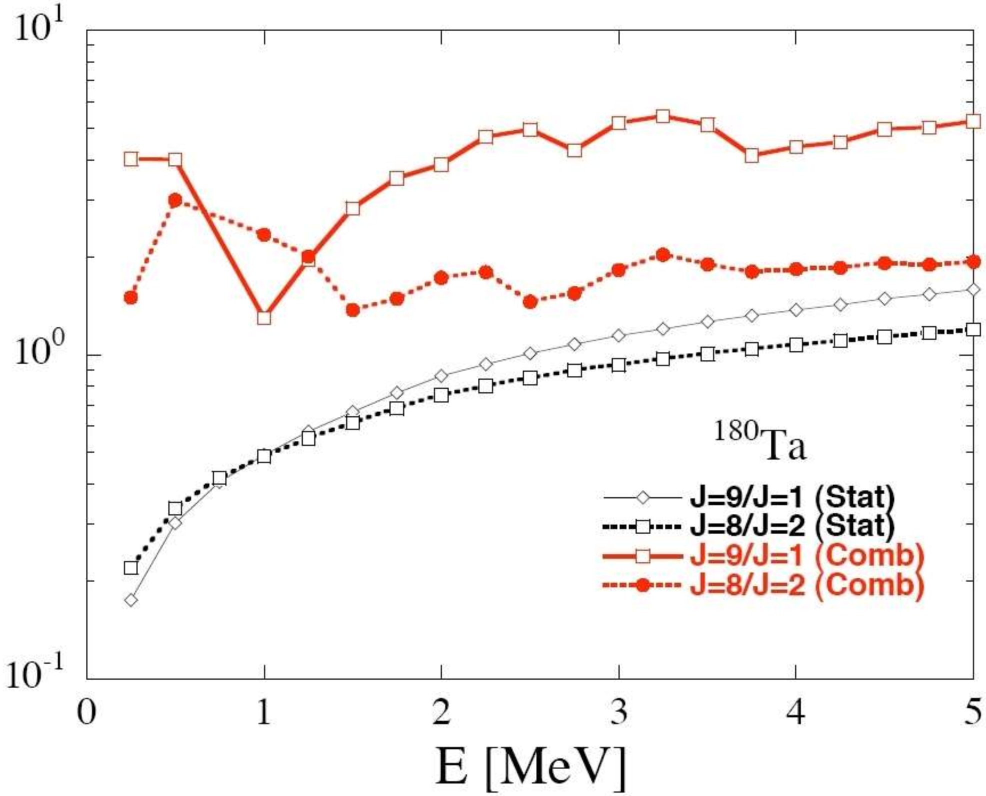
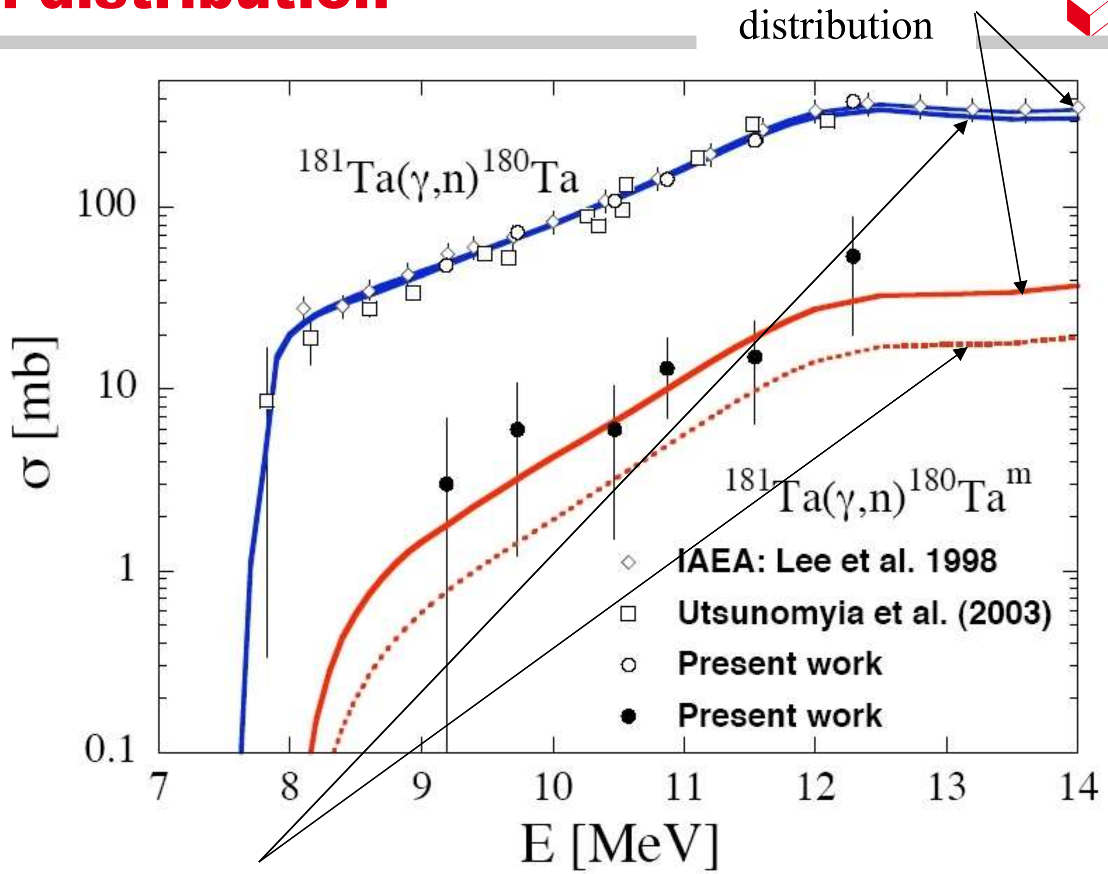
Level densities : parity non-equipartition





Level densities : non-Gaussian spin distribution



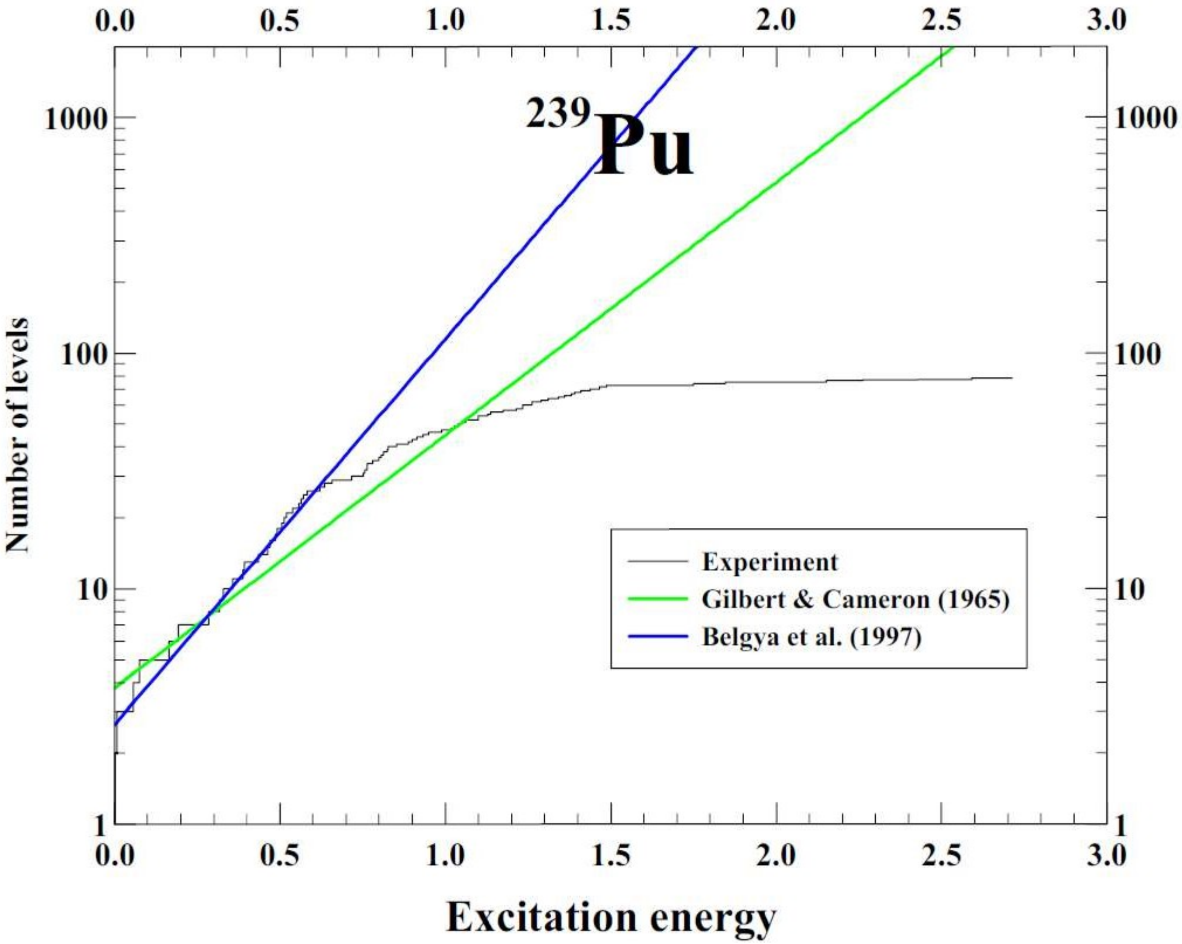


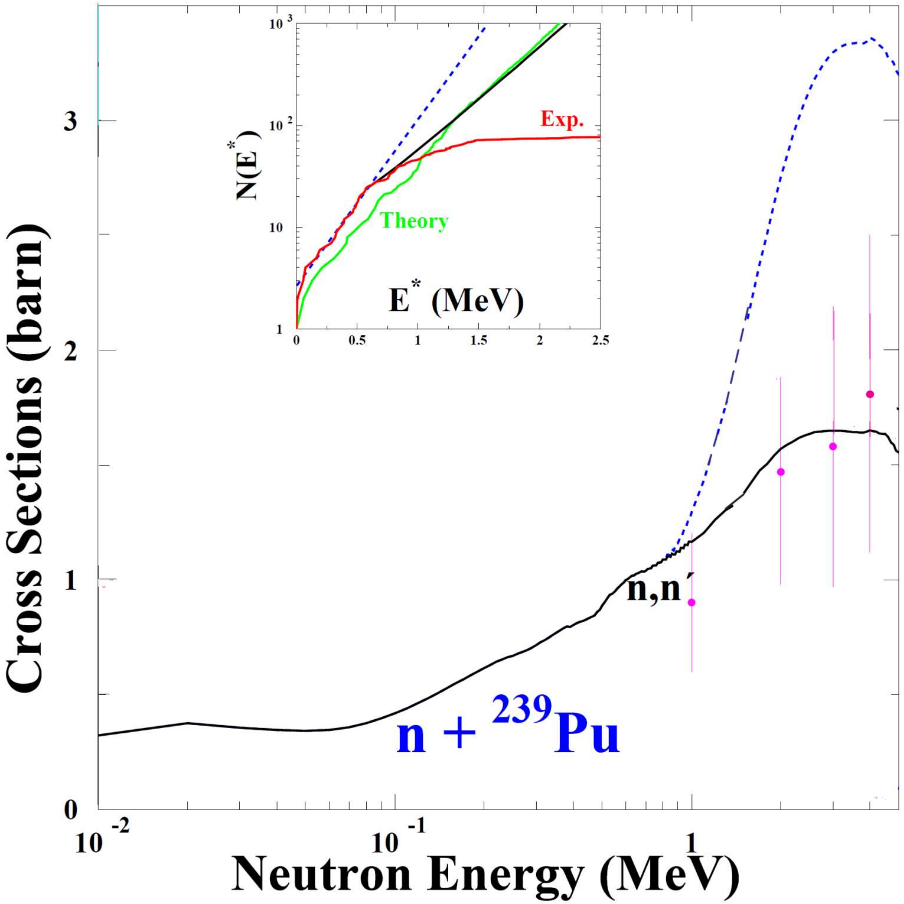
Combinatorial distribution

Gaussian distribution

➡ **Non-statistical feature imply significant deviations from the usual gaussian spin dependence which have significant impact on isomeric production**

Level densities : govern competition





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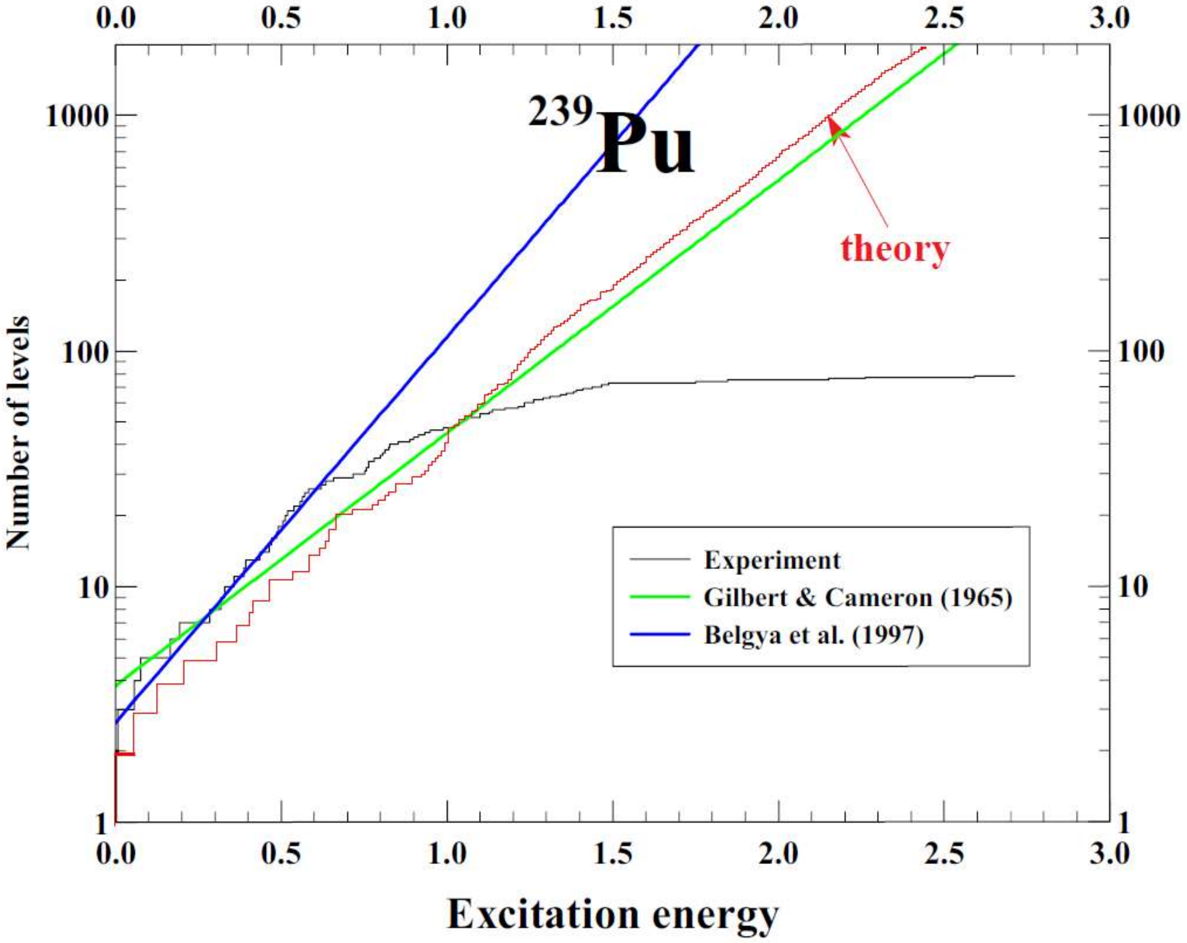
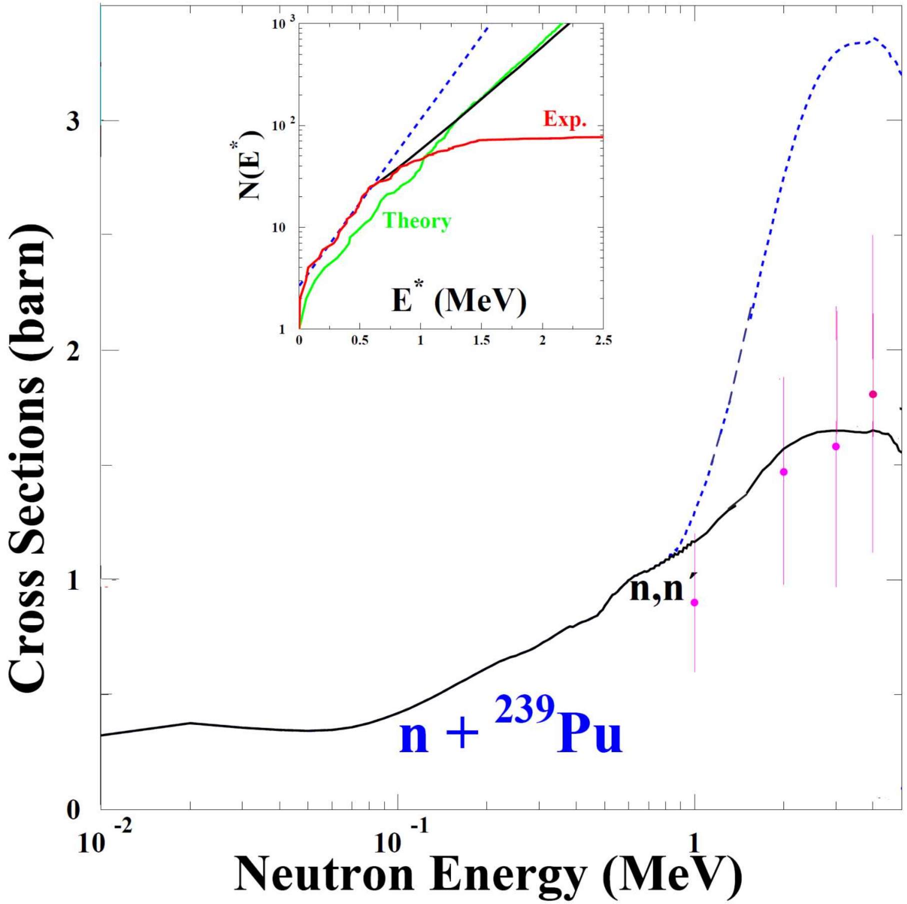
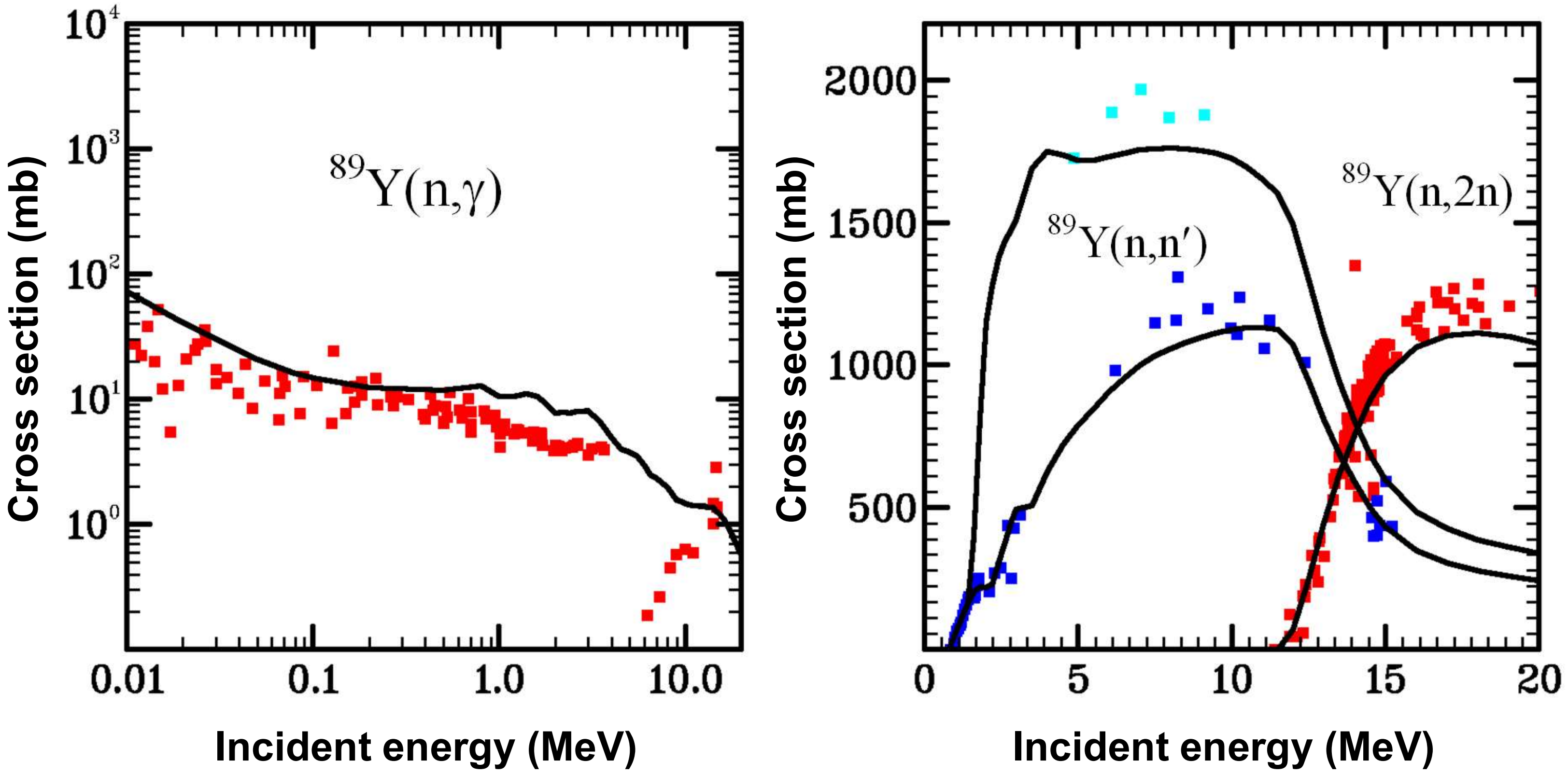




Level densities : table adjustment

$$\rho_{\text{renorm}}(U) = e^{\alpha\sqrt{(U-\delta)}}\,\rho_{\text{global}}(U-\delta)$$



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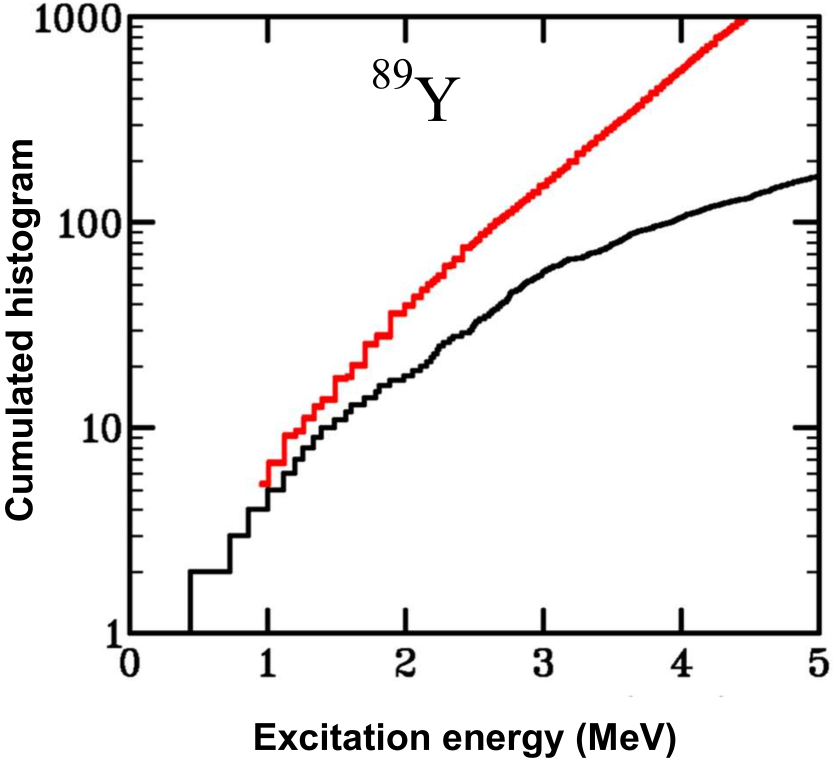

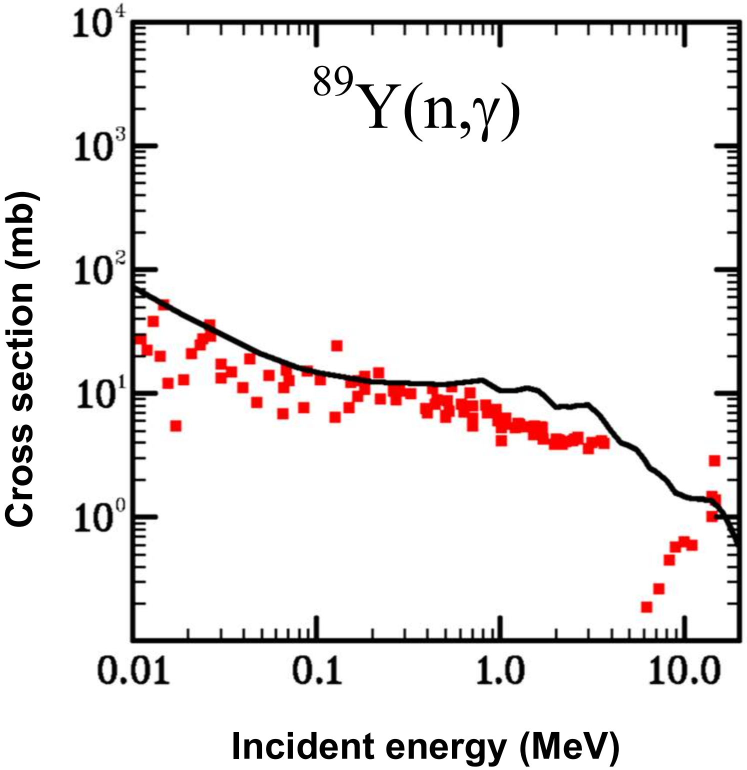

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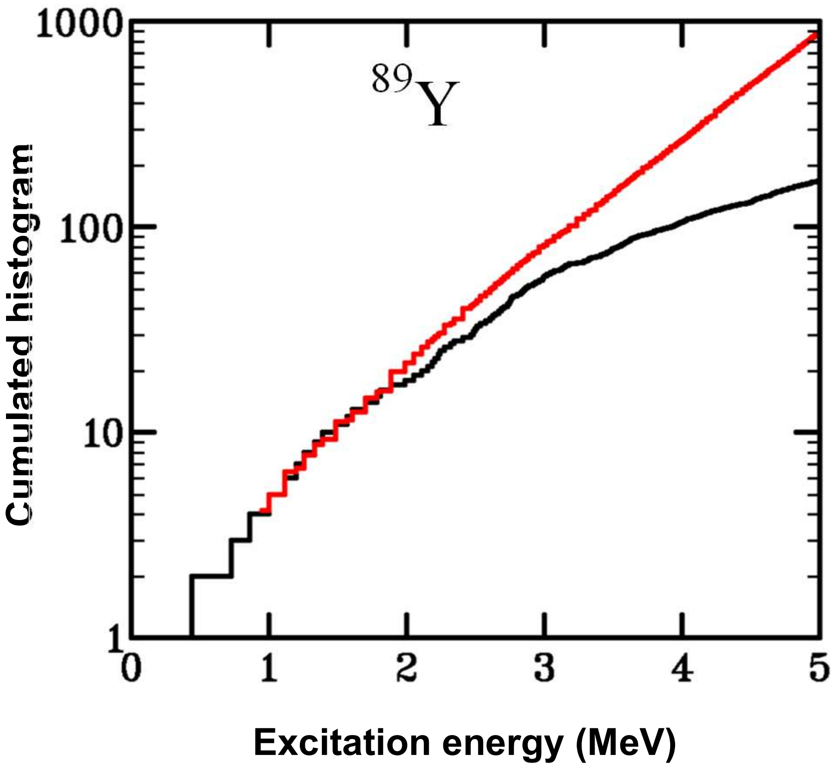
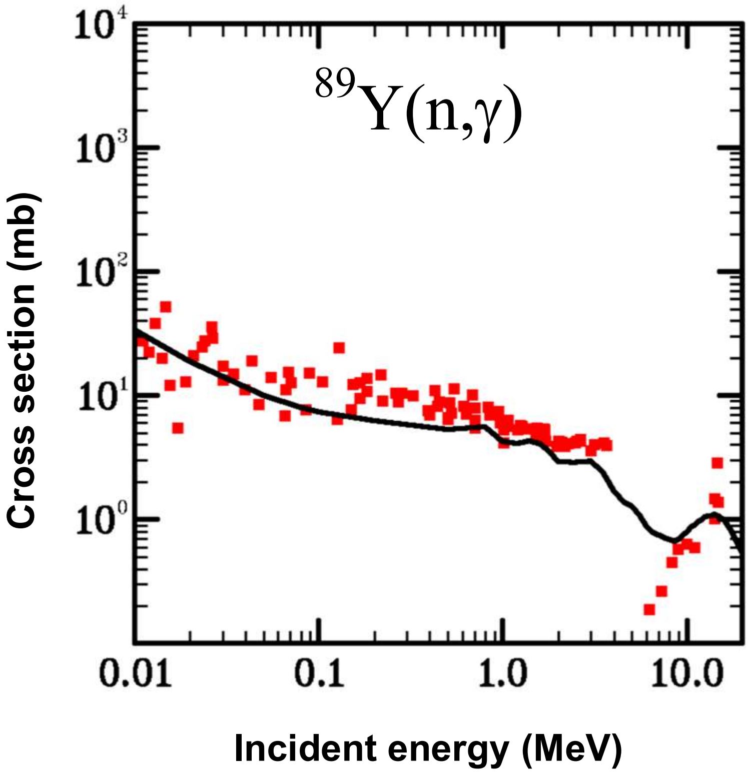
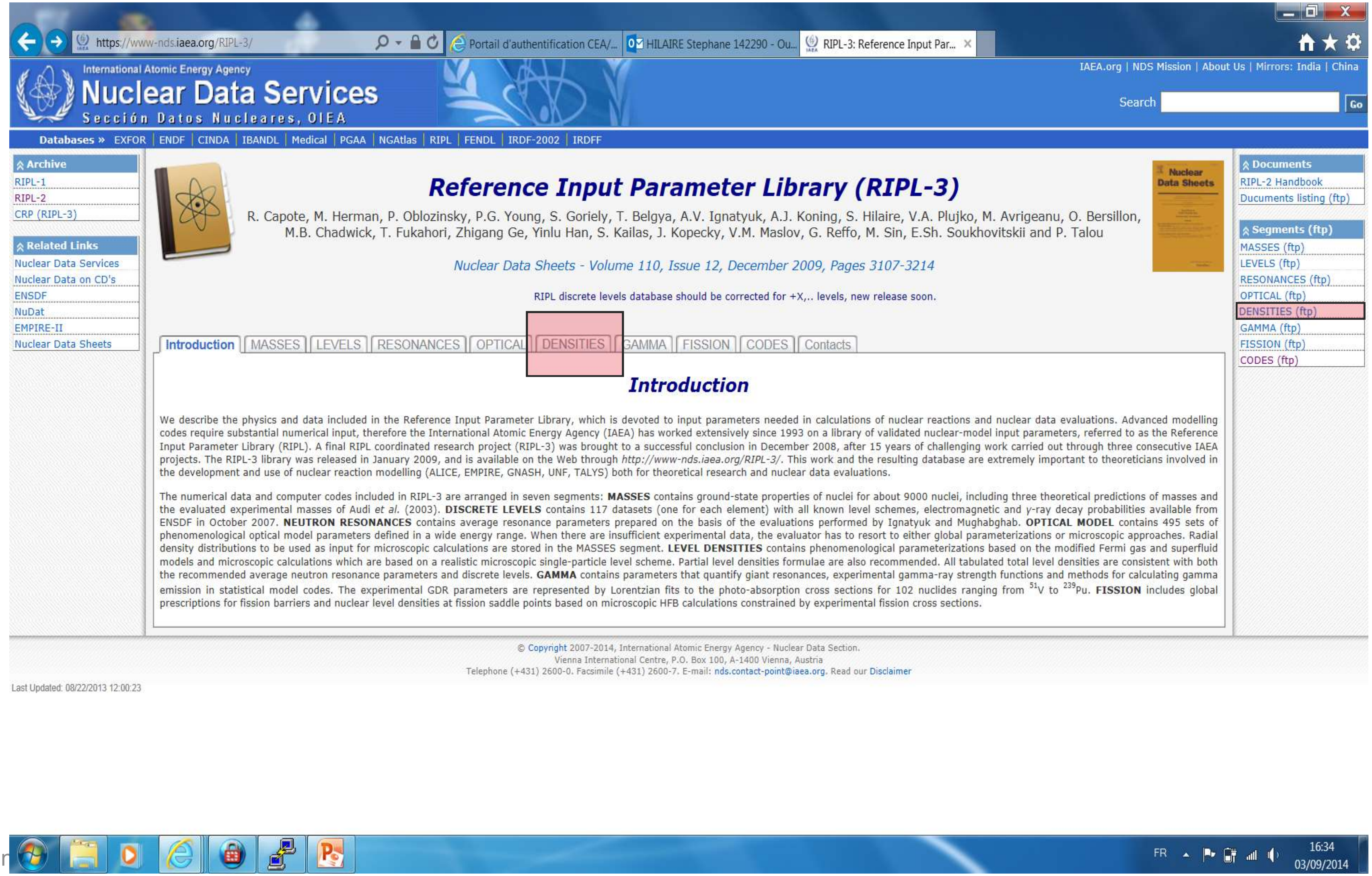




Level densities : summary



Reference Input Parameter Library (RIPL-3)

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Nuclear Data Sheets - Volume 110, Issue 12, December 2009, Pages 3107-3214

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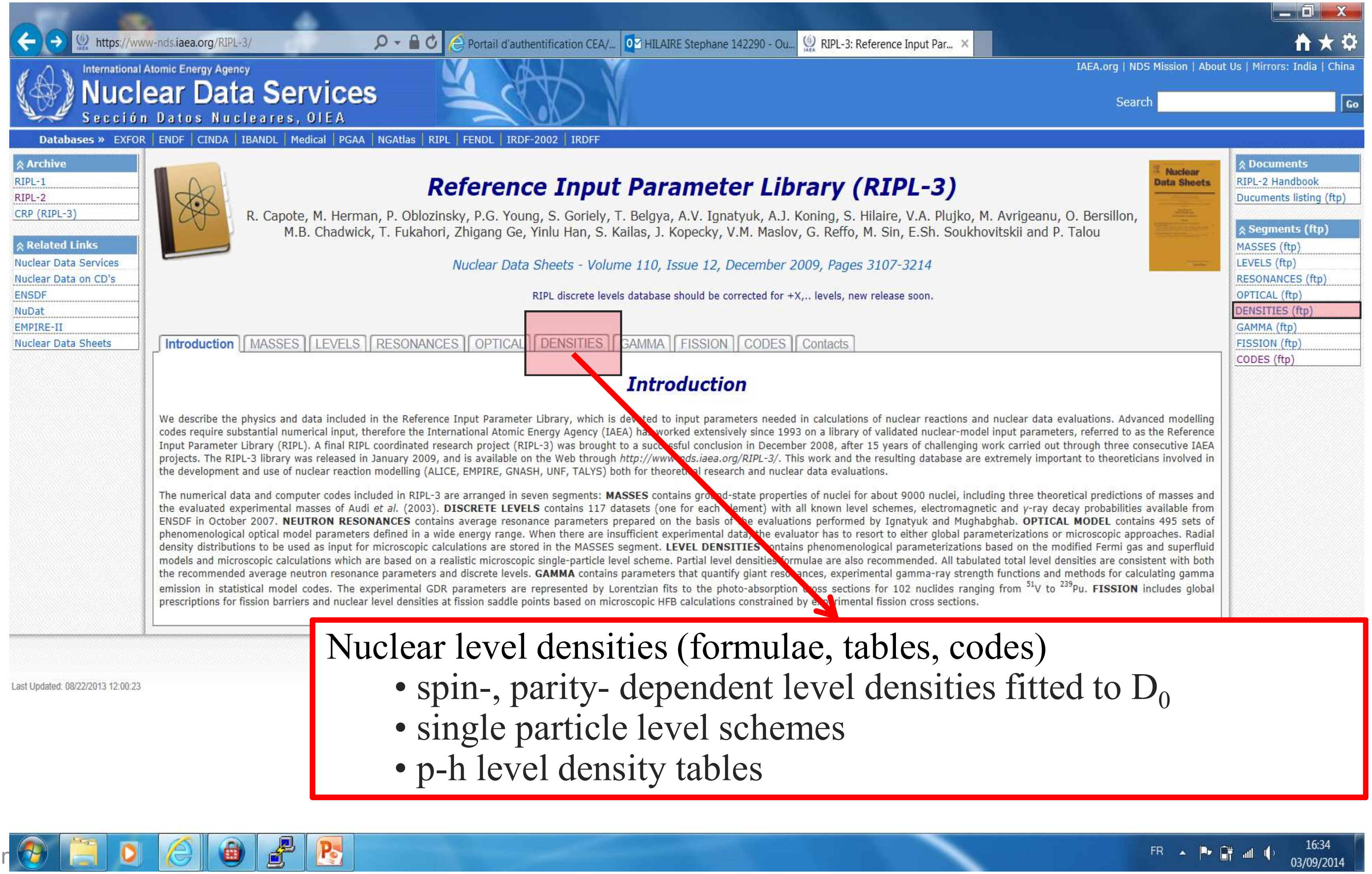
Last Updated: 08/22/2013 12:00:23

Level densities : summary



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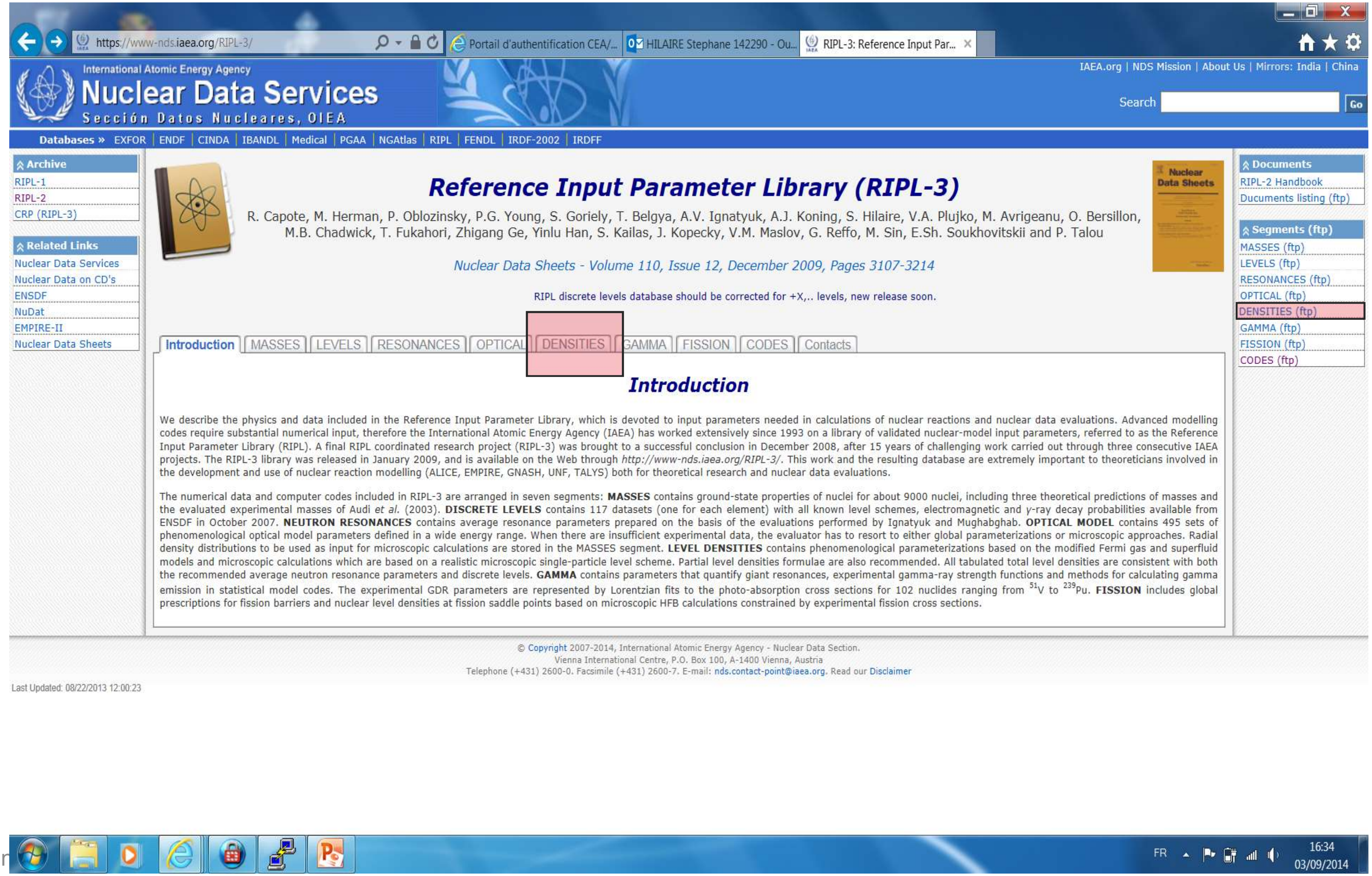
Nuclear level densities (formulae, tables, codes)
- spin-, parity- dependent level densities fitted to D_0
- single particle level schemes
- p-h level density tables

Level densities : summary



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3. GAMMA-RAY STRENGTHS

Gamma-ray strengths

- Qualitative features

- Analytical approaches

- Microscopic approaches

- HFBCS-RPA
- HFB+QRPA
- Shell Model

- Impacts on cross sections

- Normalizations
- Exotic nuclei
- Hot topics

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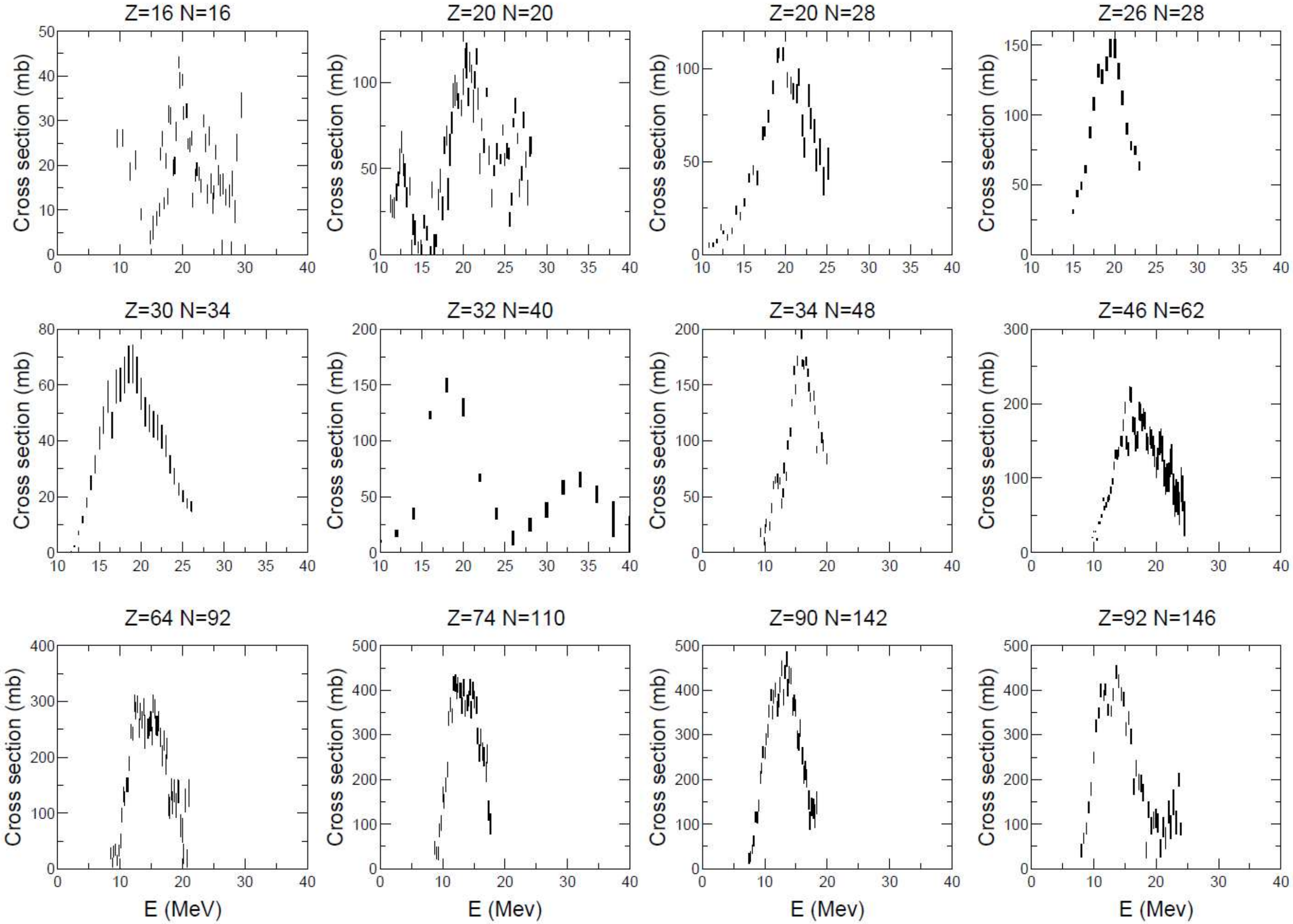
Gamma-ray strengths : qualitative aspects from photoabsorption



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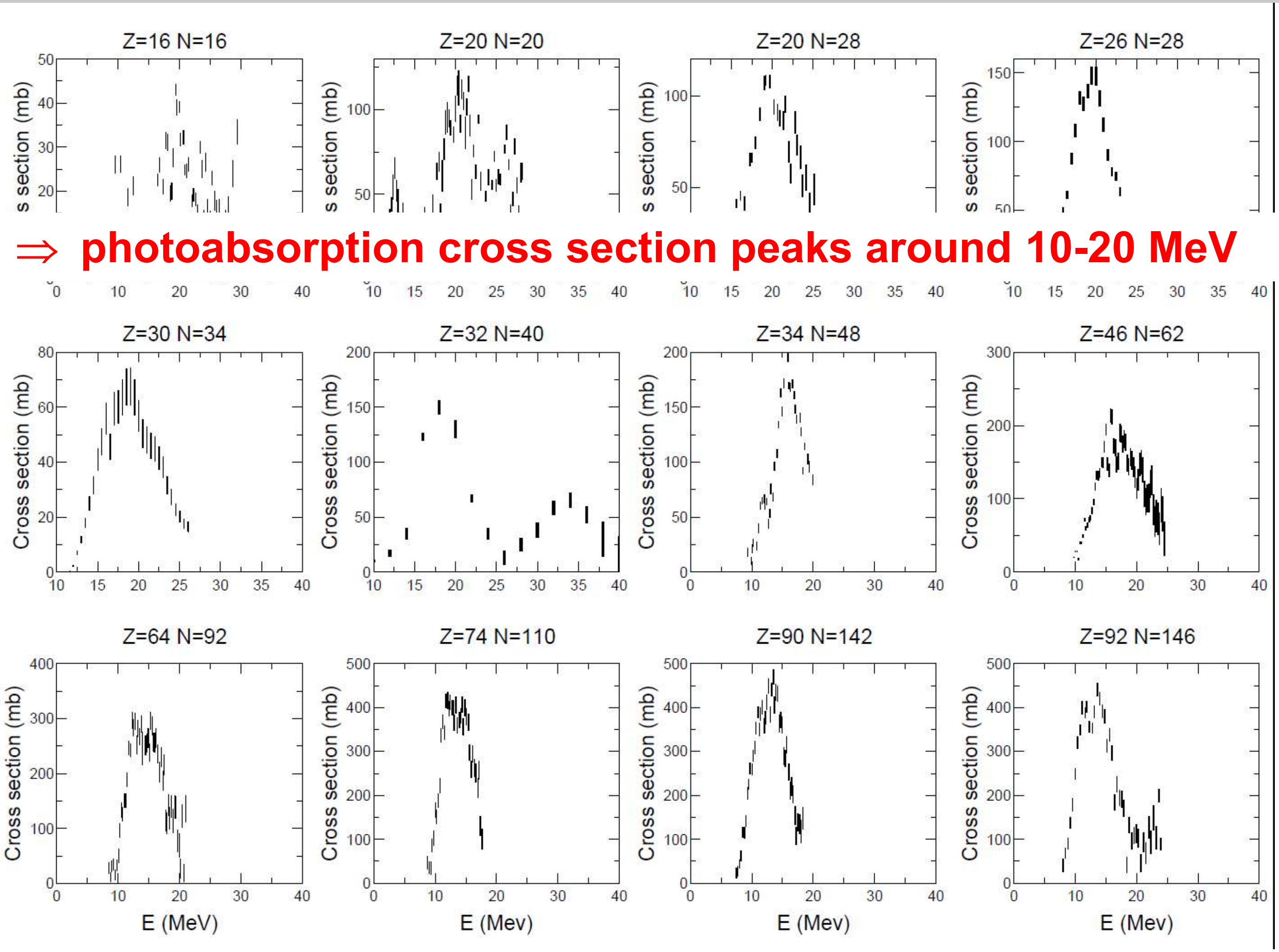
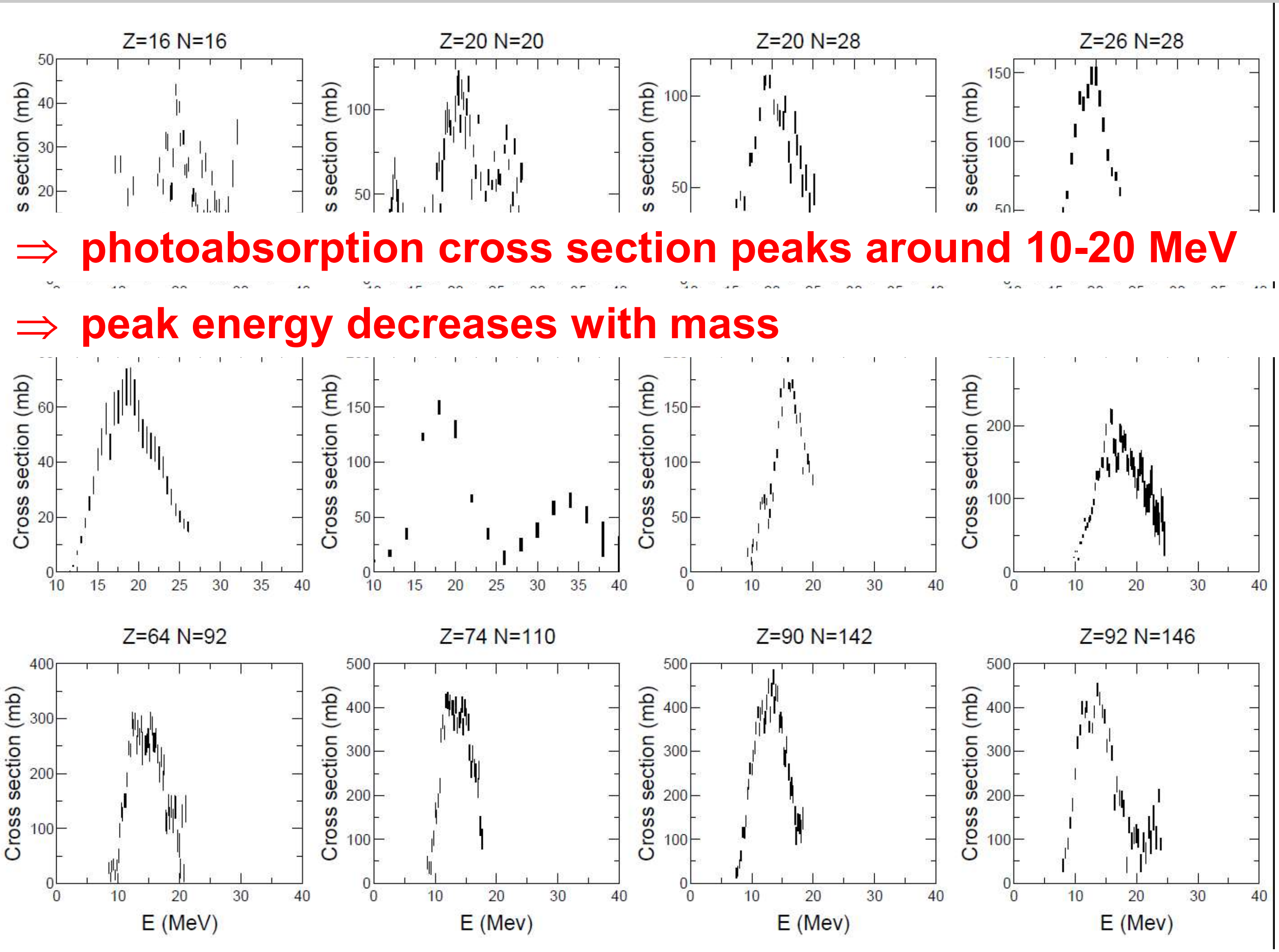


⇒ **photoabsorption cross section peaks around 10-20 MeV**

Gamma-ray strengths : qualitative aspects from photoabsorption



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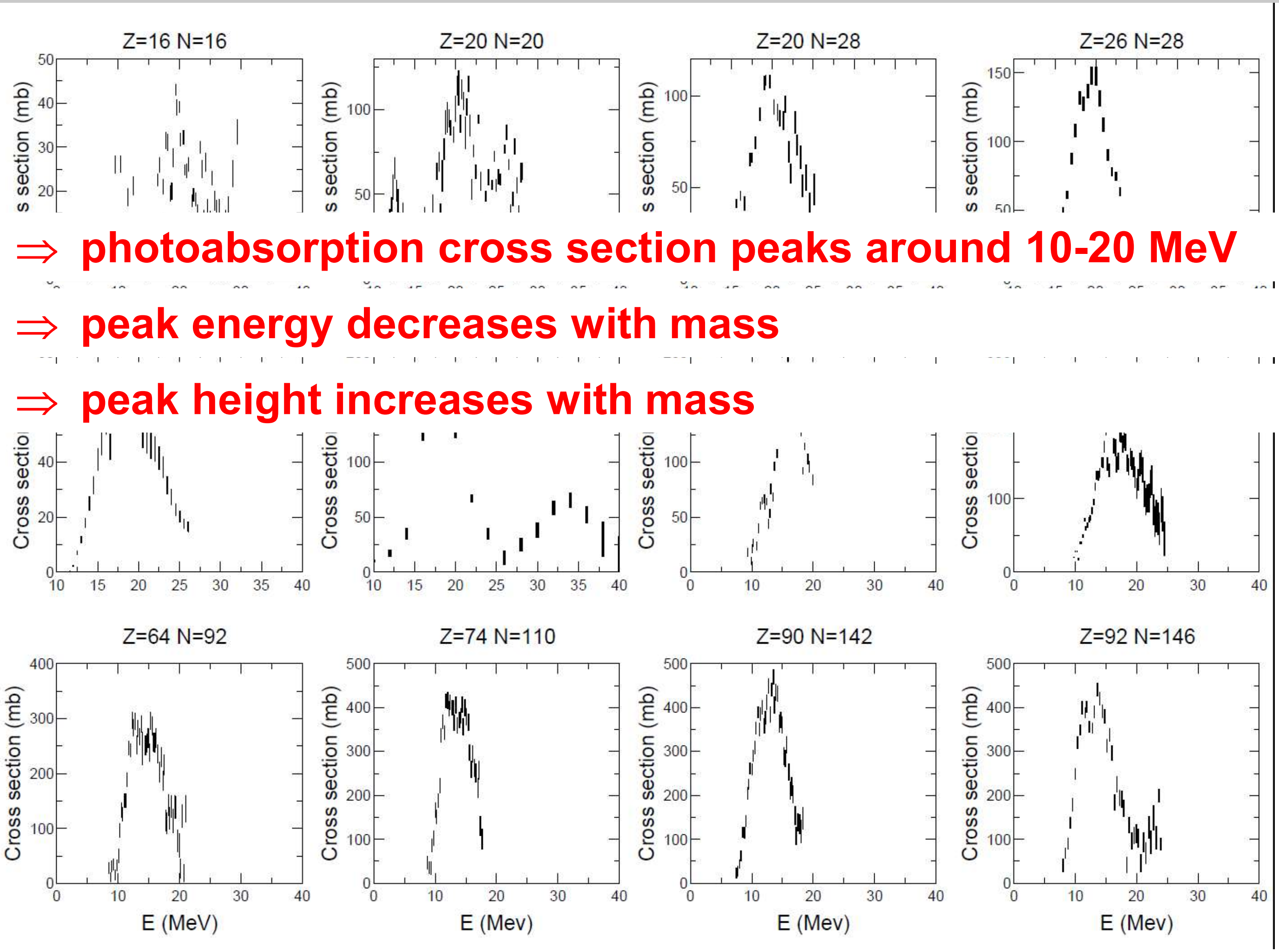

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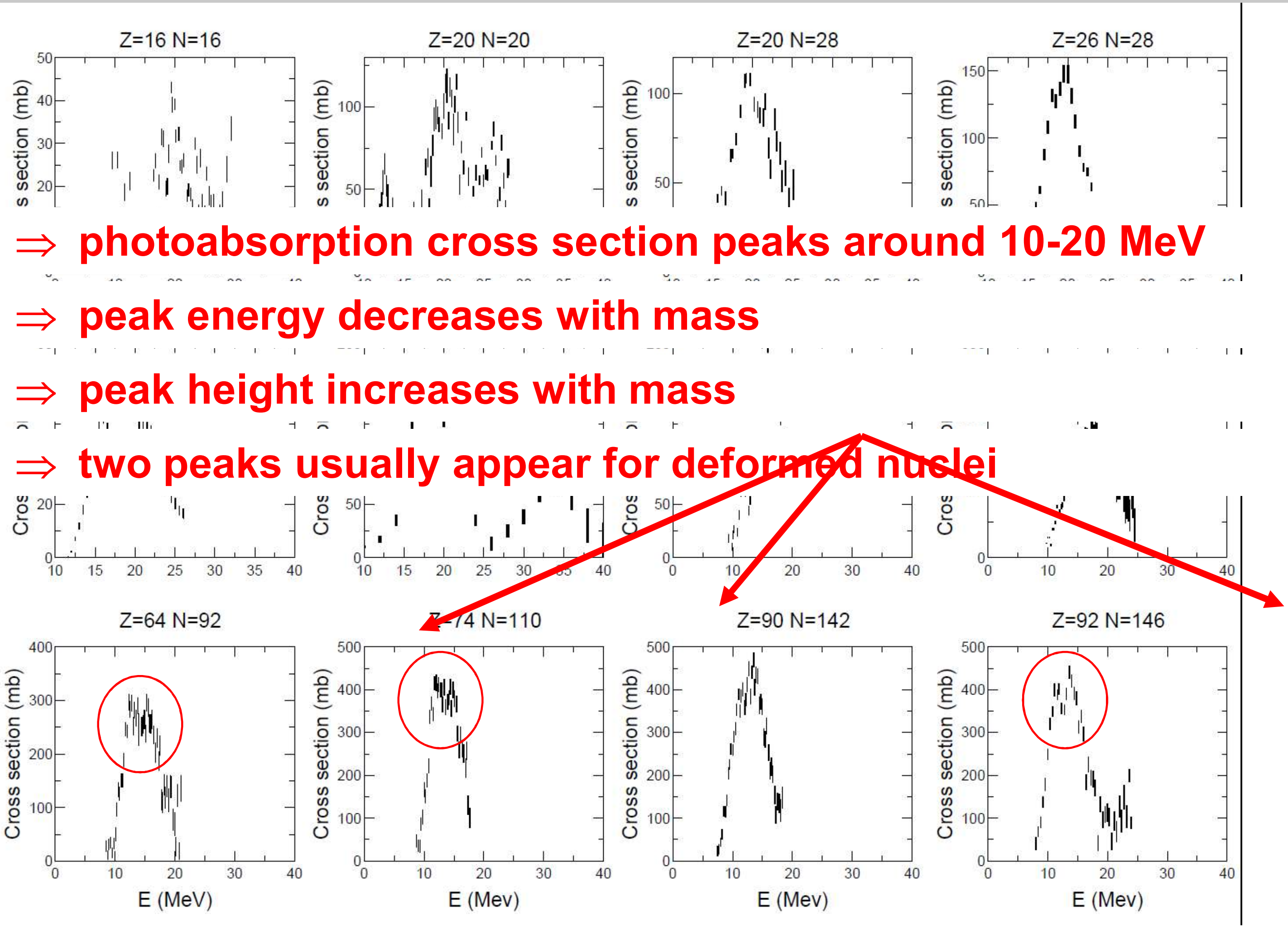

⇒ photoabsorption cross section peaks around 10-20 MeV

⇒ peak energy decreases with mass

⇒ peak height increases with mass

⇒ two peaks usually appear for deformed nuclei

Gamma-ray strengths : Brink-Axel hypothesis

Two types of strength functions :

- the « upward » related to photoabsorption

$$\overrightarrow{f}_{\mathrm{XL}}(\epsilon_\gamma) = \frac{\epsilon_\gamma^{-2L+1}}{(\pi\hbar c)^2}\frac{\langle\sigma_{\mathrm{XL}}(\epsilon_\gamma)\rangle}{2L+1}.$$

- the « downward » related to g-decay

$$\overleftarrow{f}_{\mathrm{XL}}(\epsilon_\gamma) = \epsilon_\gamma^{-(2L+1)}\frac{\langle\Gamma_{\mathrm{XL}}(\epsilon_\gamma)\rangle}{\boxed{D_l}}$$

Spacing of states from which the decay occurs

Standard Lorentzian (SLO)

[D.Brink. PhD Thesis(1955); P. Axel. PR 126(1962)]

$$\overleftarrow{f} = \overrightarrow{f} \sim \frac{E_\gamma \Gamma_r^2}{(E_\gamma^2 - E_r^2)^2 + E_\gamma \Gamma_r^2} \Rightarrow 0 \quad E_\gamma \to 0$$

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Gamma-ray strengths : transmission coefficients

$$T^{k\lambda}(E,\varepsilon_\gamma) = 2\pi\int_{E}^{E+\Delta E} f(k,\lambda,\varepsilon_\gamma)\ \varepsilon_\gamma^{2\lambda+1}\ \rho(E-\varepsilon_\gamma)\ dE$$

k : transition type (E or M)

λ : transition multipolarity

ε_γ : outgoing gamma energy

$\mathbf{f(k,\lambda,\varepsilon_\gamma)}$ **:** gamma strength function (several models)

Decay selection rules $S(k,\lambda,J_i^{\pi i},J_f^{\pi f})$ from a level $J_i^{\pi i}$ to a level $J_f^{\pi f}$:

For Eλ: $\pi_f=(-1)^{\lambda}\ \pi_i$

For Mλ: $\pi_f=(-1)^{\lambda+1}\ \pi_i$

$|J_i-\lambda| \leq J_f \leq J_i+\lambda$

(E1 ≈ 10 – 100 M1)
(XL ≈ 10^{-3} XL-1)

Renormalisation method for thermal neutrons

experiment

$$<T_\gamma> = C \sum_{J_i,\pi_i}\sum_{k\lambda}\sum_{J_f,\pi_f}\int_{0}^{B_n} T^{k\lambda}(\varepsilon)\ \rho(B_n-\varepsilon,J_f,\pi_f)\ S(k,\lambda,J_i,\pi_i,J_i,\pi_f)\ d\varepsilon = 2\pi\ <\Gamma_\gamma>\ \frac{1}{D_0}$$

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Improved analytical expressions :

- 2 Lorentzians for deformed nuclei

- Account for low energy deviations from standard Lorentzians for E1
  - . Kadmenskij-Markushef-Furman model (1983)
    - ⇒ Enhanced Generalized Lorentzian model of Kopecky-Uhl (1990)
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- Update of SMLO in 2019
    - ⇒ Temperature dependence
    - ⇒ Adding extra-M1 strength at low energies
    - ⇒ guided by microscopic results

Gamma-ray strengths : Brink-Axel & Kopecky-Uhl

Brink-Axel *(option 2 in TALYS)*

$$f_{X\ell}(E_\gamma) = K_{X\ell}\frac{\sigma_{X\ell}E_\gamma\Gamma^2_{X\ell}}{(E^2_\gamma - E^2_{X\ell})^2 + E^2_\gamma\Gamma^2_{X\ell}} \quad \text{with} \quad K_{X\ell} = \frac{1}{(2\ell+1)\pi^2\hbar^2c^2}.$$

Kopecky-Uhl (for E1) *(option 1 in TALYS)*

$$f_{E1}(E_\gamma, T) = K_{E1}\left[\frac{E_\gamma\tilde{\Gamma}_{E1}(E_\gamma)}{(E^2_\gamma - E^2_{E1})^2 + E^2_\gamma\tilde{\Gamma}_{E1}(E_\gamma)^2} + \frac{0.7\Gamma_{E1}4\pi^2T^2}{E^3_{E1}}\right]\sigma_{E1}\Gamma_{E1}$$

$$\text{with} \quad \tilde{\Gamma}_{E1}(E_\gamma) = \Gamma_{E1}\frac{E^2_\gamma + 4\pi^2T^2}{E^2_{E1}} \quad \text{and} \quad T = \sqrt{\frac{E_n + S_n - \Delta - E_\gamma}{a(S_n)}}$$

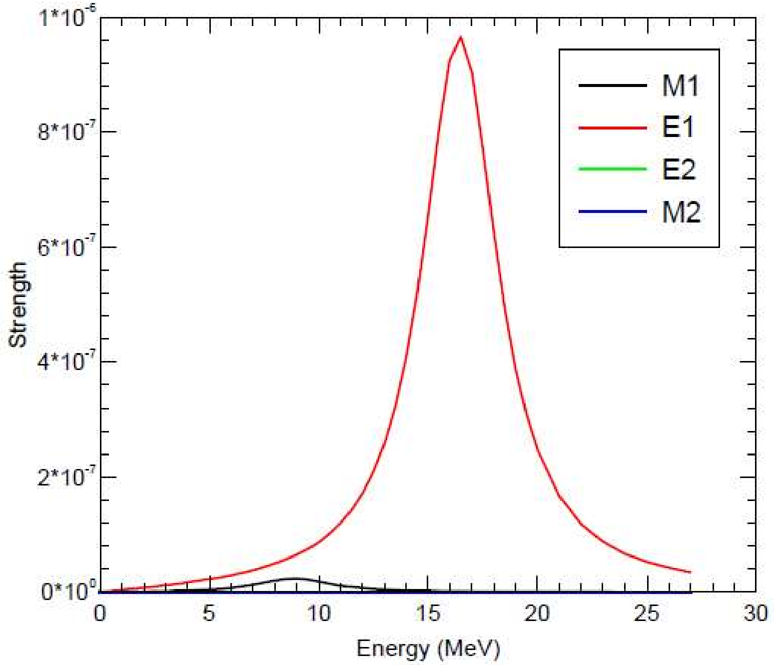
⇒ Deformed nuclei : incoherent sum of two Lorentzians
⇒ Parameters taken from experimental fit of data (RIPL-III) for measured nuclei
⇒ From global systematics otherwise

$$\sigma_{E1} = 1.2\times120NZ/(A\pi\Gamma_{E1})\ \text{mb}, \quad E_{E1} = 31.2A^{-1/3}+20.6A^{-1/6}\ \text{MeV}, \quad \Gamma_{E1} = 0.026E^{1.91}_{E1}\ \text{MeV}.$$

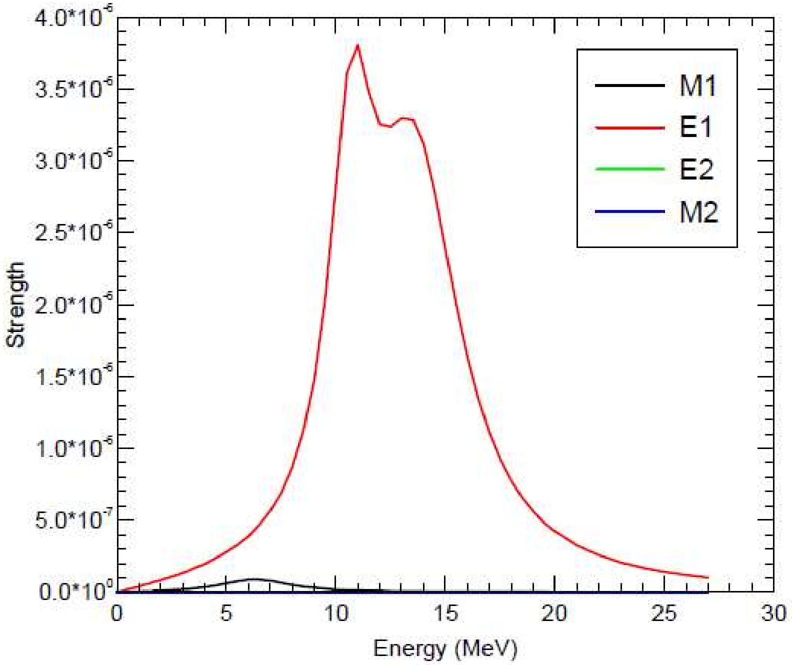
$$\sigma_{E2} = 0.00014Z^2E_{E2}/(A^{1/3}\Gamma_{E2})\ \text{mb}, \quad E_{E2} = 63.A^{-1/3}\ \text{MeV}, \quad \Gamma_{E2} = 6.11 - 0.012A\ \text{MeV}.$$

Gamma-ray strengths : Brink-Axel

^{90}Zr (spherical)

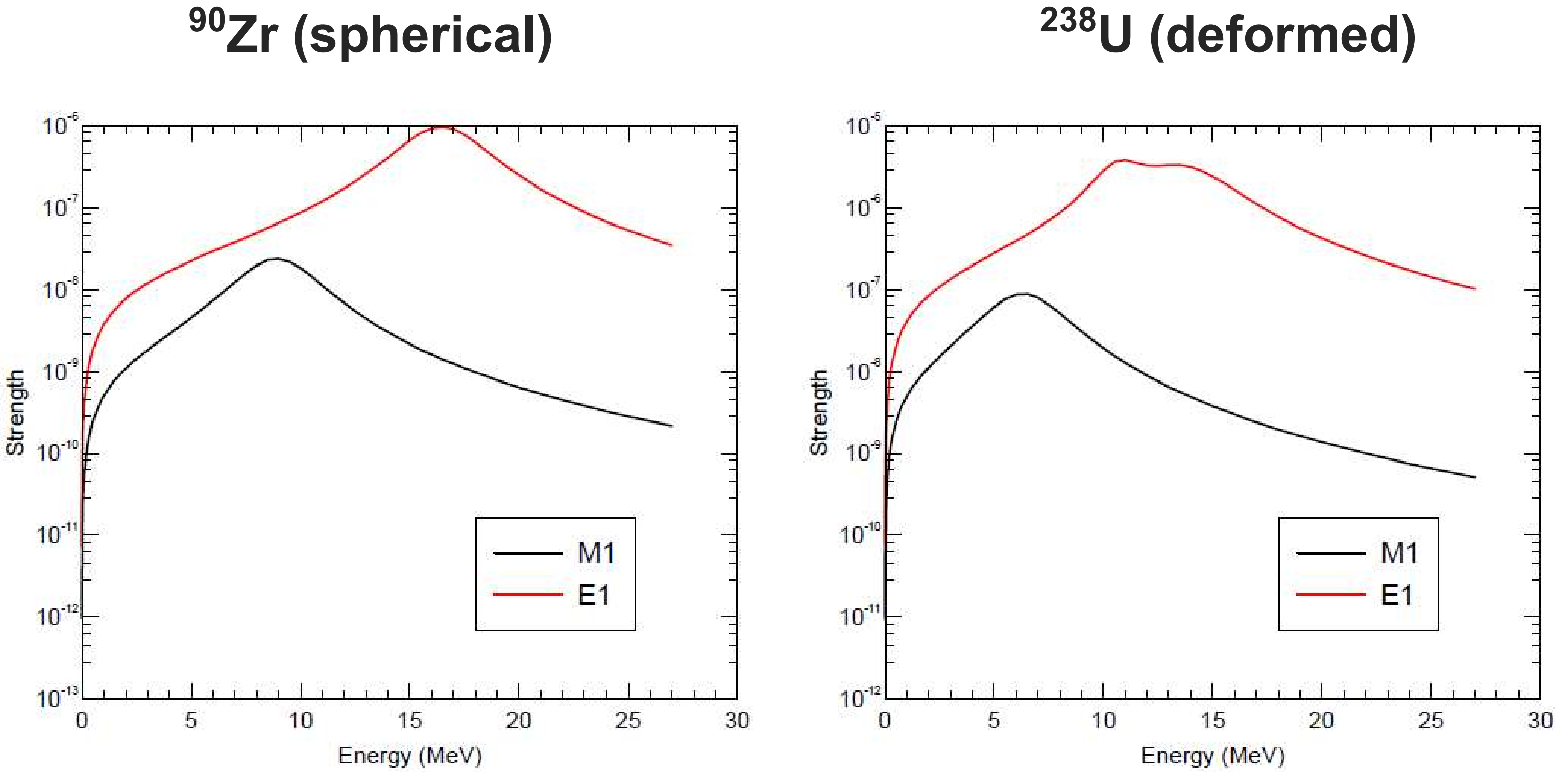


^{238}U (deformed)



⇒ Deformed nuclei : two Lorentzians = two peaks
⇒ Lorentzian centroid energy decreasing with A
⇒ M1 much weaker than E1 ⇒**log scale**

Gamma-ray strengths : Brink-Axel in log scale



^{90}Zr (spherical)

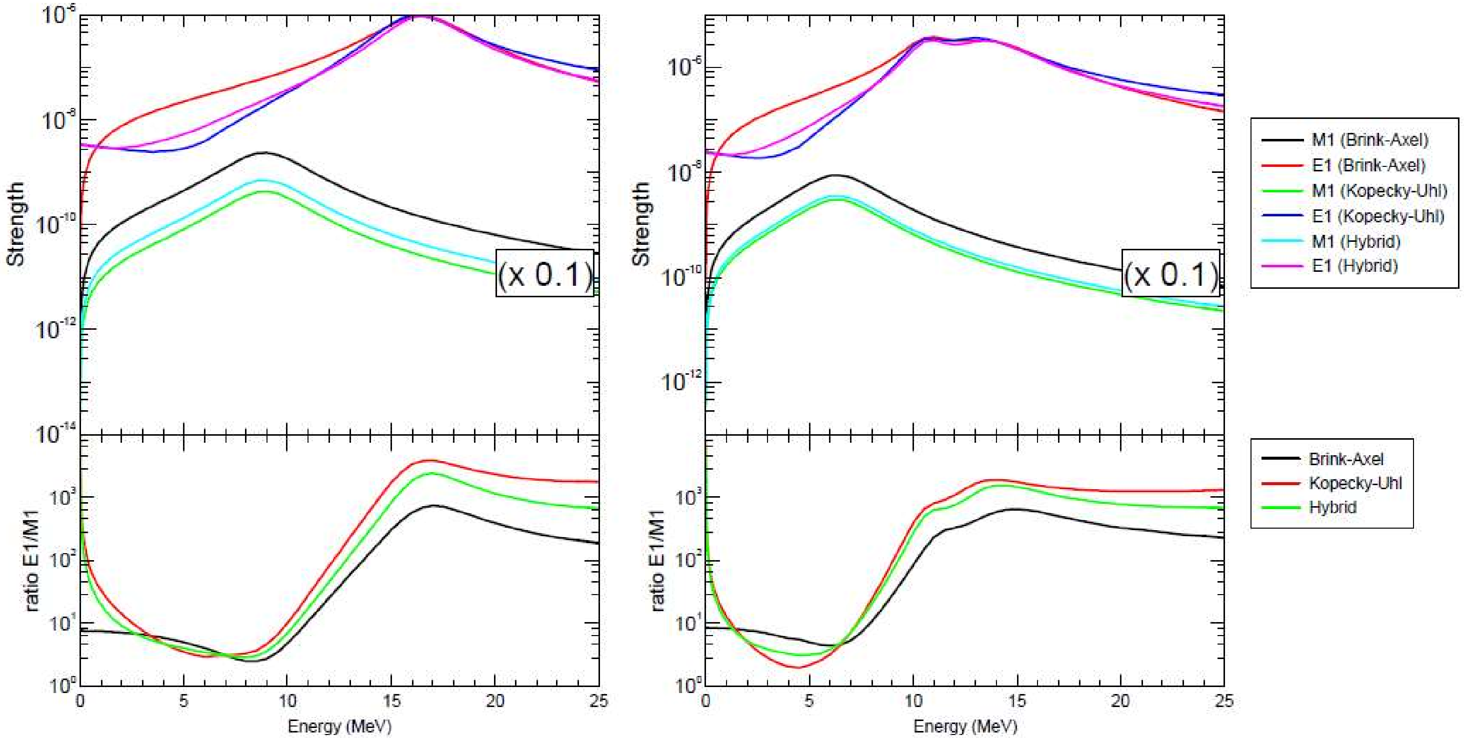
^{238}U (deformed)

⇒ Deformed nuclei : two Lorentzians = two peaks

⇒ Lorentzian centroid energy decreasing with A

⇒ Strength → 0 for E → 0 (ok for gamma absorption but not for gamma decay)

Gamma-ray strengths : various models in TALYS



^{90}Zr (spherical)

^{238}U (deformed)

⇒ Deformed nuclei : two Lorentzians = two peaks

⇒ Lorentzian centroid energy decreasing

⇒ E1 = (10 – 100) M1 « where it counts »

⇒ Kopecky-Uhl or Hybrid model correct low energy behavior of Brink-Axel when considering gamma decay rather than gamma absorption

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⇒ Many choices and parameters : extrapolation at your own risks !

- Re

Except maybe the latest SMLO !

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Gamma-ray strengths : SMLO 2019

The newly proposed Simplified M1 Lorentzian Model (SMLO)

$$\overrightarrow{f_{M1}}(\varepsilon_\gamma) = \frac{1}{3\pi^2\hbar^2c^2}\sigma_{sc}\frac{\varepsilon_\gamma\,\Gamma_{sc}^2}{(\varepsilon_\gamma^2 - E_{sc}^2)^2+\varepsilon_\gamma^2\Gamma_{sc}^2}$$

Scissors mode for deformed nuclei

$$+\frac{1}{3\pi^2\hbar^2c^2}\sigma_{sf}\frac{\varepsilon_\gamma\,\Gamma_{sf}^2}{(\varepsilon_\gamma^2 - E_{sf}^2)^2+\varepsilon_\gamma^2\Gamma_{sf}^2}$$

Spin-Flip mode

where the SMLO M1 properties are inspired from the D1M+QRPA predictions

$$\overleftarrow{f_{M1}}(\varepsilon_\gamma) = \overrightarrow{f_{M1}}(\varepsilon_\gamma) + C\exp(-\eta\varepsilon_\gamma)$$

M1 upbend for de-excitation

where the upbend properties are inspired from the Shell Model predictions

$C = 3.5\ 10^{-8}\exp(-6\beta_2)\ \mathrm{MeV}^{-3}$

$\eta = 0.8$

Schwengner et al. 2017
Sieja 2017
Midtbø et al. 2018
...

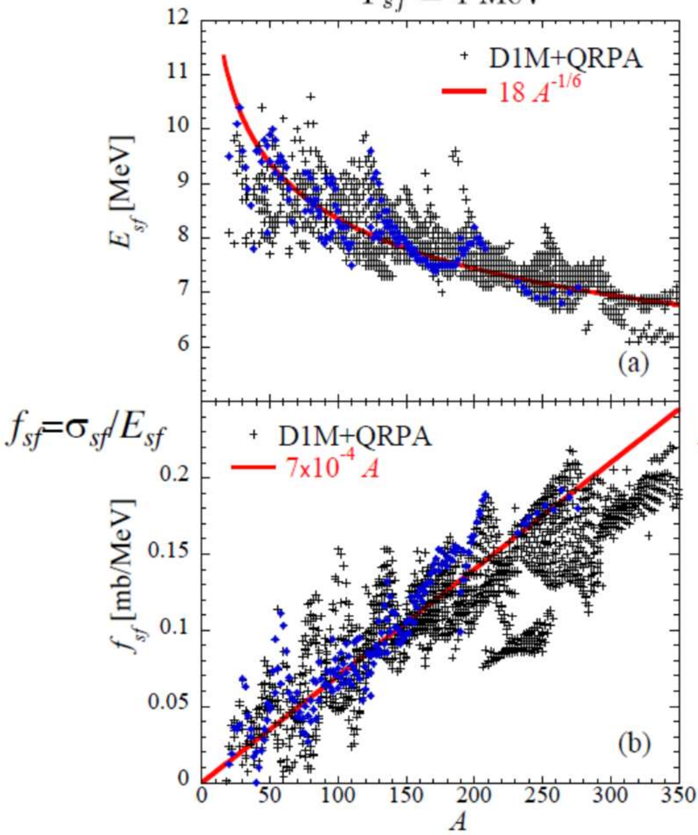
Gamma-ray strengths : SMLO 2019

Spin-Flip mode

$$\sigma_{sf} = 0.03 A^{5/6} \text{ mb}$$

$$E_{sf} = 18 A^{-1/6} \text{ MeV}$$

$$\Gamma_{sf} = 4 \text{ MeV}$$



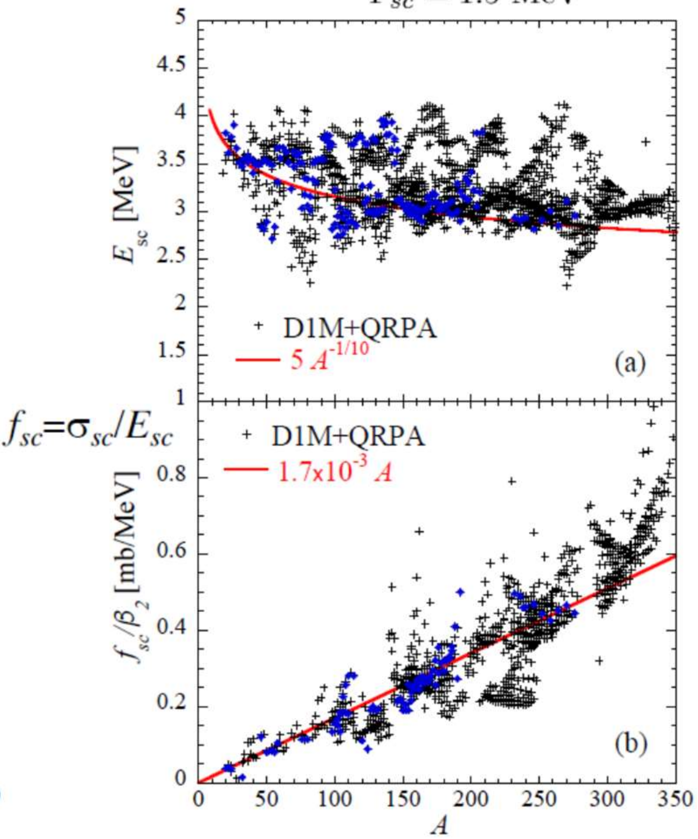
$f_{sf}=\sigma_{sf}/E_{sf}$

Scissors mode

$$\sigma_{sc} = 10^{-2} |\beta_2| A^{9/10} \text{ mb}$$

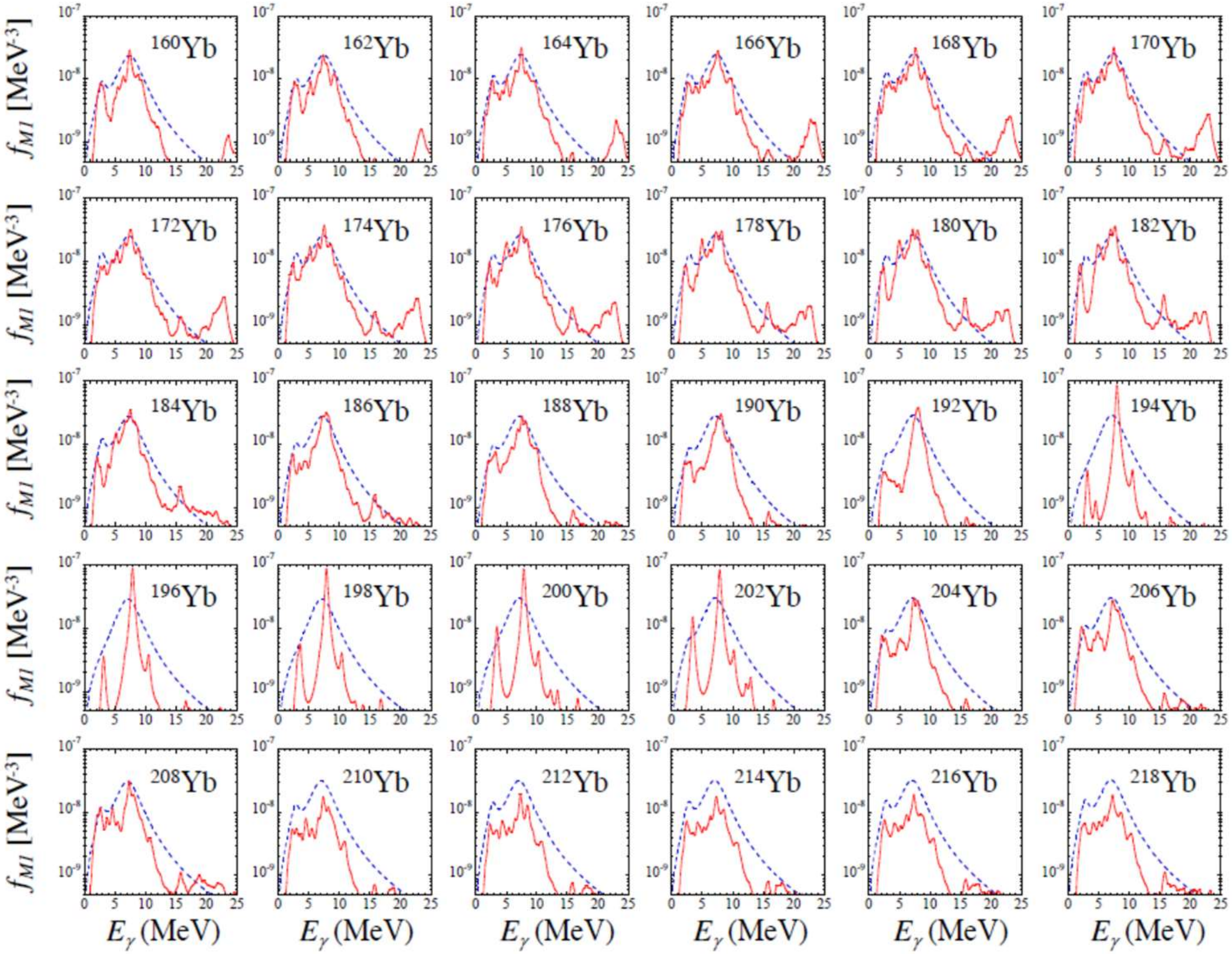
$$E_{sc} = 5 \times A^{-1/10} \text{ MeV}$$

$$\Gamma_{sc} = 1.5 \text{ MeV}$$



$f_{sc}=\sigma_{sc}/E_{sc}$

Gamma-ray strengths : SMLO 2019



Gamma-ray strengths

- Qualitative features

- Analytical approaches

- Microscopic approaches

- HFBCS-RPA
- HFB+QRPA
- Shell Model

- Impacts on cross sections

- Normalizations
- Exotic nuclei
- Hot topics

Gamma-ray strengths

- Qualitative features

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Gamma-ray strengths : microscopic approaches

Systematic approaches : all nuclei feasible

« *Those who know what is (Q)RPA don't care about details,*
those who don't know don't care either », private communication

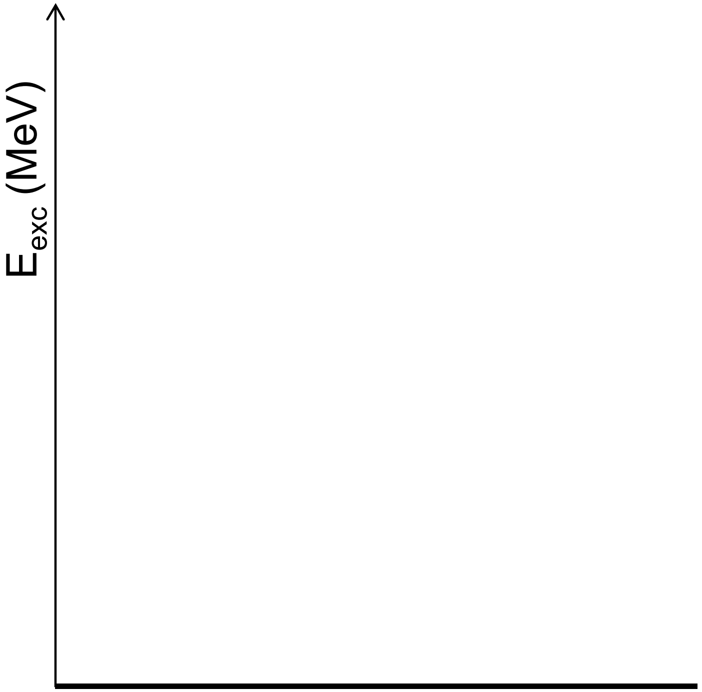
⇒ Systematic QRPA with Skm/RMF forces

⇒ Systematic QRPA with Gogny force

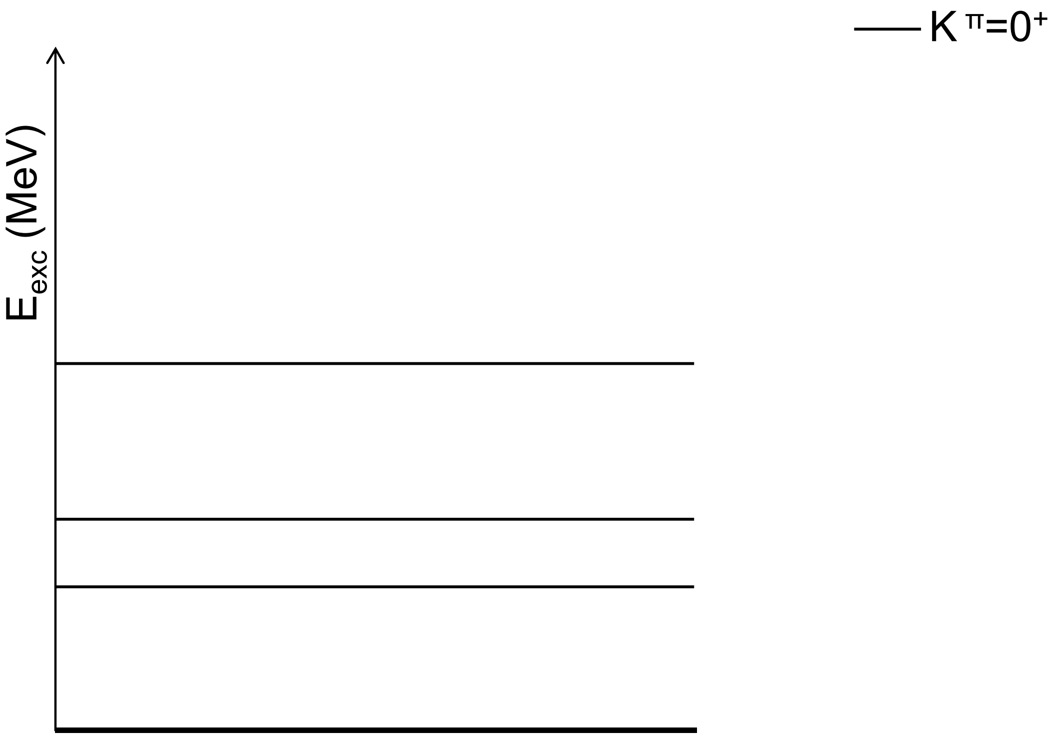
Local approaches : regional study only

⇒ Shell Model approach

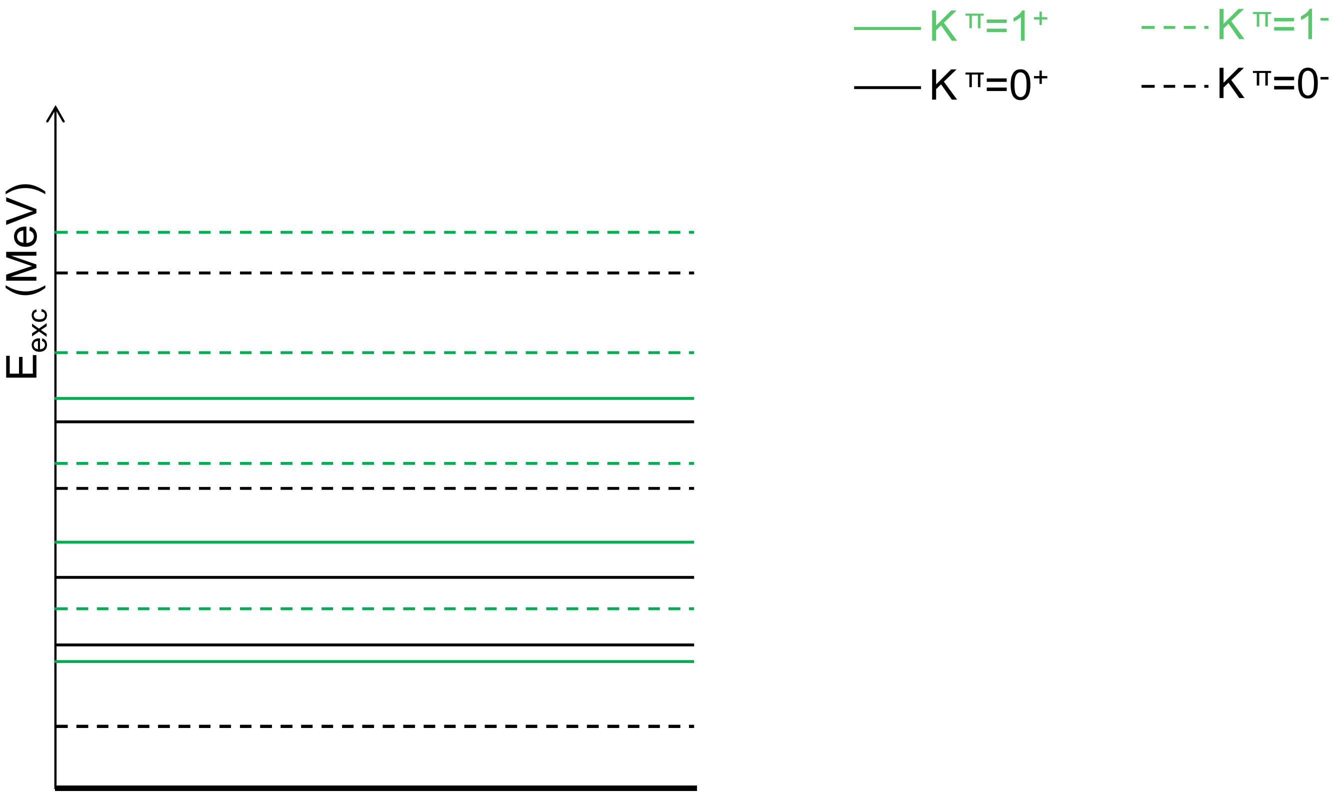
Gamma-ray strengths : microscopic approaches principle



Gamma-ray strengths : microscopic approaches principle

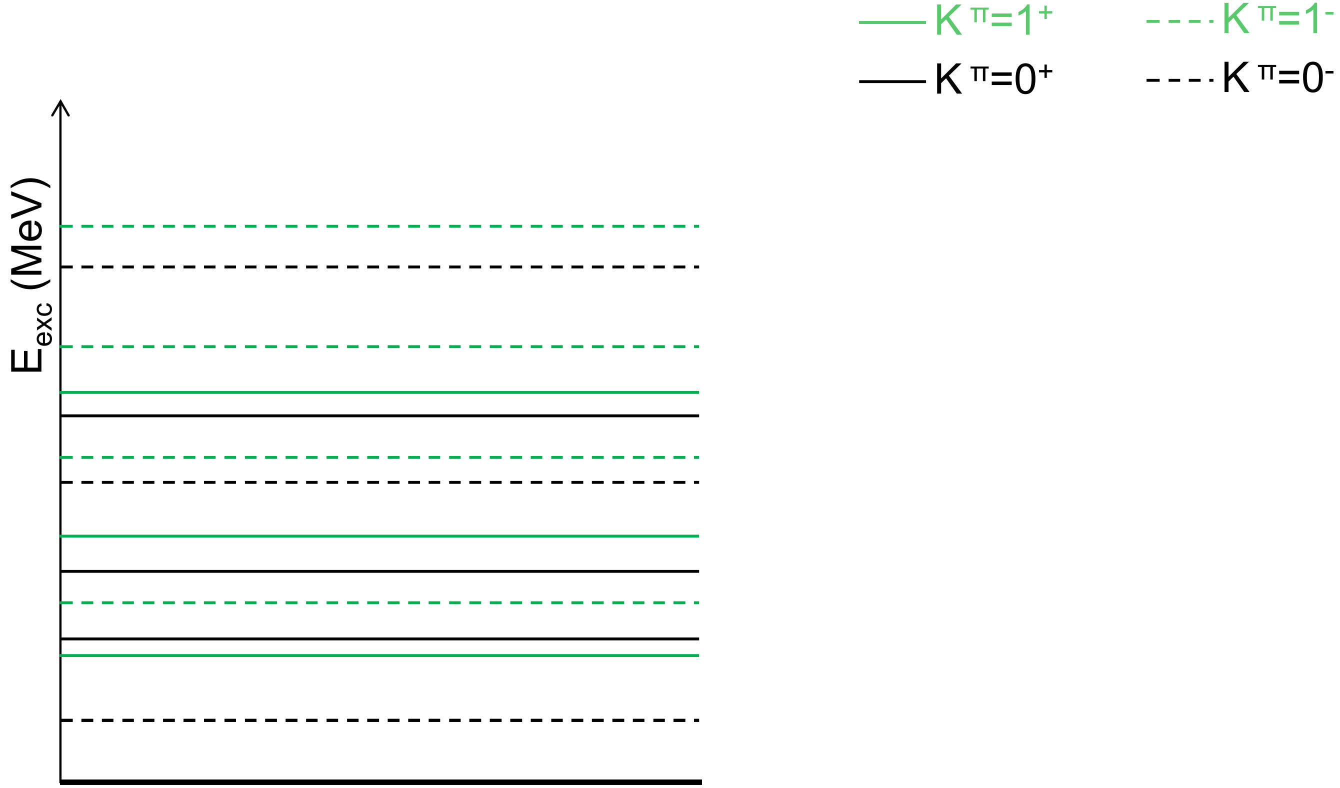


Gamma-ray strengths : microscopic approaches principle



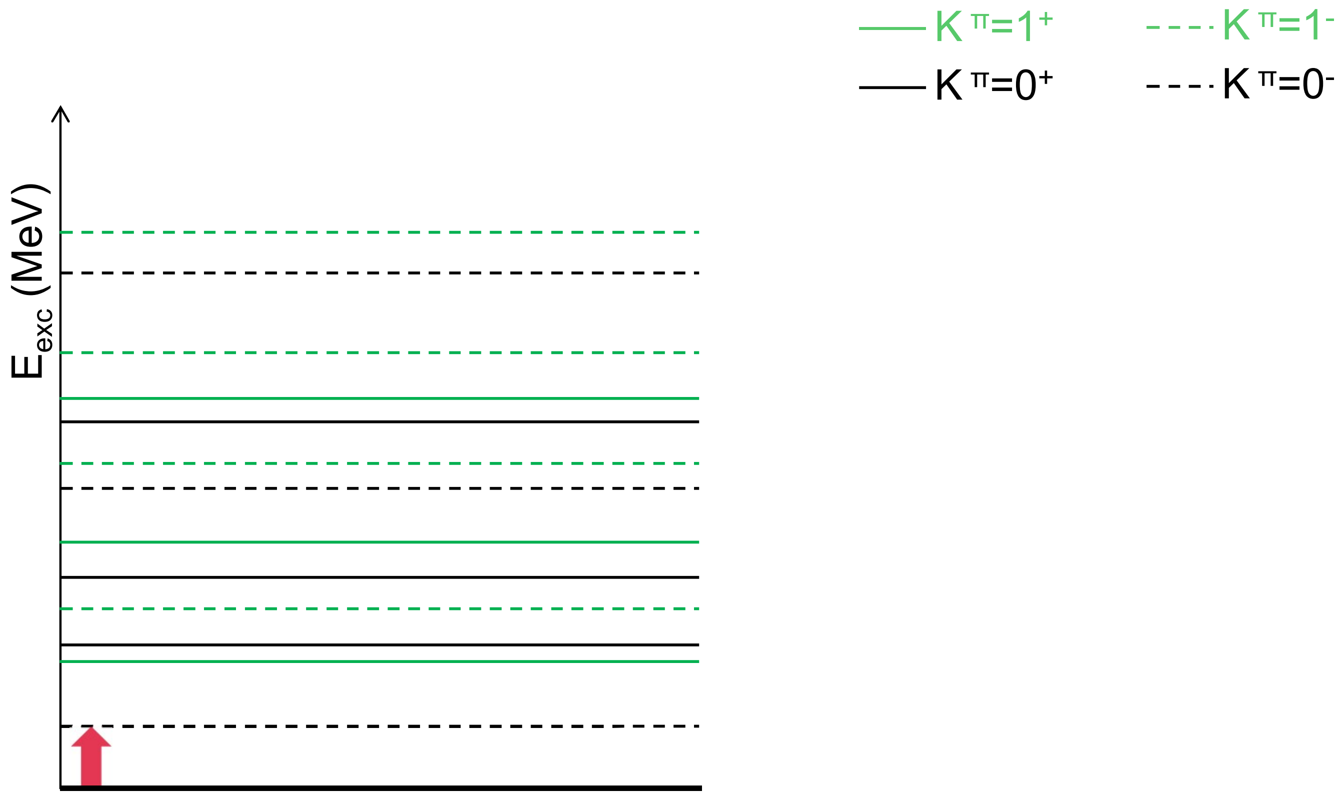
Gamma-ray strengths : microscopic approaches principle

Photoabsorption : E1 transitions dominate $0^+ \Rightarrow 0^-, 1^-$



Gamma-ray strengths : microscopic approaches principle

Photoabsorption : E1 transitions dominate $0^{+} \Rightarrow 0^{-}, 1^{-}$



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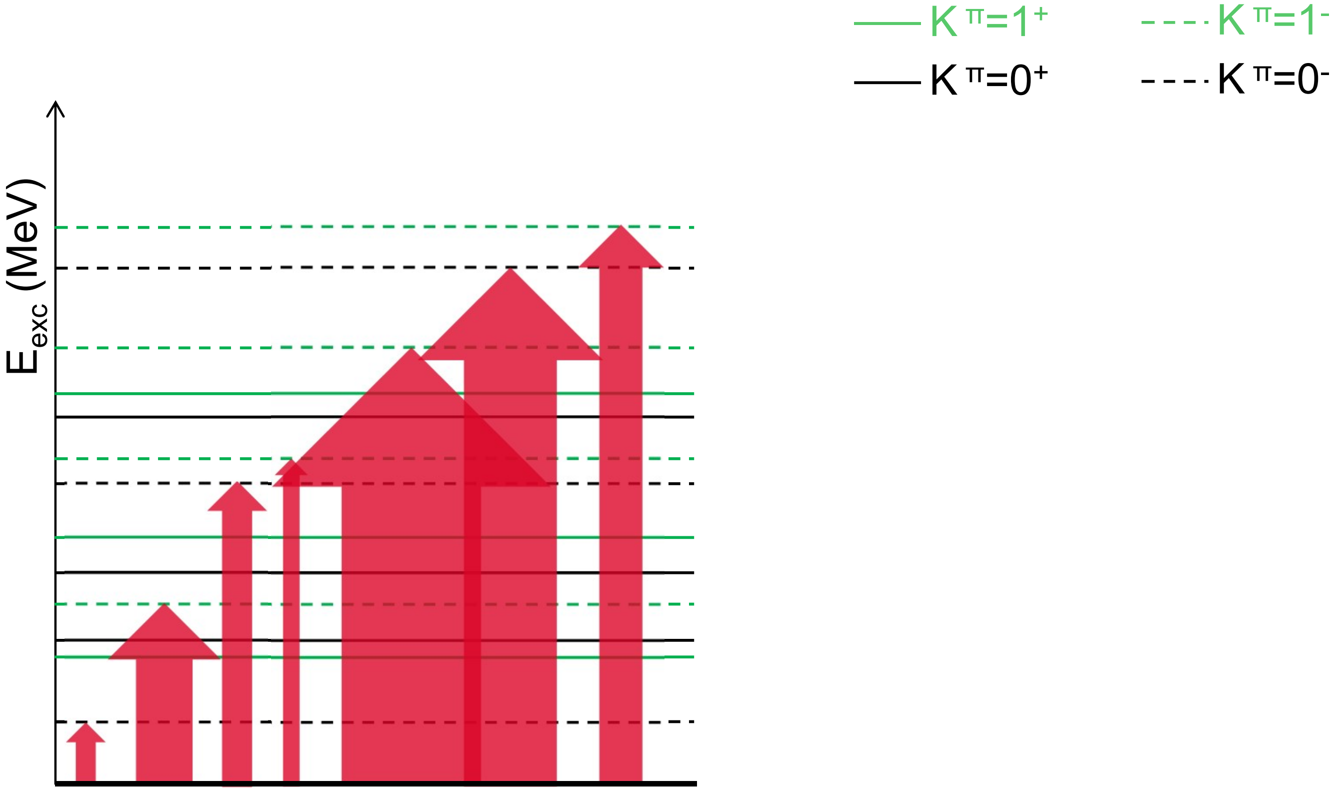

Gamma-ray strengths : microscopic approaches principle

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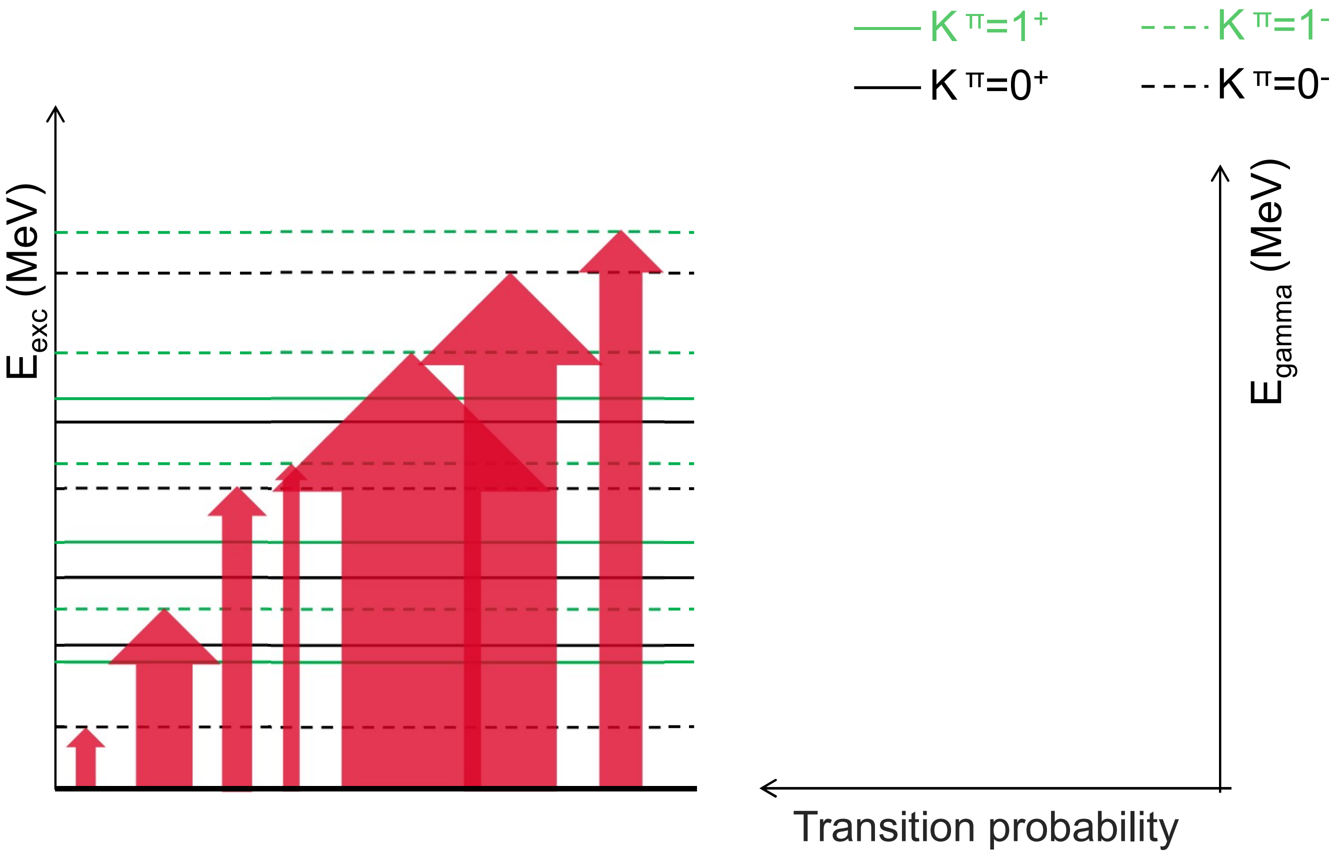

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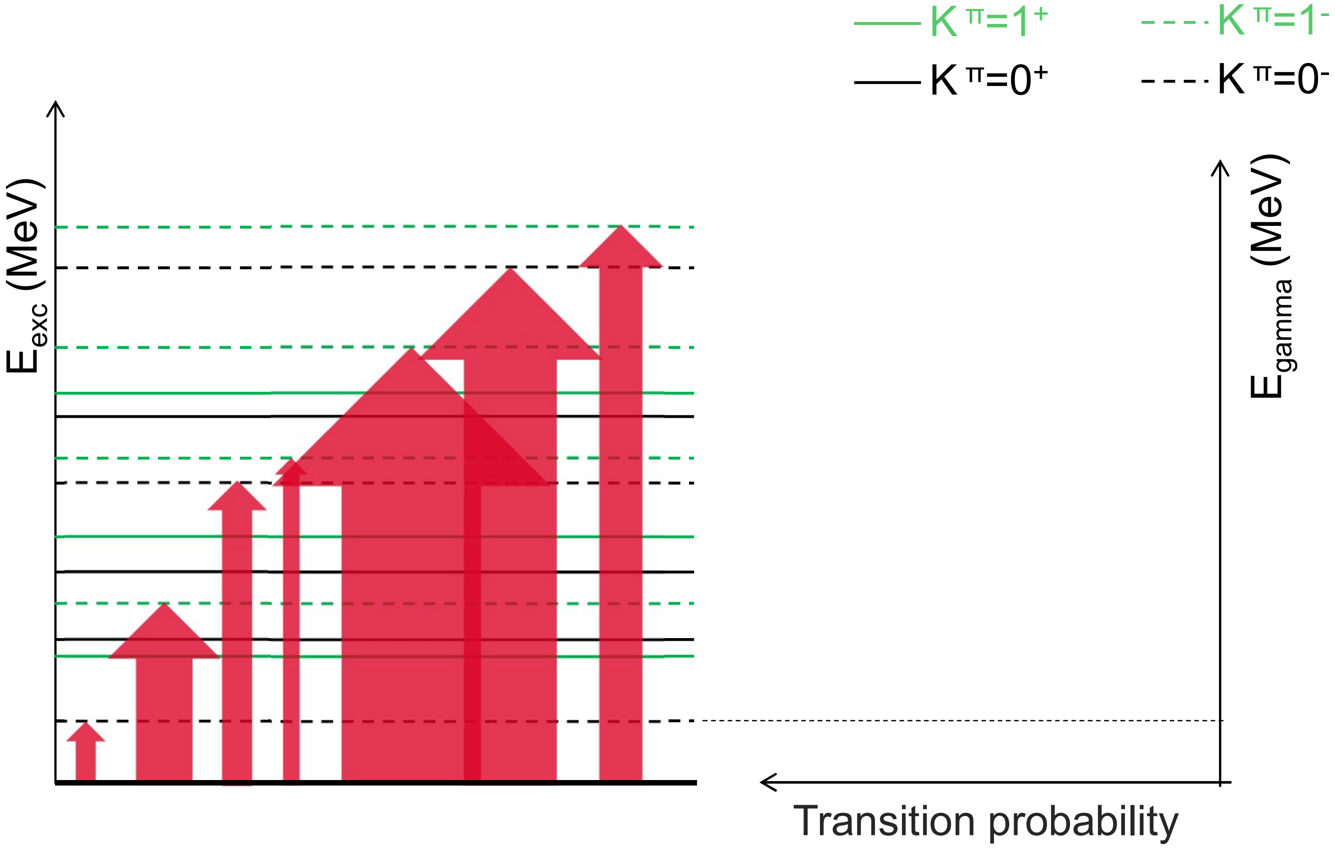

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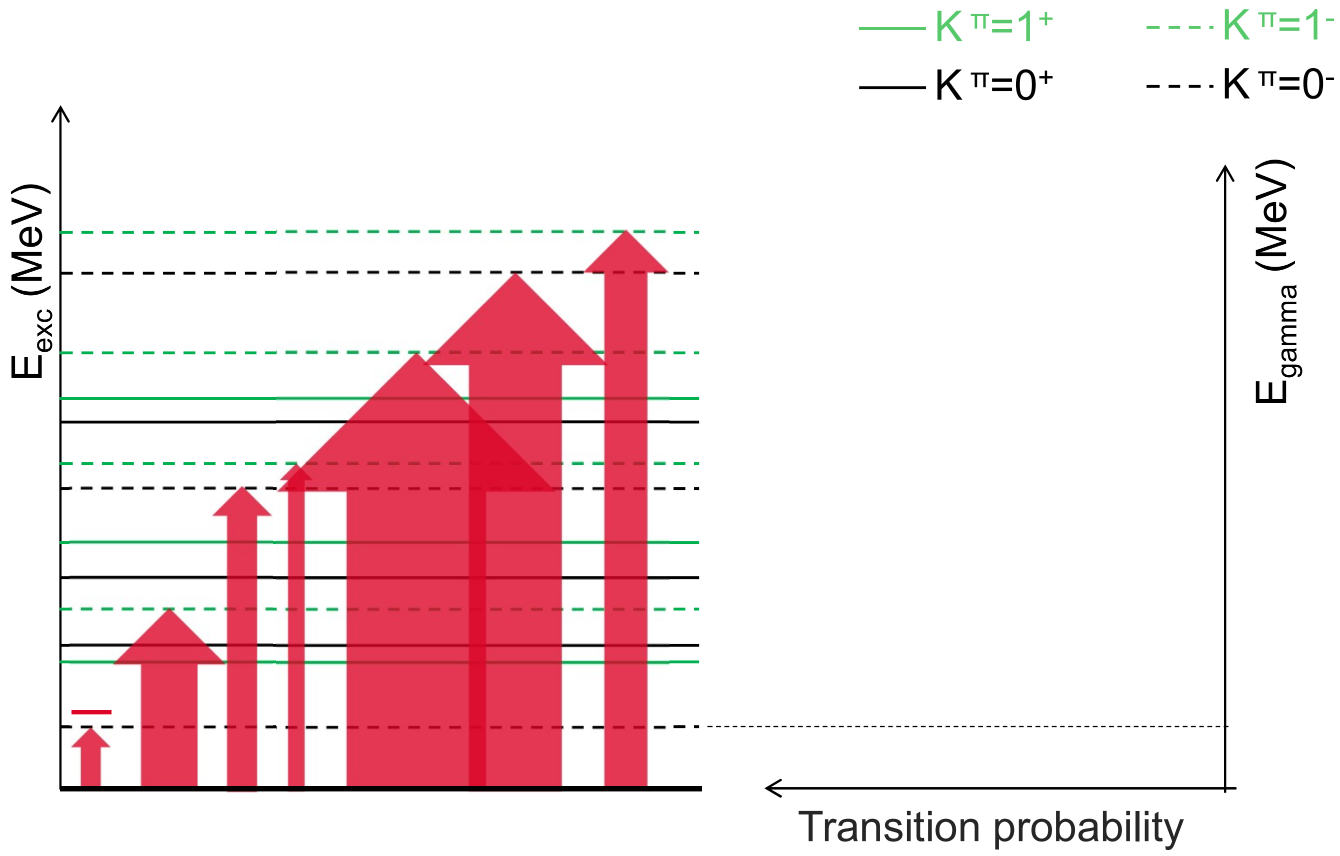

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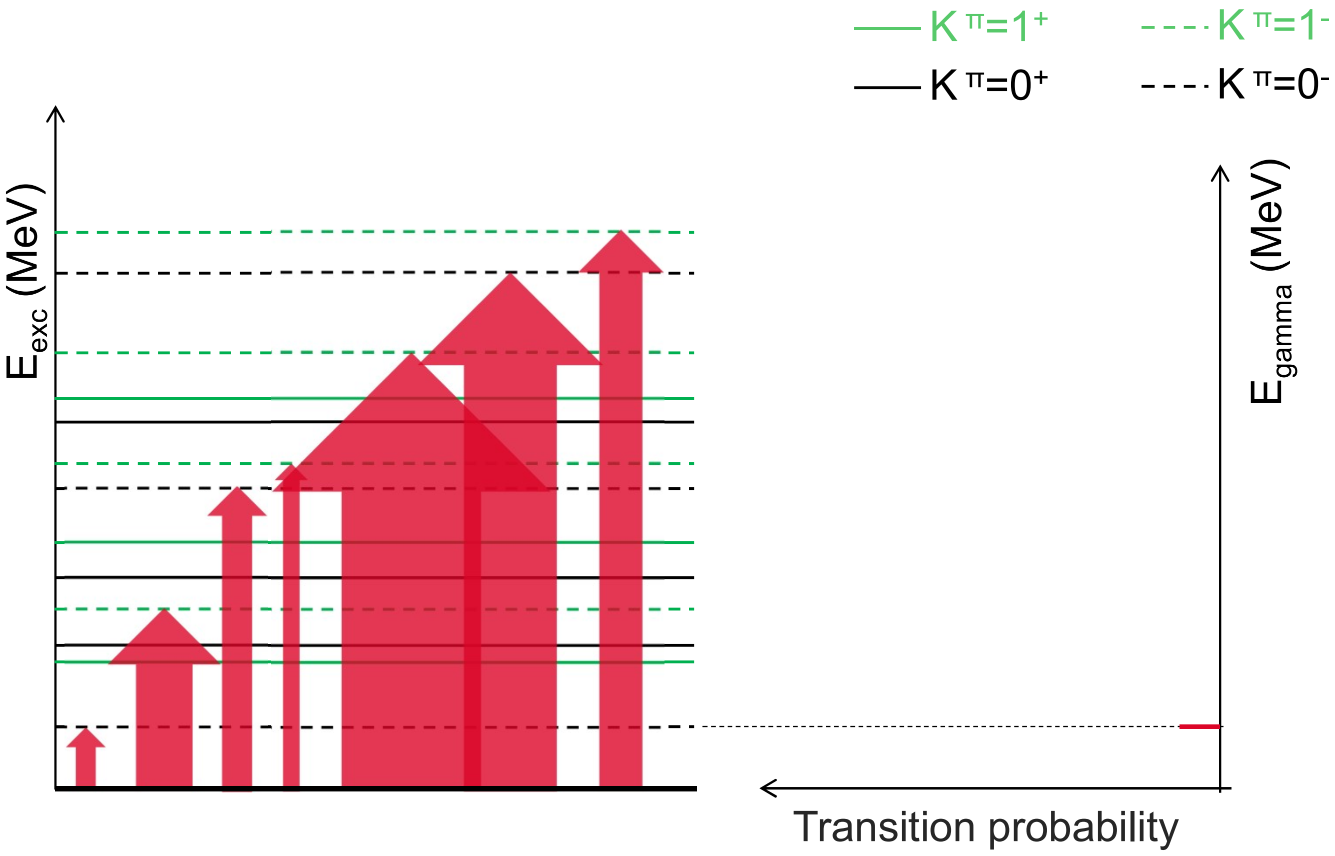

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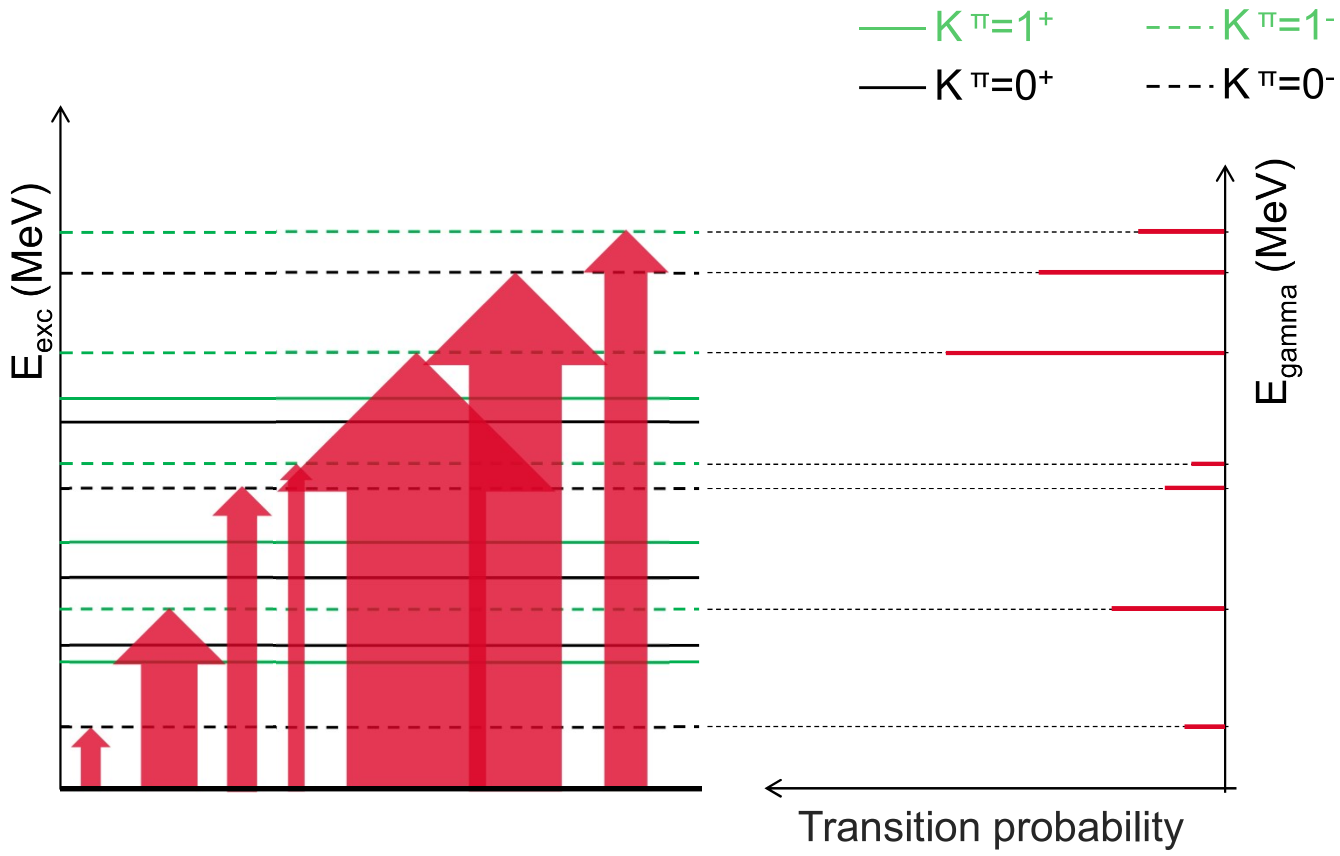

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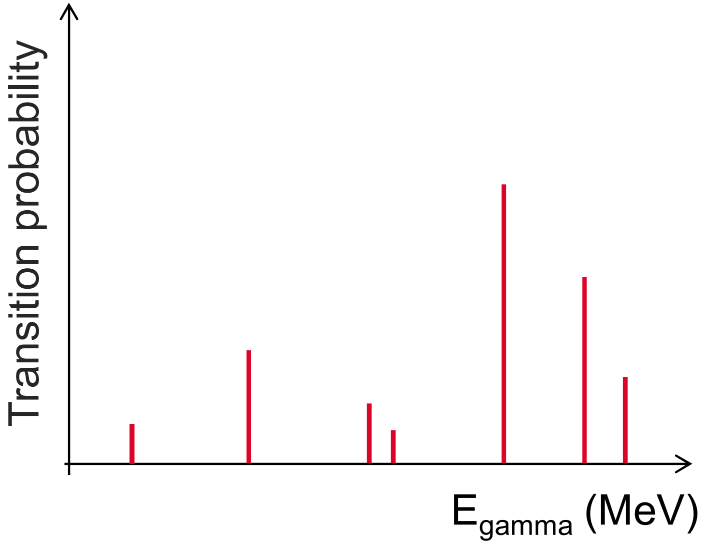
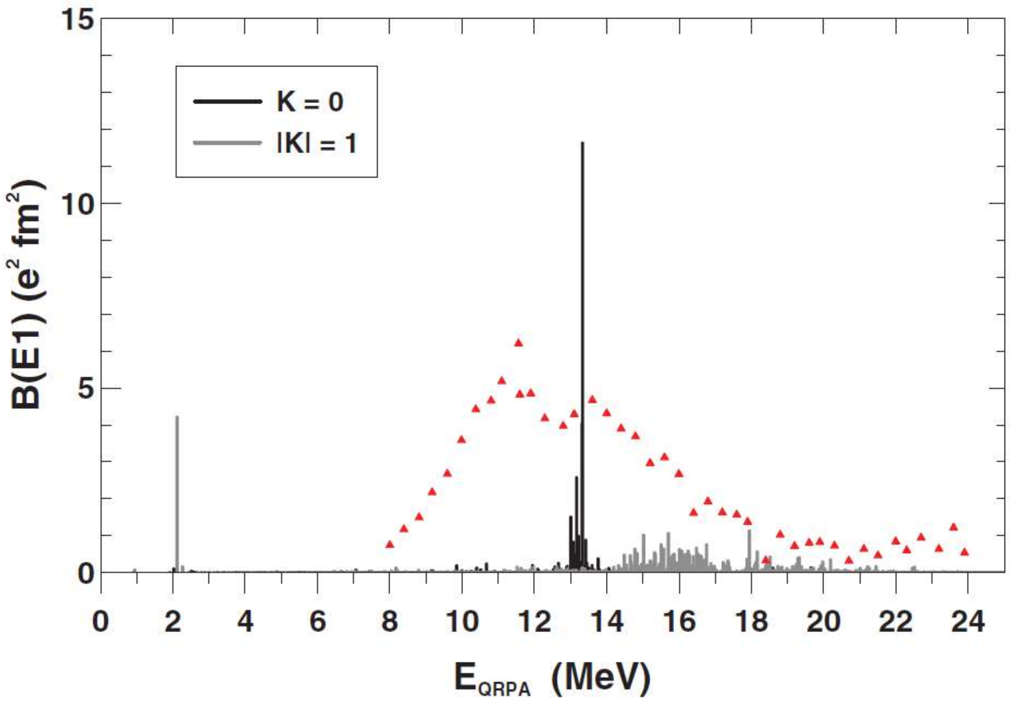


+ Broadening with a Lorentzian

$$S_{E_1}(E) = \sum_i \frac{1}{\pi} \frac{\Gamma\, E^2}{[E^2 - (\omega_i - \Delta(\omega_i))^2]^2 + \Gamma^2 E^2} B_{E_1}(\omega_i)$$

Gamma-ray strengths : microscopic approaches principle

Photoabsorption : E1 transitions dominate $0^+ \Rightarrow 0^-, 1^-$



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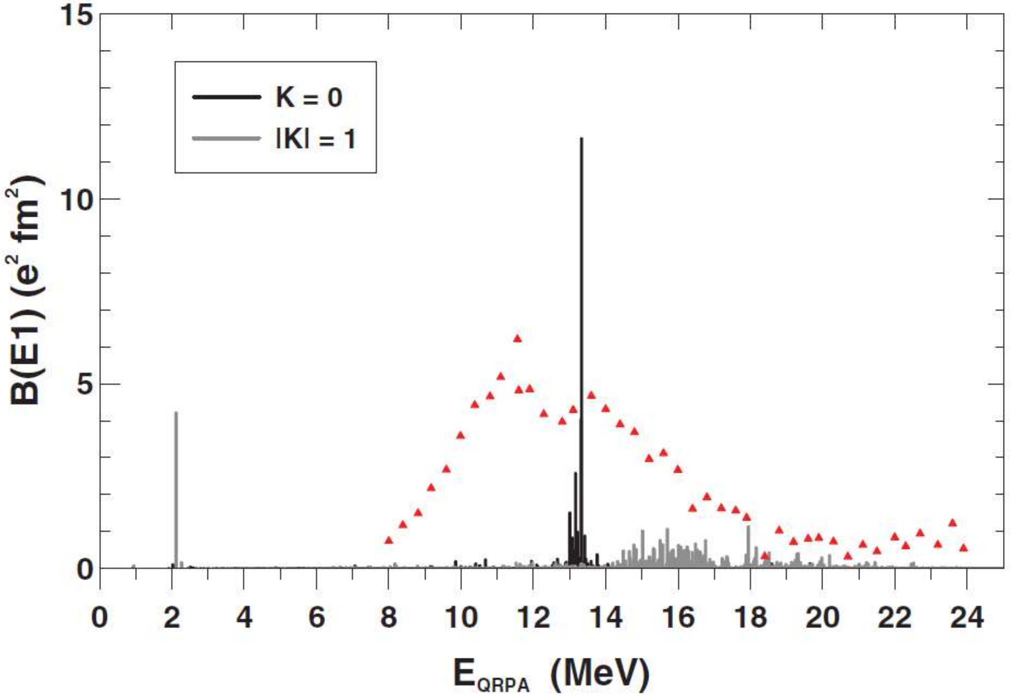

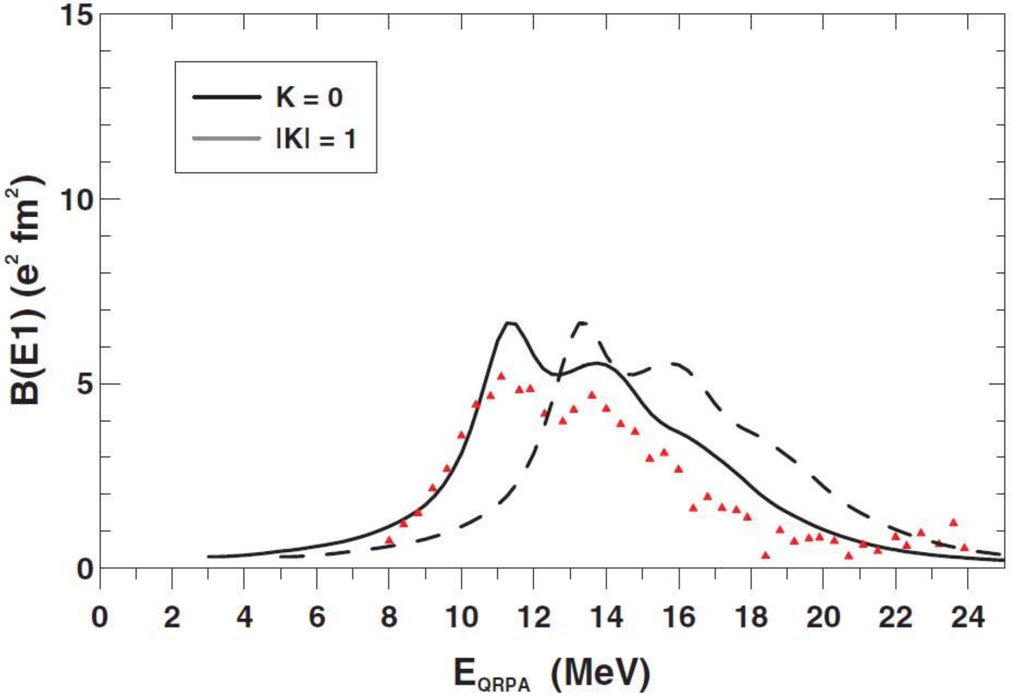

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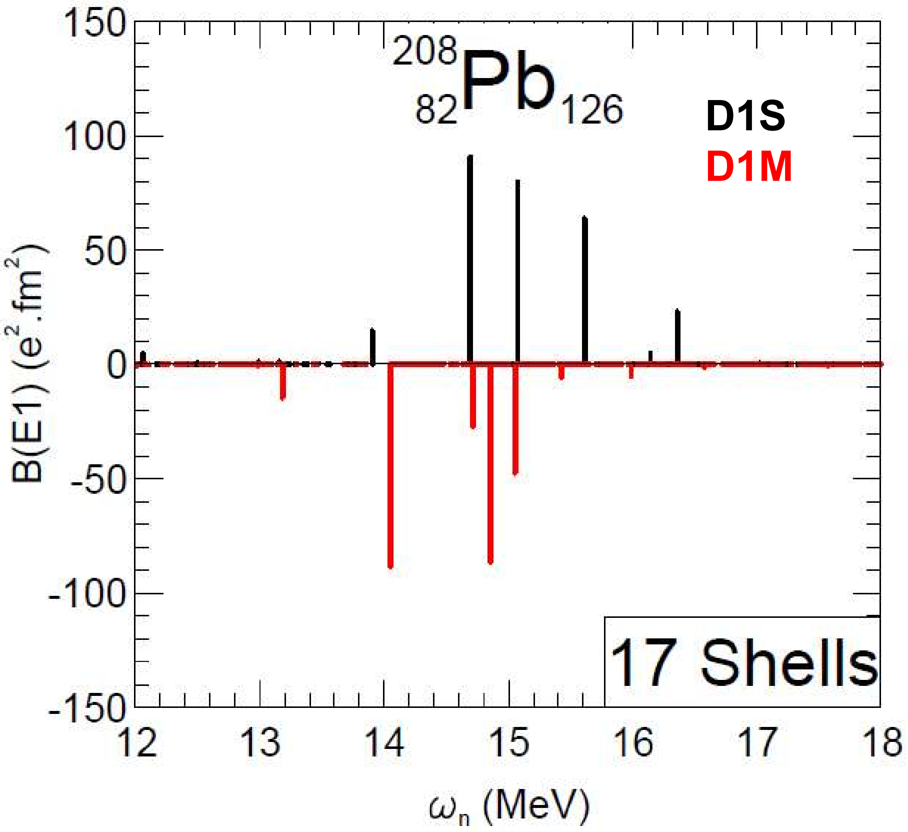
Gamma-ray strengths : QRPA raw results

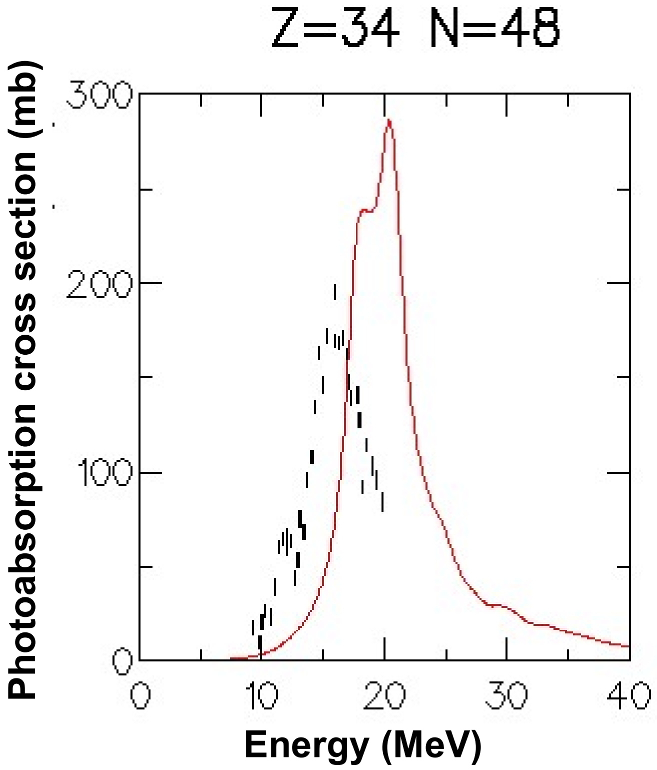
QRPA provides with emission probability between an excited state and the GS



⇒ Broadening necessary to account for damping of collective motion

Gamma-ray strengths : QRPA broadened results

QRPA provides with emission probability between an excited state and the GS



⇒ Shift to account for phonon couplings + beyond 1p-1h approximation
⇒ Peak normalization to improve experimental data fitting

Gamma-ray strengths : QRPA peak normalization

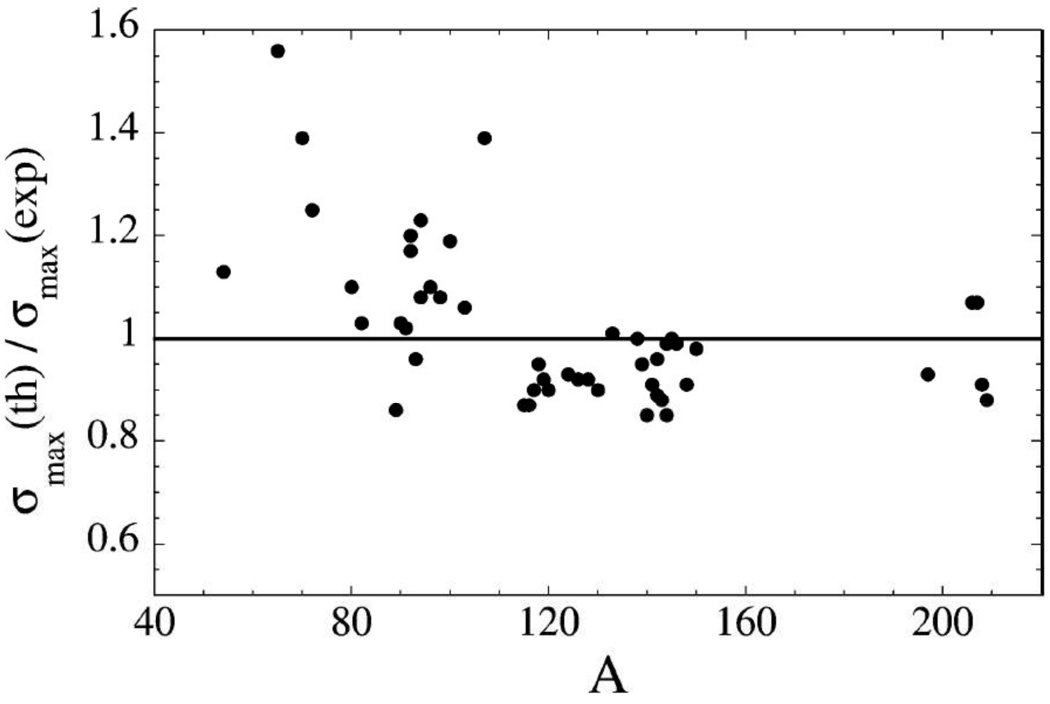


Fig. 4. Ratio of the peak cross section $\sigma_{\max}(\text{th})$ estimated within the HFB + QRPA model with the BSk7 Skyrme force to the experimental value $\sigma_{\max}(\text{exp})$ for the 48 spherical nuclei as a function of the mass number A.

See S. Goriely & E. Khan, NPA 706 (2002) 217.
S. Goriely et al., NPA739 (2004) 331.

Gamma-ray strengths : deformed nuclei

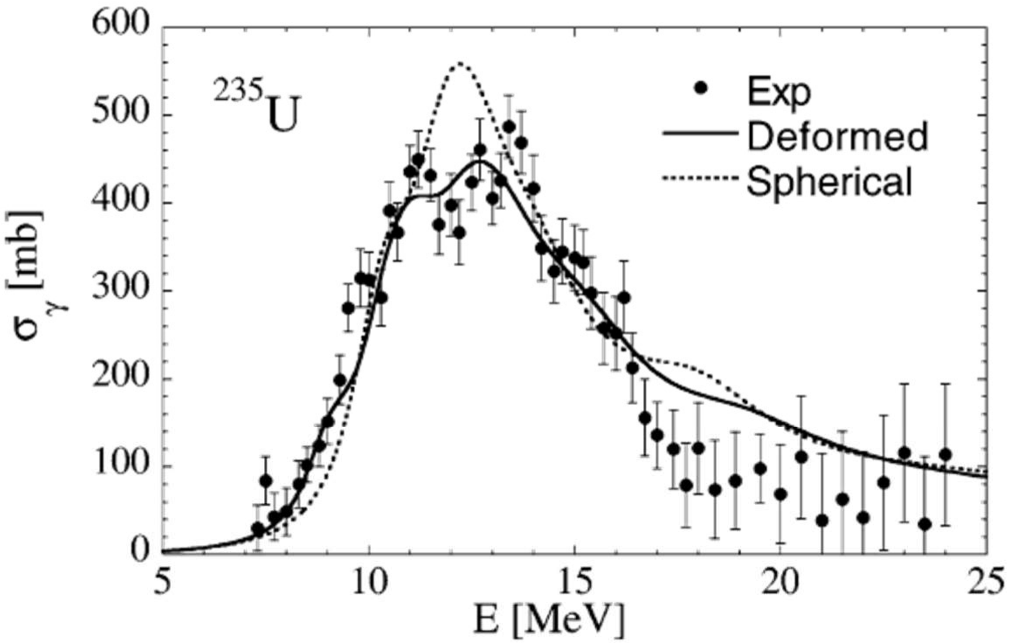
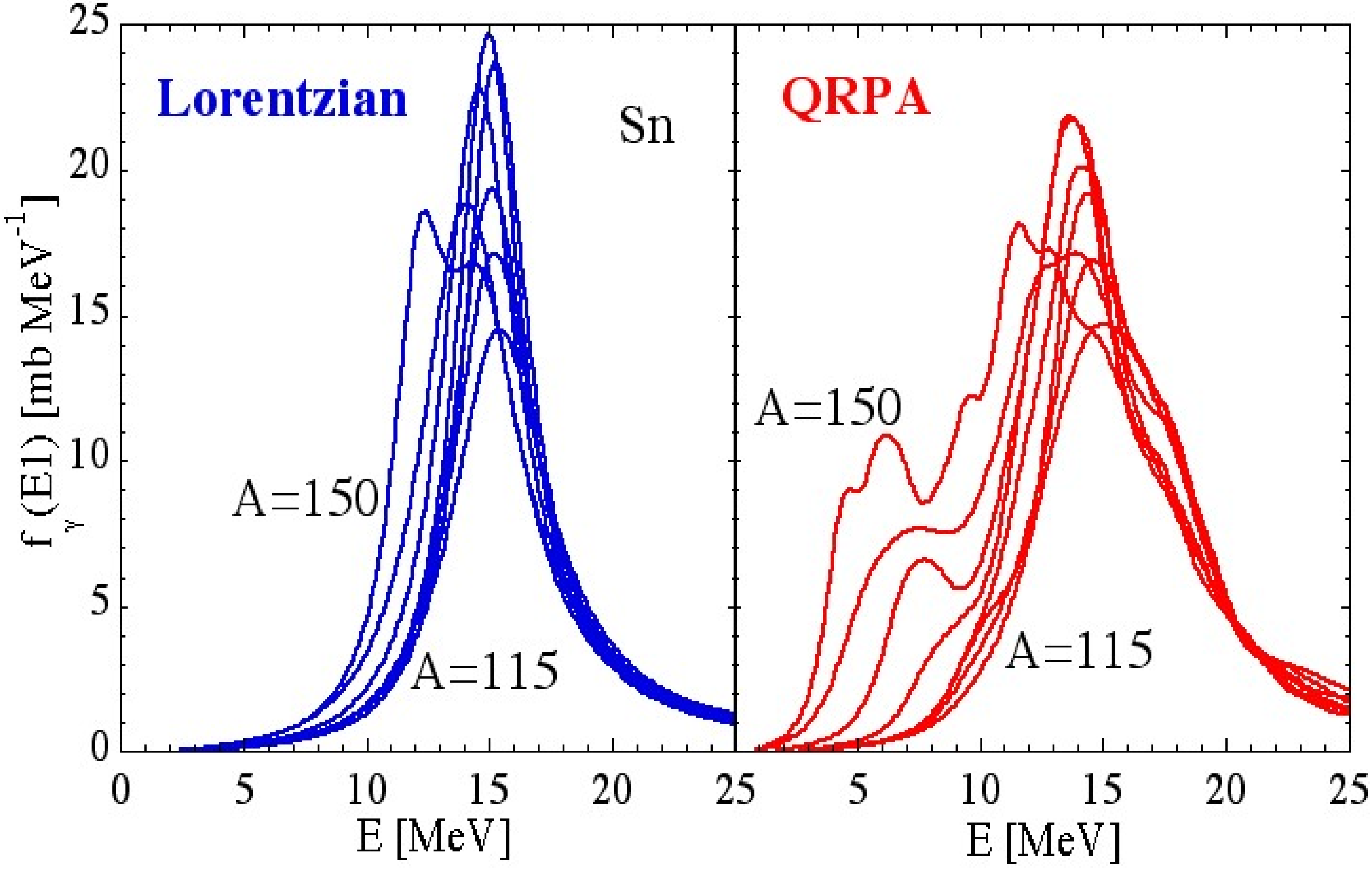


Fig. 5. Photoabsorption cross section for ^{235}U. The dots correspond to experimental data [16]. The dotted line is the HFB + QRPA calculation obtained with the BSk7 force in the spherical approximation (applying the damping method) and the full line when applying in addition our phenomenological procedure to describe deformation effects. Both cross sections have been shifted by 0.5 MeV upwards to reproduce the low energy tail.

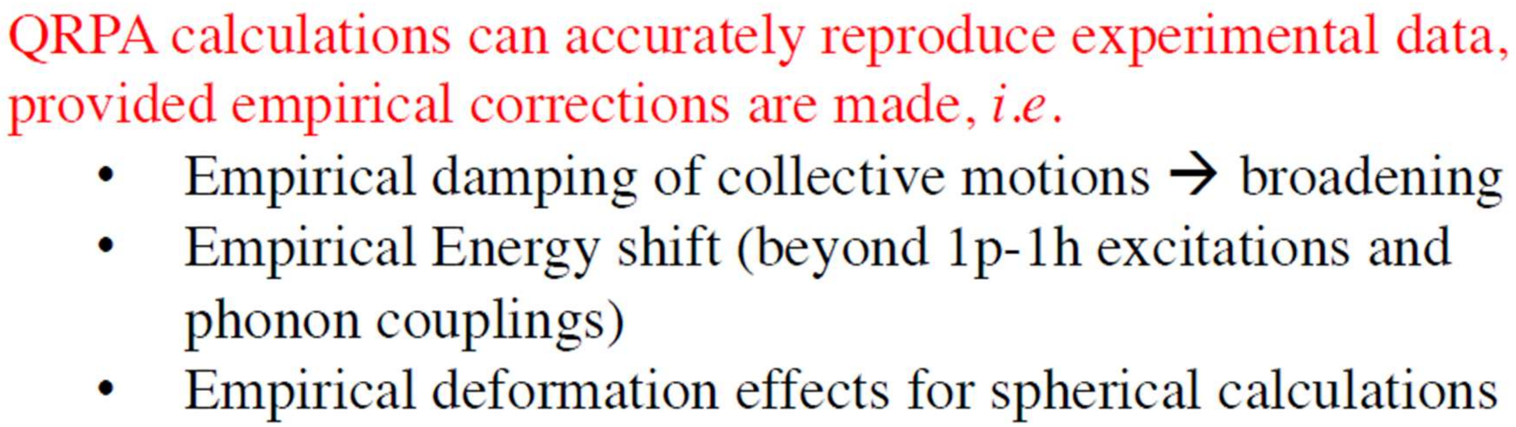
See S. Goriely & E. Khan, NPA 706 (2002) 217.

S. Goriely et al., NPA739 (2004) 331.

Gamma-ray strengths : QRPA for exotic nuclei



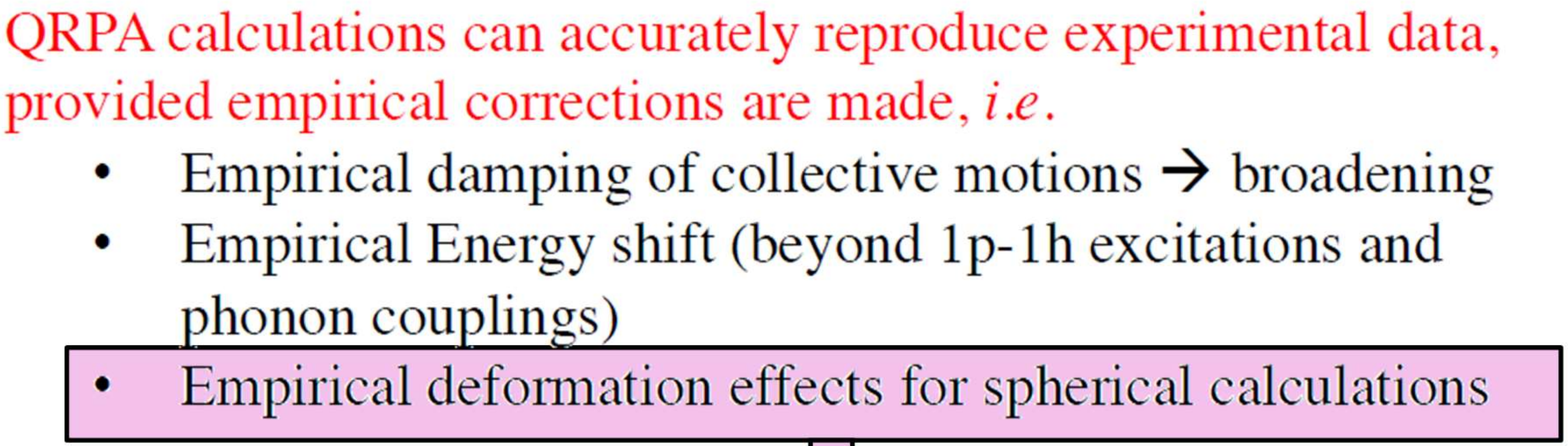
Gamma-ray strengths : beyond spherical approximation



QRPA calculations can accurately reproduce experimental data, provided empirical corrections are made, *i.e.*

- Empirical damping of collective motions → broadening
- Empirical Energy shift (beyond 1p-1h excitations and phonon couplings)
- Empirical deformation effects for spherical calculations

Gamma-ray strengths : beyond spherical approximation



QRPA calculations can accurately reproduce experimental data, provided empirical corrections are made, *i.e.*

- Empirical damping of collective motions → broadening
- Empirical Energy shift (beyond 1p-1h excitations and phonon couplings)
- Empirical deformation effects for spherical calculations

Can be removed within the axial Gogny QRPA framework but high computational cost

Gamma-ray strengths : axial Gogny QRPA approach

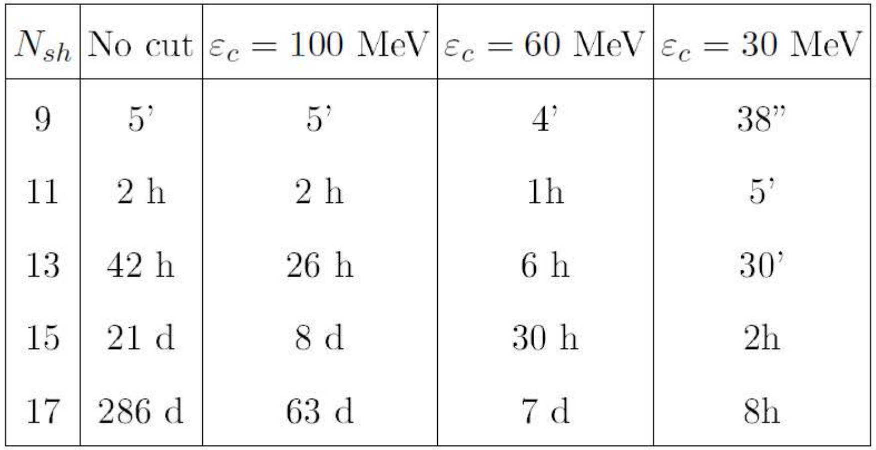
Extremely high computational cost !

QRPA calculations performed to

1) perform sensitivity analyses w.r.t :
    - effective interaction (D1S vs D1M)
    - nuclear deformation
    - quasiparticle energy cut-off e_c
    - number of major shells N_{sh}

compromise accuracy vs computing time

computing time for a given K^π with 1024 cpu



N_{sh}	No cut	$\varepsilon_c = 100$ MeV	$\varepsilon_c = 60$ MeV	$\varepsilon_c = 30$ MeV
9	5’	5’	4’	38”
11	2 h	2 h	1h	5’
13	42 h	26 h	6 h	30’
15	21 d	8 d	30 h	2h
17	286 d	63 d	7 d	8h

2) compute QRPA strengths for all nuclei included in the IAEA RIPL-3 database
3) compute low energy collective states
4) Add “global” corrections to theoretical predictions to fit data
5) Produce tables for all nuclei

Gamma-ray strengths : adjustment method

folded strength ⇩ raw strength ⇩

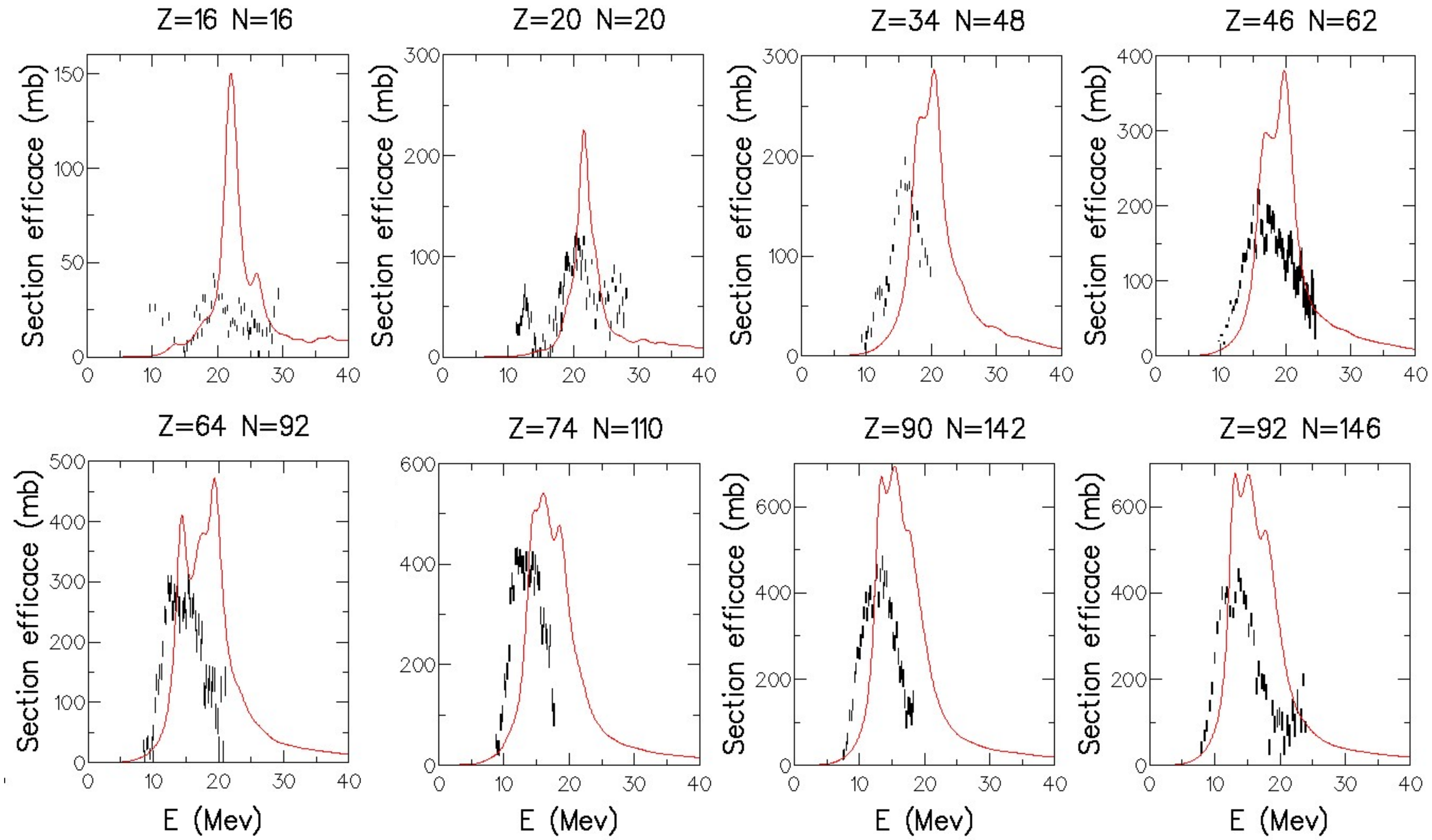
$$S_{E1}(E) = \sum_n L(E,\omega_n) B_{E1}(\omega_n)$$

with

$$L(E,\omega) = \frac{K}{\pi} \frac{\Gamma E^2}{[E^2 - (\omega - \Delta)^2]^2 + \Gamma^2 E^2}$$

where ***K***, Δ and Γ can be adjusted

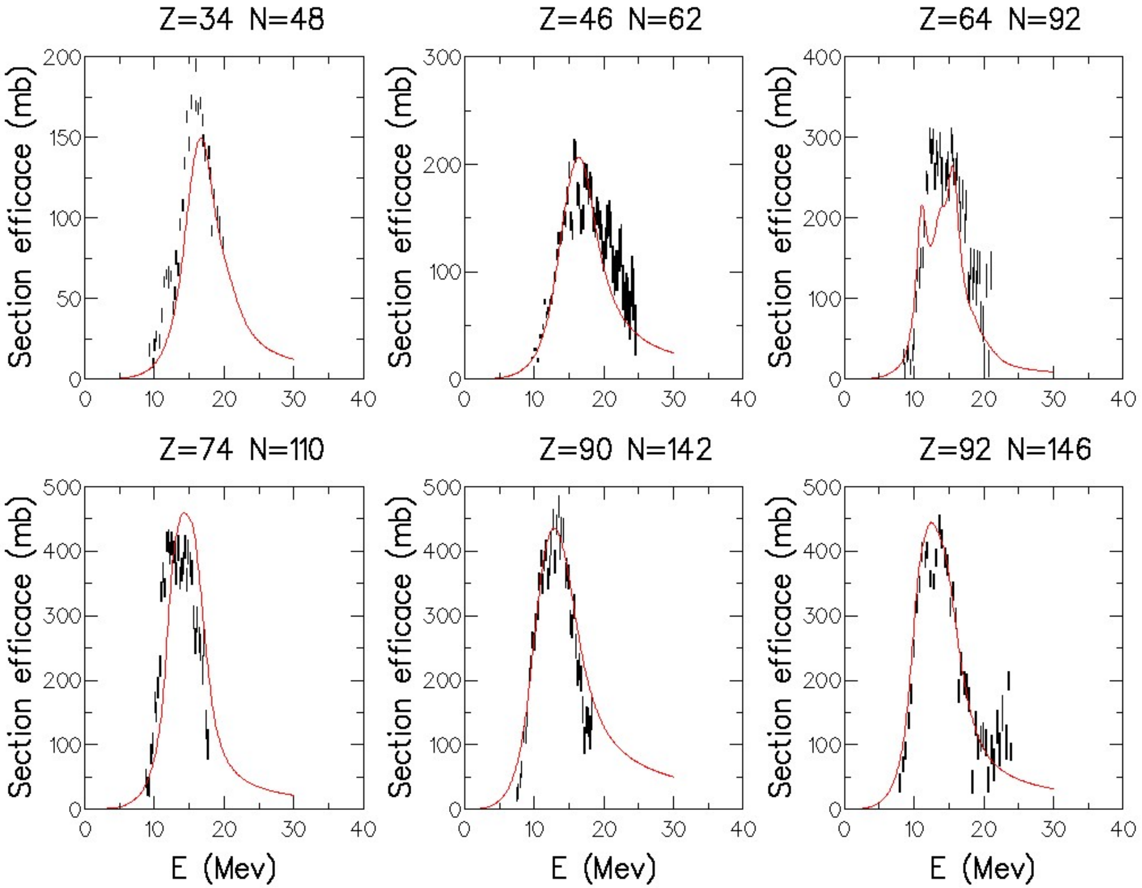
Gamma-ray strengths : broadening of 2 MeV only



⇒ Shift to account for phonon couplings + beyond 1p-1h approximation

⇒ Peak normalization to improve experimental data fitting

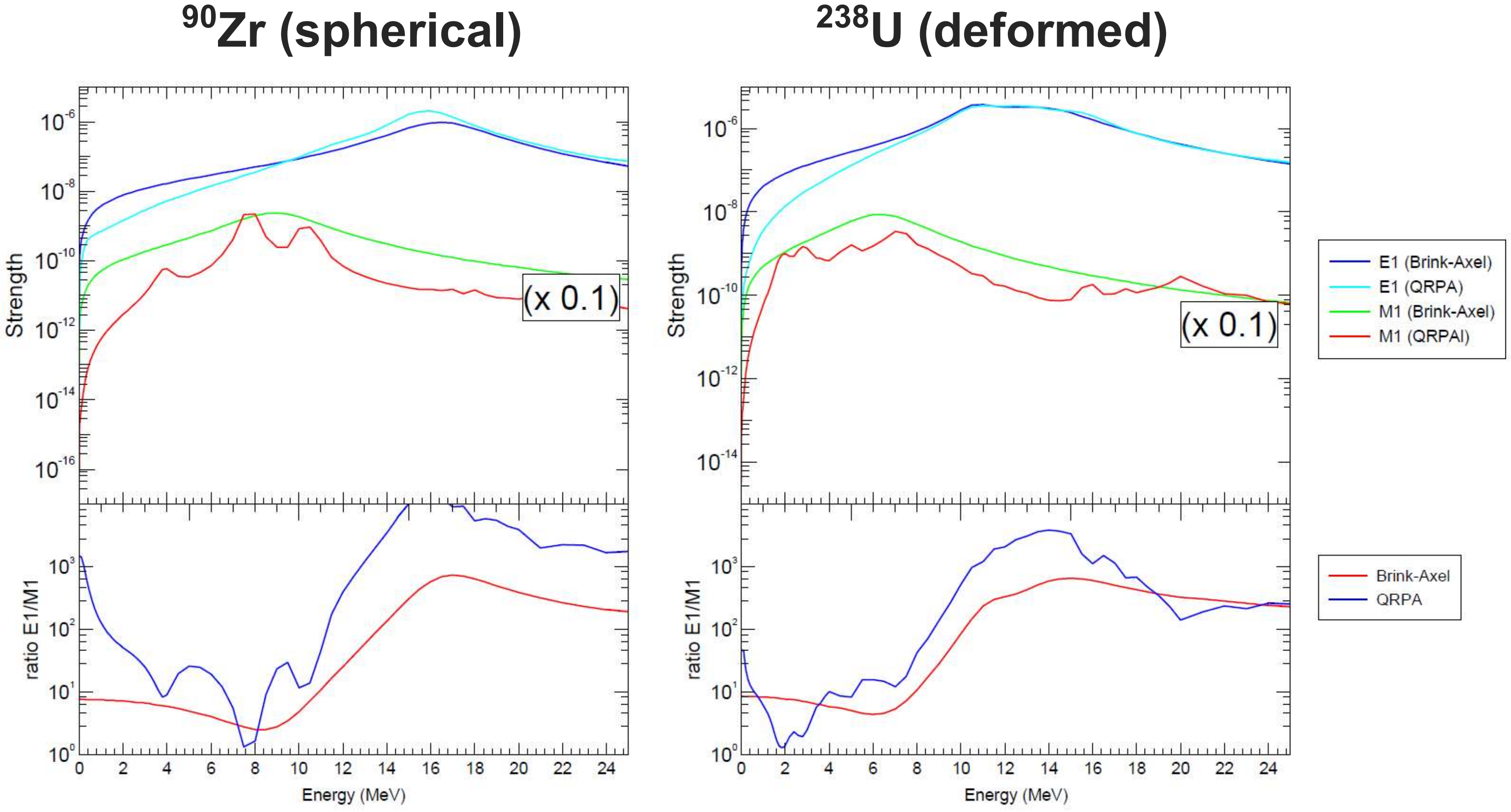
Gamma-ray strengths : all parameters adjusted



⇒ Good agreement with data

⇒ Systematic predictions can be performed

Gamma-ray strengths : deformed QRPA vs Brink-Axel



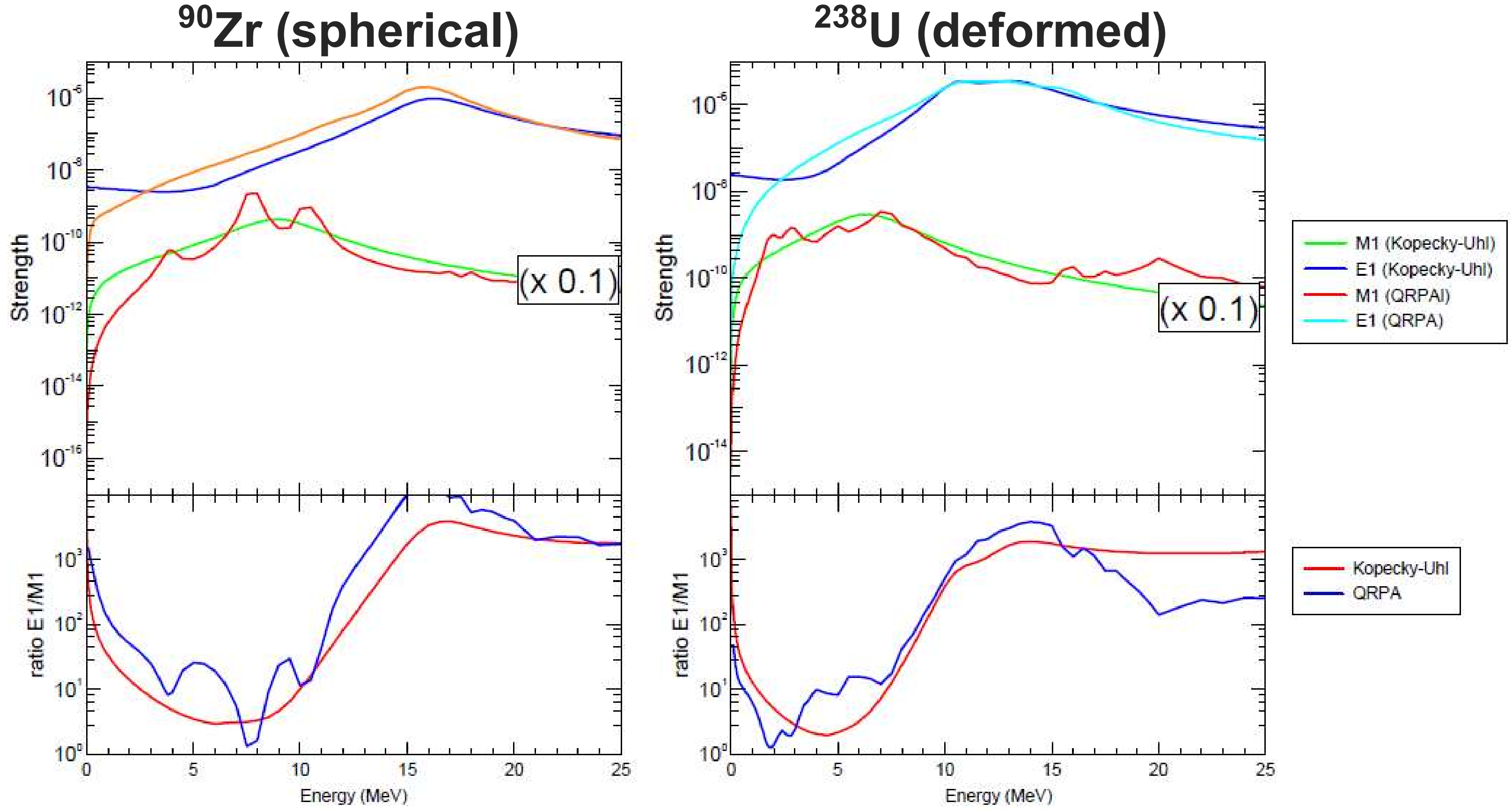
^{90}Zr (spherical)

^{238}U (deformed)

⇒ OK for photoabsorption

⇒ Significant structure for M1 transitions

Gamma-ray strengths : deformed QRPA vs Kopecky-Uhl



^{90}Zr (spherical)

^{238}U (deformed)

⇒ Missing low energy strength for E1
⇒ Significant structure for M1 transitions

Gamma-ray strengths : shell model

- **Shell Model approach**

E. Caurier et al., Rev. Mod. Phys. ***77*** *(2005) p410-427*

⇒ Very precise
⇒ Even-even, odd-A, odd-odd nuclei treated on the same footing
⇒ Possibility to predict within the same framework

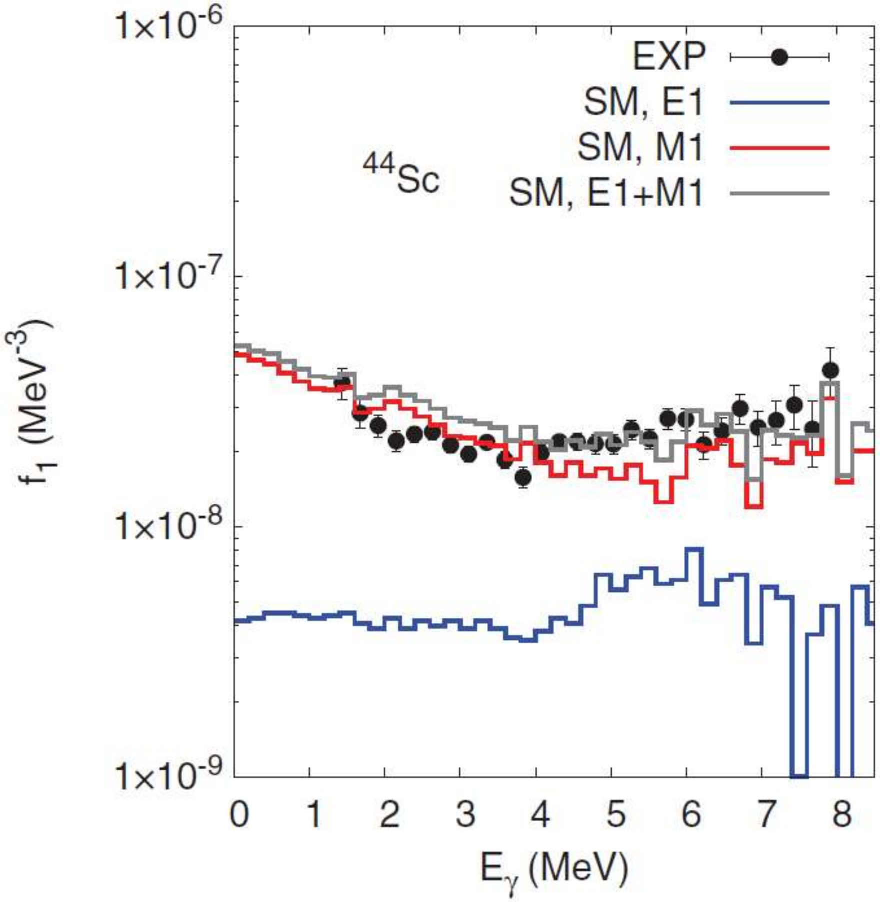
  - spectra
  - transitions between **any** excited state
  - weak decays (beta, double-beta, …)
  - pairing, deformation, …

Courtesy K. Sieja

But

⇒ local (parameters adjusted on exp. data for each mass region)
⇒ Not applicable everywhere due to the dimension of the matrices to diagonalize when large valence spaces are required

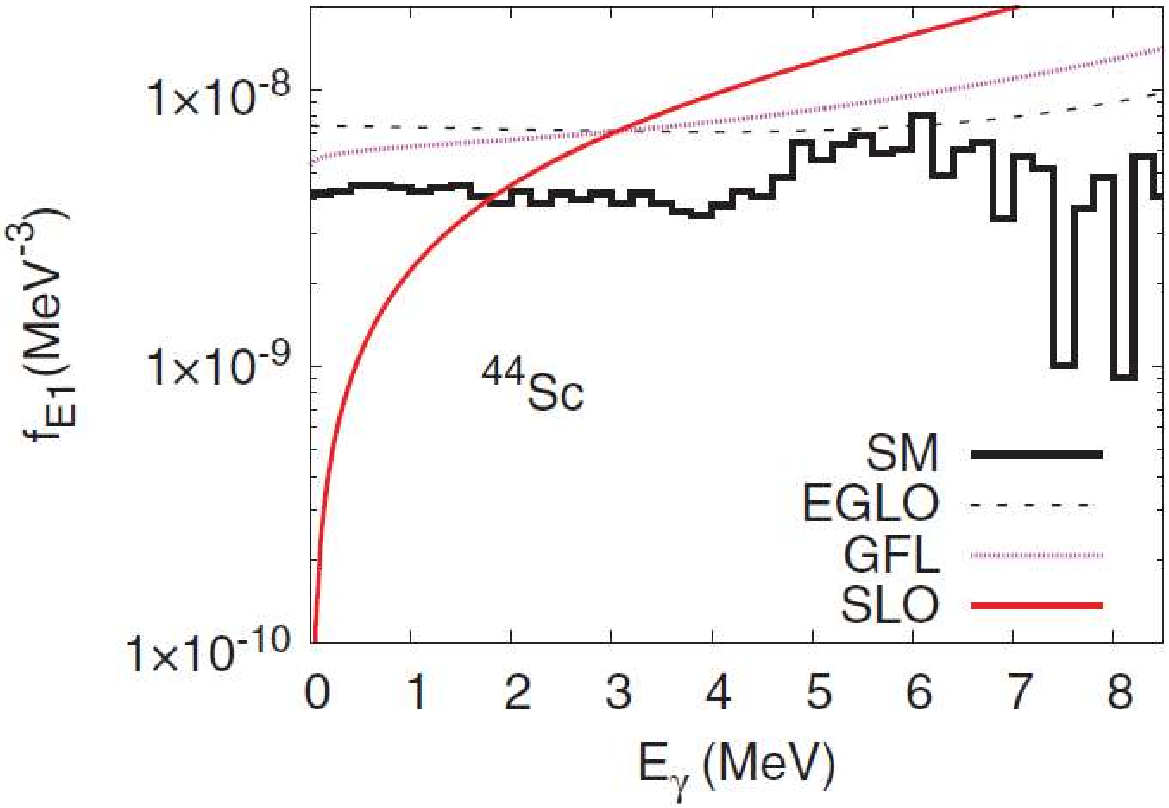
Gamma-ray strengths : shell model



Courtesy K. Sieja

⇒ Shell model : first microscopic model reproducing low energy experimental data related to gamma decay

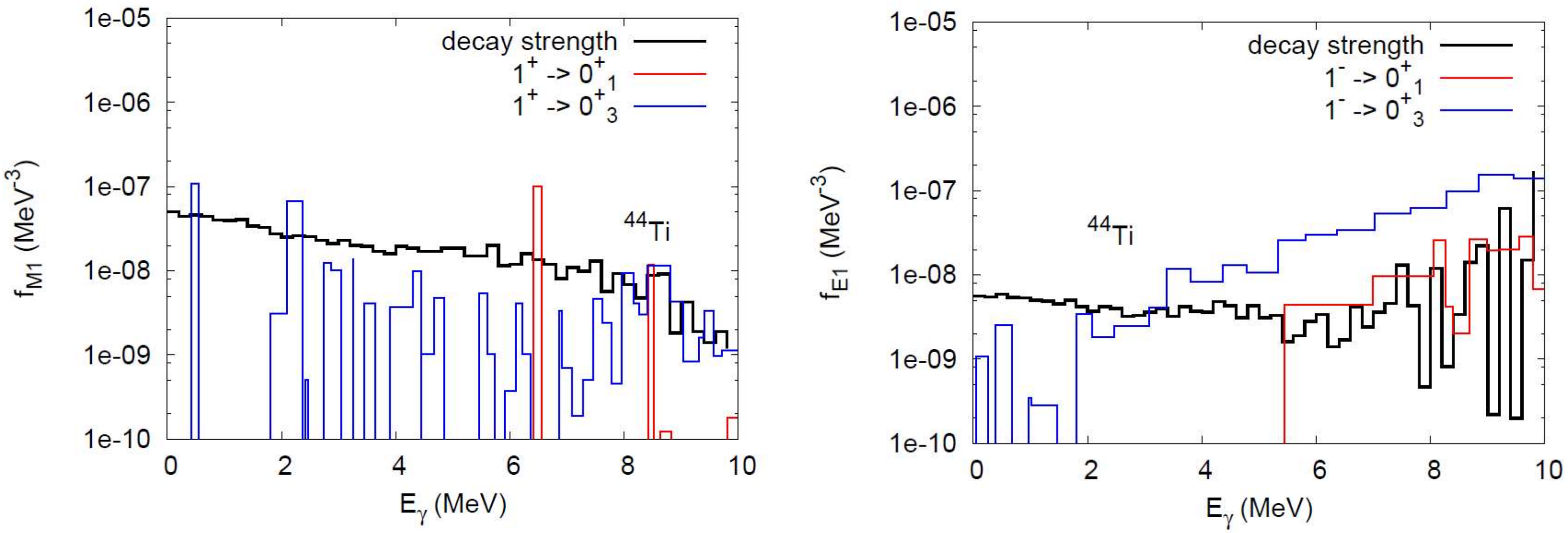
Gamma-ray strengths : shell model vs analytical approaches



Courtesy K. Sieja

⇒ Shell model validates the non-vanishing of the strength at low energy as phenomenologically introduced in some analytical formulae

Gamma-ray strengths : shell model lesson



⇒ Shell model shows that both E1 and M1 non vanishing low energy strength stem from intra-band transitions.

Courtesy K. Sieja

Gamma-ray strengths

- Qualitative features

- Analytical approaches

- Microscopic approaches

- HFBCS-RPA
- HFB+QRPA
- Shell Model

- Impacts on cross sections

- Normalizations
- Exotic nuclei
- Hot topics

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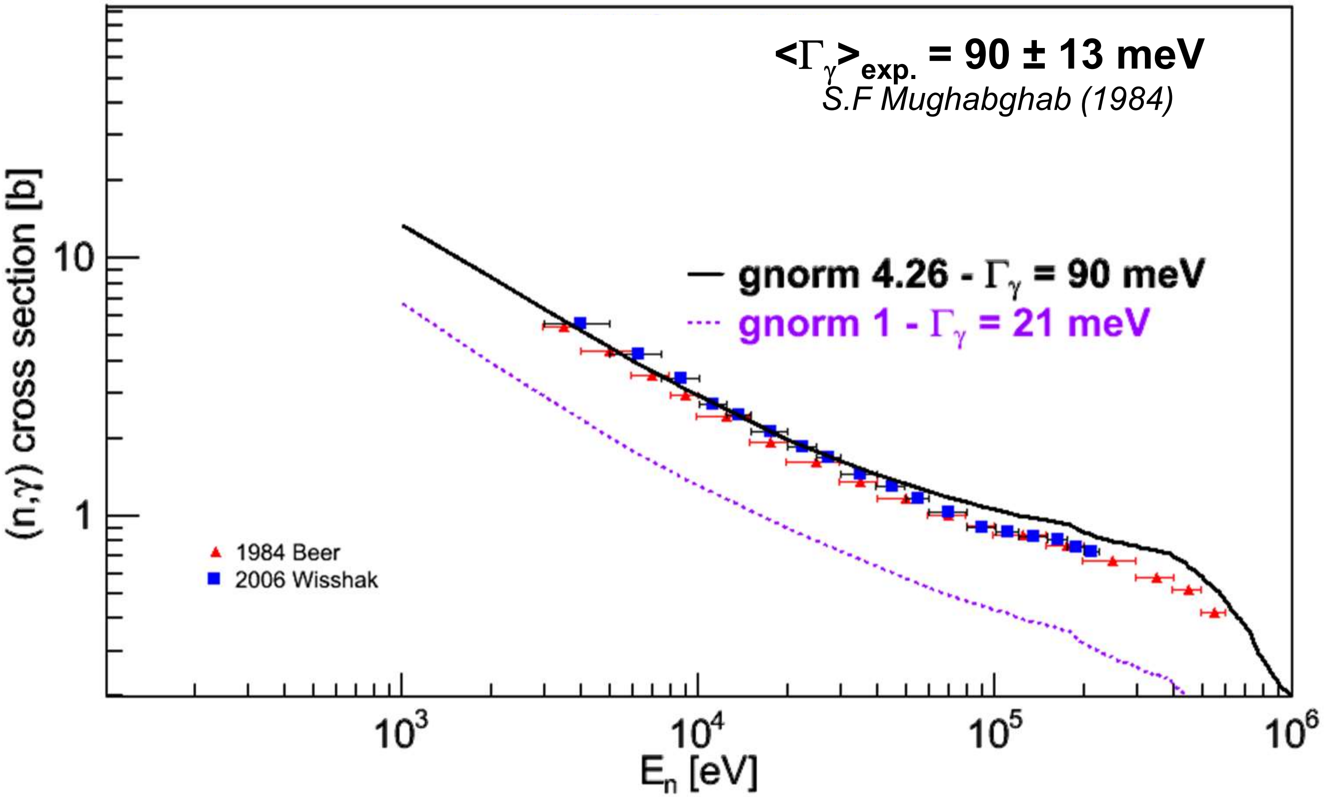
Gamma-ray strengths : normalizations

Normalisation method for thermal neutrons

experiment

$$\langle T_\gamma \rangle = C \sum_{J_i,\pi_i} \sum_{k\lambda} \sum_{J_f,\pi_f} \int_0^{B_n} T^{k\lambda}(\varepsilon)\, \rho(B_n-\varepsilon, J_f, \pi_f)\, S(k,\lambda,J_i,\pi_i, J_i,\pi_f)\, d\varepsilon = 2\pi \langle \Gamma_\gamma \rangle \frac{1}{D_0}$$



Gamma-ray strengths : normalizations

Normalisation method for thermal neutrons

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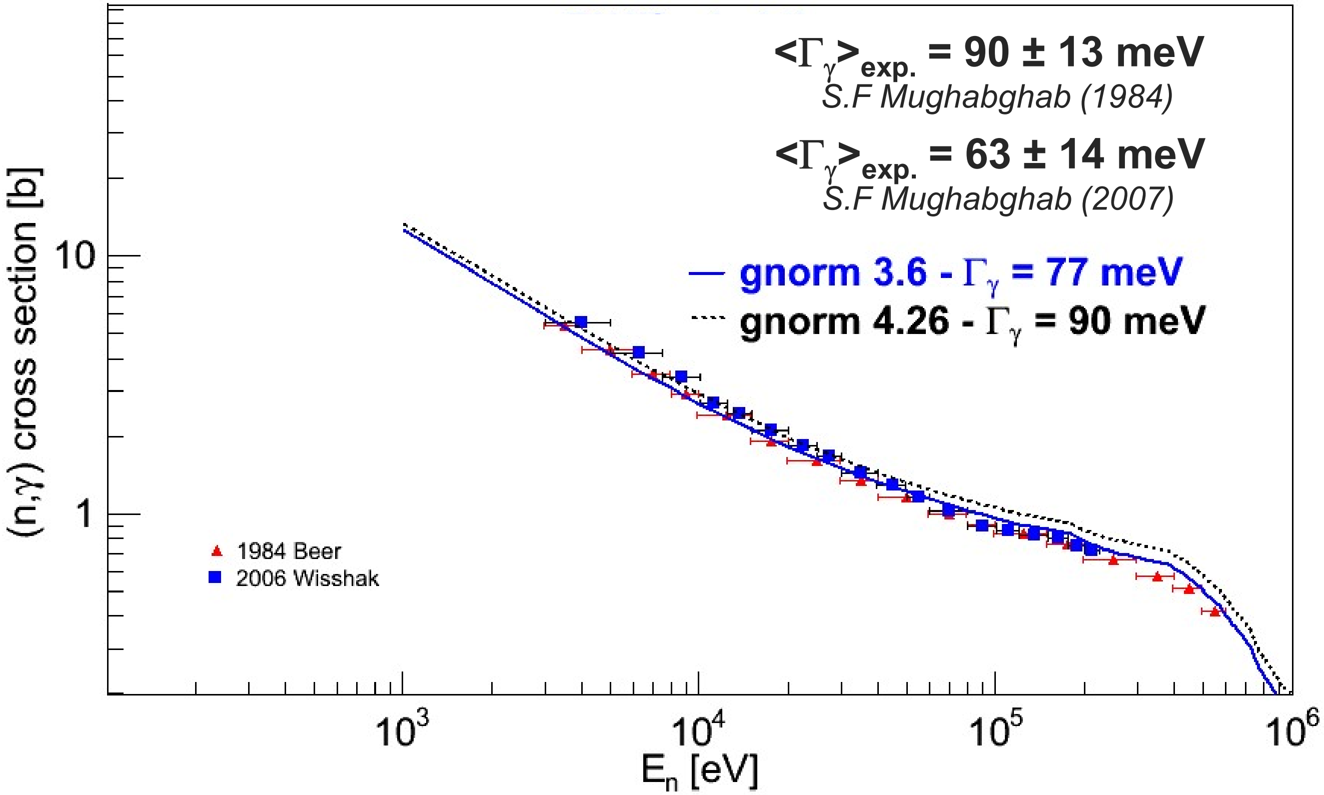


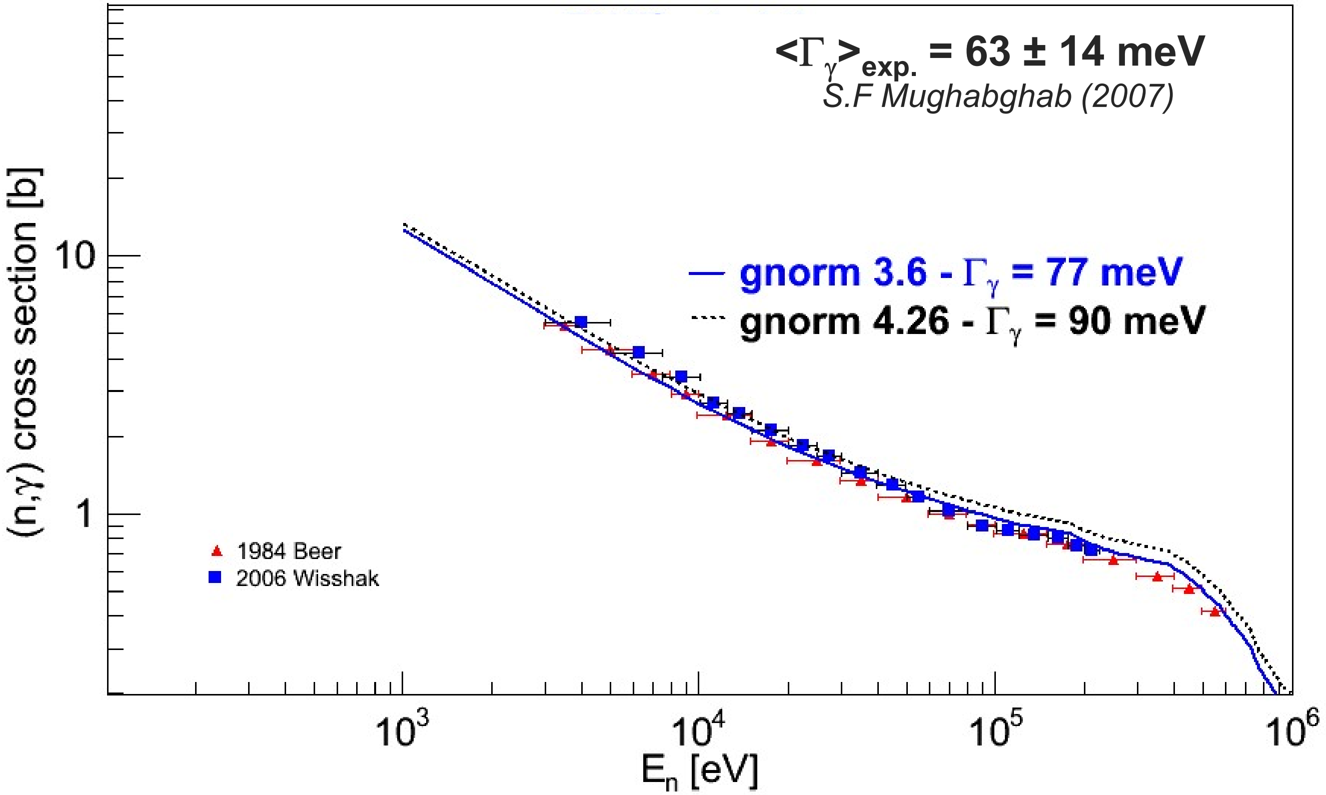
Experiment revisited

Gamma-ray strengths : normalizations

Normalisation method for thermal neutrons

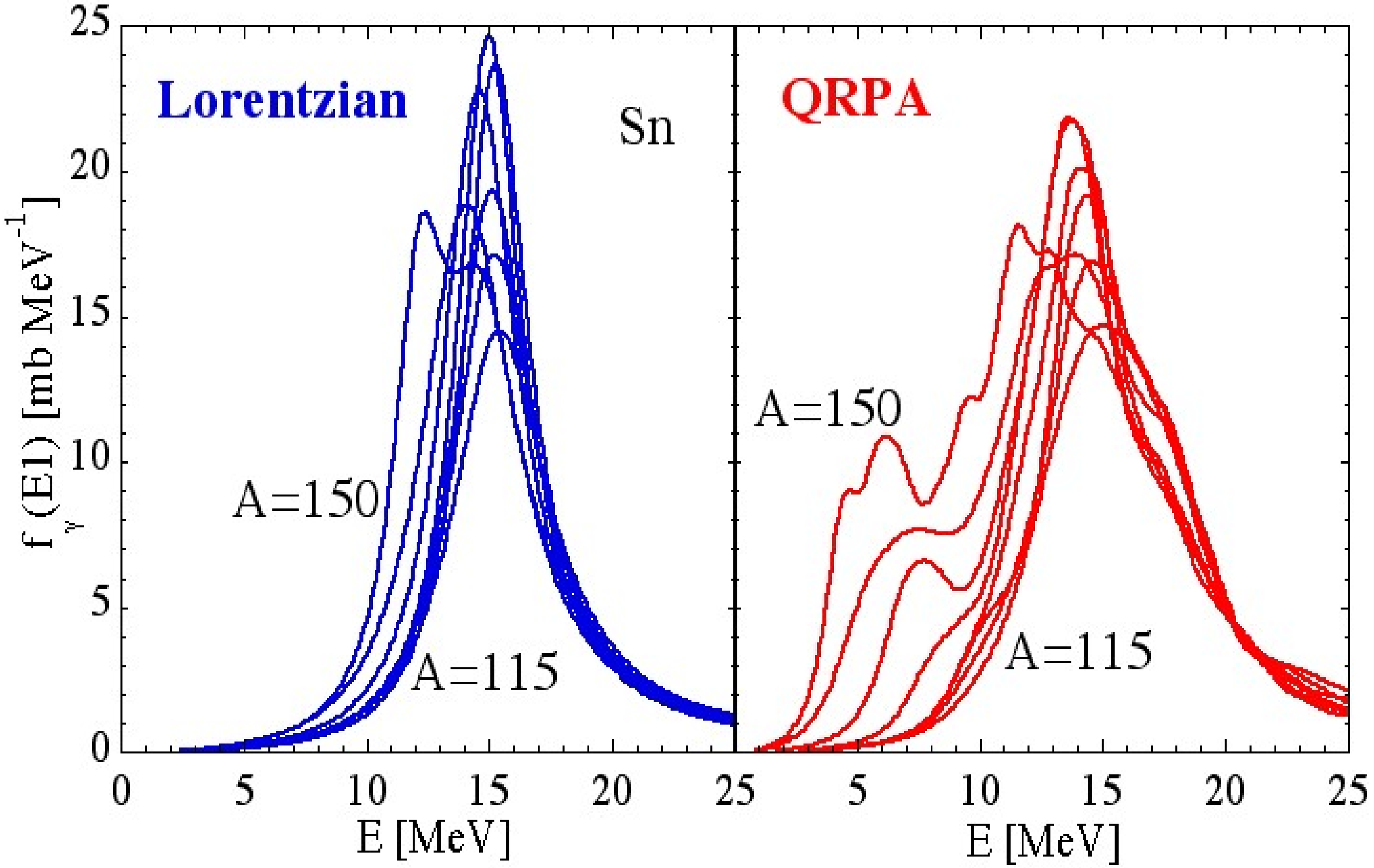
experiment

$$<T_\gamma> = C \sum_{J_i,\pi_i} \sum_{k\lambda} \sum_{J_f,\pi_f} \int_0^{B_n} T^{k\lambda}(\varepsilon)\, \rho(B_n-\varepsilon,J_f,\pi_f)\, S(k,\lambda,J_i,\pi_i, J_i,\pi_f)\, d\varepsilon = 2\pi <\Gamma_\gamma> \frac{1}{D_0}$$



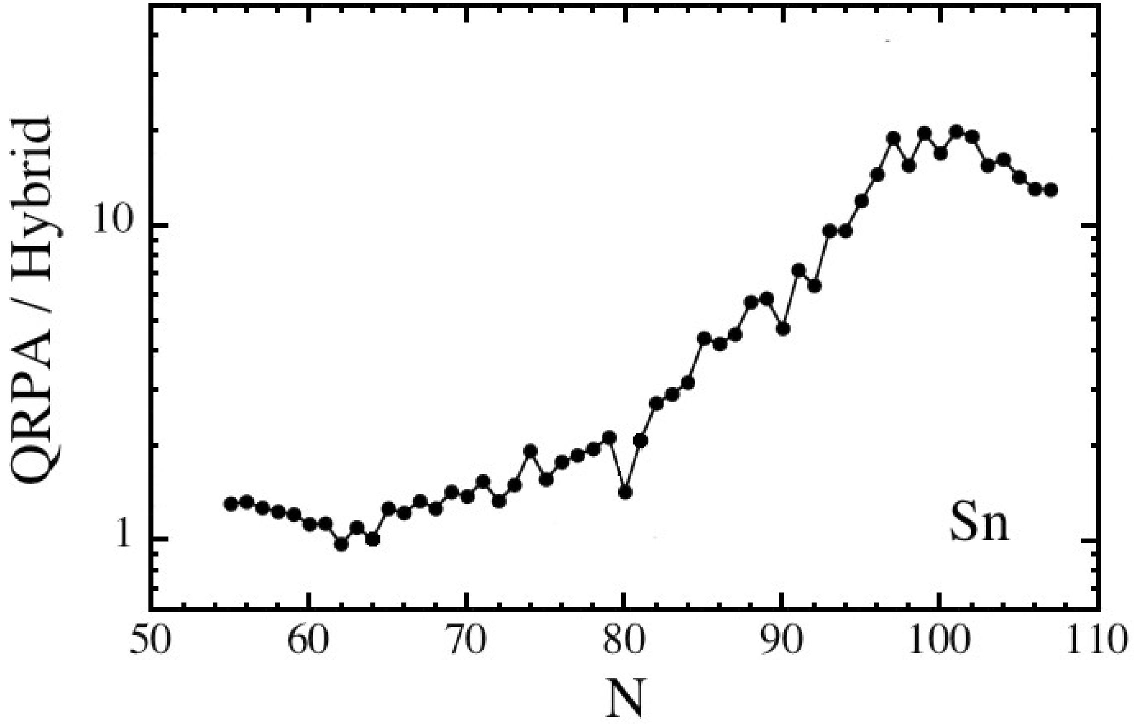
Experiment revisited

Gamma-ray strengths : exotic nuclei



Gamma-ray strengths : exotic nuclei

Capture cross section @ E_n=10 MeV for Sn isotopes

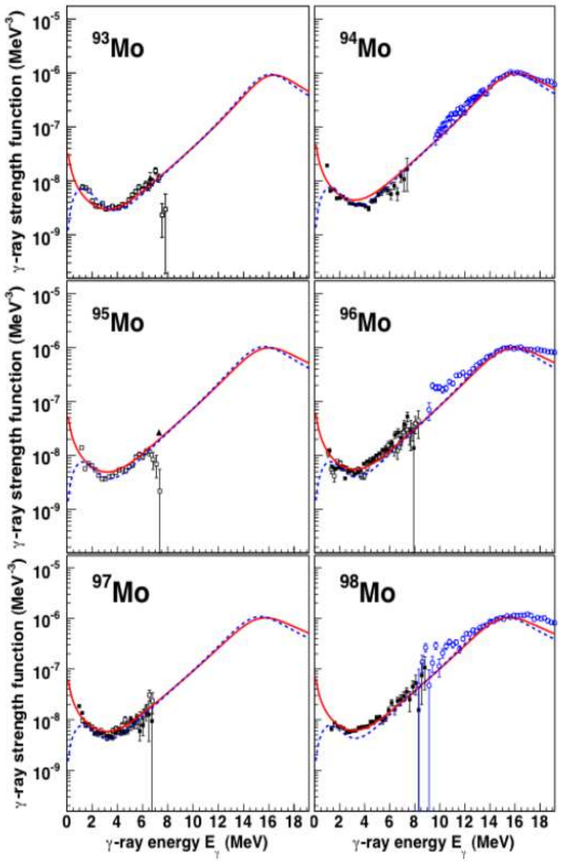


⇒ **Weak impact close to stability but large for exotic nuclei**

Gamma-ray strengths : Hot topics

Low energy upbend of gamma-ray strength observed in several experiment

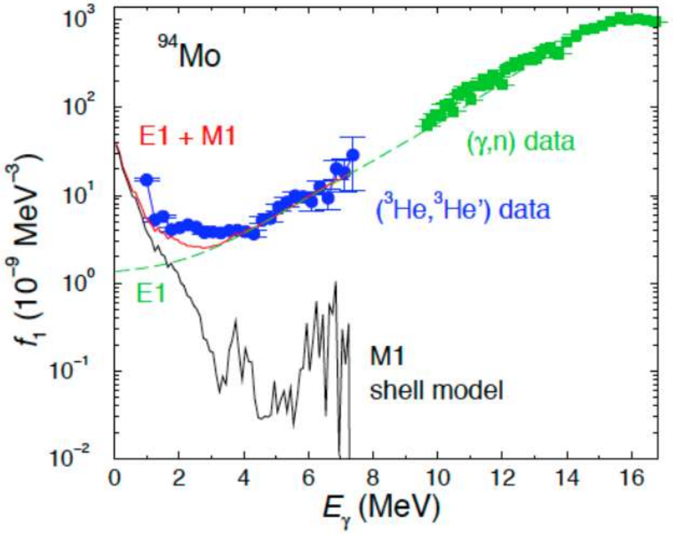
particle−γ coincidence in the (^{3}He,αγ) & (^{3}He,^{3}He' γ) reactions



A.-C. Larsen et al. (2009)

Upbend observed for ^{44,45}Sc, ^{50,51}V, ^{56,57}Fe, $^{73\text{-}74}$Ge, $^{93\text{-}98}$Mo, Sm but not (yet) for Sn, Dy, Er or Yb

The *M*1 character of the upbend seems to be confirmed by shell model calculations (though an *E*1 character cannot be excluded yet)



R. Schwengner et al. (2013); Brown & Larsen (2014); Sieja (2016)

Gamma-ray strengths : Hot topics

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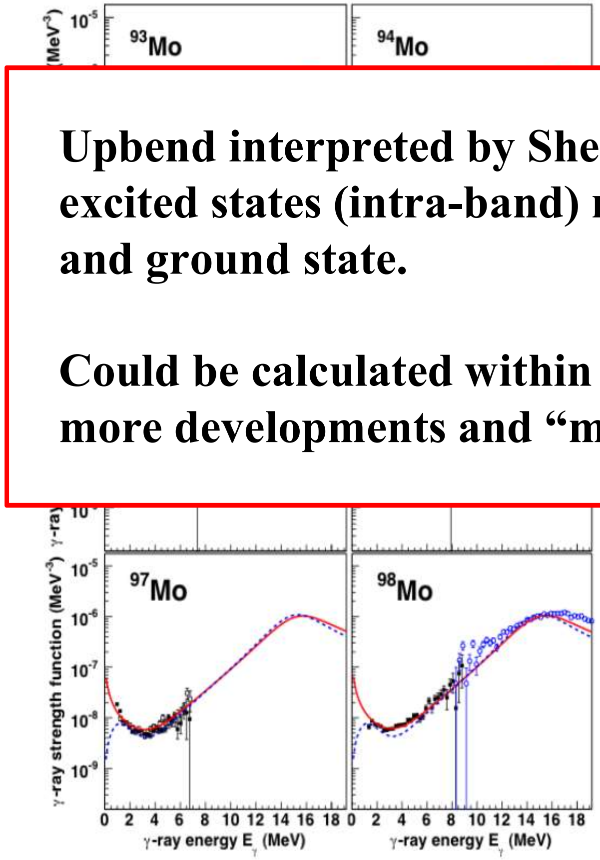
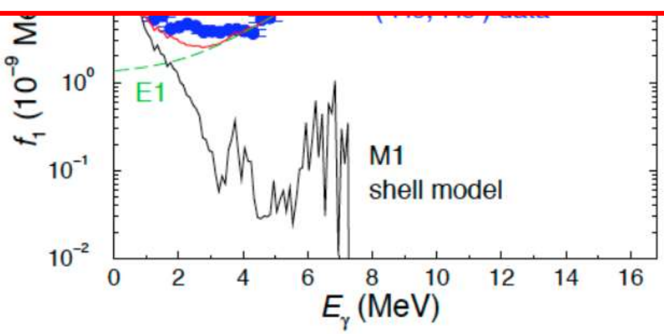


A.-C. Larsen et al. (2009)



R. Schwengner et al. (2013); Brown & Larsen (2014); Sieja (2016)

Upbend interpreted by Shell model as transitions between excited states (intra-band) rather than between excited states and ground state.

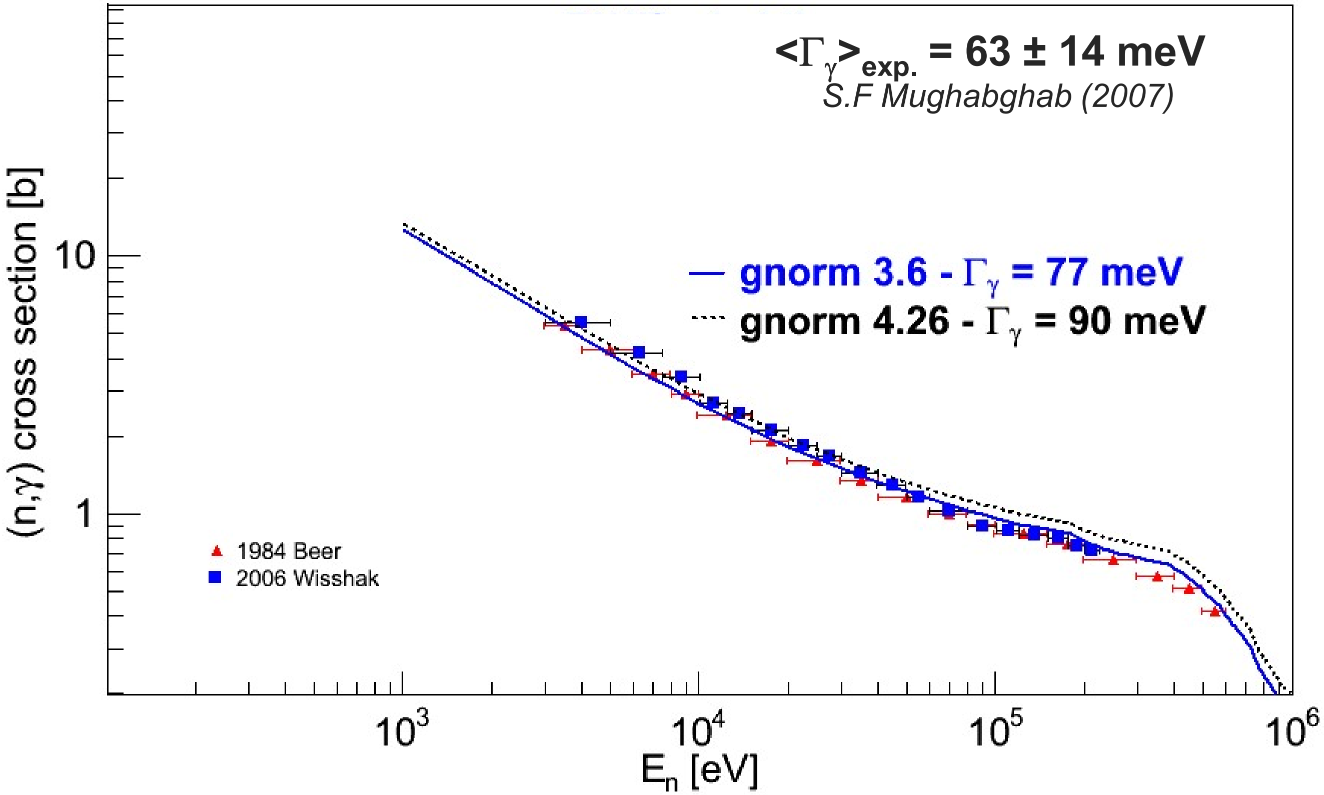
Could be calculated within QRPA framework provided a few more developments and "much more calculation"

Gamma-ray strengths : low energy missing strength

Normalisation method for thermal neutrons

experiment

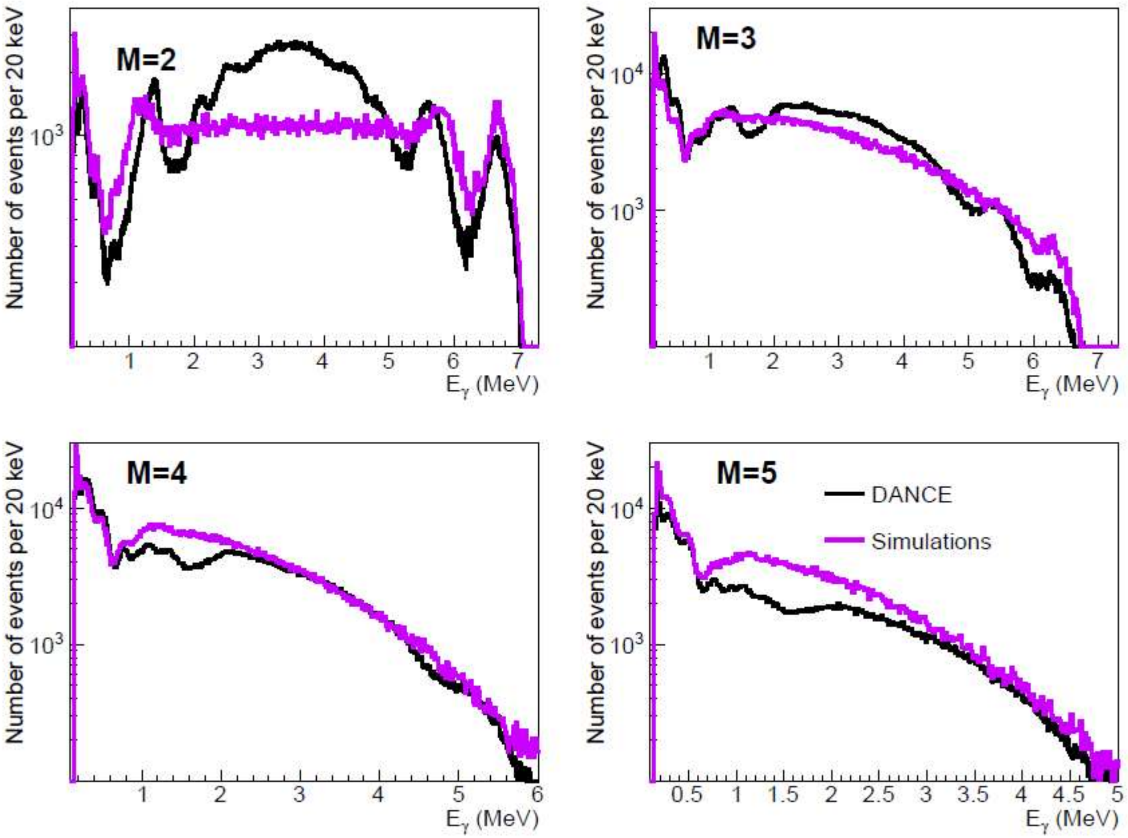
$$<T_\gamma> = C \sum_{J_i,\pi_i} \sum_{k\lambda} \sum_{J_f,\pi_f} \int_0^{B_n} T^{k\lambda}(\varepsilon)\, \rho(B_n-\varepsilon,J_f,\pi_f)\, S(k,\lambda,J_i,\pi_i, J_i,\pi_f)\, d\varepsilon = 2\pi <\Gamma_\gamma> \frac{1}{D_0}$$



Experiment revisited

Gamma-ray strengths : low energy missing strength

Capture cross section OK but gamma spectra constrained by multiplicity not reproduced !



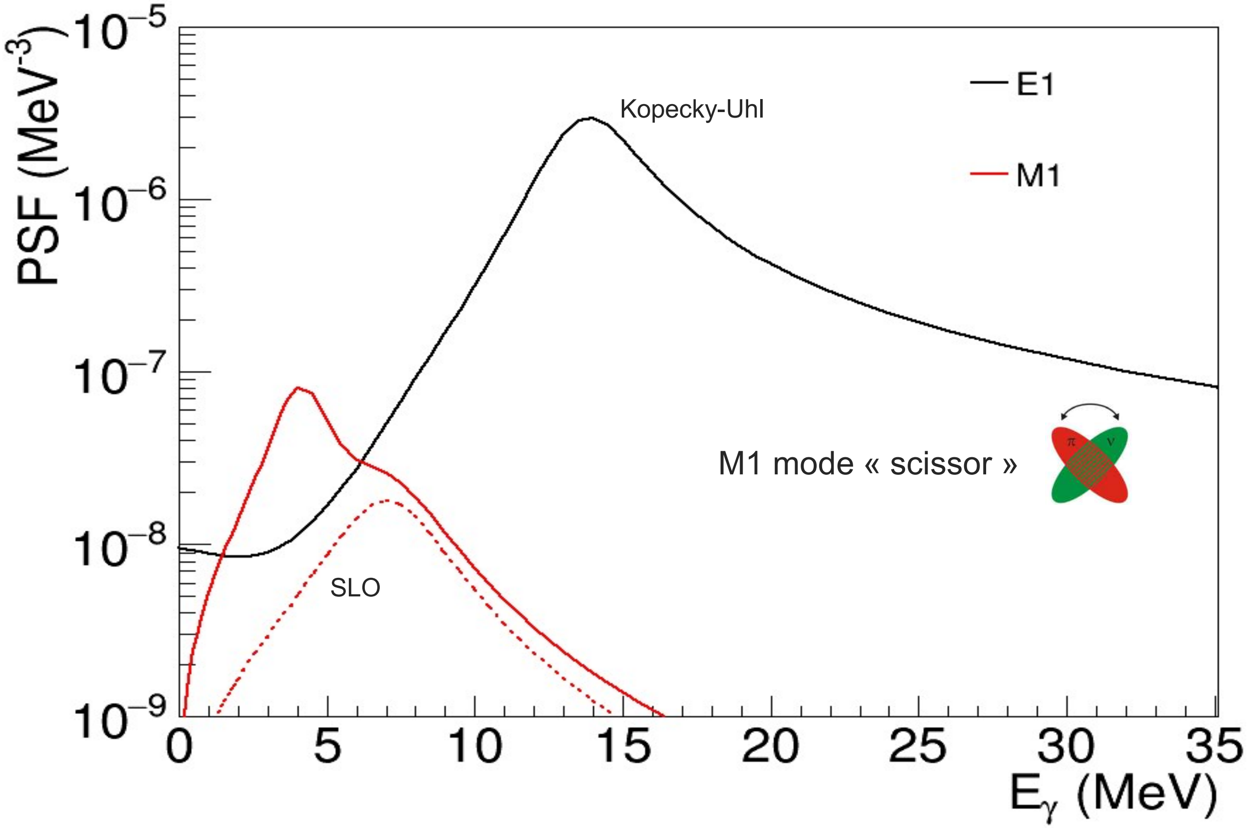
Gamma-ray strengths : low energy missing strength

Capture cross section OK but gamma spectra constrained by multiplicity not reproduced !

Gamma-ray strengths : low energy missing strength

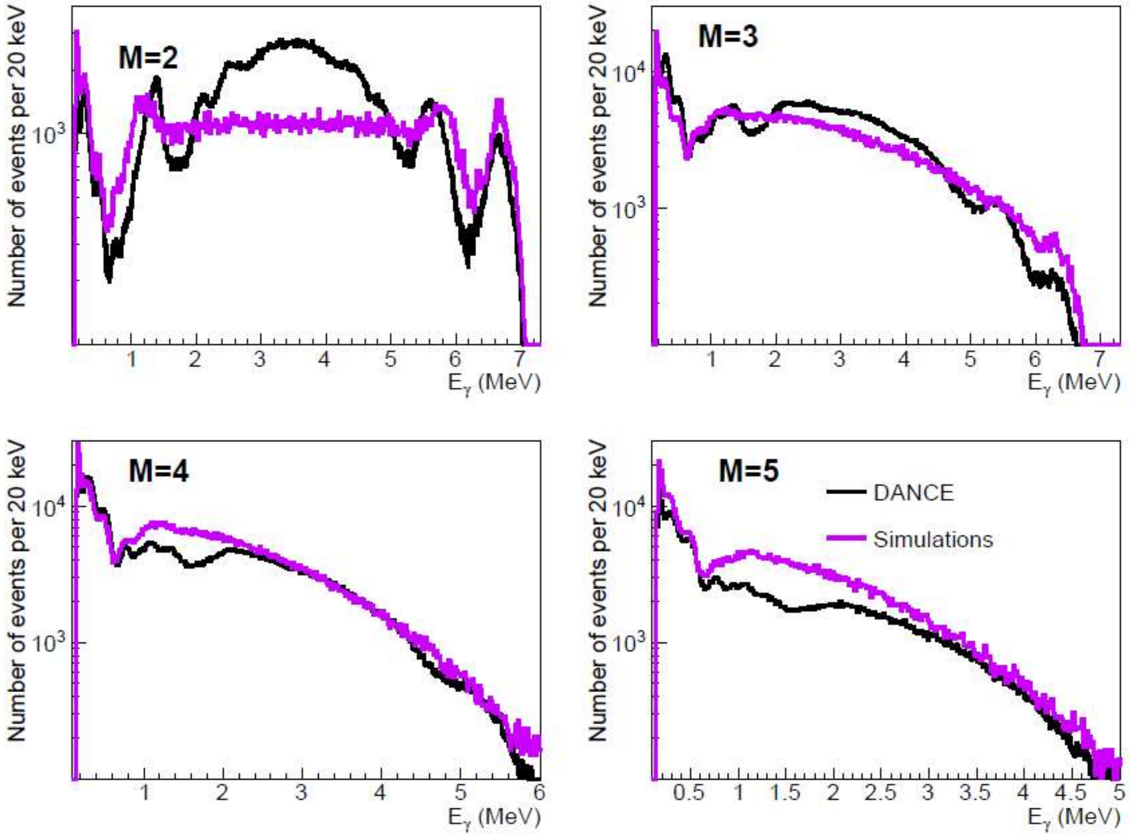
Capture cross section OK but gamma spectra constrained by multiplicity not reproduced !

⇒ **New resonance added at energies around 4 MeV (E1 or E2 pygmy resonance or M1 scissor mode)**



Gamma-ray strengths : low energy missing strength

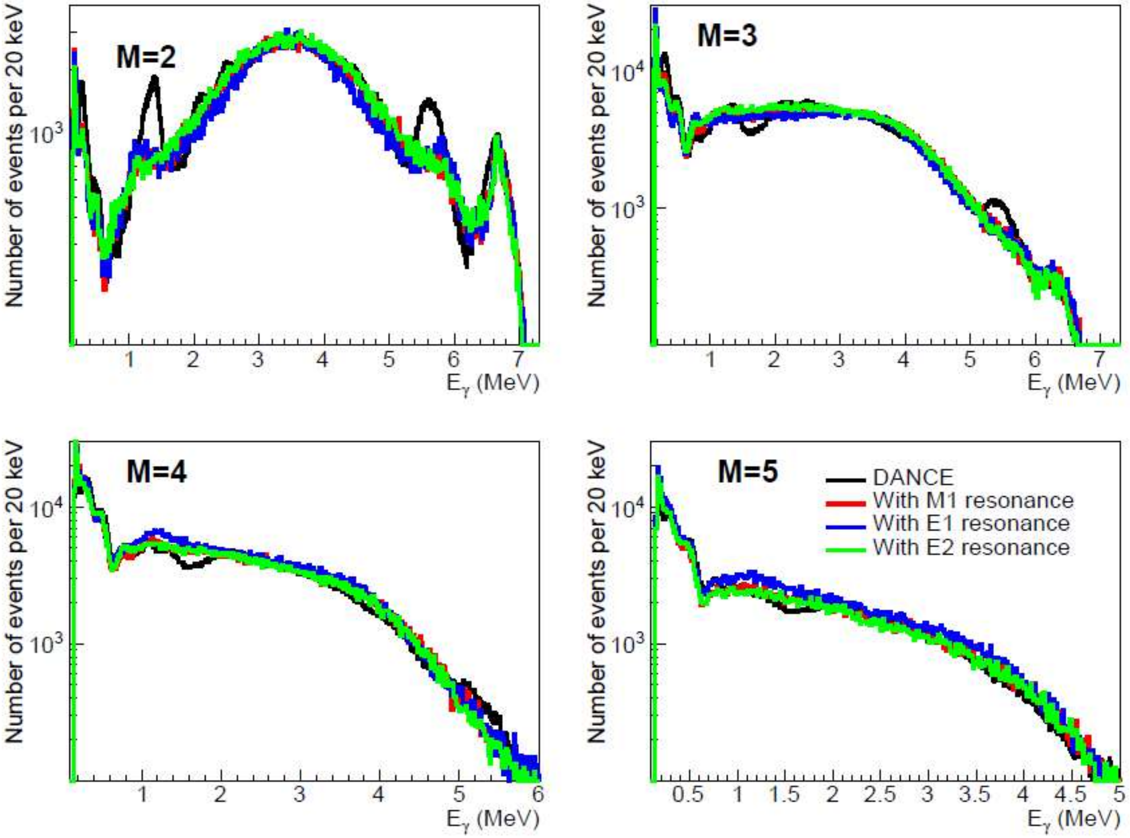
Capture cross section OK but gamma spectra constrained by multiplicity not reproduced !



Gamma-ray strengths : low energy missing strength

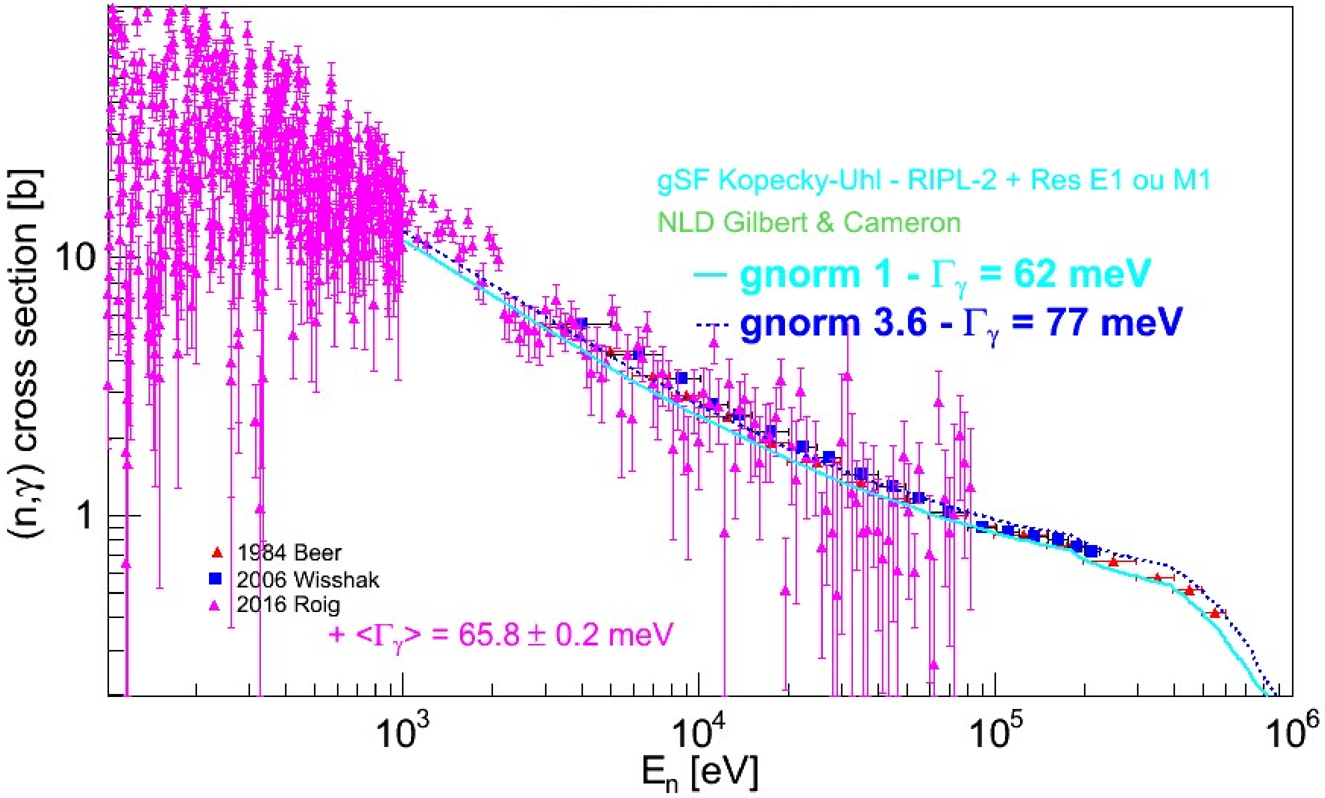
Capture cross section OK but gamma spectra constrained by multiplicity not reproduced !

⇒ New resonance added at energies around 4 MeV (E1 or E2 pygmy resonance or M1 scissor mode)



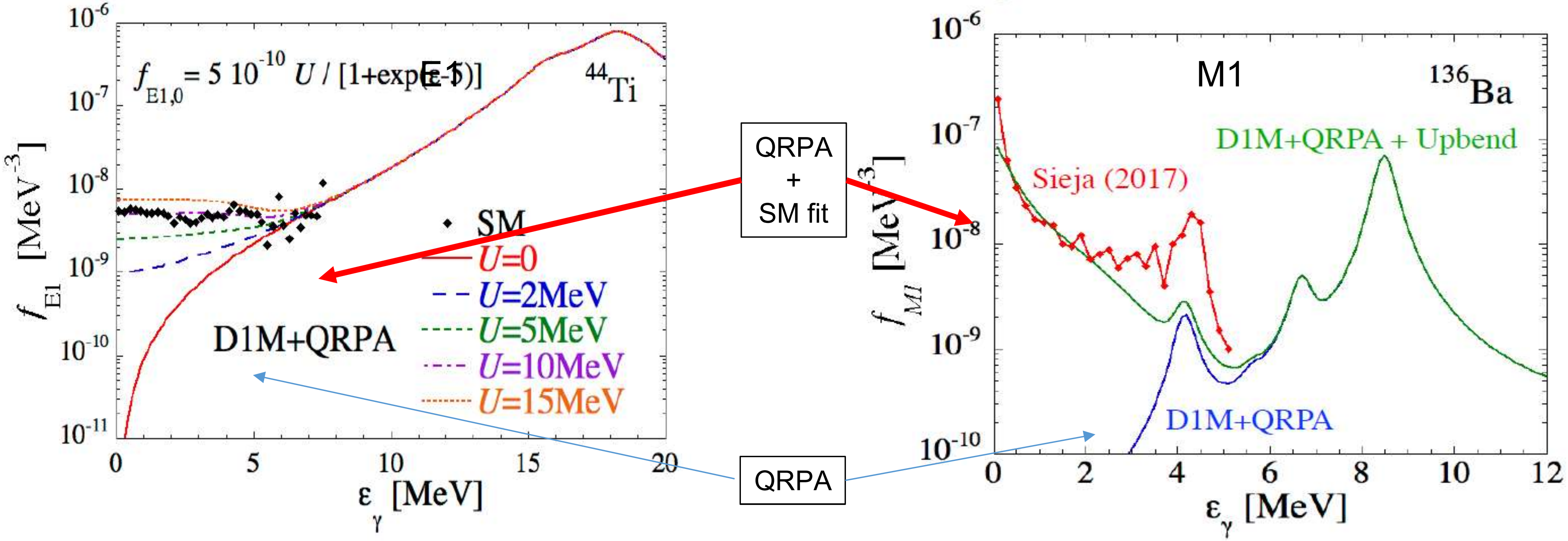
Gamma-ray strengths : low energy missing strength

Capture cross section OK + gamma spectra OK and no more arbitrary normalization



Gamma-ray strengths : low energy missing strength

⇒ Shell model based correction added to QRPA predictions



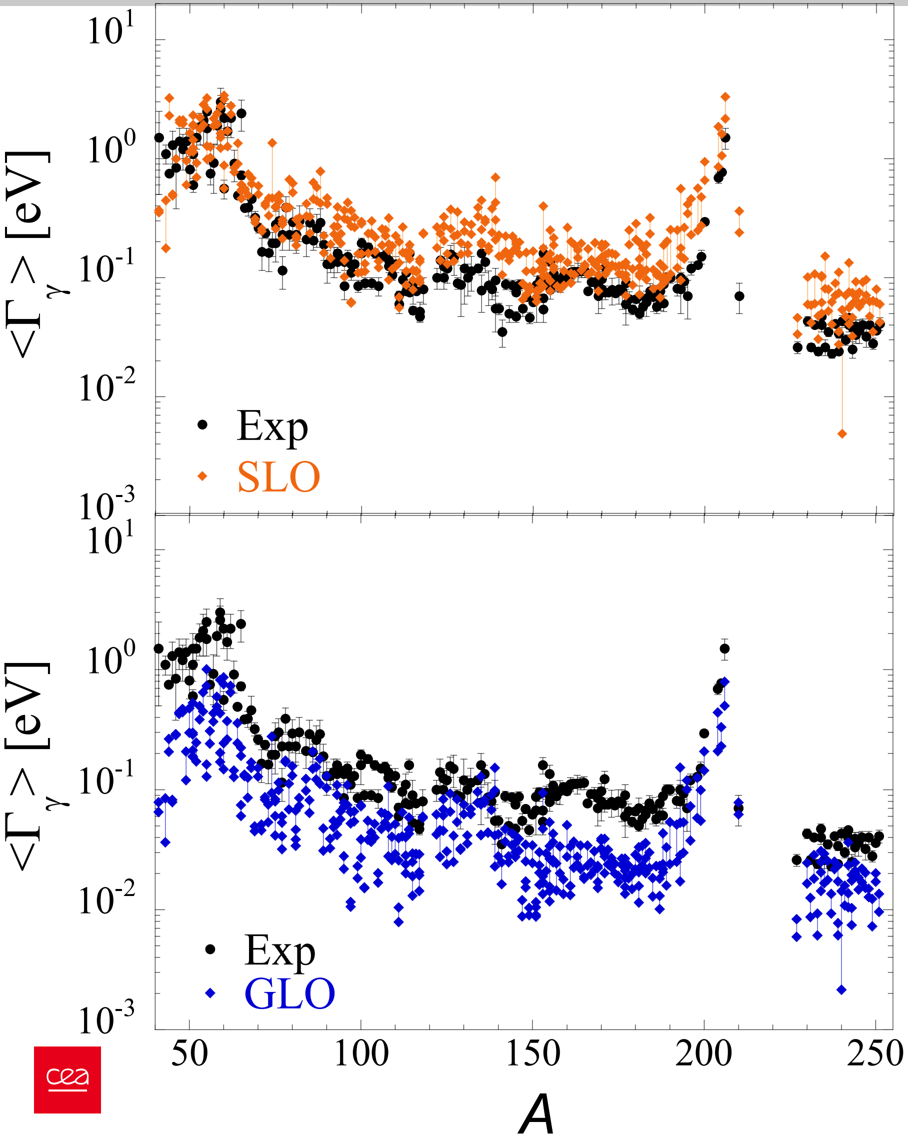
QRPA
+
SM fit

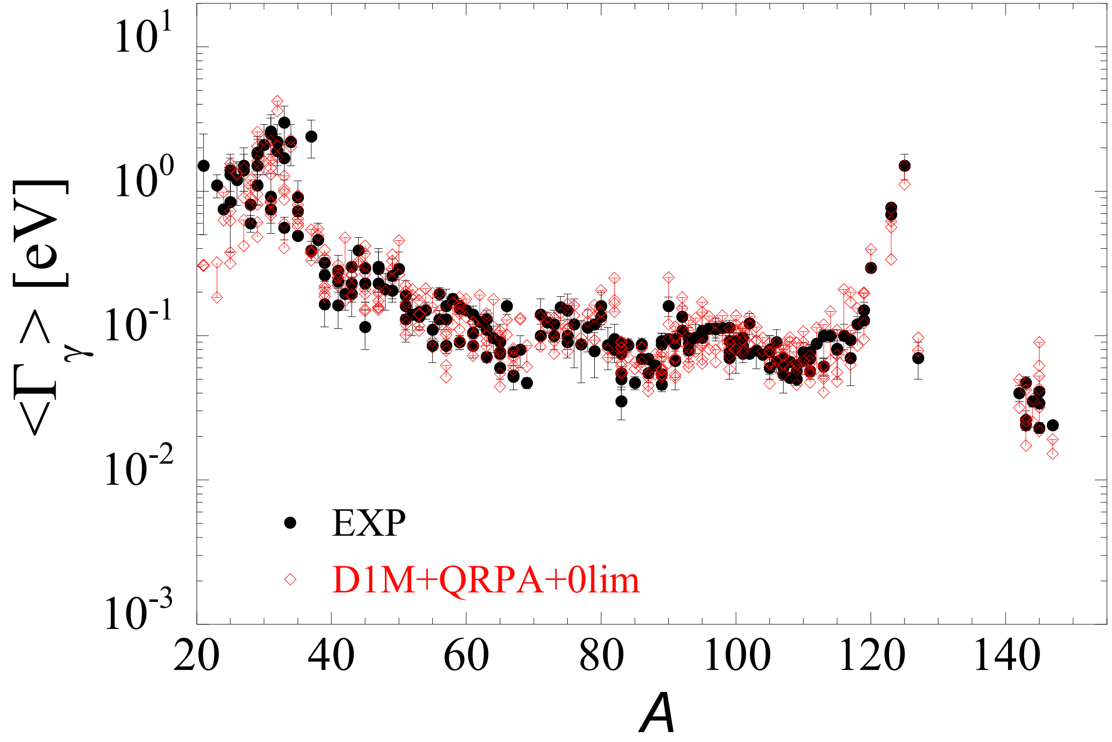
QRPA

$$\overleftarrow{f}_{E1}^{QRPA}(E\gamma) = \overrightarrow{f}_{E1}^{QRPA}(E\gamma) + \frac{f_0 U}{1 + e^{(E_\gamma - E_0)}}$$

$$\overleftarrow{f}_{M1}^{QRPA}(E\gamma) = \overrightarrow{f}_{M1}^{QRPA}(E\gamma) + C e^{-\eta E_\gamma}$$

Gamma-ray strengths : Gogny QRPA vs analytical

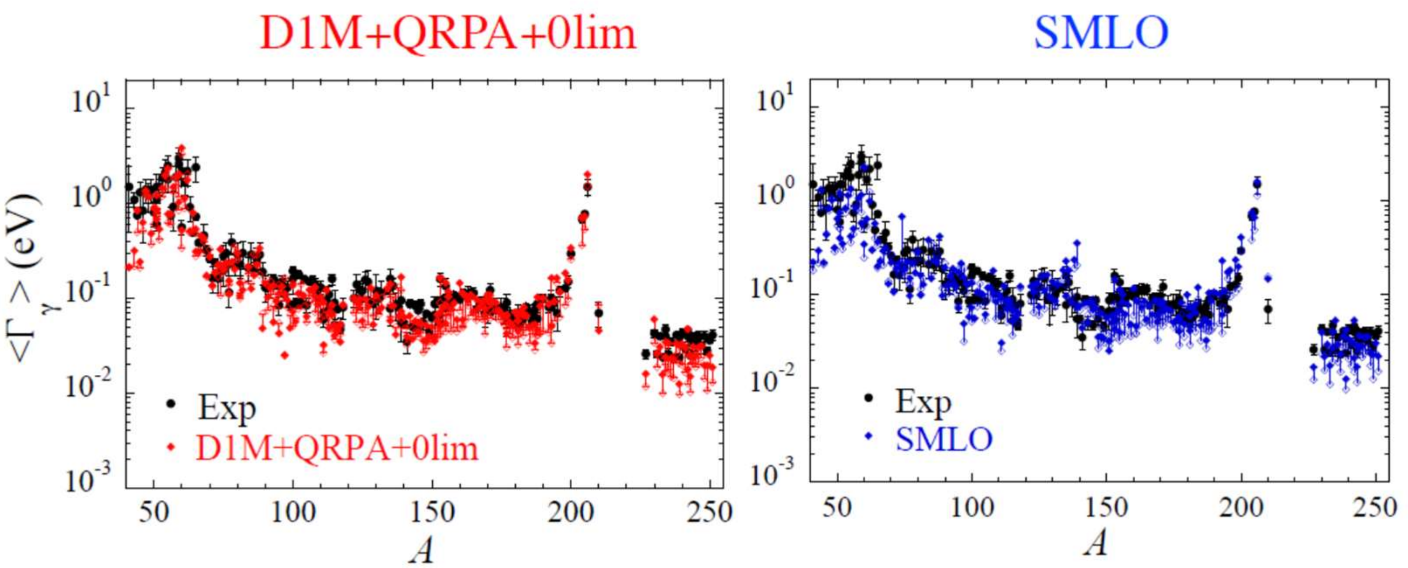




Gamma-ray strengths : Gogny QRPA vs analytical

Comparison of D1M+QRPA+0lim and SMLO with <Γ_γ> data

$$\langle \Gamma_\gamma \rangle = \frac{D_0}{2\pi} \sum_{X,L,J,\pi} \int_0^{S_n+E_n} T_{XL}(\varepsilon_\gamma) \times \rho(S_n + E_n - \varepsilon_\gamma, J, \pi) d\varepsilon_\gamma$$



Open diamonds = CT + BSFG

Full diamonds = HFB + Combinatorial

Both PSF models reproduce ~230 <Γ_γ> within ~ 30-50%

Gamma-ray strengths : various options in TALYS

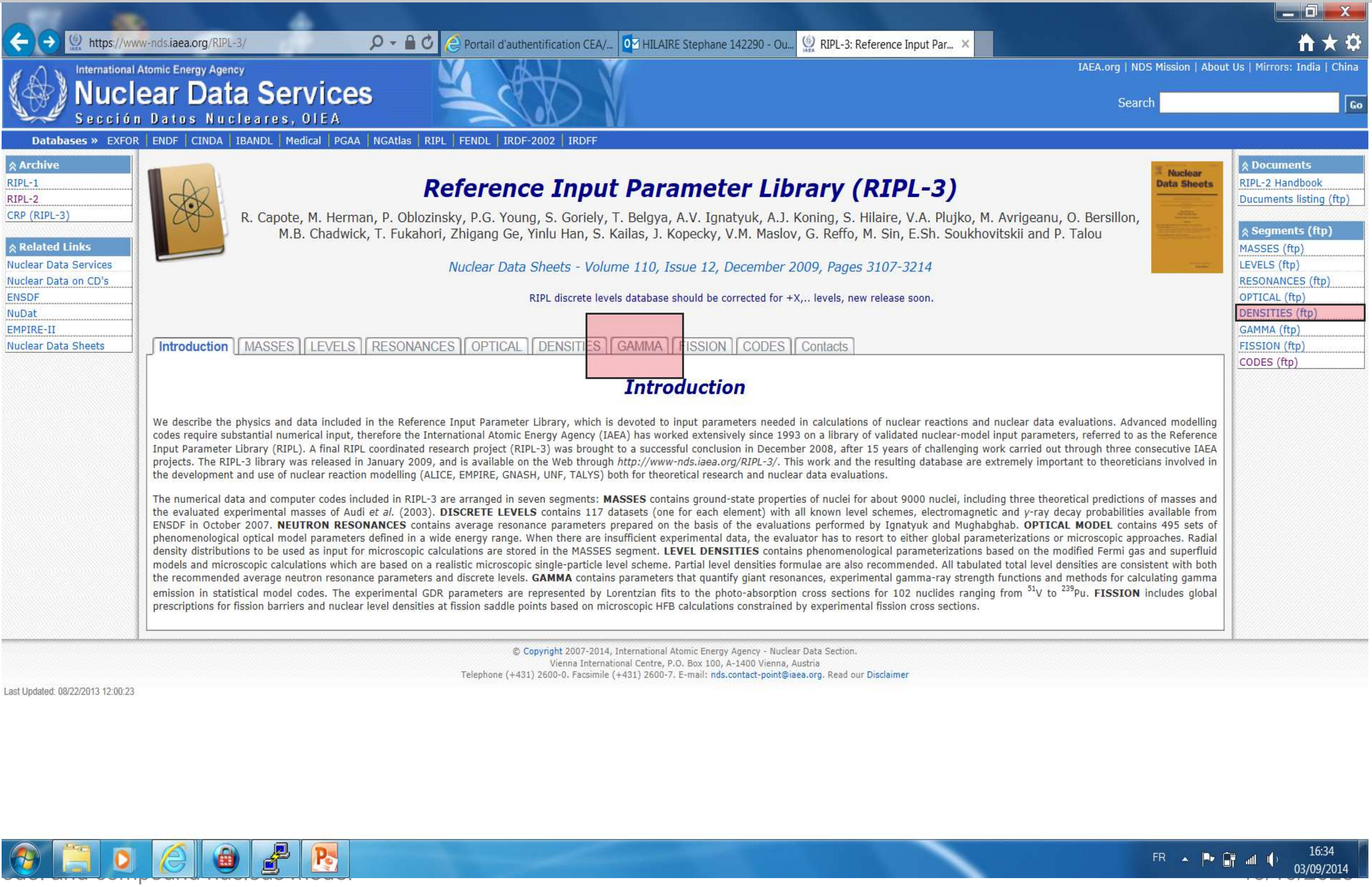
projectile n
element u
mass 278
energy 1.
strength 1 → 10

- strength = 1 : GLO model (Kopecky & Uhl 1990)
- strength = 2 : SLO model
- strength = 3 : Skyrme-HFBCS + QRPA
- strength = 4 : Skyrme-HFB + QRPA
- strength = 5 : Hybrid model
- strength = 6 : *T*-dependent Skyrme-HFB + QRPA
- strength = 7 : *T*-dependent RMF-HFB + QRPA
- strength = 8 : Gogny-HFB + QRPA
- strength = 9 : SMLO 2019
- strength =10 : T-dependent Bsk27-HFB + QRPA

With many options to modify/adjust the strength parameters

- Analytical formulas (strength=1,2,5): σ_i, Γ_i, E_i, … for GR and PR
- Microscopic formulas (strength=3-4,6-8): “etable”, “ftable”, “wtable“

Gamma-ray strengths : summary



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Nuclear Data Sheets - Volume 110, Issue 12, December 2009, Pages 3107-3214

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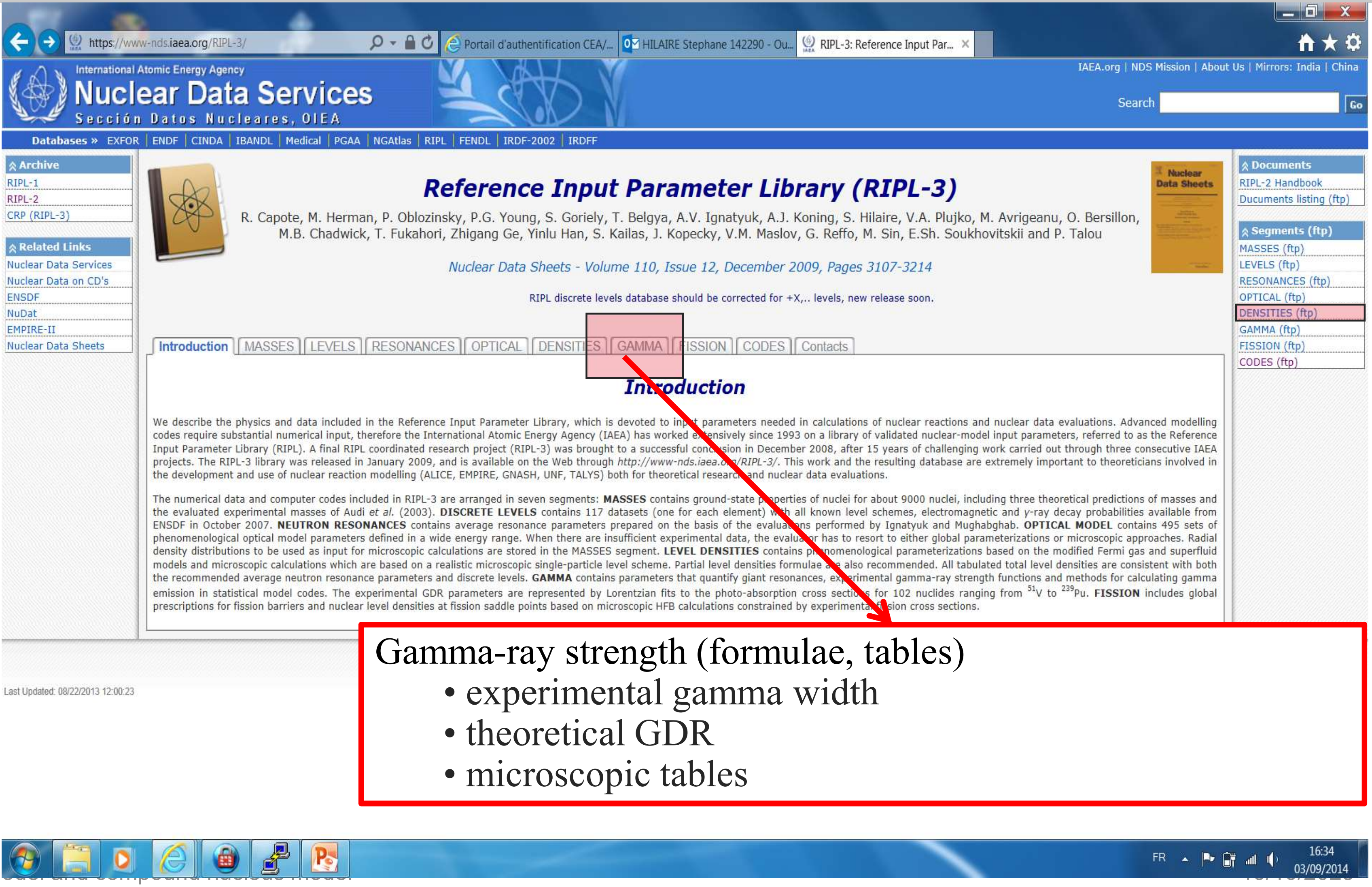
Gamma-ray strengths : summary



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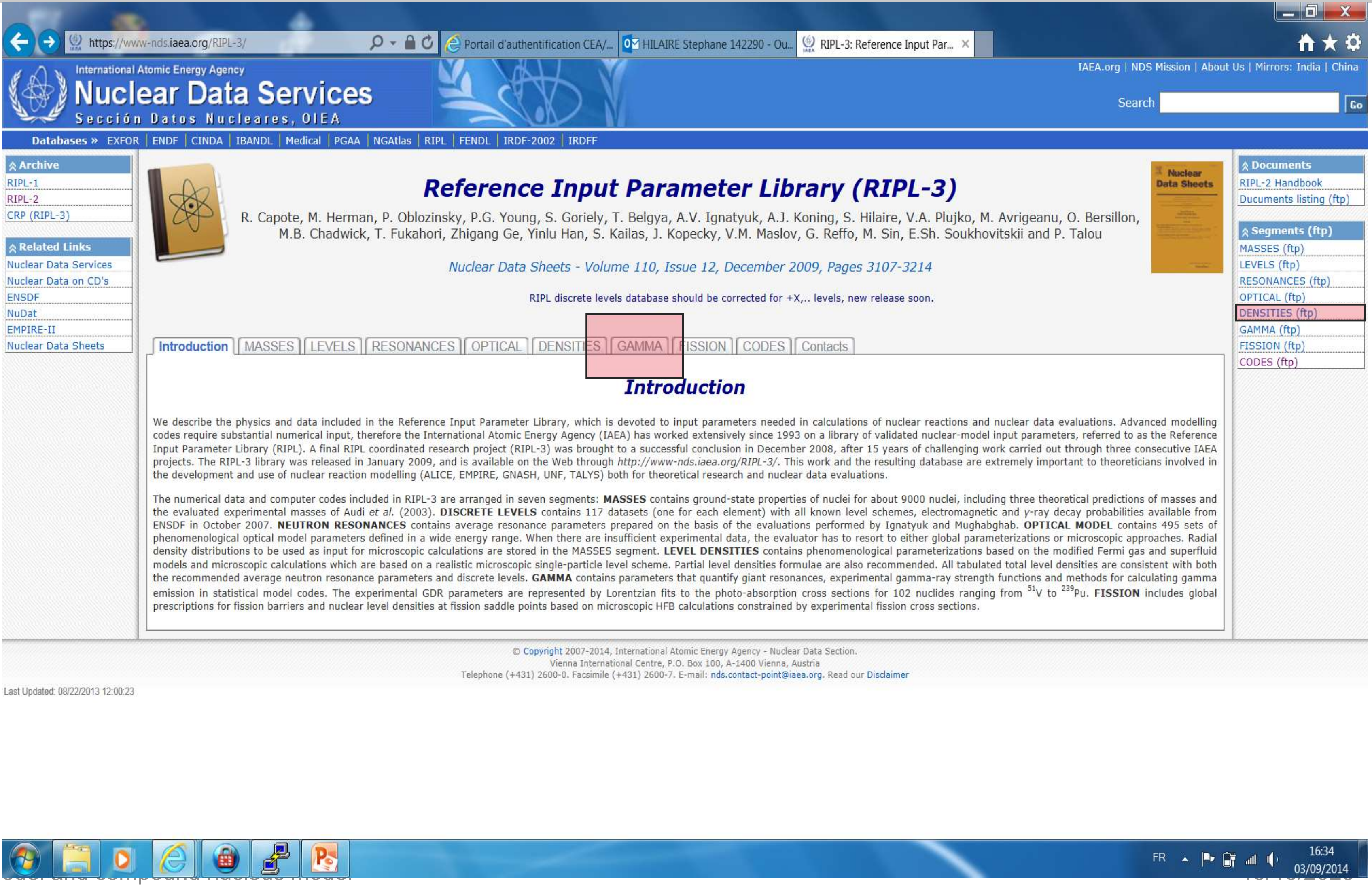
Gamma-ray strength (formulae, tables)
- experimental gamma width
- theoretical GDR
- microscopic tables

Gamma-ray strengths : summary



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2. FISSION TRANSMISSION COEFFICIENTS

FISSION TRANSMISSION NTS

To be discussed on thursday !