DE LA RECHERCHE À L'INDUSTRIE

Level densities and gamma-ray strengths

S. Hilaire - CEA,DAM,DIF

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Content

Content

YESTERDAY

Content

- Introduction

- General features about nuclear reactions

- Time scales and associated models
- Types of data needed
- Data format = f (users)

- Nuclear Models

- Basic structure properties
- Optical model
- Pre-equilibrium model
- Compound Nucleus model

- Model ingredients

TODAY

- 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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- Gamma-ray strengths
- Fission transmission coefficients

- Fission reactions

TOMORROW

- Generalities about fission
- Fission neutrons and gammas
- Fission yields
- Fission cross sections

- Prospects

Content

The references today

Available online at www.sciencedirect.com
ScienceDirect
Nuclear Data Sheets 110 (2009) 3107–3214
ELSEVIER
Nuclear Data Sheets
www.elsevier.com/locate/nds

RIPL – Reference Input Parameter Library for Calculation of Nuclear Reactions and Nuclear Data Evaluations

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We describe the physics and data included in the Reference Input Parameter Library, which is devoted to input parameters needed in calculations of nuclear reactions and nuclear data evaluations. Advanced modelling codes require substantial numerical input, therefore the International Atomic Energy Agency (IAEA) has worked extensively since 1993 on a library of validated nuclear-model input parameters, referred to as the Reference Input Parameter Library (RIPL). A final RIPL coordinated research project (RIPL-3) was brought to a successful conclusion in December 2008, after 15 years of challenging work carried out through three consecutive IAEA projects. The RIPL-3 library was released in January 2009, and is available on the Web through *http://www-nds.iaea.org/RIPL-3/*. This work and the resulting database are extremely important to theoreticians involved in the development and use of nuclear reaction modelling (ALICE, EMPIRE, GNASH, UNF, TALYS) both for theoretical research and nuclear data evaluations.

The numerical data and computer codes included in RIPL-3 are arranged in seven segments: **MASSES** contains ground-state properties of nuclei for about 9000 nuclei, including three theoretical predictions of masses and the evaluated experimental masses of Audi *et al.* (2003). **DISCRETE LEVELS** contains 117 datasets (one for each element) with all known level schemes, electromagnetic and γ-ray decay probabilities available from ENSDF in October 2007. **NEUTRON RESONANCES** contains average resonance parameters prepared on the basis of the evaluations performed by Ignatyuk and Mughabghab. **OPTICAL MODEL** contains 495 sets of phenomenological optical model parameters defined in a wide energy range. When there are insufficient experimental data, the evaluator has to resort to either global parameterizations or microscopic approaches. Radial density distributions to be used as input for microscopic calculations are stored in the MASSES segment. **LEVEL DENSITIES** contains phenomenological parameterizations based on the modified Fermi gas and superfluid models and microscopic calculations which are based on a realistic microscopic single-particle level scheme. Partial level densities formulae are also recommended. All tabulated total level densities are consistent with both the recommended average neutron resonance parameters and discrete levels. **GAMMA** contains parameters that quantify giant resonances, experimental gamma-ray strength functions and methods for calculating gamma emission in statistical model codes. The experimental GDR parameters are represented by Lorentzian fits to the photo-absorption cross sections for 102 nuclides ranging from ^{51}V to ^{239}Pu. **FISSION** includes global prescriptions for fission barriers and nuclear level densities at fission saddle points based on microscopic HFB calculations constrained by experimental fission cross sections.

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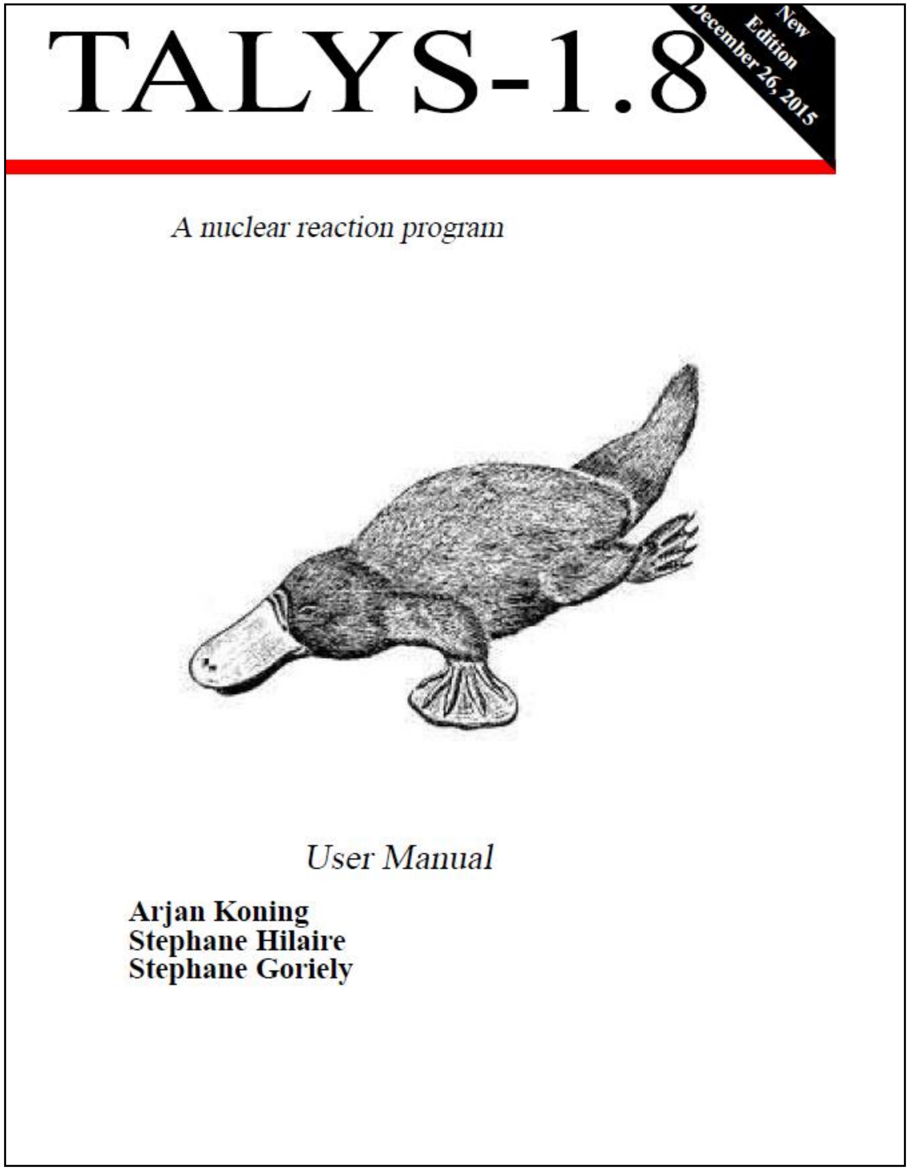


TALYS-1.8

New Edition
December 26, 2015

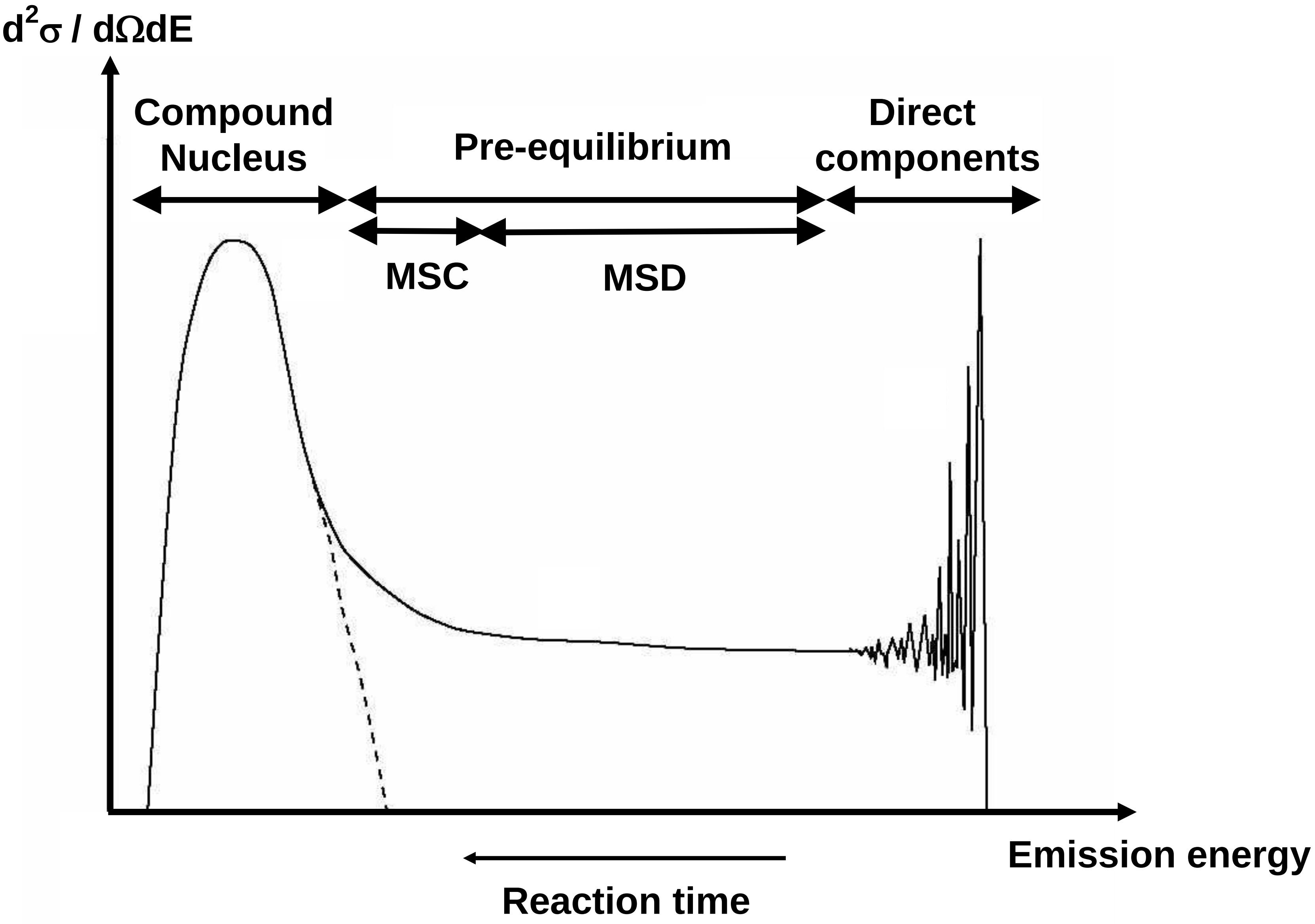
A nuclear reaction program

User Manual

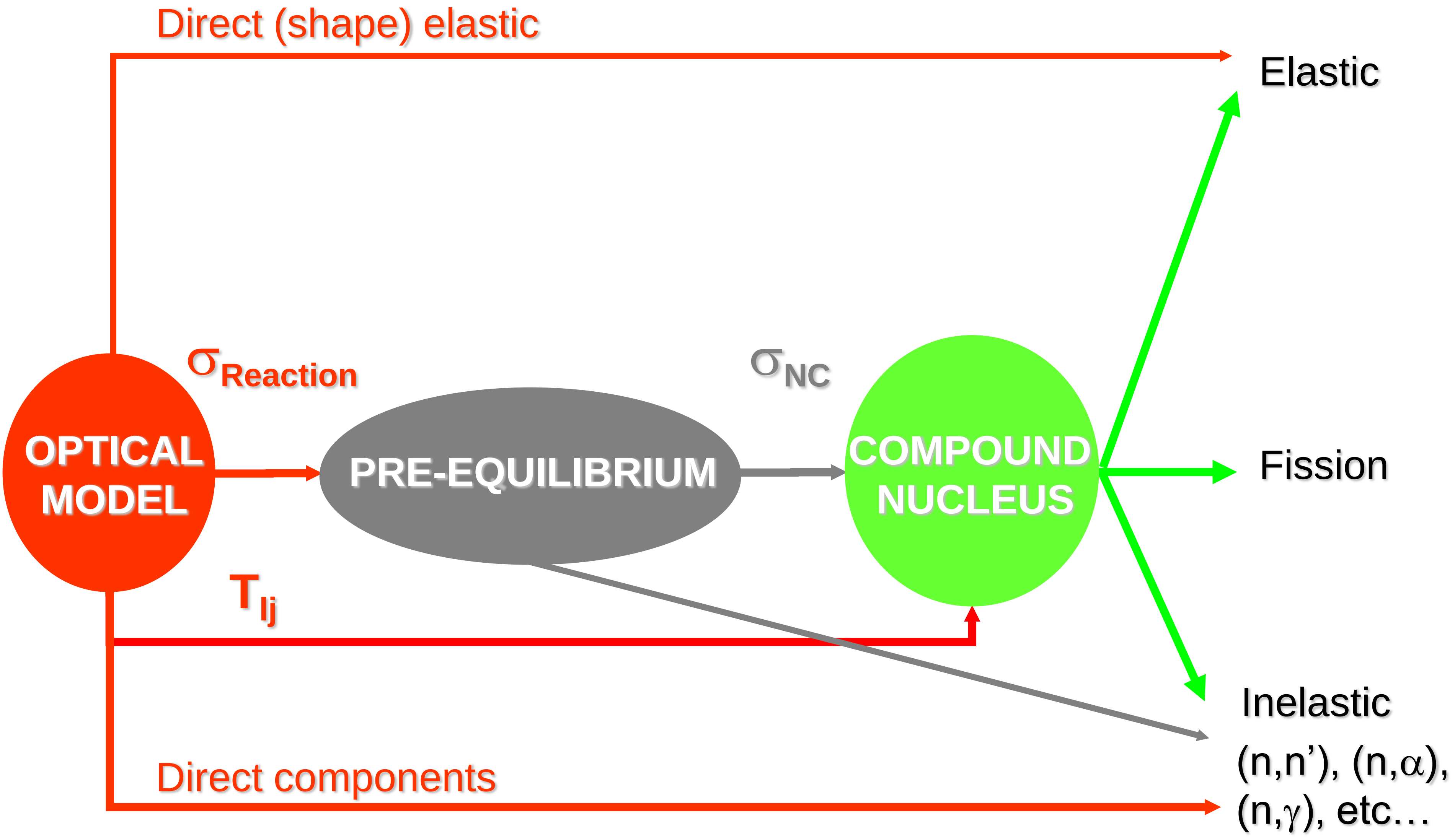
Arjan Koning
Stephane Hilaire
Stephane Goriely

FEW REMINDERS

TIME SCALES AND ASSOCIATED MODELS



TIME SCALES AND ASSOCIATED MODELS



Direct (shape) elastic

$\sigma_{Reaction}$

σ_{NC}

OPTICAL MODEL

PRE-EQUILIBRIUM

COMPOUND NUCLEUS

T_{lj}

Direct components

Elastic

Fission

Inelastic

(n,n’), (n,α), (n,γ), etc…

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

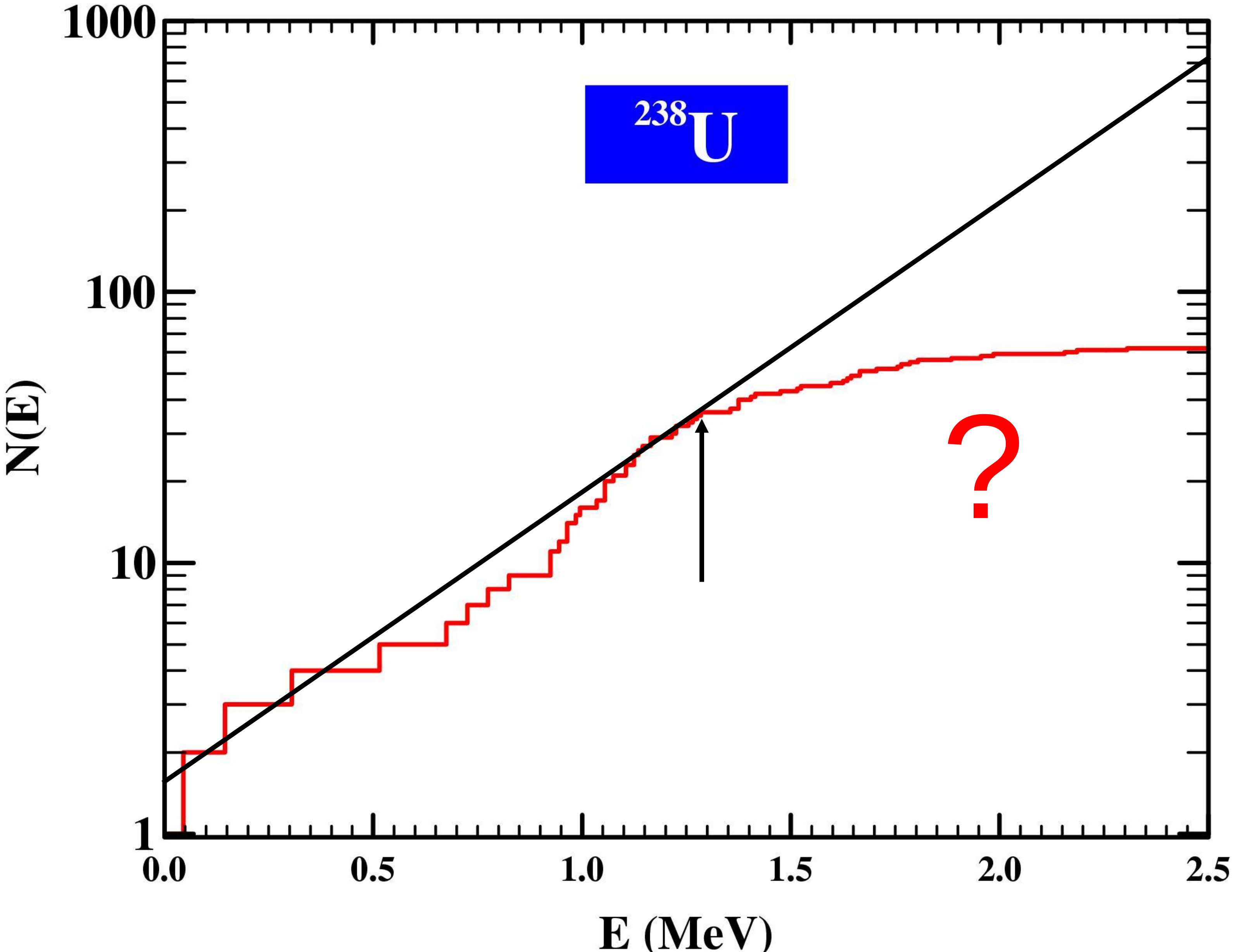
- Total level densities

- 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

LEVEL DENSITIES
(Why do we need them ?)



LEVEL DENSITIES
(Where do we need them ?)

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

THE PRE-EQUILIBRIUM MODEL
(Master equation exciton model)

$P(n,E,t)$ = **Probability** to find for a given 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

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

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

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

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

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

Original formulation

Corrections for proton-neutron distinguishability & complex particle emission

State densities

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

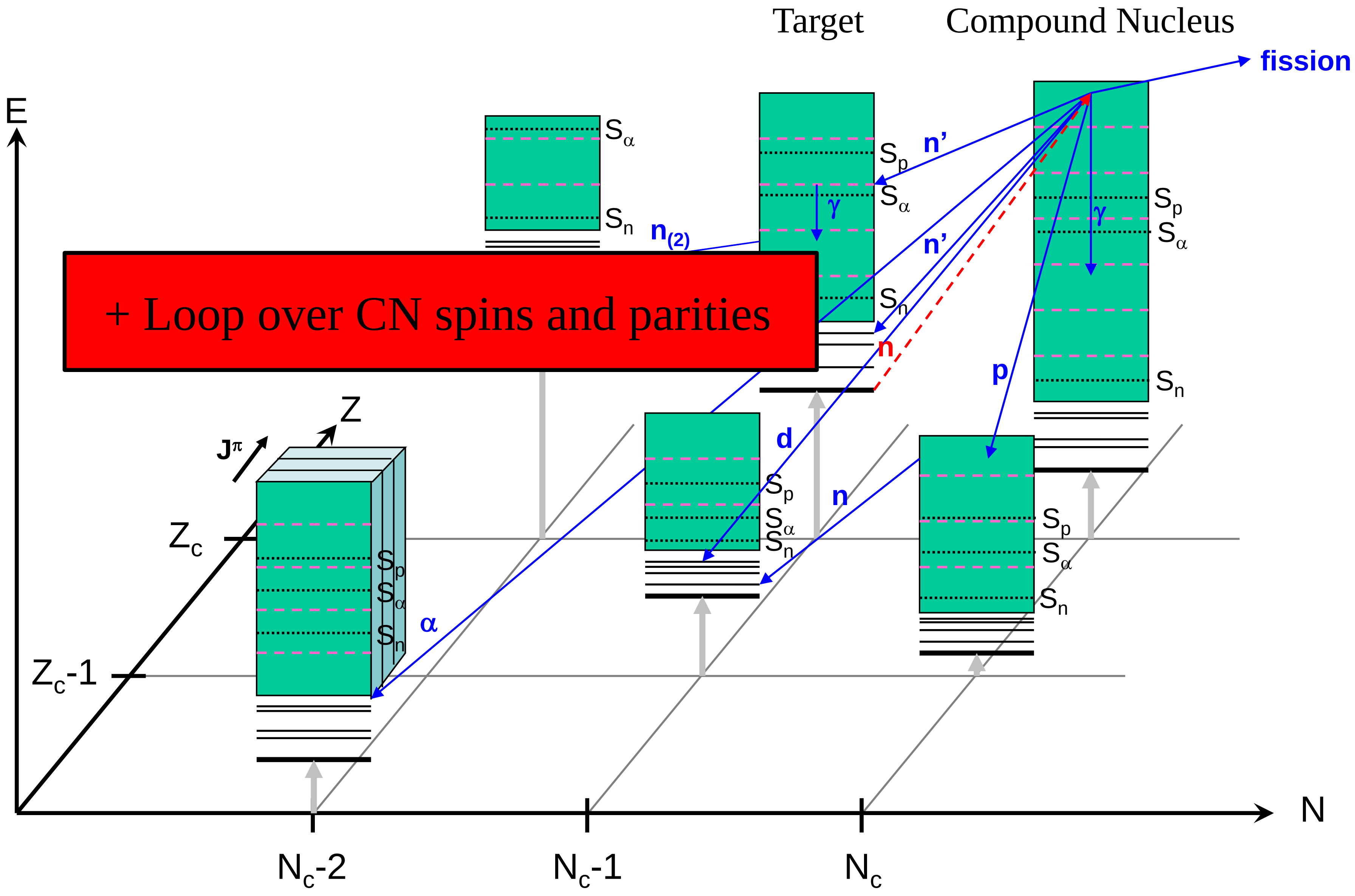
LEVEL DENSITIES
(Where do we need them ?)

⇒ 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)



+ Loop over CN spins and parities

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.

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
(the GOE triple integral)

$$
\begin{aligned}
W_{a,l_a,j_a,b,l_b,j_b} = {} & \int_0^{+\infty} d\lambda_1 \int_0^{+\infty} d\lambda_2 \int_0^{1} d\lambda \, \frac{\lambda(1-\lambda)|\lambda_1-\lambda_2|}{\sqrt{\lambda_1(1+\lambda_1)\lambda_2(1+\lambda_2)(\lambda+\lambda_1)^2(\lambda+\lambda_2)^2}} \\
& \prod_c \frac{(1-\lambda\, T^J_{c,l_c,j_c})}{\sqrt{(1+\lambda_1\, T^J_{c,l_c,j_c})(1+\lambda_2\, T^J_{c,l_c,j_c})}} \quad \left\{ \delta_{ab}(1-T^J_{a,l_a,j_a}) \right. \\
& \left[\frac{\lambda_1}{1+\lambda_1\, T^J_{a,l_a,j_a}} + \frac{\lambda_2}{1+\lambda_2\, T^J_{a,l_a,j_a}} + \frac{2\lambda}{1-\lambda\, T^J_{a,l_a,j_a}} \right]^2 + (1+\delta_{ab}) \\
& \left[\frac{\lambda_1(1+\lambda_1)}{(1+\lambda_1\, T^J_{a,l_a,j_a})(1+\lambda_1\, T_{b,l_b,j_b})} + \frac{\lambda_2(1+\lambda_2)}{(1+\lambda_2\, T^J_{a,l_a,j_a})(1+\lambda_2\, T_{b,l_b,j_b})} \right. \\
& \left. \left. + \frac{2\lambda(1-\lambda)}{(1-\lambda\, T^J_{a,l_a,j_a})(1-\lambda\, T_{b,l_b,j_b})} \right] \right\}
\end{aligned}
$$

T < 1

LEVEL DENSITIES

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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**
- **Běták and Dobeš 1976 : account for finite number of hole states**

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

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)

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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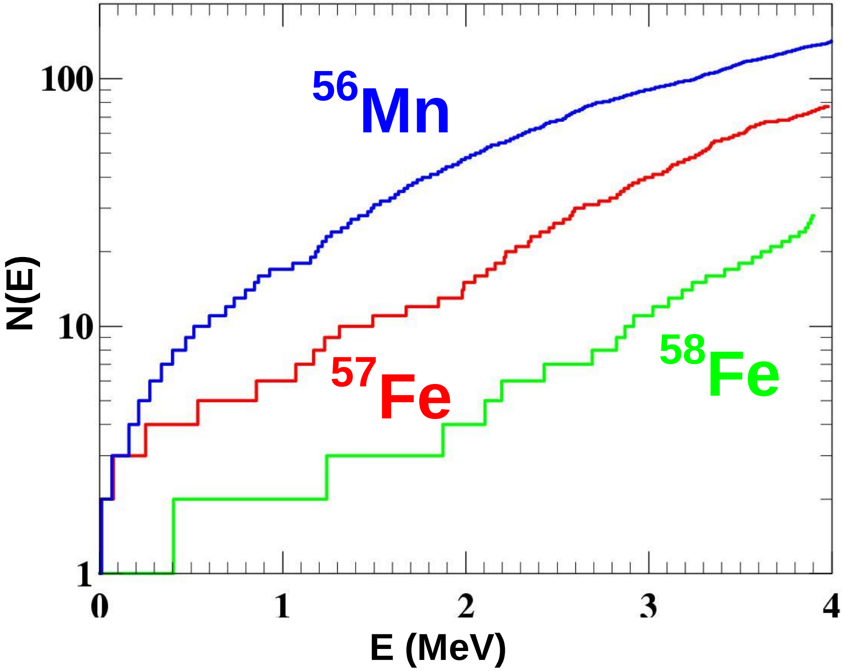
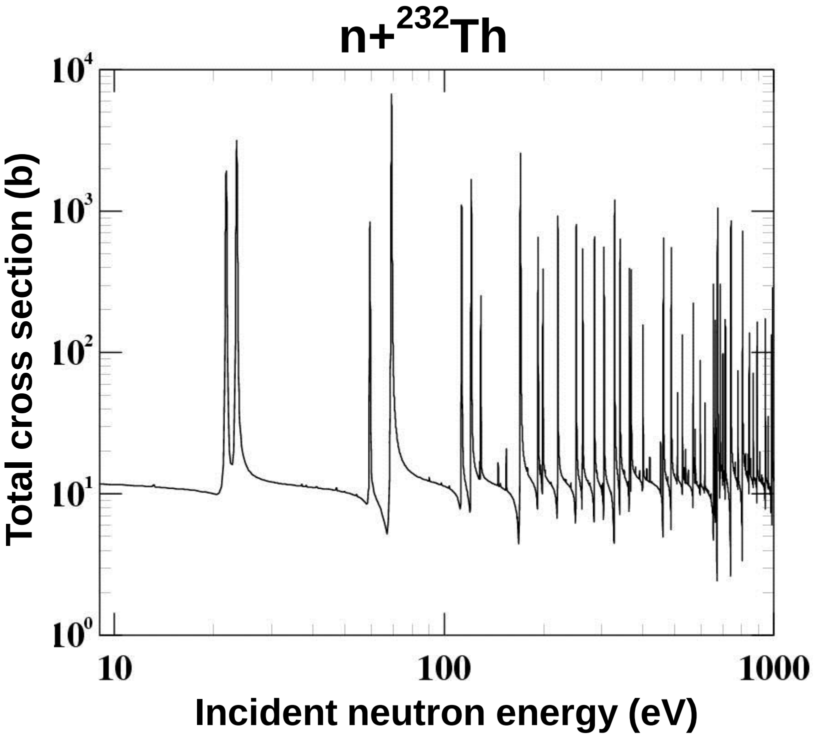
LEVEL DENSITIES
(Qualitative aspects from experimental data)





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

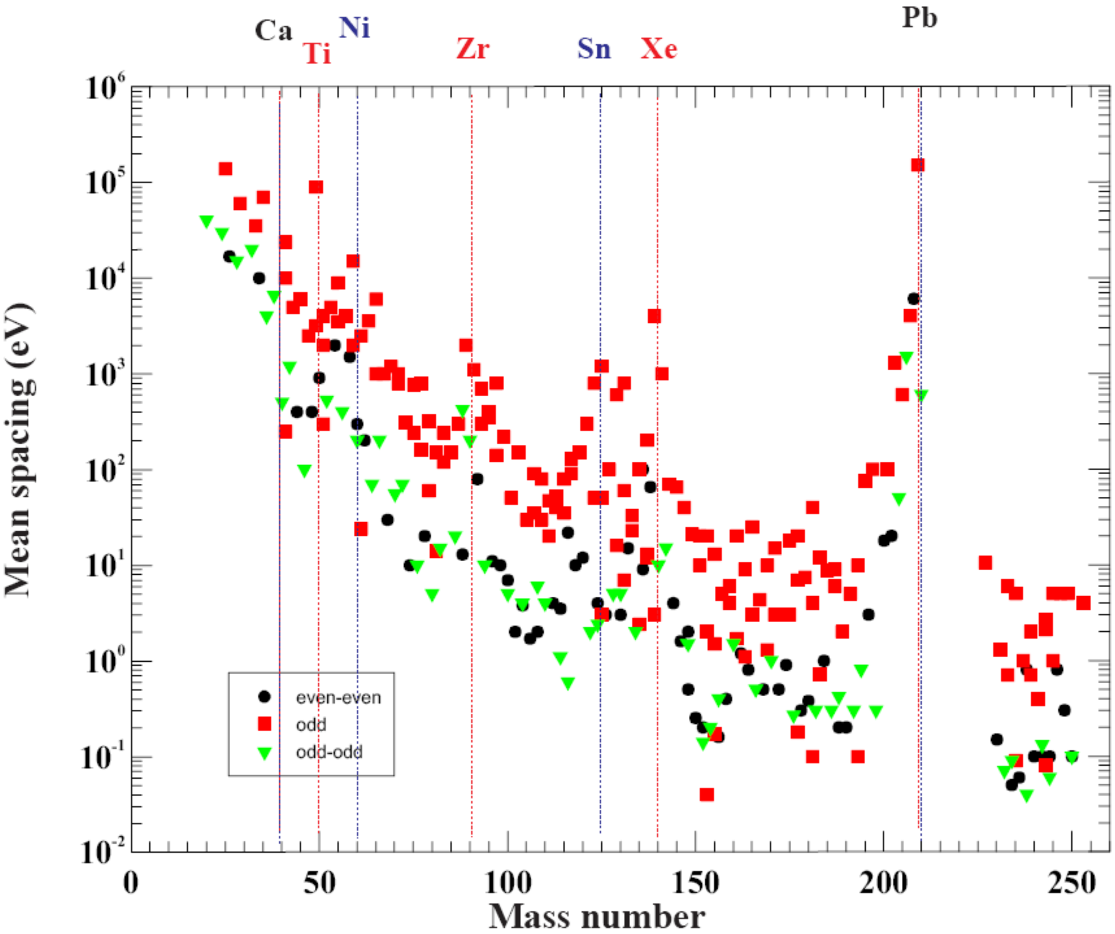
$$\Rightarrow \rho(E)= \frac{dN(E)}{dE} \quad \text{increases exponentially}$$

$\Rightarrow$ 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 from D_0 vs A)



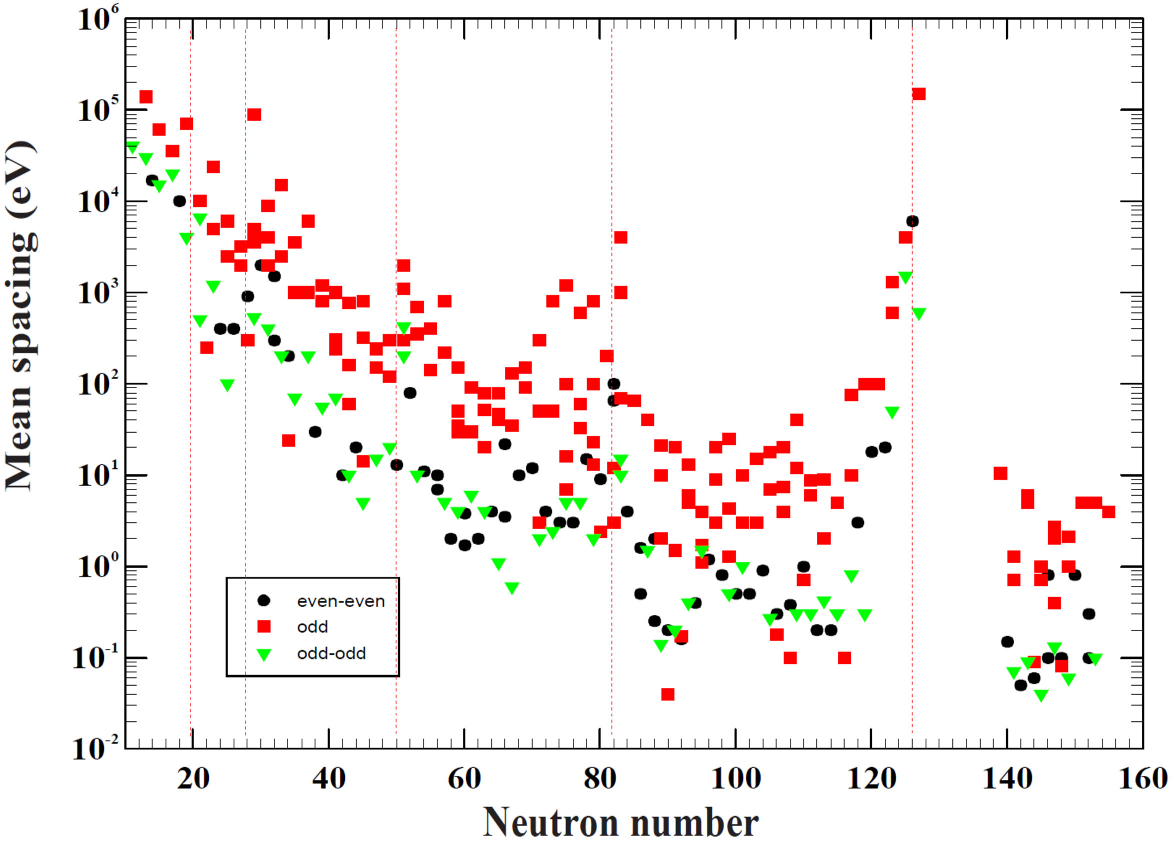
Iljinov et al., NPA 543 (1992) 517.

⇒ **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 from D_0 vs N)



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$\Rightarrow$ **Mass dependency**

Odd-even effects

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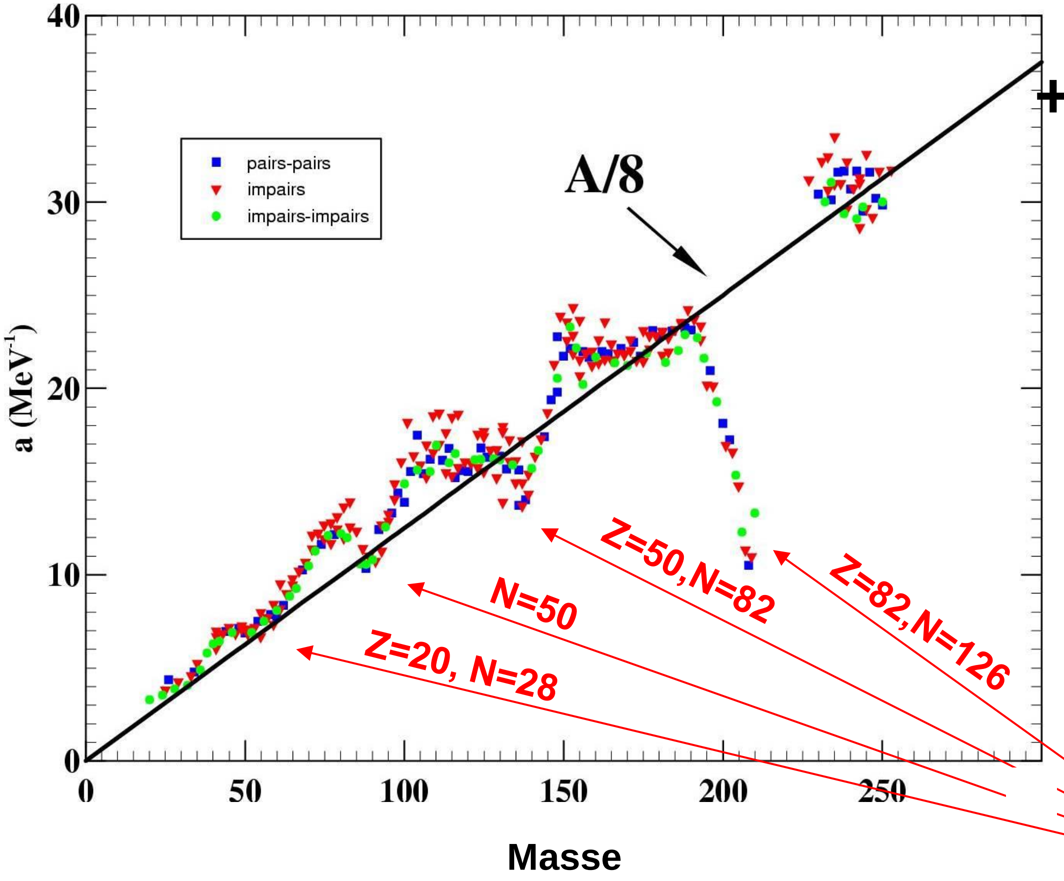
$$= \rho\,(B_n, I_t+1/2, \pi_t) + \rho\,(B_n, I_t-1/2, \pi_t) \text{ otherwise}$$

LEVEL DENSITIES
(Quantitative analysis)

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

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



Odd-even effects accounted for

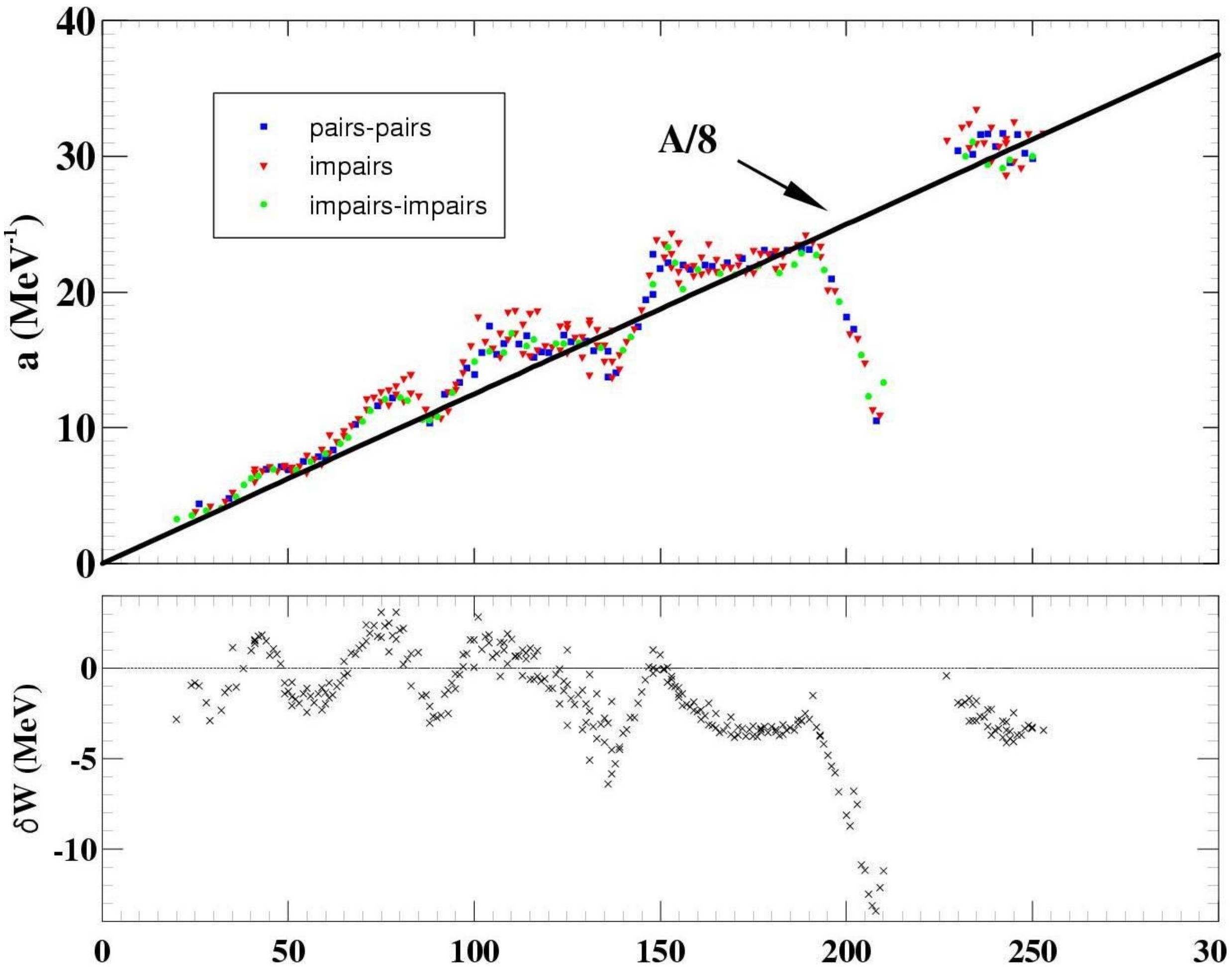
$$U \rightarrow U^* = U - \Delta$$

$$\Rightarrow \text{odd-even effects}$$

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

Shell effects

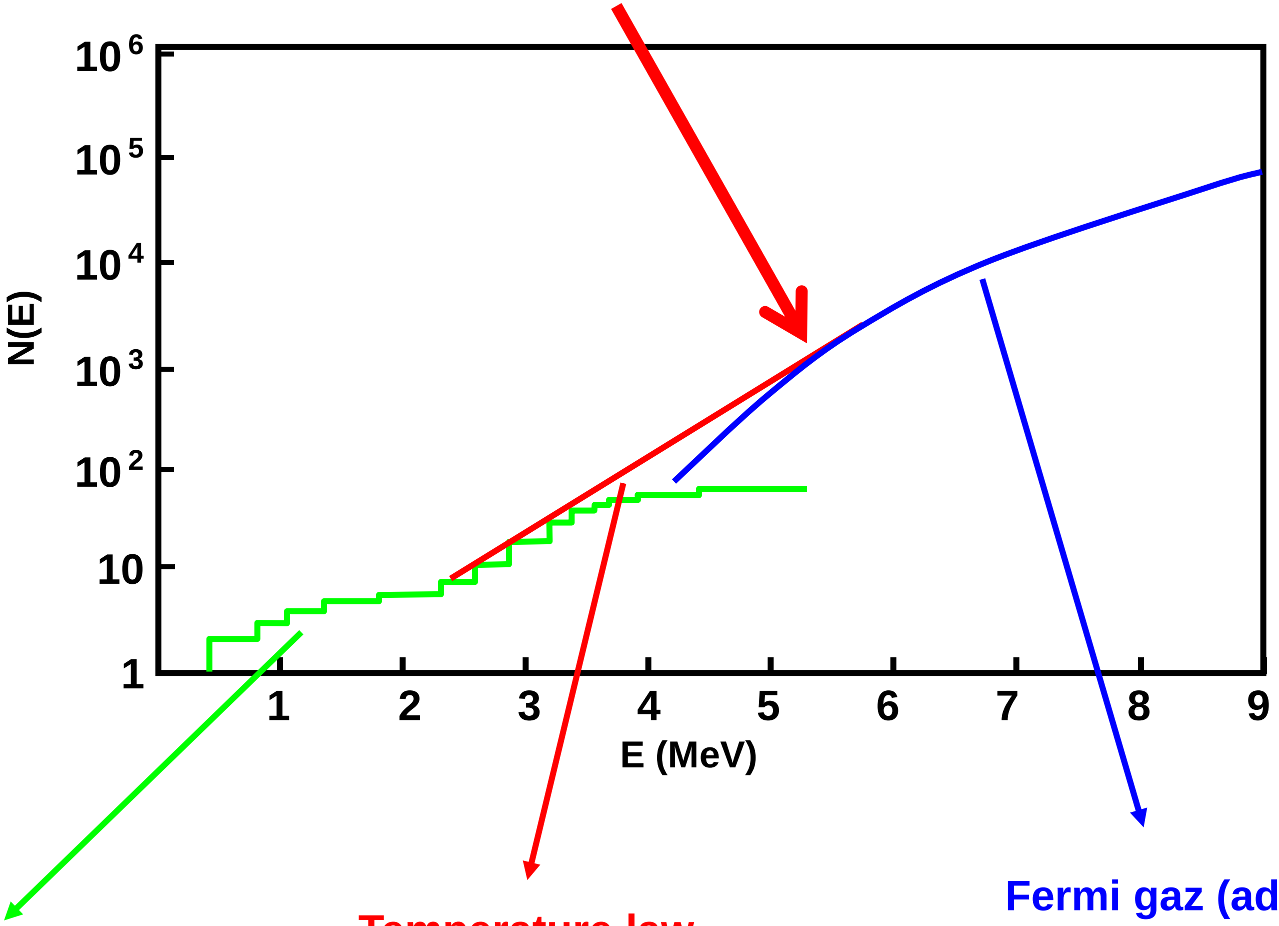
LEVEL DENSITIES
(Ignatyuk formula)



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

LEVEL DENSITIES
(Summary of most simple analytical description)

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



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
(More sophisticated analytical approaches)

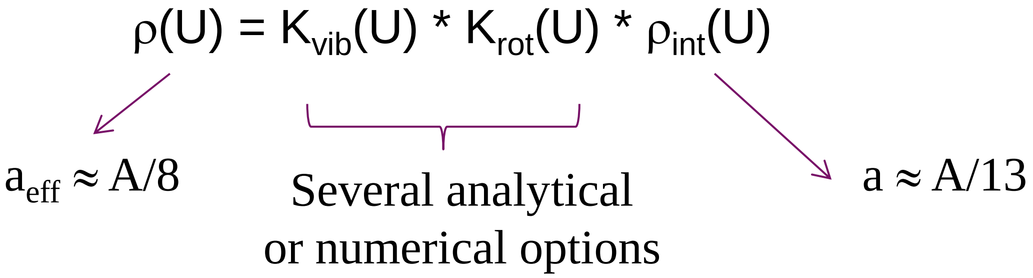
- **Superfluid model & Generalized superfluid model**

  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



$$\rho(U) = \underbrace{K_{vib}(U) * K_{rot}(U)}_{\text{Several analytical or numerical options}} * \rho_{int}(U)$$

$a_{eff} \approx A/8$

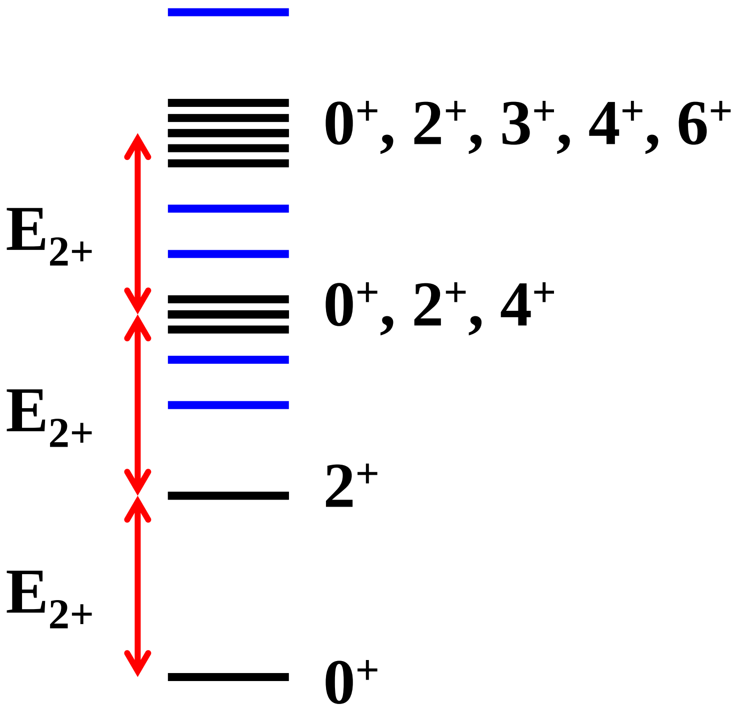
Several analytical
or numerical options

$a \approx A/13$

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

LEVEL DENSITIES
(Collective levels)

⇒ vibrational level sequence for a spherical even-even nucleus



$0^+, 2^+, 3^+, 4^+, 6^+$

$0^+, 2^+, 4^+$

2^+

0^+

E_{2+}

E_{2+}

E_{2+}

3 coupled phonons

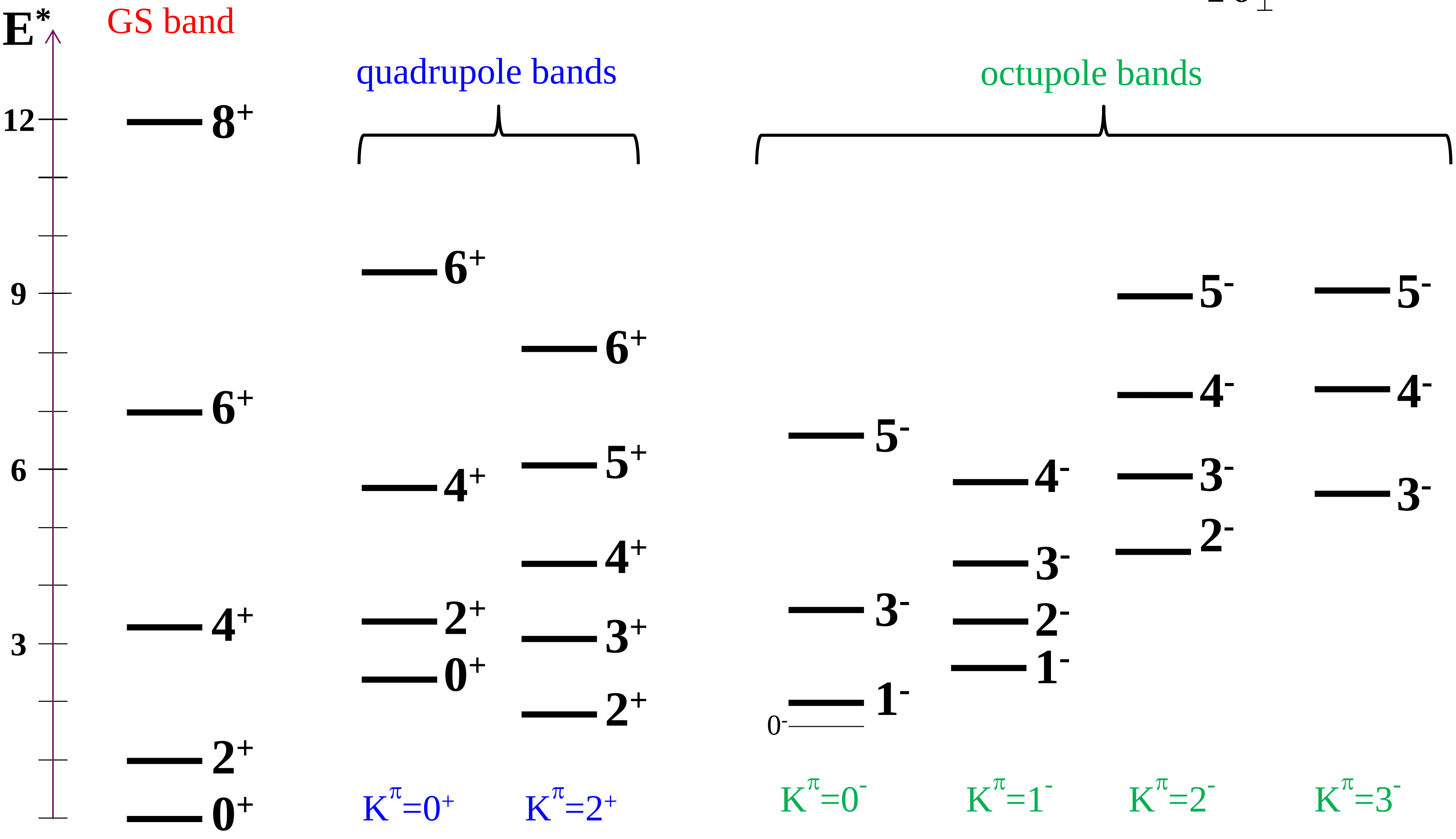
2 coupled phonons

1 phonon

other levels

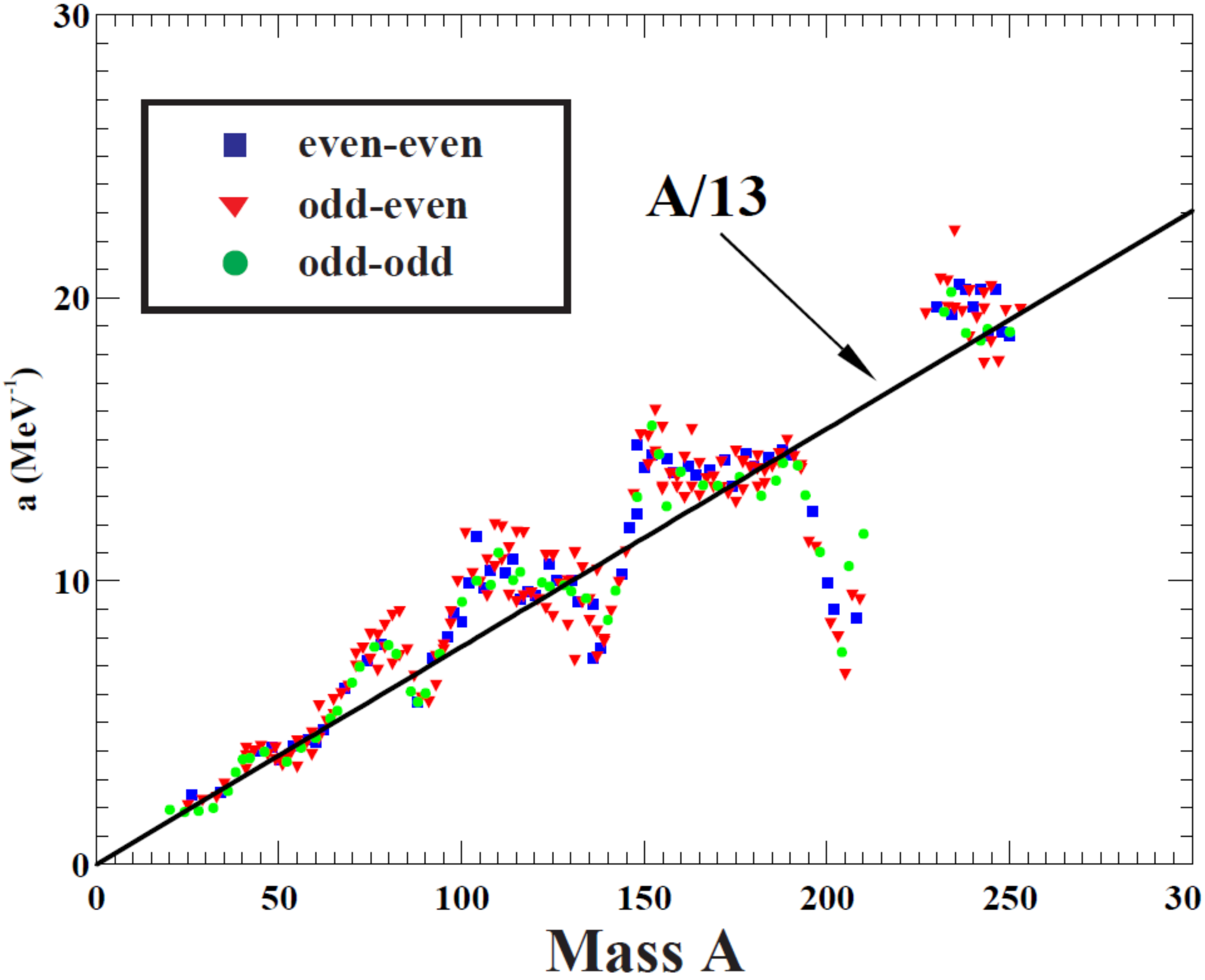
LEVEL DENSITIES
(Collective levels)

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



LEVEL DENSITIES
(Explicit treatment of collective levels)

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



LEVEL DENSITIES
(Shell Model Monte Carlo approach)

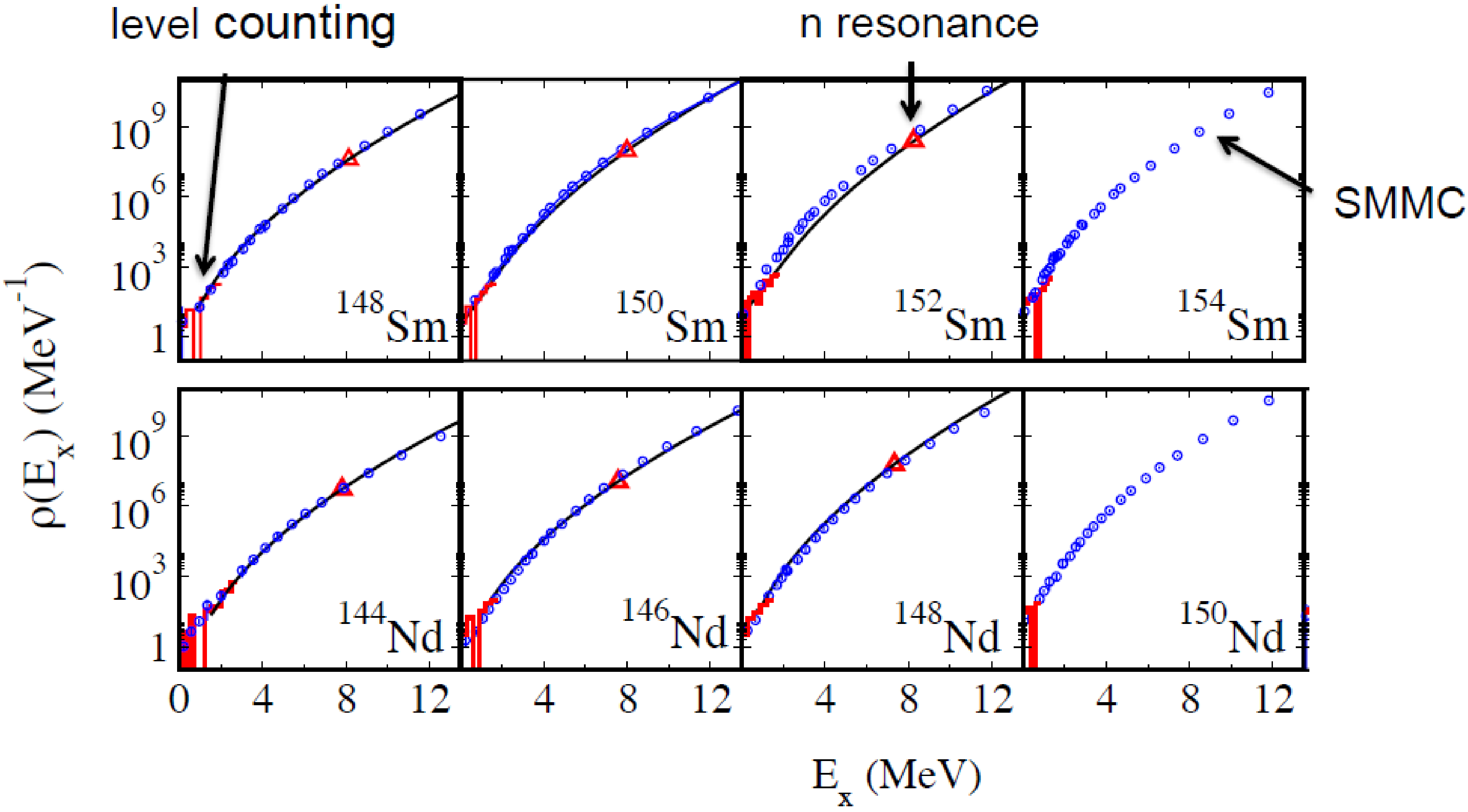
- **Shell Model Monte Carlo approach**

  Agrawal et al., PRC 59 (1999) 3109 + Koonin et al, Phys. Rep. 278 (1997) 1.

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

LEVEL DENSITIES
(SMMC results)

Level densities in samarium and neodymium isotopes

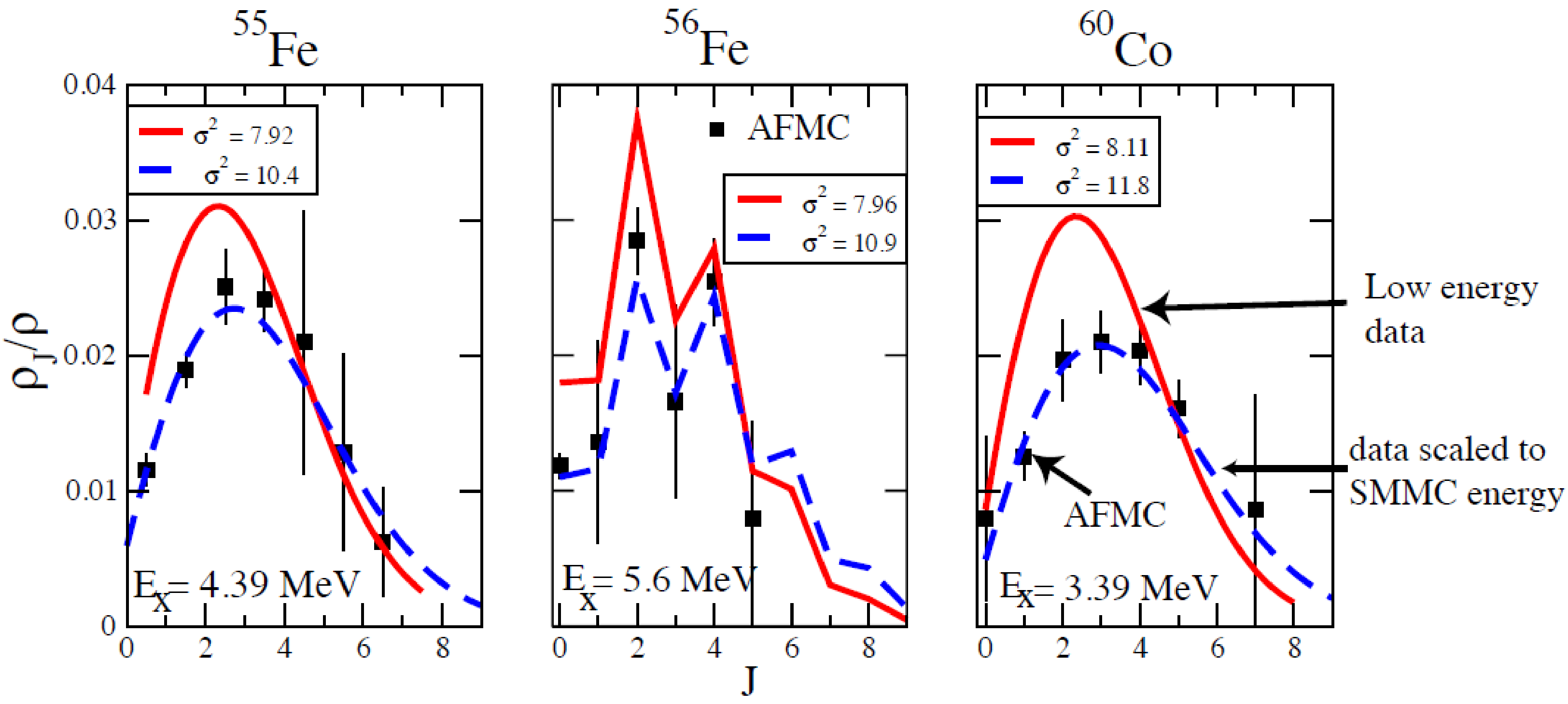


Courtesy Y. Alhassid

LEVEL DENSITIES
(SMMC results)

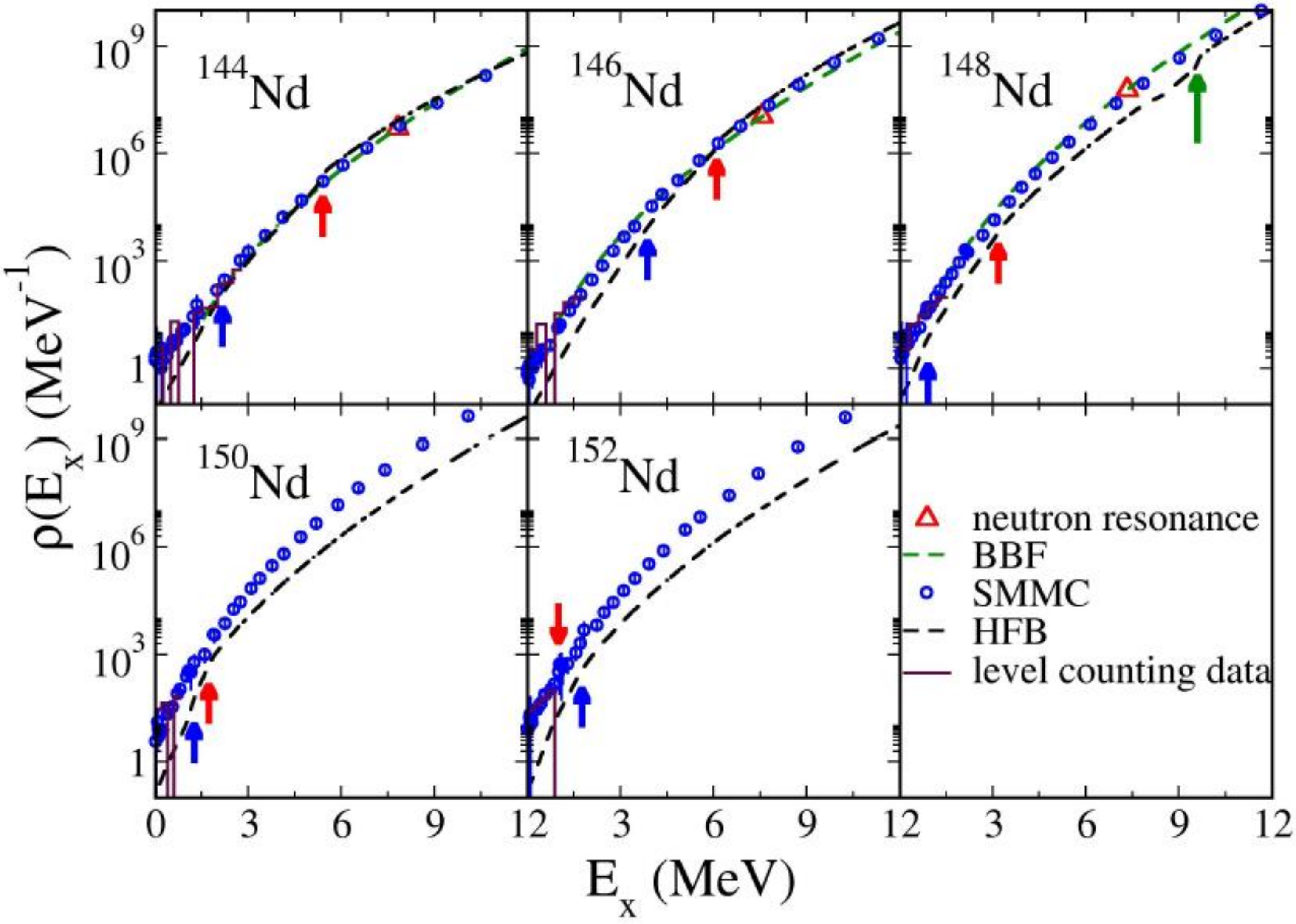
Spin distributions in SMMC

Y. Alhassid, S. Liu and H. Nakada, Phys. Rev. Lett. **99**, 162504 (2007)



Courtesy Y. Alhassid

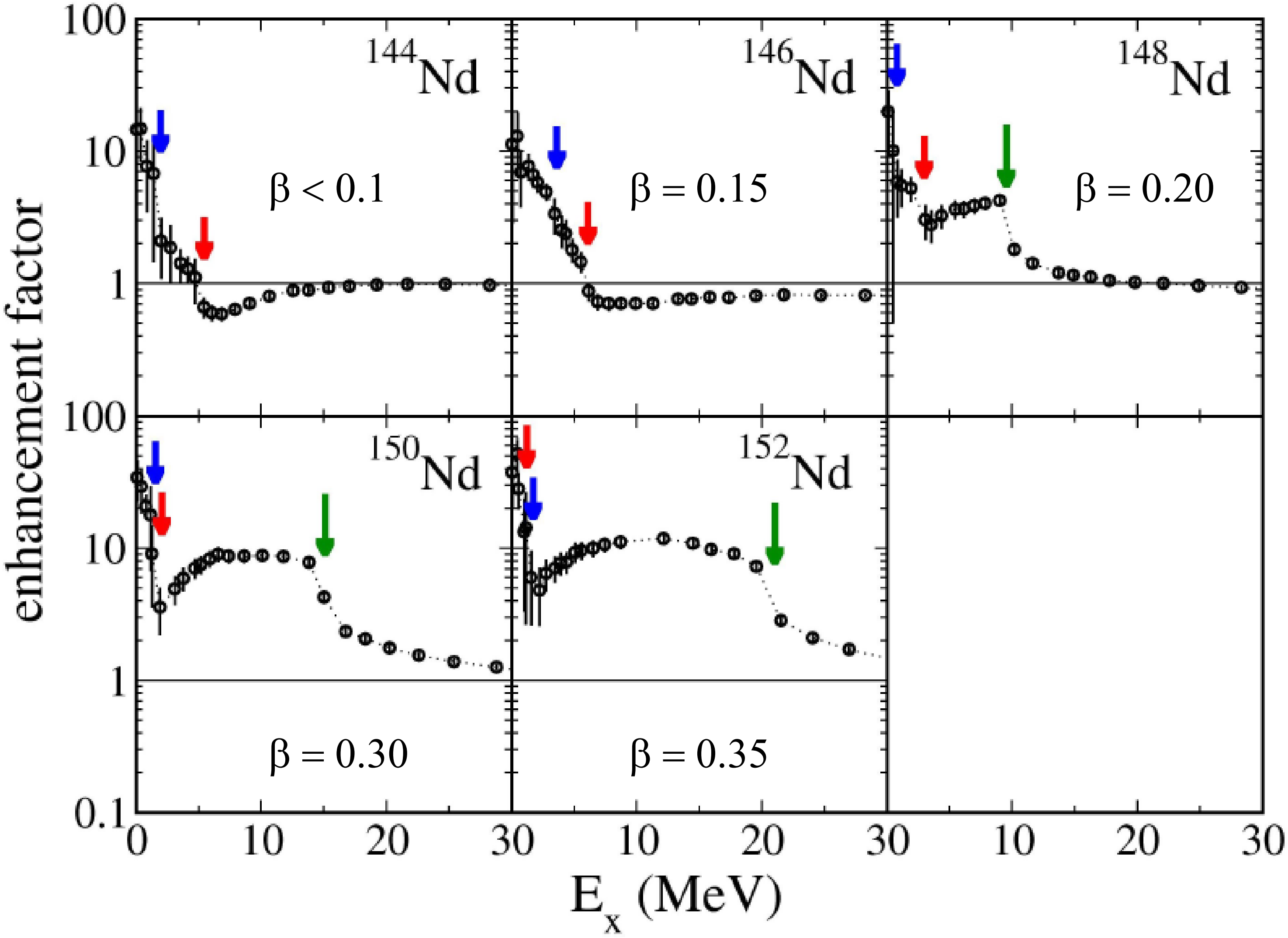
LEVEL DENSITIES
(SMMC results)



Courtesy Y. Alhassid

neutron pair breaking proton pair breaking shape transition

LEVEL DENSITIES
(SMMC results)



Courtesy Y. Alhassid

neutron pair breaking proton pair breaking shape transition

LEVEL DENSITIES
(HFB+BCS Statistical approach)

Mean Field + Statistical NLD formula

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

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

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

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

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

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

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

Courtesy S. Goriely

LEVEL DENSITIES
(HFB+BCS Statistical approach)

Mean Field + Statistical NLD formula

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

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

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

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

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

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

Courtesy S. Goriely

LEVEL DENSITIES
(HFB+BCS Statistical approach)

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

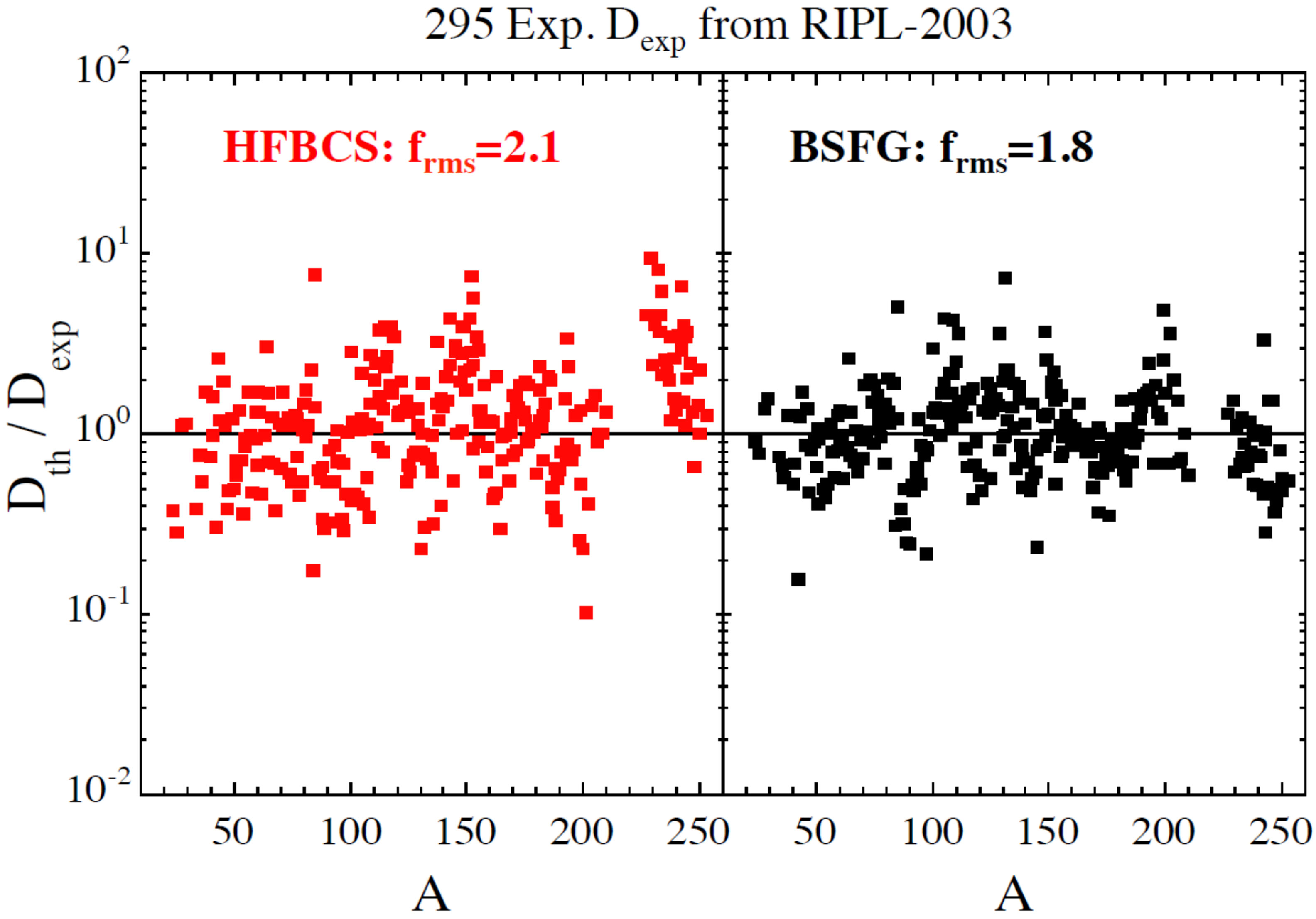
→ **Reliability**: Exact solution the analytical formulas tries to mimic

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

Courtesy S. Goriely

LEVEL DENSITIES
(HFB+BCS Statistical approach)

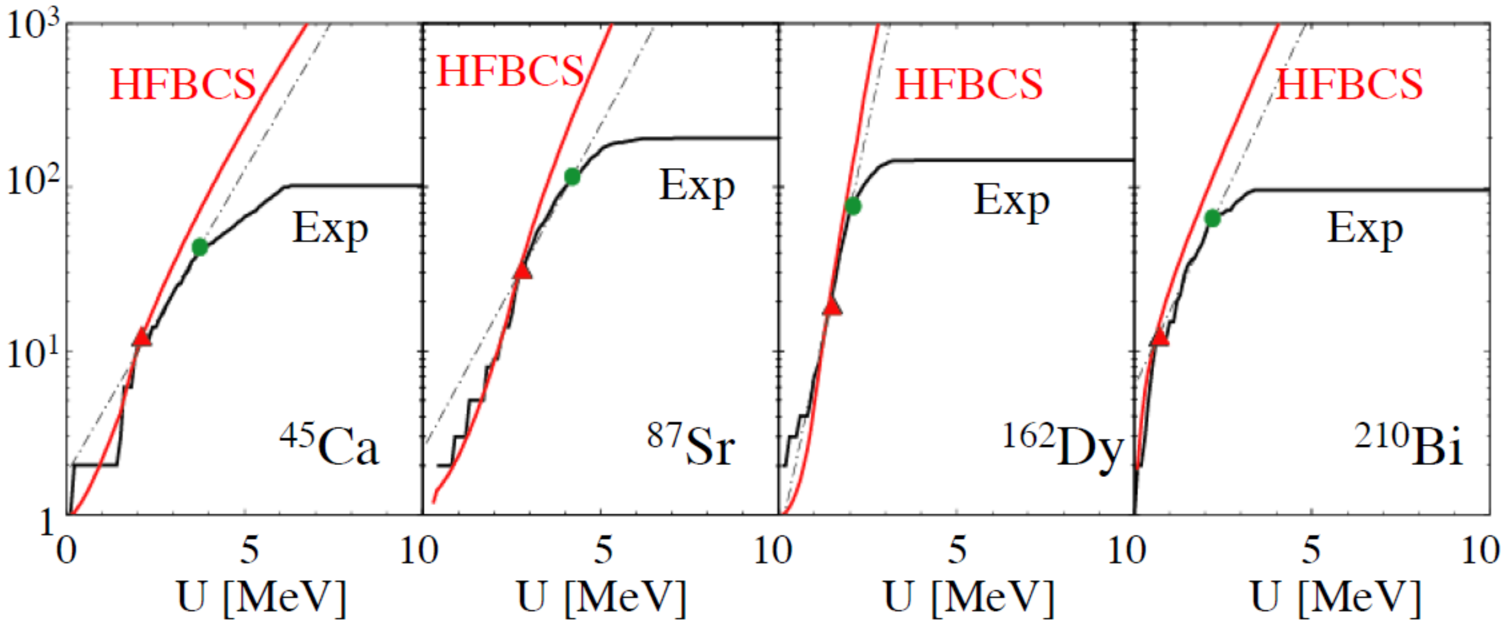
Comparison with experimental neutron resonance spacings



Courtesy S. Goriely

LEVEL DENSITIES
(HFB+BCS Statistical approach)

Comparison with experimental low-lying levels



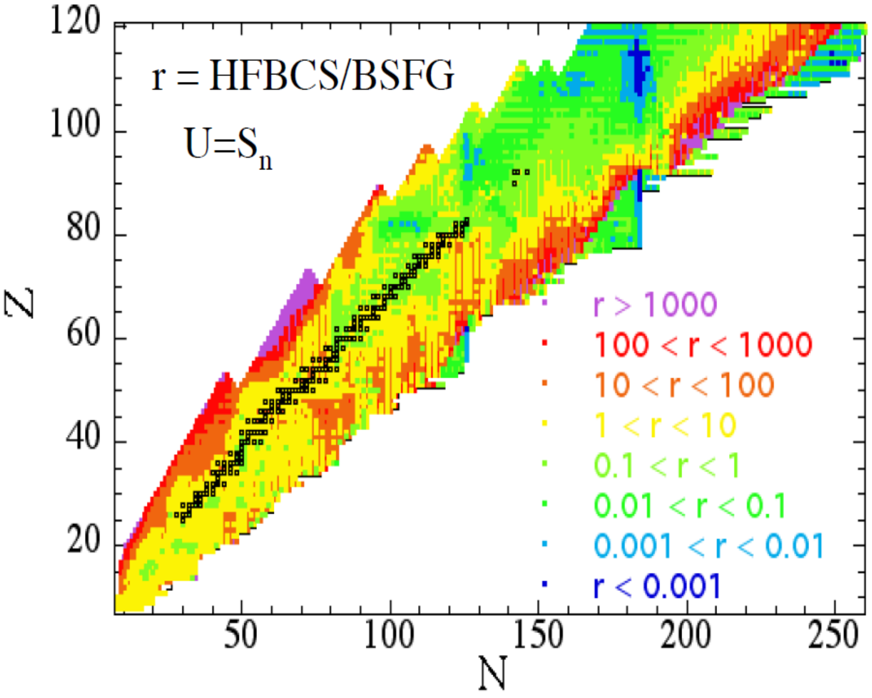
Courtesy S. Goriely

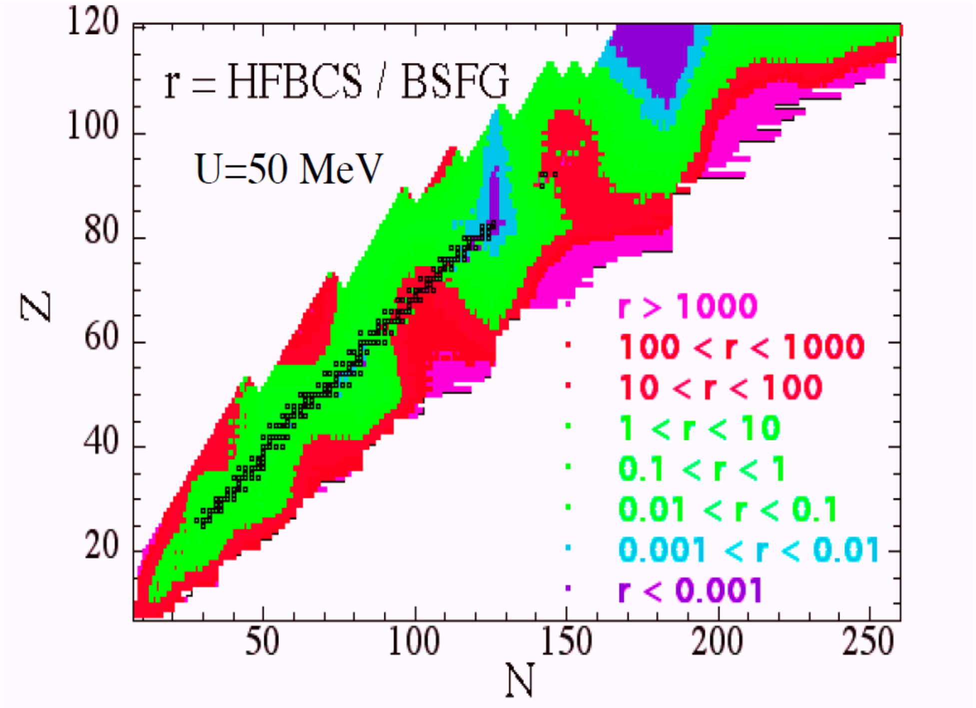
NLD provided for all ~8000 $8 \leq Z \leq 110$ nuclei in table format

LEVEL DENSITIES
(HFB+BCS Statistical approach)

Comparison of NLD predictions

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





Courtesy S. Goriely

LEVEL DENSITIES
(HFB+BCS Statistical approach)

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**

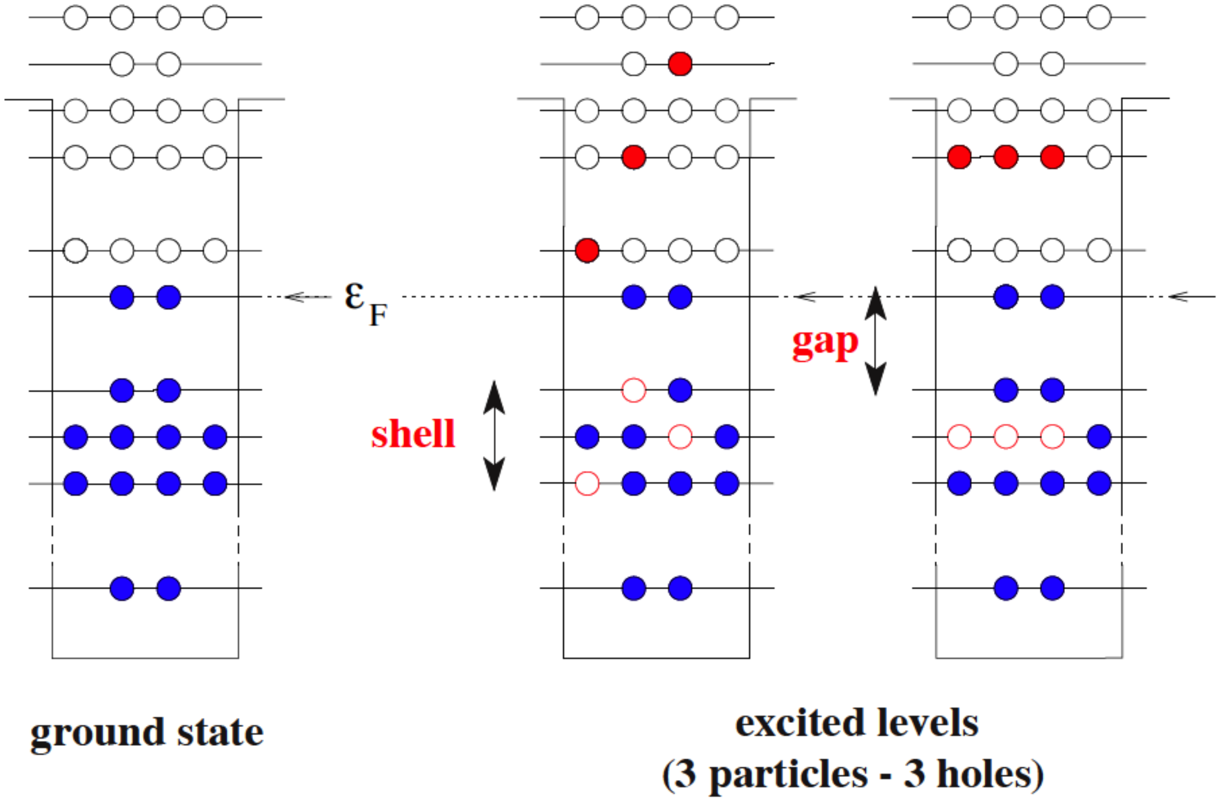
  S. Hilaire & S. Goriely, NPA 779 (2006) 63 & PRC 78 (2008) 064307.

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

LEVEL DENSITIES
(The combinatorial method)

Level density estimate is a counting problem: $\rho(U)=\mathrm{d}N(U)/\mathrm{d}U$

$N(U)$ is the number of ways to distribute the nucleons among the available levels for a fixed excitation energy U



LEVEL DENSITIES
(The combinatorial method)

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

- **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

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

trivial relation for spherical nuclei

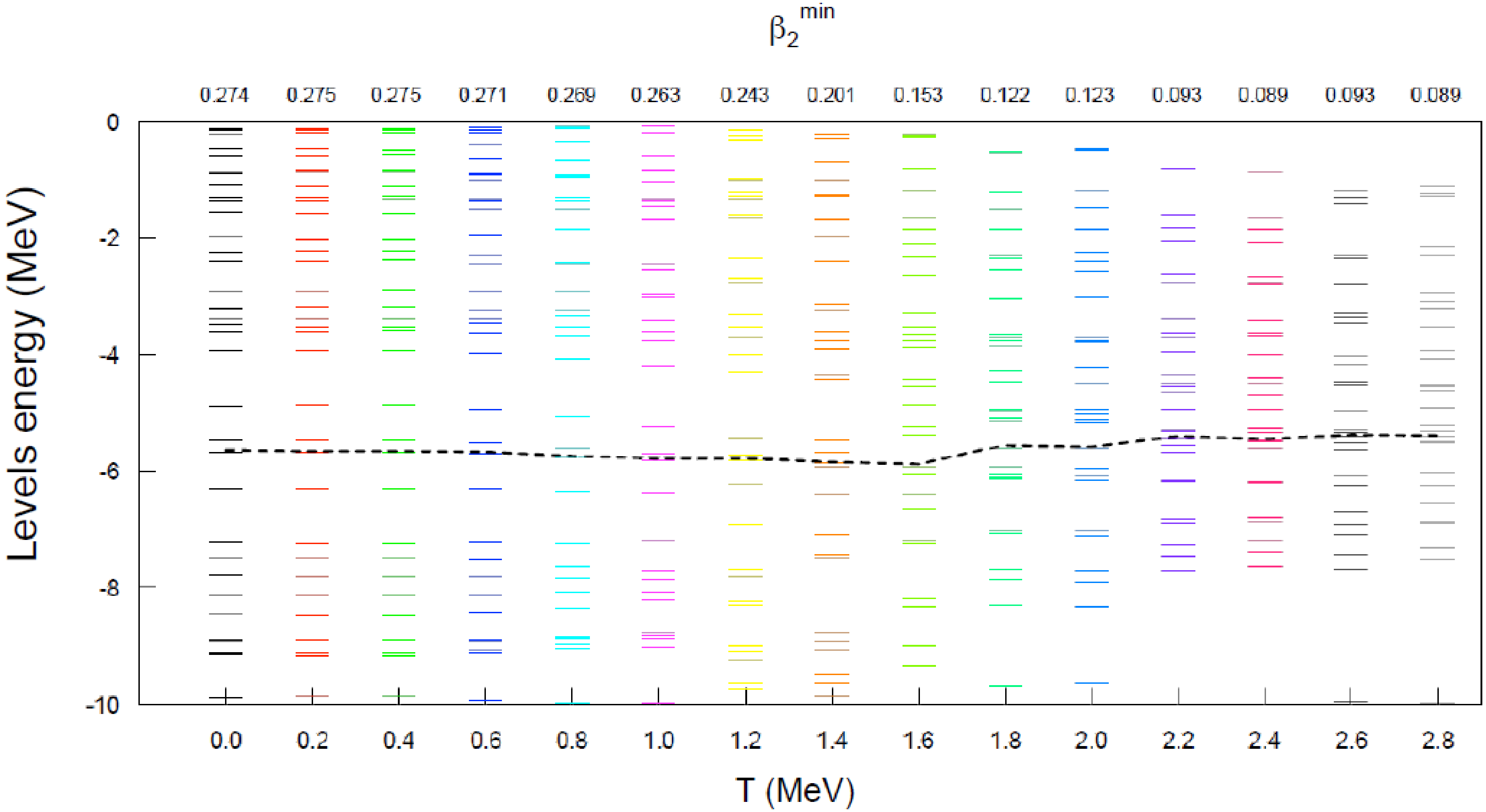
$$\rho(U, J, \pi) = \omega\,(U, K{=}J, \pi) - \omega\,(U, K{=}J{+}1, \pi)$$

Predicted within the same theoretical framework (coherence)

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

LEVEL DENSITIES
(The combinatorial method)

Neutrons levels around Fermi energy for ^{152}Sm

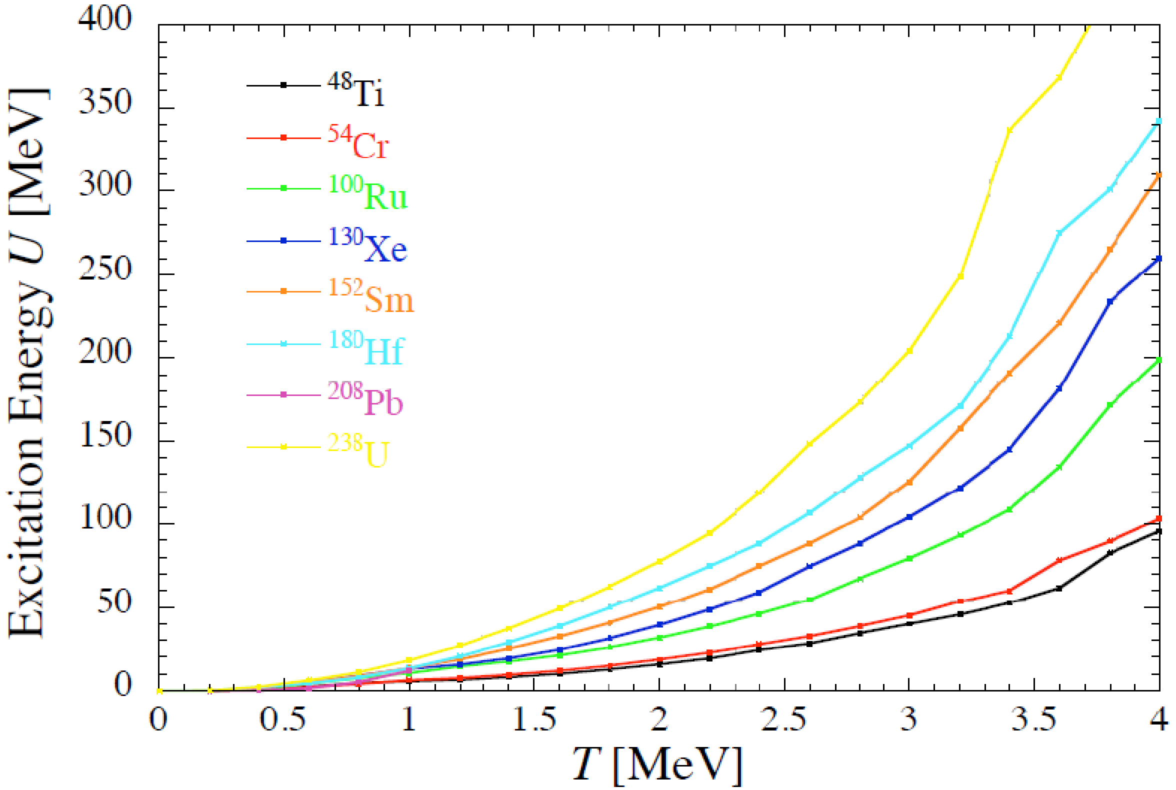


LEVEL DENSITIES
(The combinatorial method)

For each temperature, the excitation energy is determined.

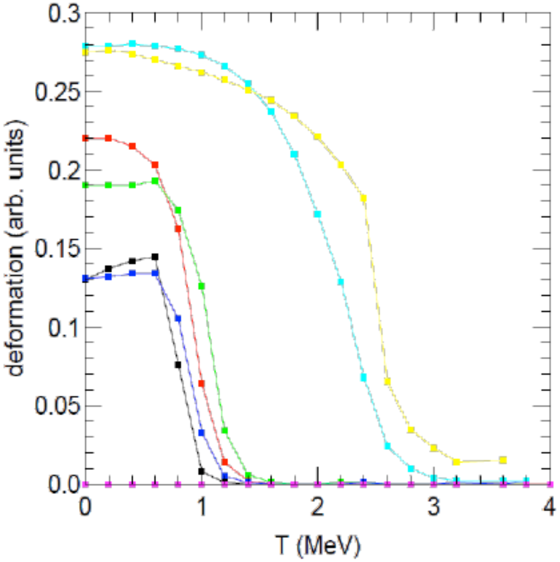
→ expected parabolic shape ($U \propto T^2$) is observed.

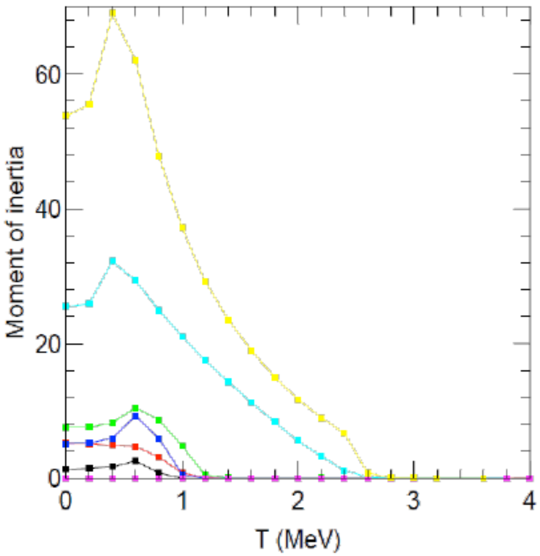
Excitation energy as a function of the temperature

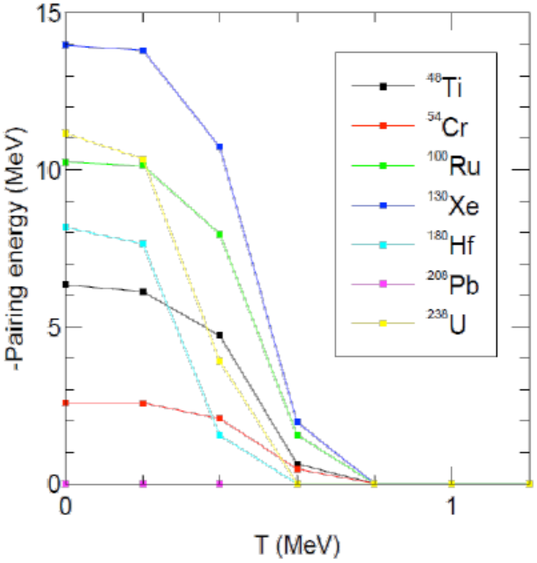


LEVEL DENSITIES
(The combinatorial method)

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


Quadrupole deformation

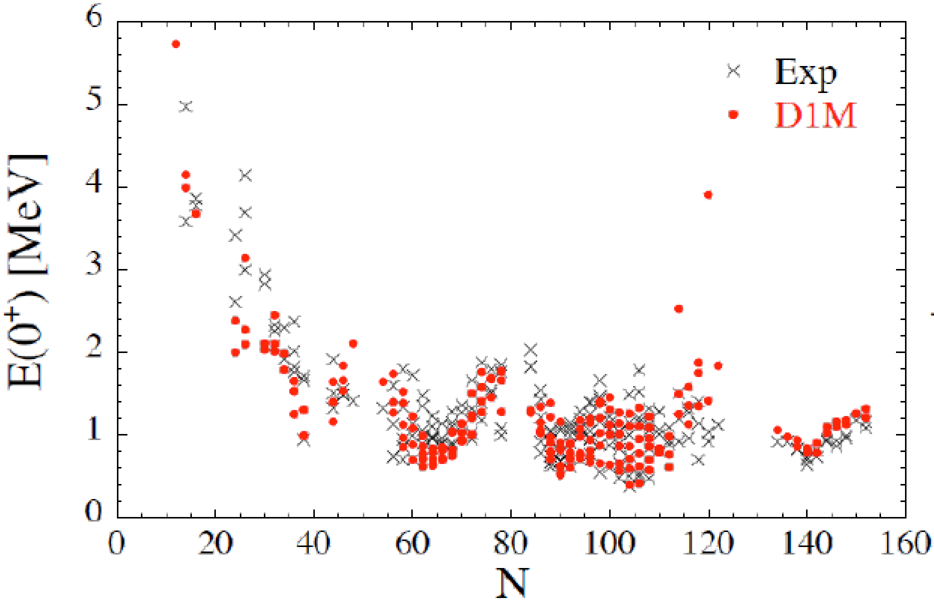

Cranking moment of Inertia


Total pairing energy

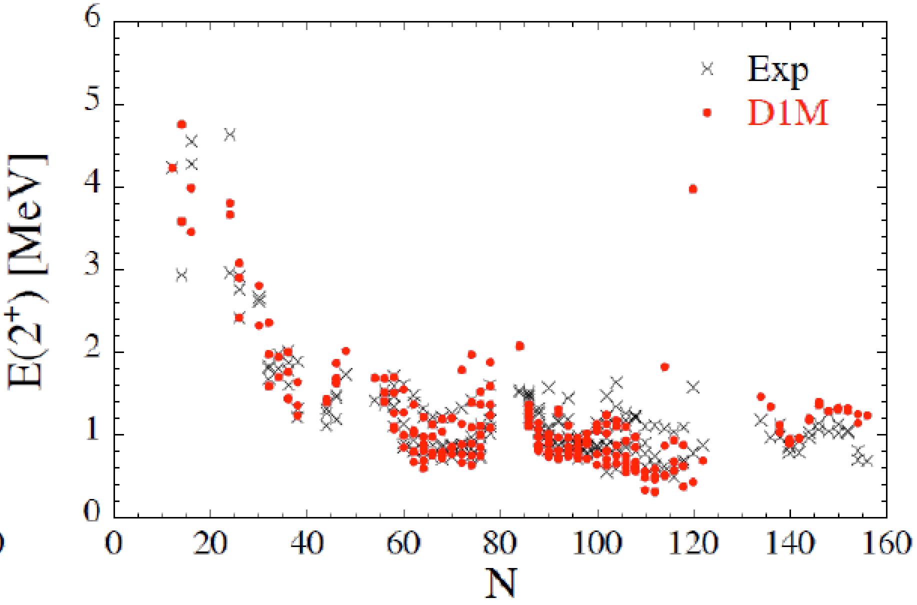
LEVEL DENSITIES
(The combinatorial method)

Quadrupole phonons' energies calculated from D1M+5DCH approach

Quadrupole 0^+ phonons energies (β band)



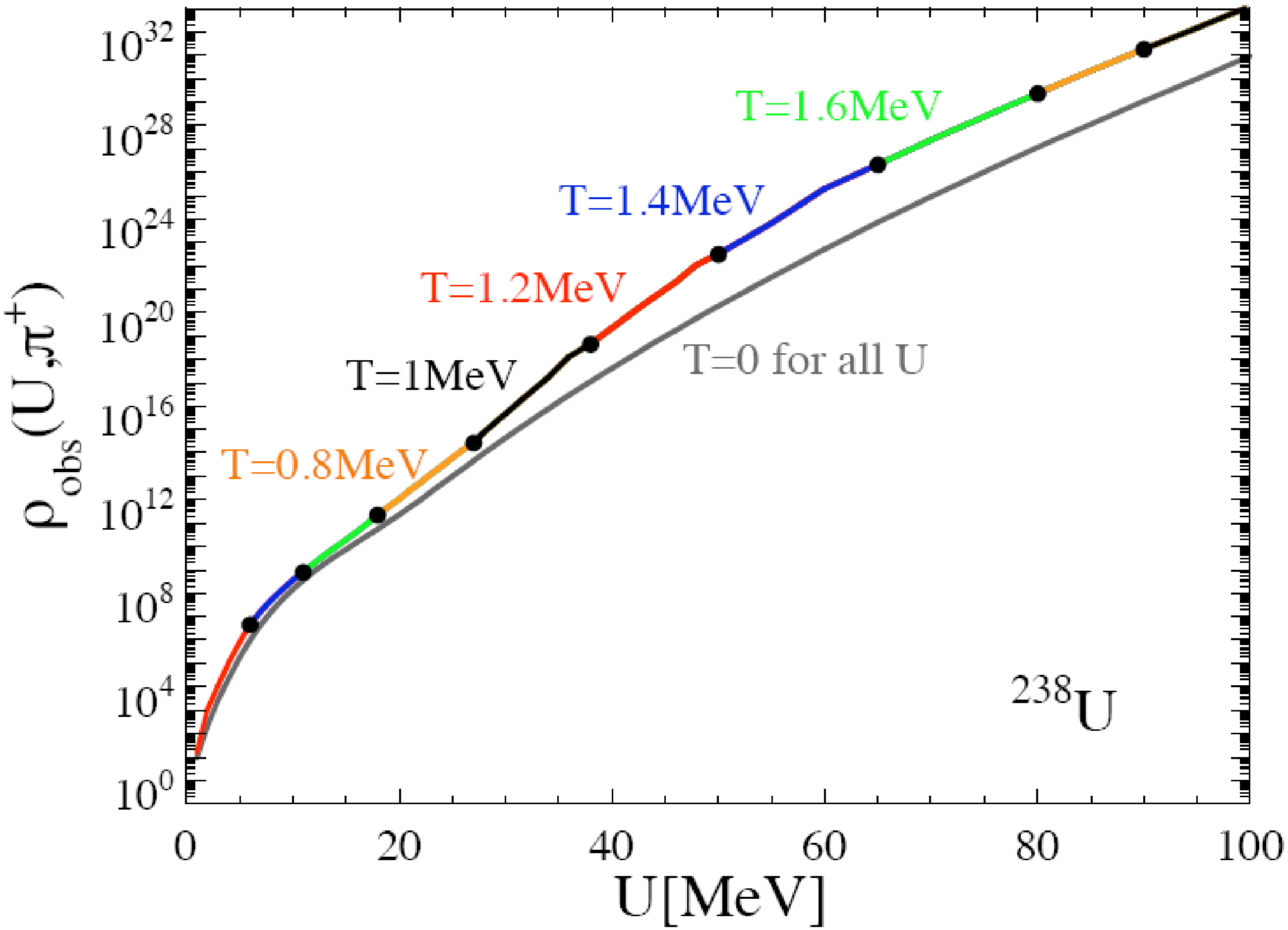
Quadrupole 2^+ phonons energies (γ band)



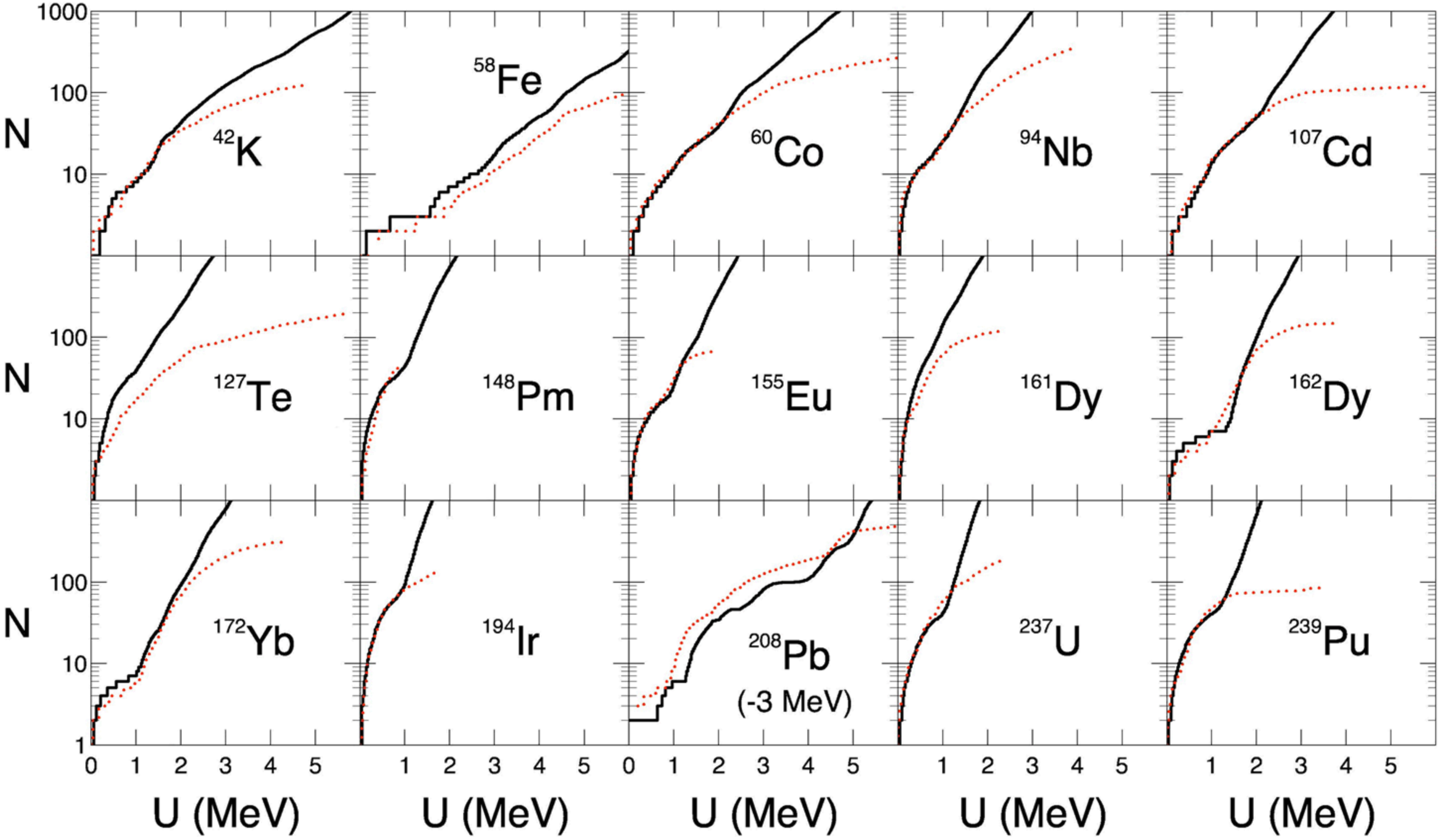
D1M+5DCH predictions overestimate experimental data on average
⇒renormalisation by 1,52 (resp. 1,22) for 0+ (resp, 2+) levels

Construction of NLD=f(T)

Level density for ^{238}U



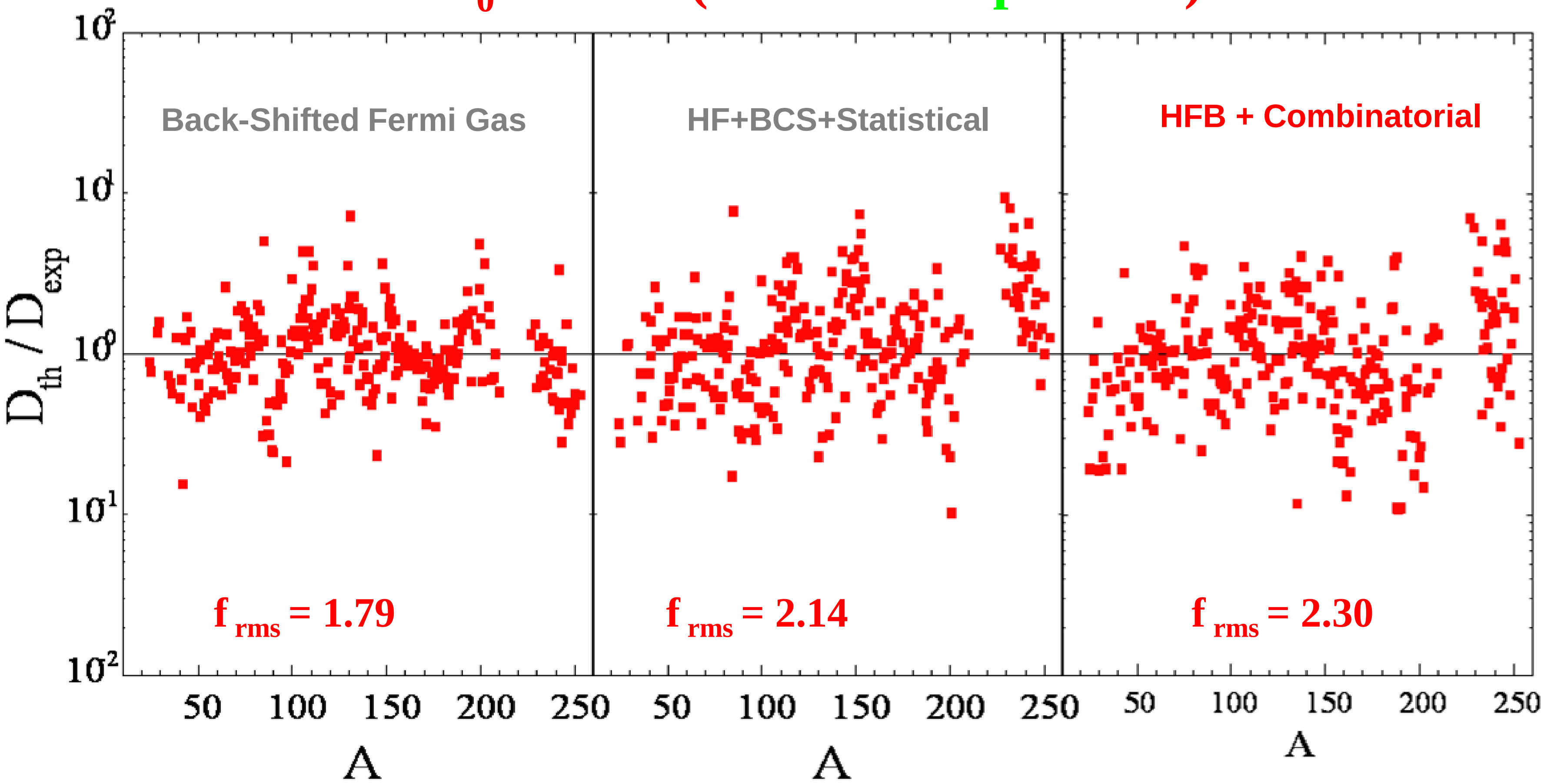
LEVEL DENSITIES
(The combinatorial method)



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

LEVEL DENSITIES
(The combinatorial method)

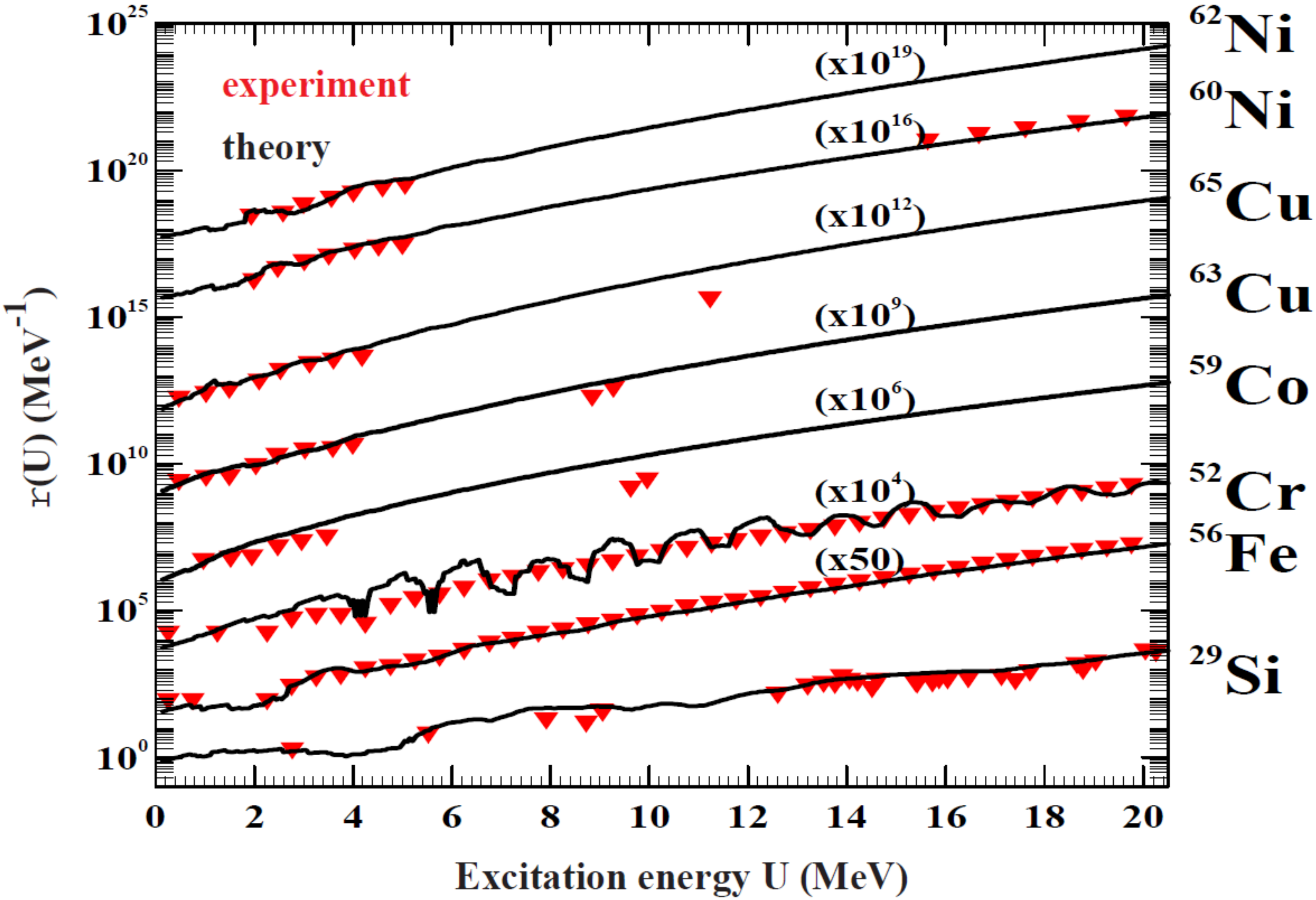
D_0 values (s-waves & p-waves)



➡ **Descrip** … **vith other**
global a

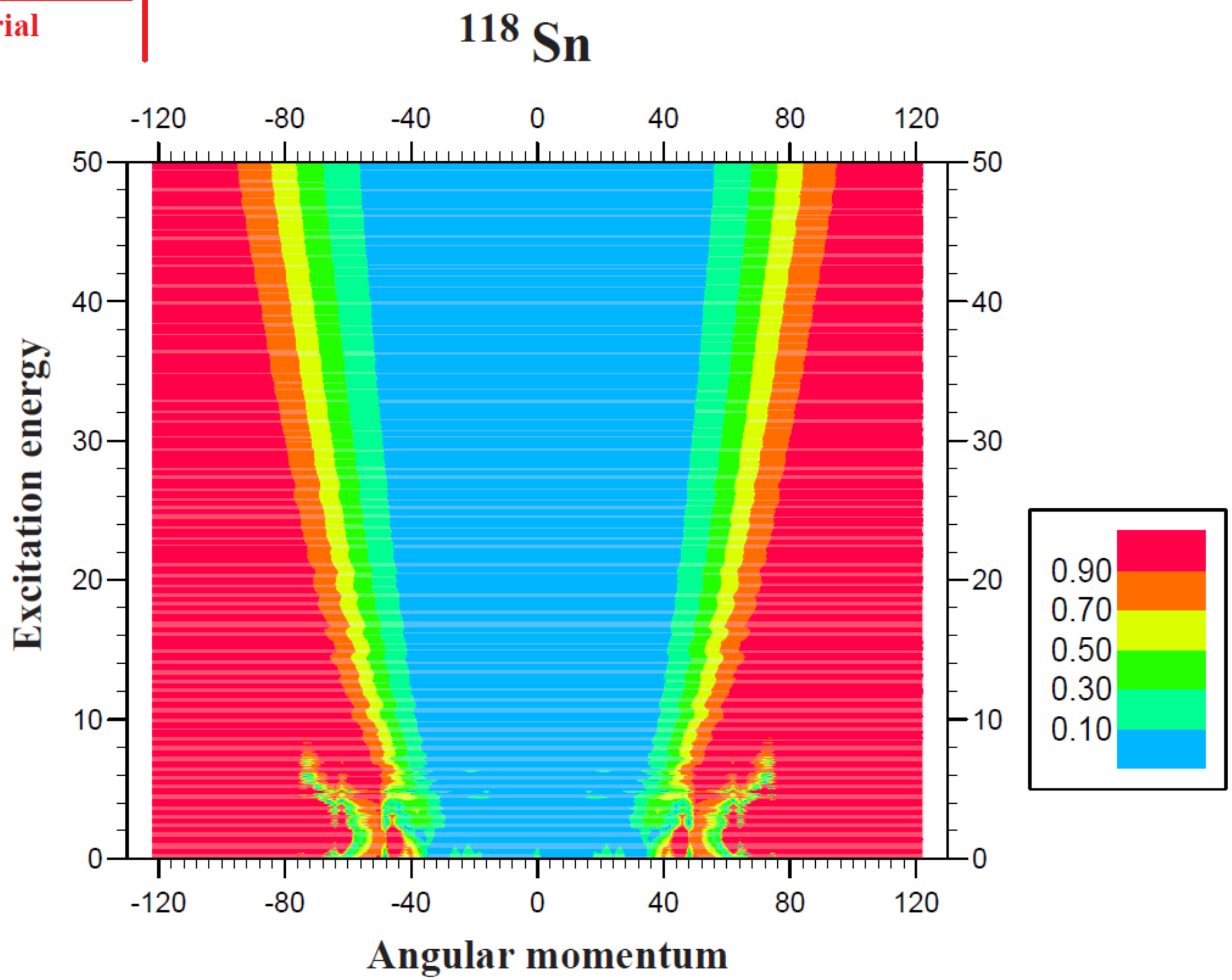
$$f_{\rm rms} = \exp\left[\frac{1}{N_e}\sum_{i=1}^{N_e} \ln^2 \frac{D^i_{\rm th}}{D^i_{\rm exp}}\right]^{1/2}$$

LEVEL DENSITIES
(The combinatorial method)



LEVEL DENSITIES
(spin distribution : combinatorial method vs Gaussian law)

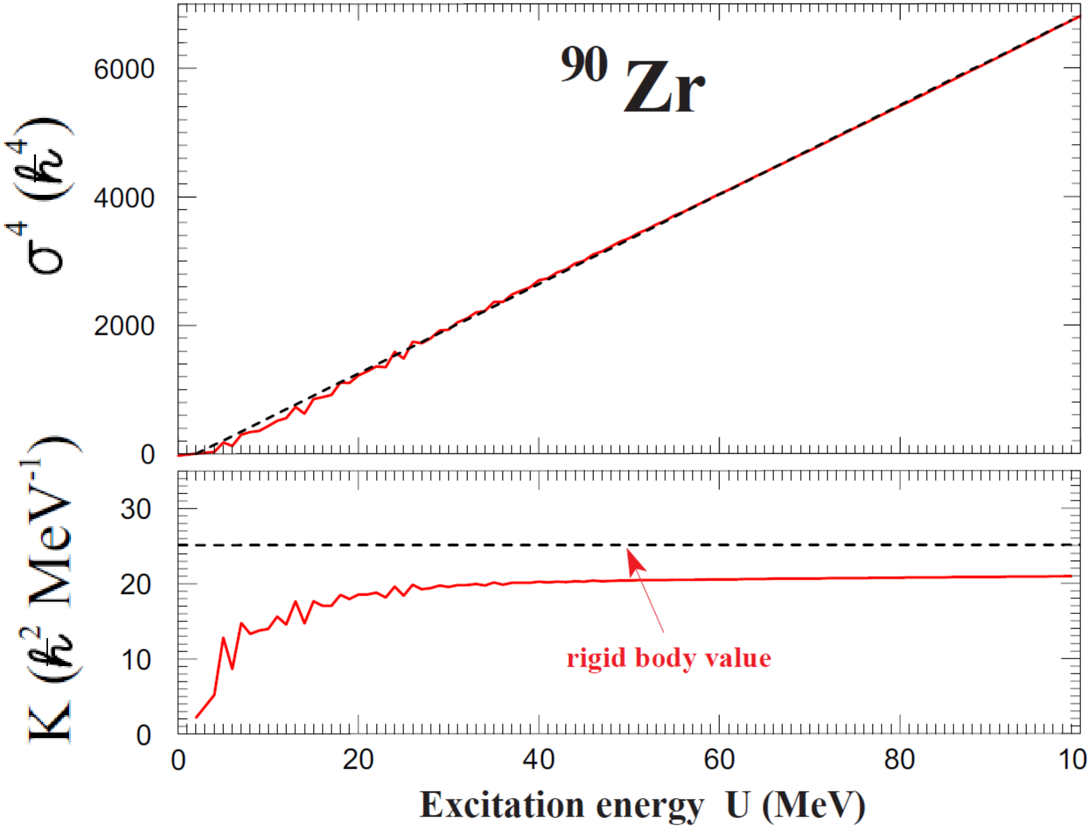
Absolute error : $$\left|\frac{\text{Gaussian - Combinatorial}}{\text{Combinatorial}}\right|$$



⇒ **significant deviations at low energy and high momentum**

LEVEL DENSITIES
(spin distribution : combinatorial spin cut-off)

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



$$\text{with } \sigma^{2} = \underbrace{\alpha\, I_{rig}}_{K}\sqrt{\frac{U}{a}}$$

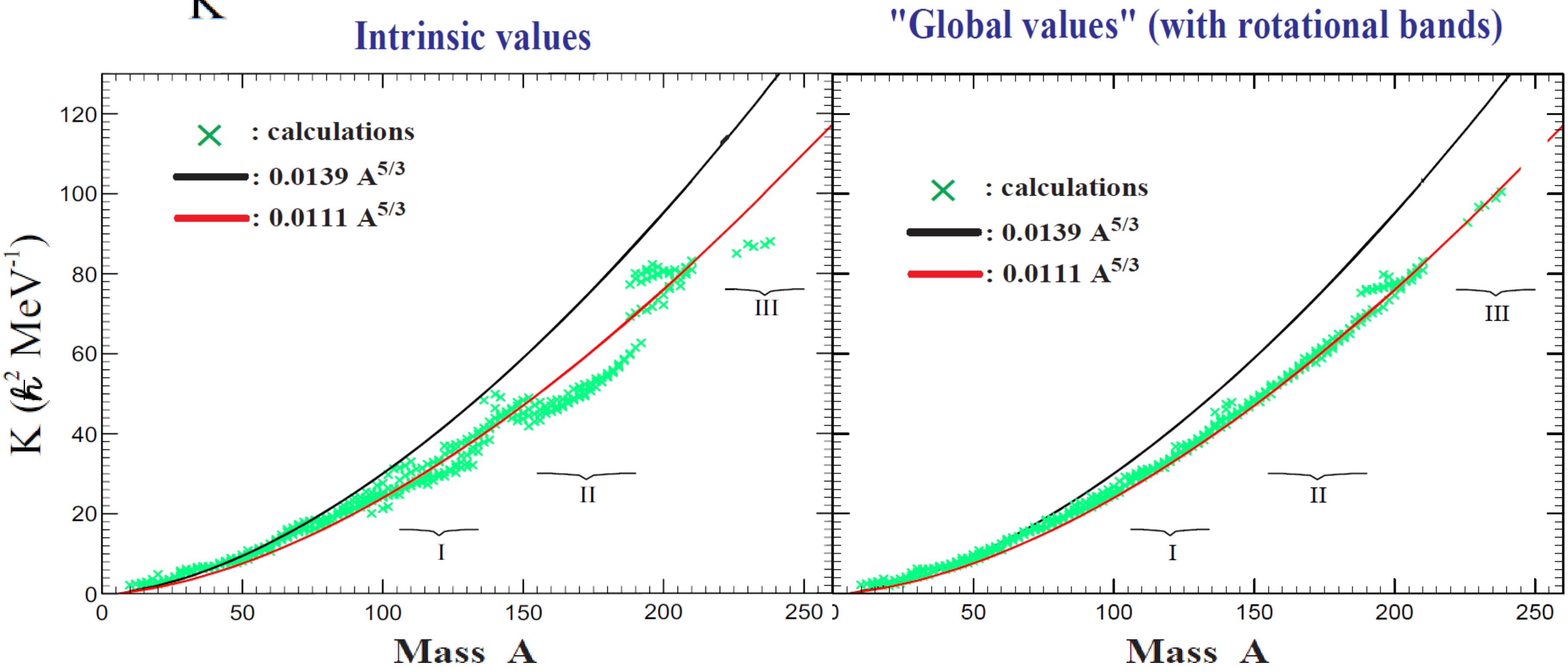
⇒ σ^4 globally linear

⇒ K lower than rigid body depends on energy

LEVEL DENSITIES
(saturated spin cut-off)

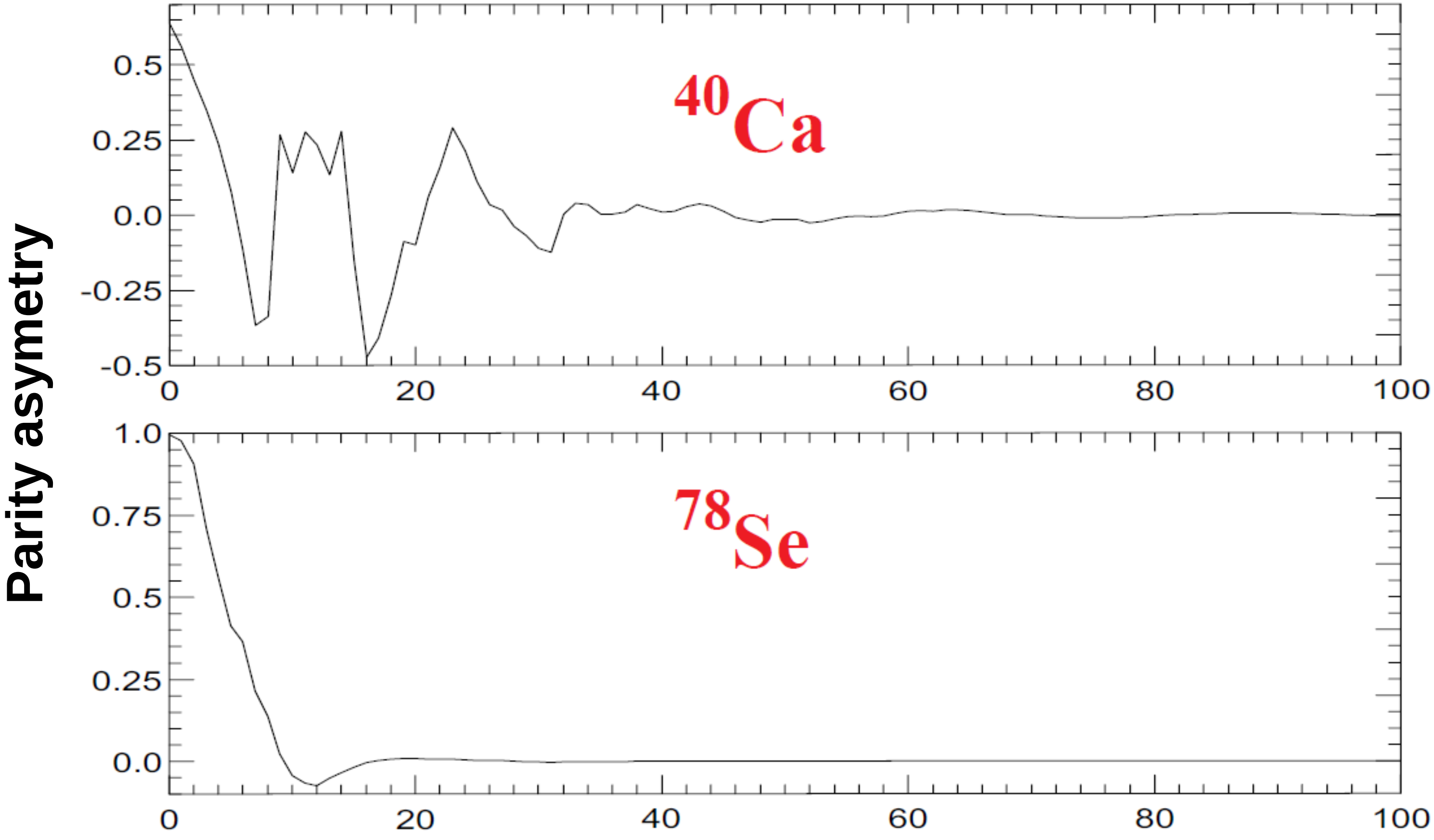
$$\sigma^{2} = \underbrace{\alpha\, I_{rig}}_{K} \sqrt{\frac{U}{a}}$$

⇒ asymptotic value of K



⇒ rotational bands required for a smooth K

LEVEL DENSITIES
(parity distributions)



Excitation energy (MeV)

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

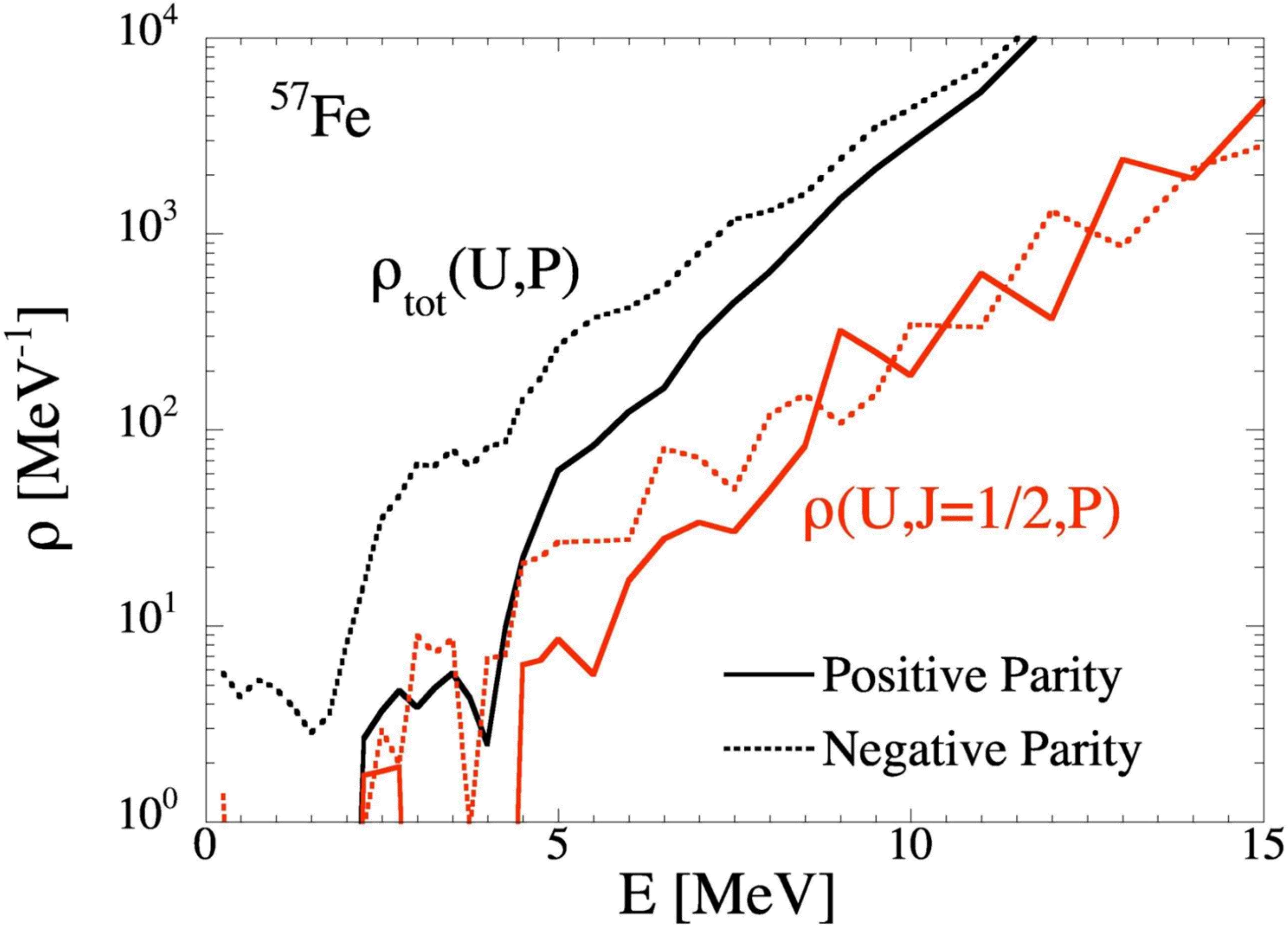
- Total level densities

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

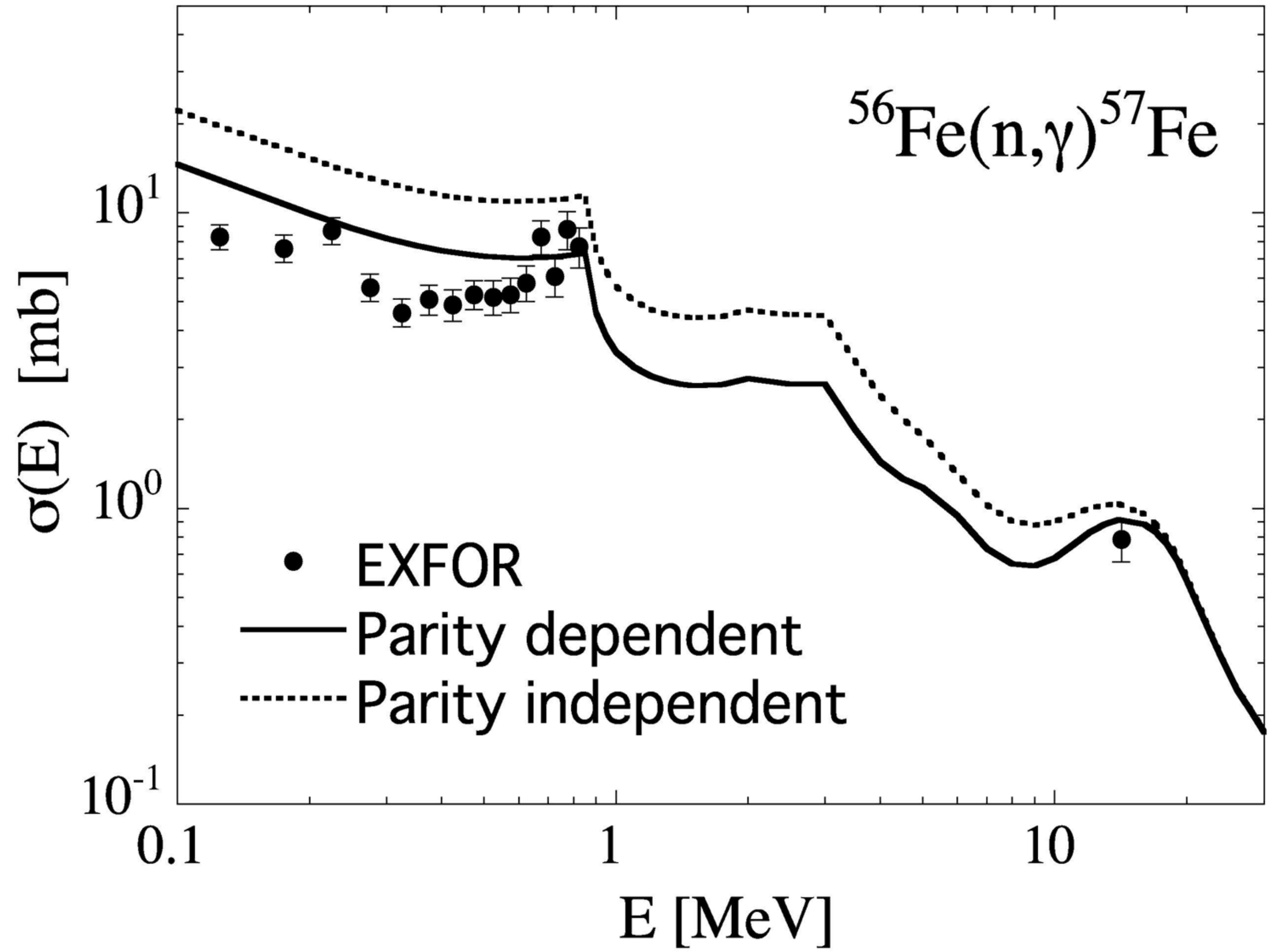
- Impacts on cross sections

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

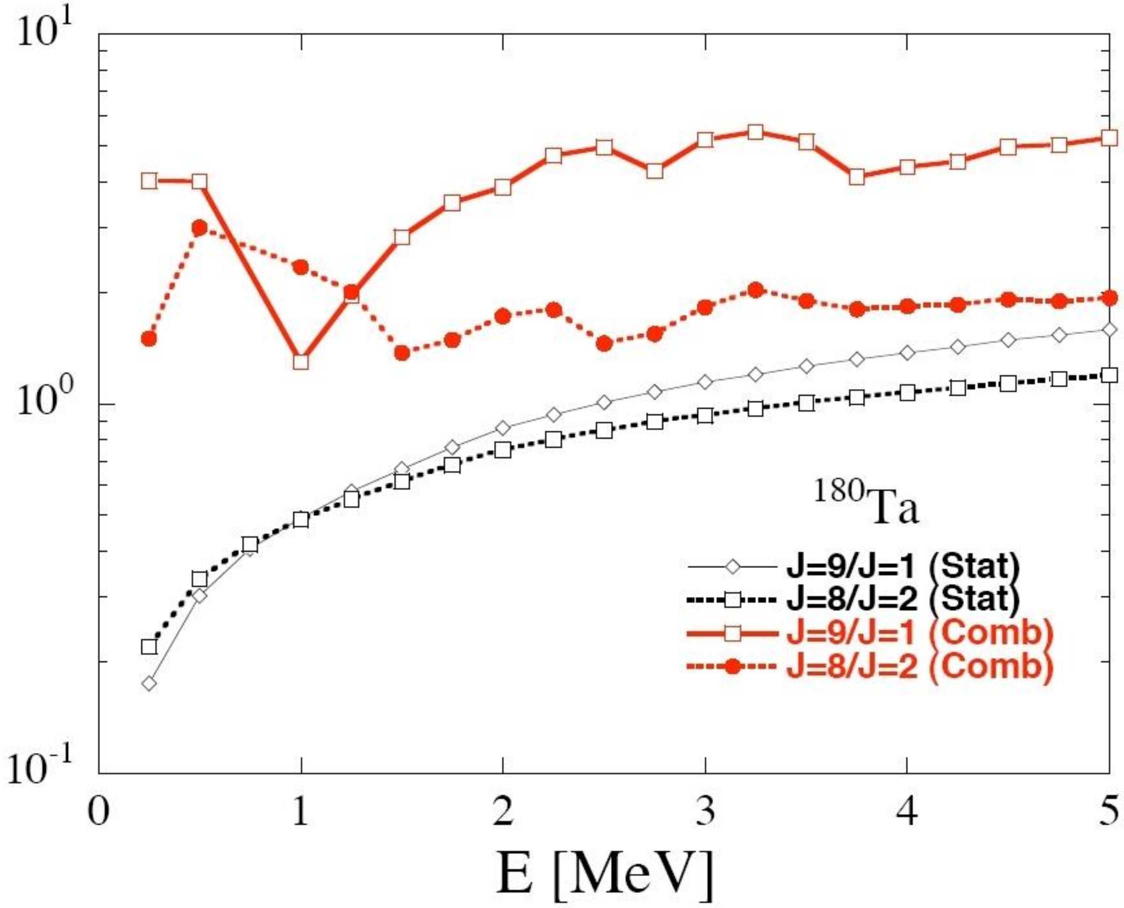
LEVEL DENSITIES
(parity non equipartition)



LEVEL DENSITIES
(parity non equipartition)

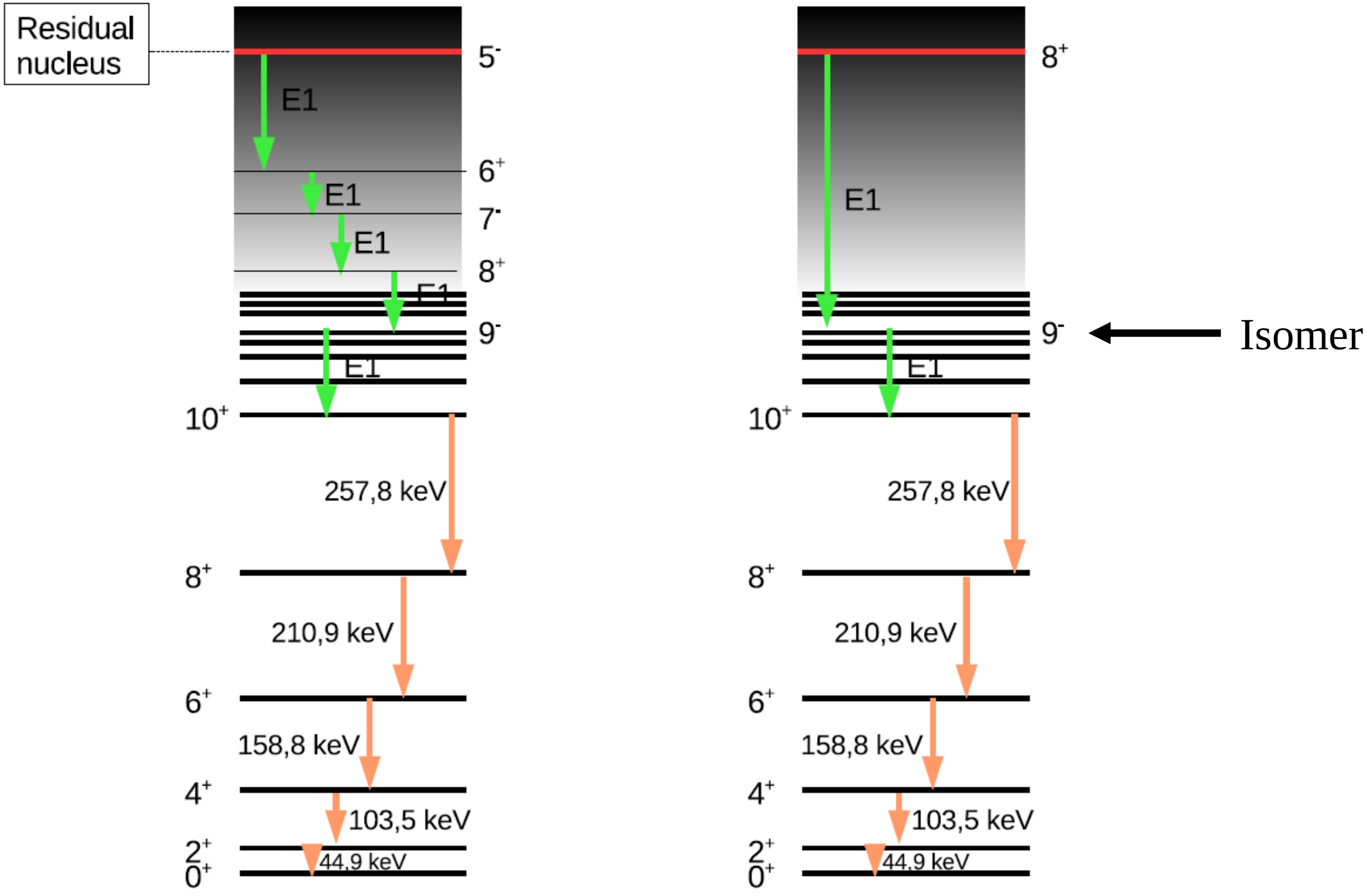


LEVEL DENSITIES
(non-Gaussian spin distribution)



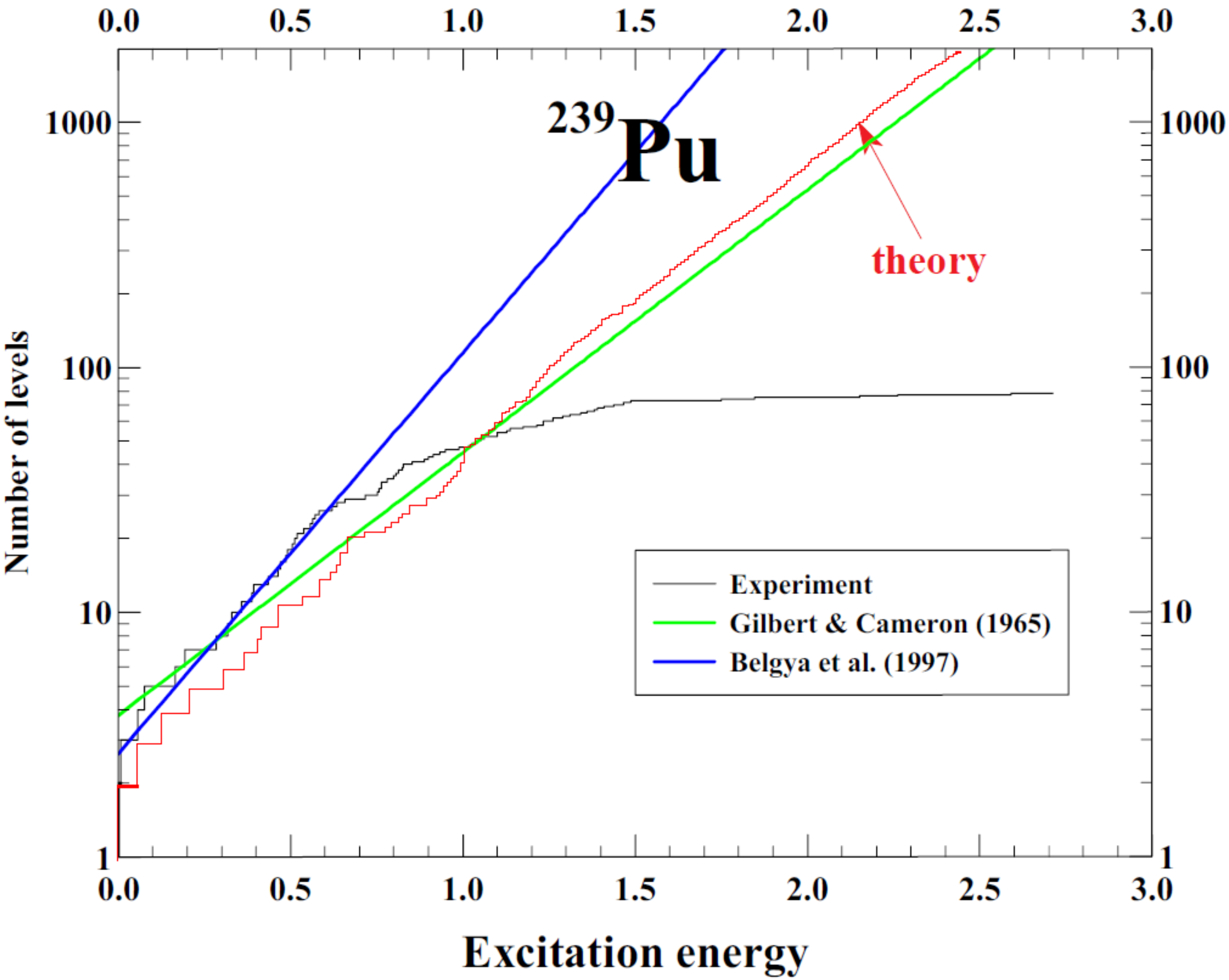
➡ **Non-statistical feature imply significant deviations from the usual gaussian spin dependence**

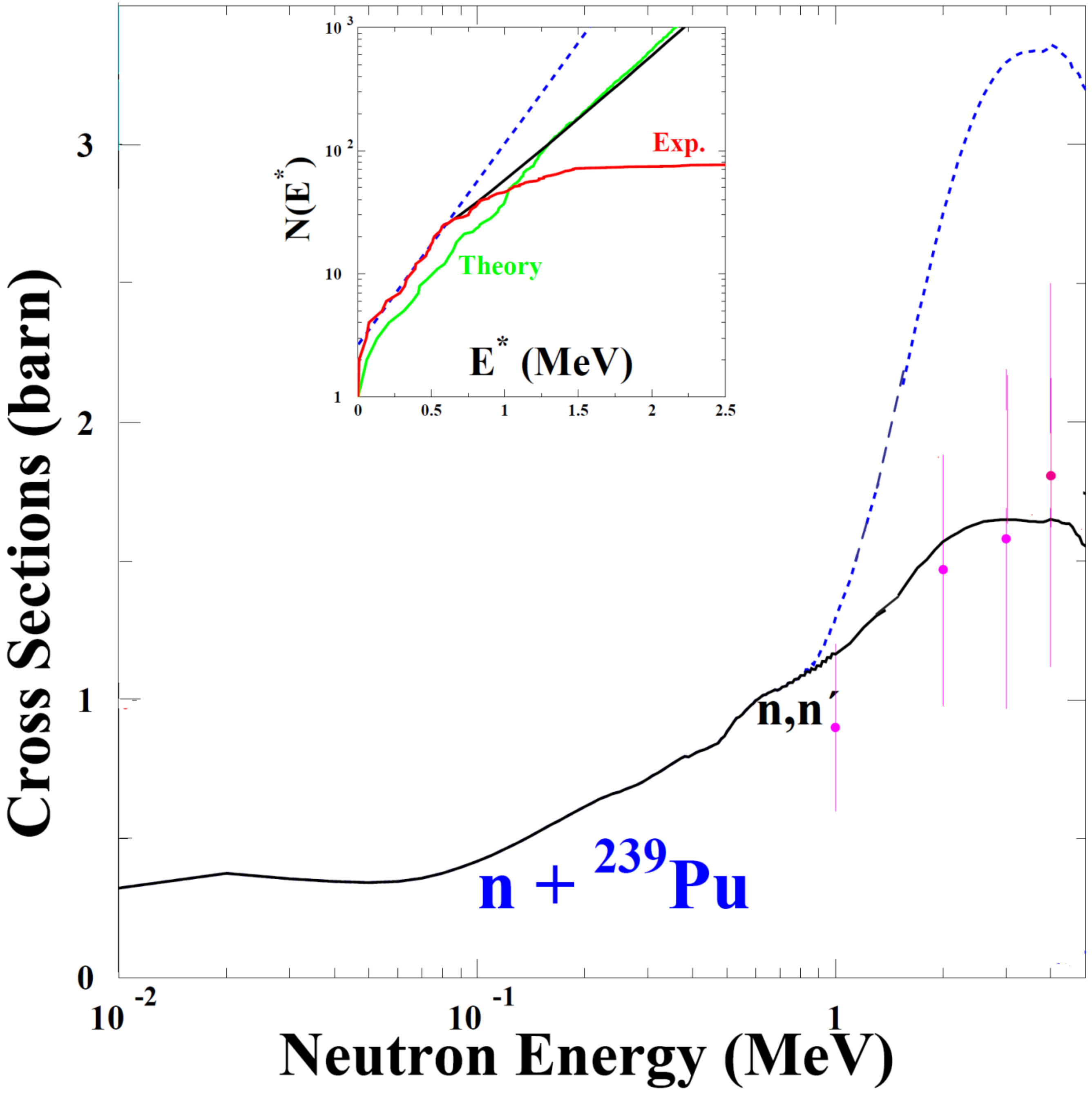
LEVEL DENSITIES
(non-Gaussian spin distribution)



See PRL 96 (2006) 192501 for details

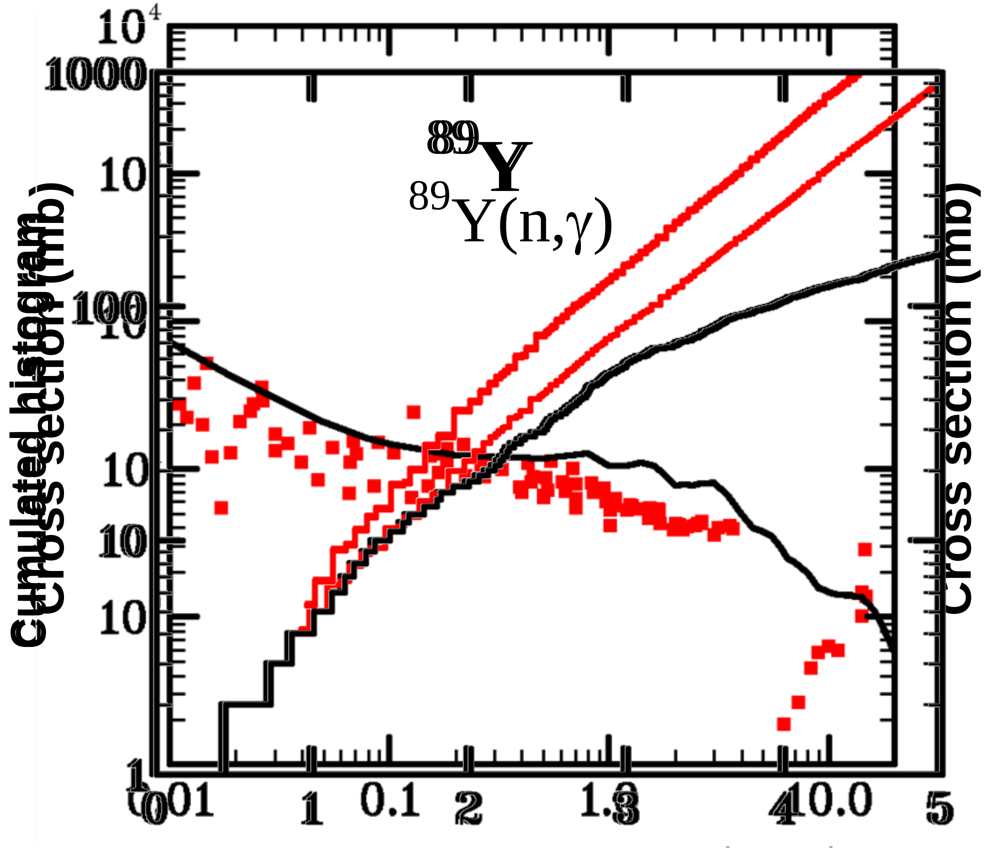
LEVEL DENSITIES
(govern competition : fission vs inelastic)

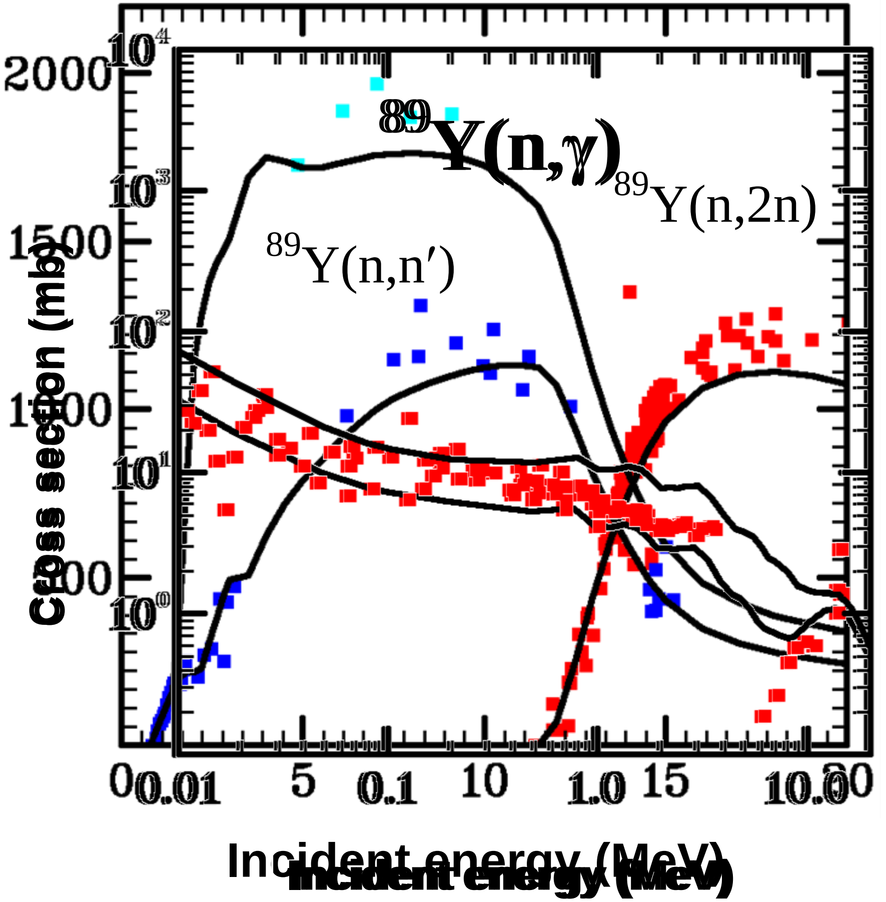


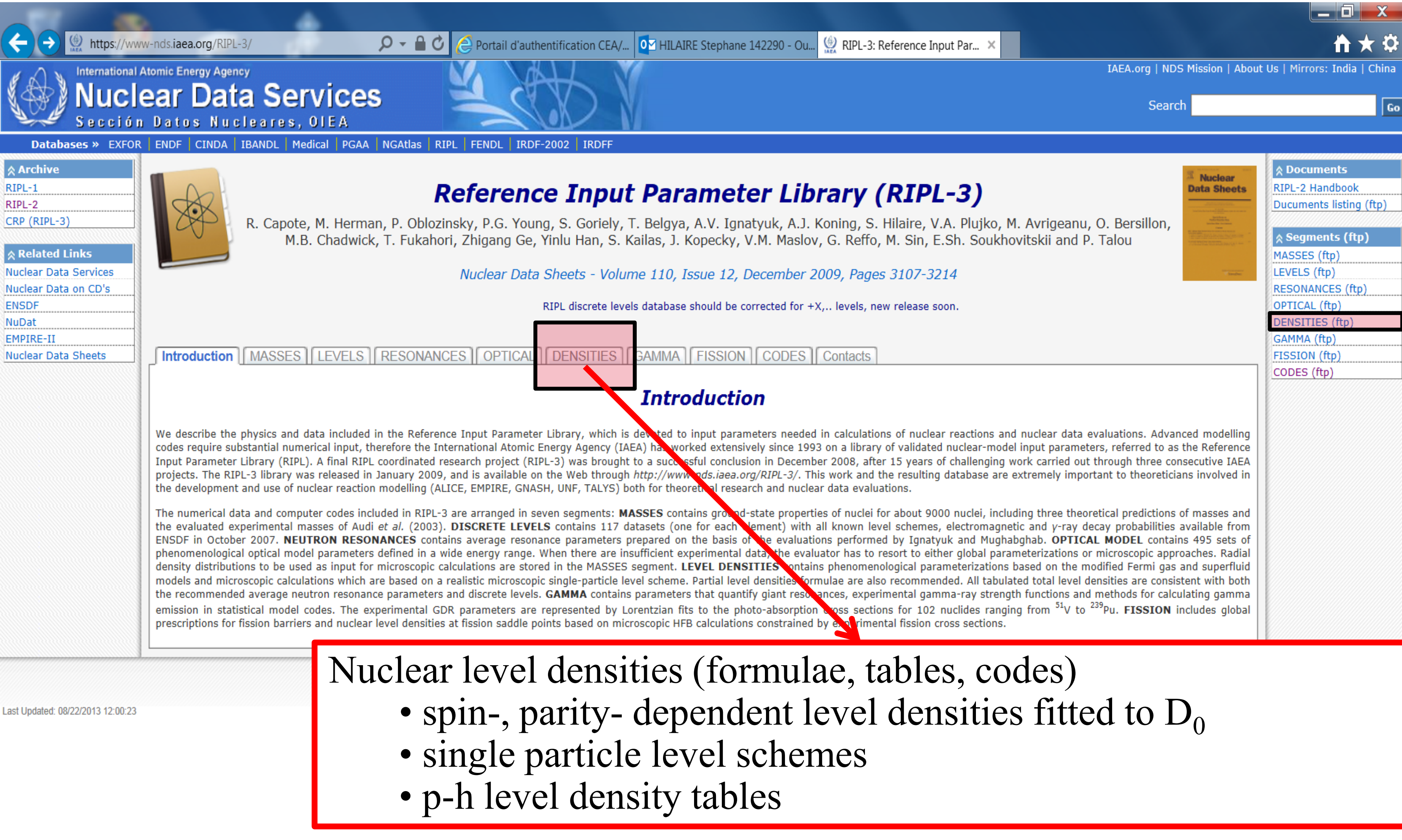

Cross Sections (barn)
0
1
2
3
10 -2
10 -1
1
Neutron Energy (MeV)
n,n´
n + ^{239}Pu
N(E*)
1
10
10 2
10 3
E* (MeV)
0
0.5
1
1.5
2
2.5
Exp.
Theory

LEVEL DENSITIES
(tabulated data adjustment)

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







Reference Input Parameter Library (RIPL-3)

R. Capote, M. Herman, P. Oblozinsky, P.G. Young, S. Goriely, T. Belgya, A.V. Ignatyuk, A.J. Koning, S. Hilaire, V.A. Plujko, M. Avrigeanu, O. Bersillon, M.B. Chadwick, T. Fukahori, Zhigang Ge, Yinlu Han, S. Kailas, J. Kopecky, V.M. Maslov, G. Reffo, M. Sin, E.Sh. Soukhovitskii and P. Talou

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

RIPL discrete levels database should be corrected for +X,.. levels, new release soon.

Introduction

We describe the physics and data included in the Reference Input Parameter Library, which is devoted to input parameters needed in calculations of nuclear reactions and nuclear data evaluations. Advanced modelling codes require substantial numerical input, therefore the International Atomic Energy Agency (IAEA) has worked extensively since 1993 on a library of validated nuclear-model input parameters, referred to as the Reference Input Parameter Library (RIPL). A final RIPL coordinated research project (RIPL-3) was brought to a successful conclusion in December 2008, after 15 years of challenging work carried out through three consecutive IAEA projects. The RIPL-3 library was released in January 2009, and is available on the Web through *http://www-nds.iaea.org/RIPL-3/*. This work and the resulting database are extremely important to theoreticians involved in the development and use of nuclear reaction modelling (ALICE, EMPIRE, GNASH, UNF, TALYS) both for theoretical research and nuclear data evaluations.

The numerical data and computer codes included in RIPL-3 are arranged in seven segments: **MASSES** contains ground-state properties of nuclei for about 9000 nuclei, including three theoretical predictions of masses and the evaluated experimental masses of Audi *et al.* (2003). **DISCRETE LEVELS** contains 117 datasets (one for each element) with all known level schemes, electromagnetic and γ-ray decay probabilities available from ENSDF in October 2007. **NEUTRON RESONANCES** contains average resonance parameters prepared on the basis of the evaluations performed by Ignatyuk and Mughabghab. **OPTICAL MODEL** contains 495 sets of phenomenological optical model parameters defined in a wide energy range. When there are insufficient experimental data, the evaluator has to resort to either global parameterizations or microscopic approaches. Radial density distributions to be used as input for microscopic calculations are stored in the MASSES segment. **LEVEL DENSITIES** contains phenomenological parameterizations based on the modified Fermi gas and superfluid models and microscopic calculations which are based on a realistic microscopic single-particle level scheme. Partial level densities formulae are also recommended. All tabulated total level densities are consistent with both the recommended average neutron resonance parameters and discrete levels. **GAMMA** contains parameters that quantify giant resonances, experimental gamma-ray strength functions and methods for calculating gamma emission in statistical model codes. The experimental GDR parameters are represented by Lorentzian fits to the photo-absorption cross sections for 102 nuclides ranging from ^{51}V to ^{239}Pu. **FISSION** includes global prescriptions for fission barriers and nuclear level densities at fission saddle points based on microscopic HFB calculations constrained by experimental fission cross sections.

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

GAMMA-RAY STRENGTHS

GAMMA-RAY STRENGTHS

- Qualitative features

- Analytical approaches

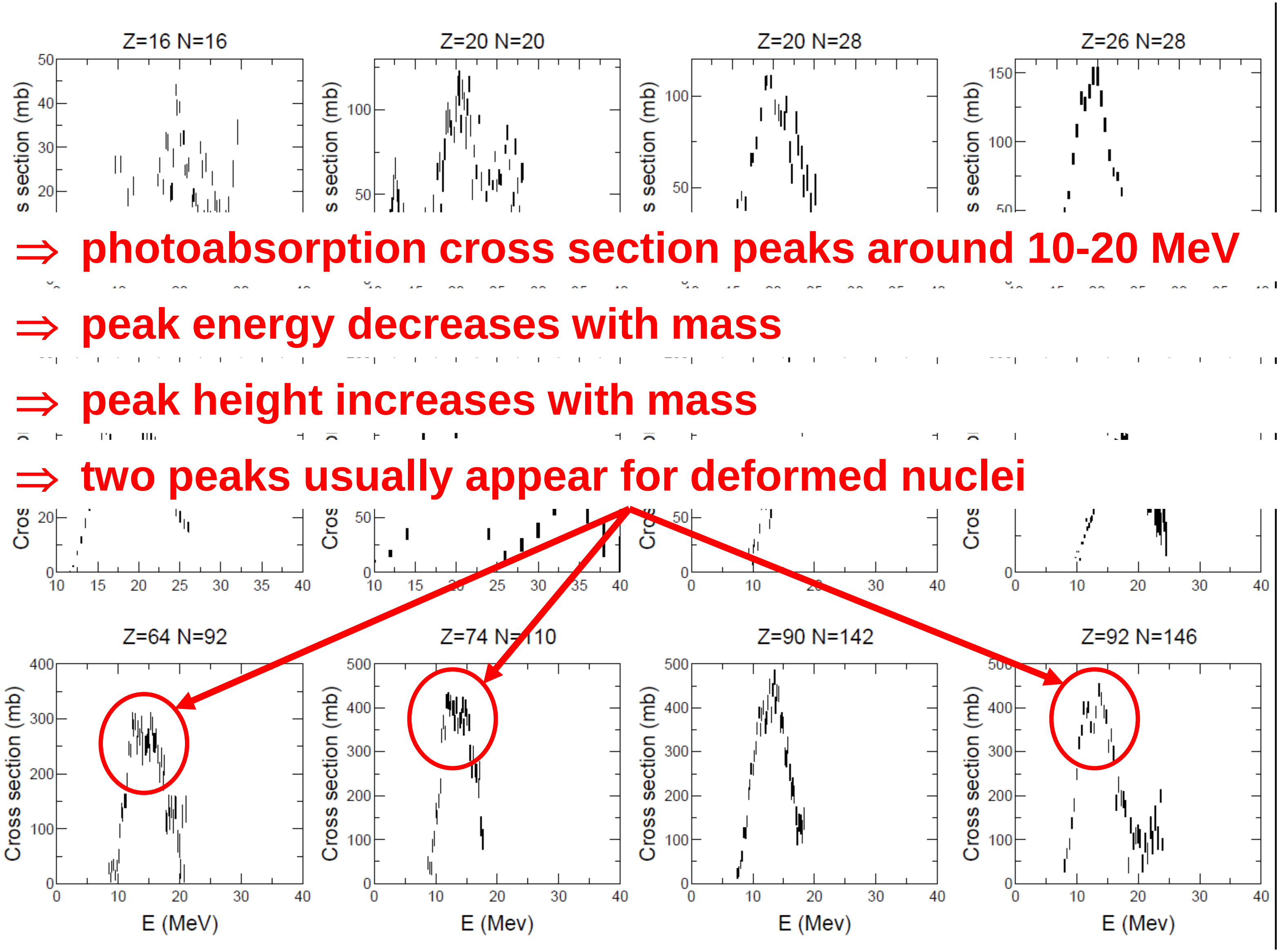
- Microscopic approaches

- HFBCS-RPA
- HFB+QRPA
- Shell Model

- Impacts on cross sections

- Normalizations
- Exotic nuclei
- Hot topics

GAMMA-RAY STENGTH
(qualitative aspects from photoabsorption)



⇒ 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 STRENGTH (upward and downward strength) (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 γ-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

BUT

Standard Lorentzian (SLO)

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

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

GAMMA-RAY STRENGTH
(transmission coefficient and selection rules)

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

$$= 2\pi\, f(k,\lambda,\varepsilon_\gamma)\, \varepsilon_\gamma^{\,2\lambda+1}$$

k : transition type (E or M)

λ : transition multipolarity

ε_γ : outgoing gamma energy

$f(k,\lambda,\varepsilon_\gamma)$: 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**: $\pi_f=(-1)^{\lambda+1}\,\pi_i$

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

$$\boxed{\begin{array}{l}(E1 \approx 10 - 100\ M1)\\ (XL \approx 10^{-3}\ XL\text{-}1)\end{array}}$$

Renormalisation 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

- Qualitative features

- Analytical approaches

- Microscopic approaches

- HFBCS-RPA
- HFB+QRPA
- Shell Model

- Impacts on cross sections

- Normalizations
- Exotic nuclei
- Hot topics

GAMMA-RAY STENGTH
(Analytical expressions)

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)
    - ⇒ Hybrid model of Goriely (1998)
    - ⇒ Generalized Fermi liquid model of Plujko-Kavatsyuk (2003)

- Reconciliation with electromagnetic nuclear response theory
  - ⇒ Modified Lorentzian model of Plujko et al. (2002)
  - ⇒ Simplified Modified Lorentzian model of Plujko et al. (2008)

GAMMA-RAY STENGTH
(Brink-Axel and Kopecky-Uhl models)

Brink-Axel *(option 2 in TALYS)*

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

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

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

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

⇒ **Deformed nuclei : incoherent sum of two Lorentzians**

⇒ **Parameters taken from experimental fit of data (RIPL-III) for measured nuclei**

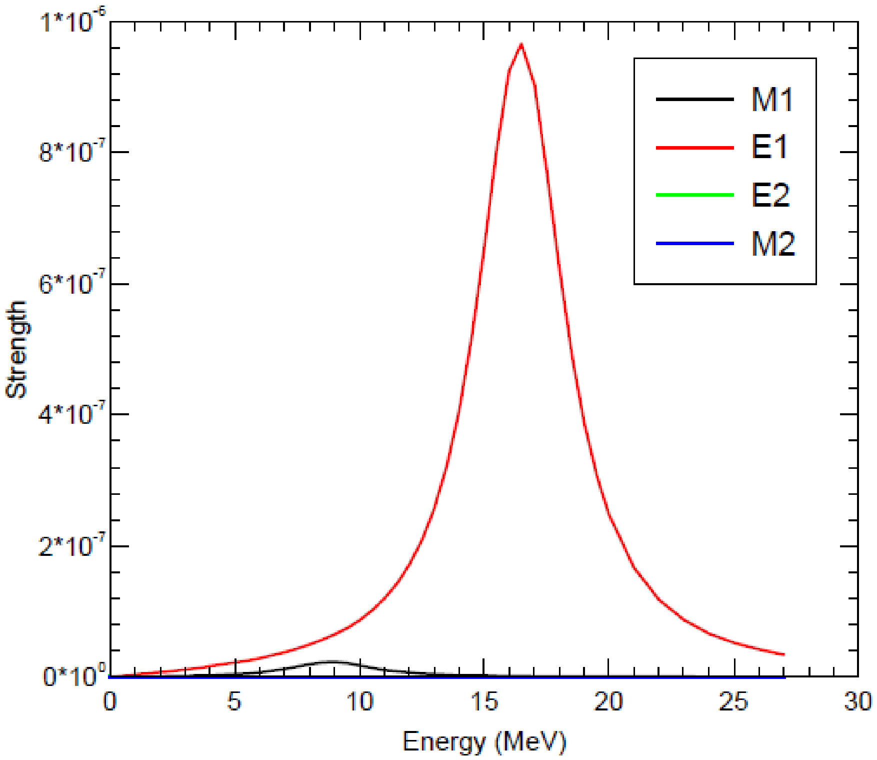
⇒ **From global systematics otherwise**

$$\sigma_{E1} = 1.2 \times 120NZ/(A\pi\Gamma_{E1}) \text{ mb}, \quad E_{E1} = 31.2A^{-1/3} + 20.6A^{-1/6} \text{ MeV}, \quad \Gamma_{E1} = 0.026E_{E1}^{1.91} \text{ MeV}.$$

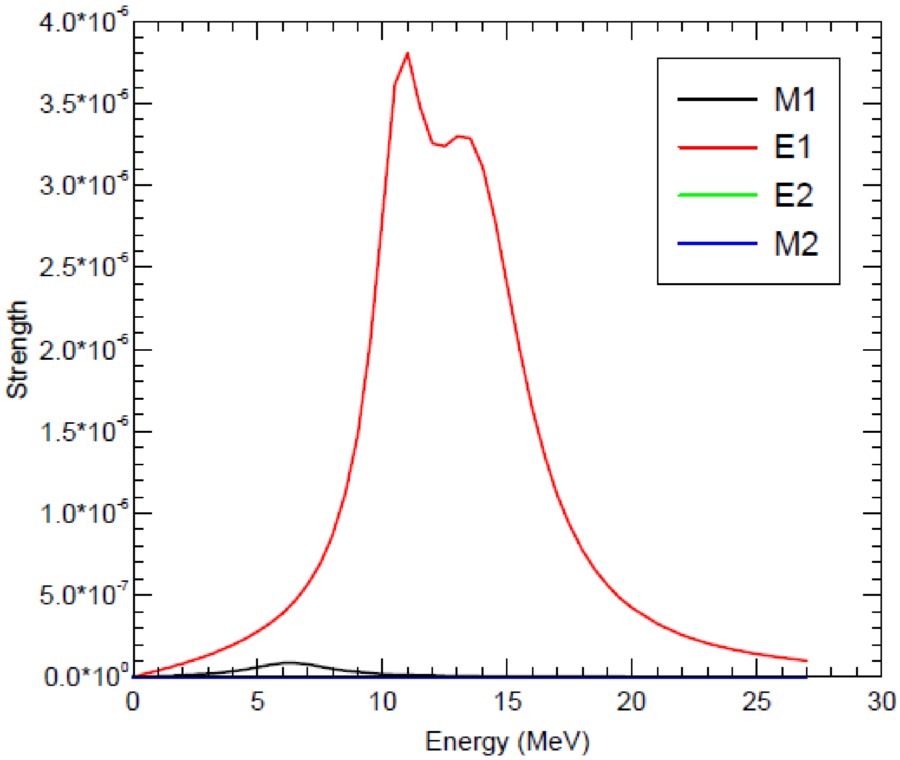
$$\sigma_{E2} = 0.00014Z^2E_{E2}/(A^{1/3}\Gamma_{E2}) \text{ mb}, \quad E_{E2} = 63.A^{-1/3} \text{ MeV}, \quad \Gamma_{E2} = 6.11 - 0.012A \text{ MeV}.$$

GAMMA-RAY STENGTH
(Brink-Axel model)

^{90}Zr (spherical)



^{238}U (deformed)



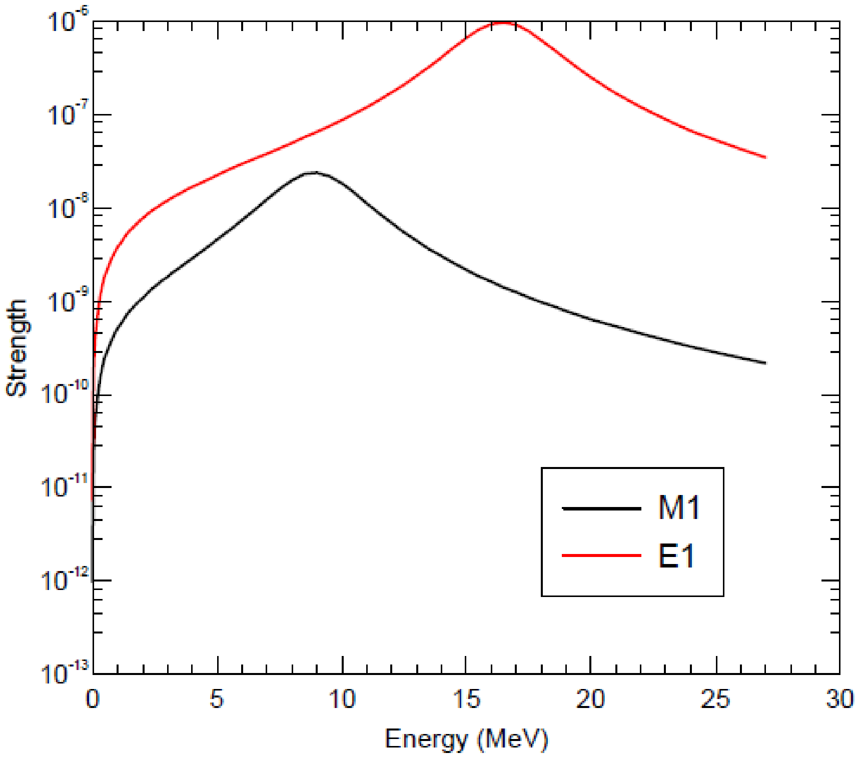
⇒ Deformed nuclei : two Lorentzians = two peaks

⇒ Lorentzian centroid energy decreasing with A

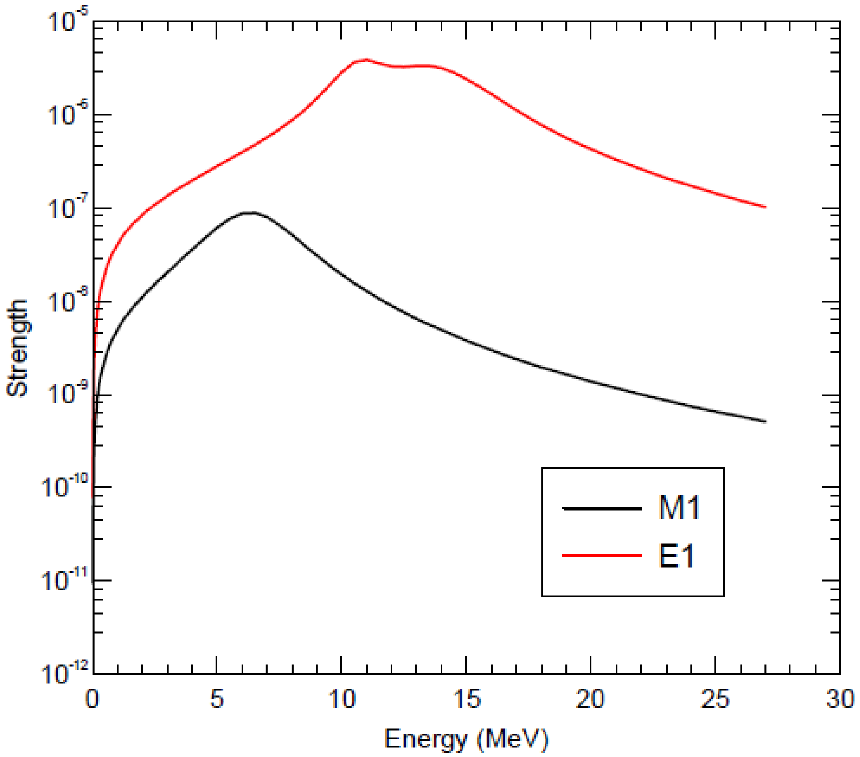
⇒ M1 much weaker than E1 ⇒**log scale**

GAMMA-RAY STENGTH (Brink-Axel model)

^{90}Zr (spherical)



^{238}U (deformed)

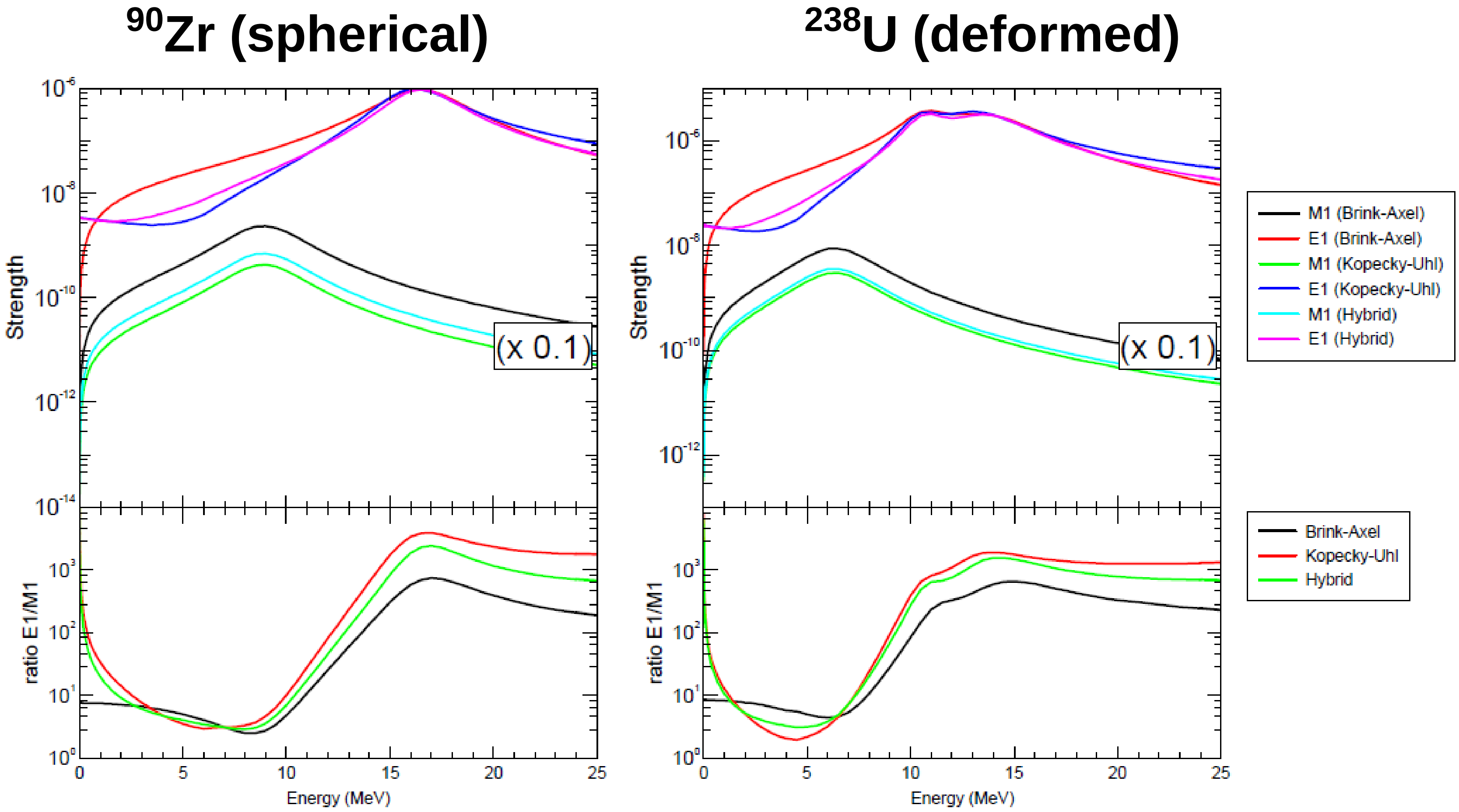


⇒ Deformed nuclei : two Lorentzians = two peaks

⇒ Lorentzian centroid energy decreasing with A

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

GAMMA-RAY STENGTH
(Brink-Axel, Kopecky-Uhl, Hybrid model)



- ⇒ 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

GAMMA-RAY STENGTH
(Brink-Axel=SLO, Kopecky-Uhl=EGLO, GFL, MLO)

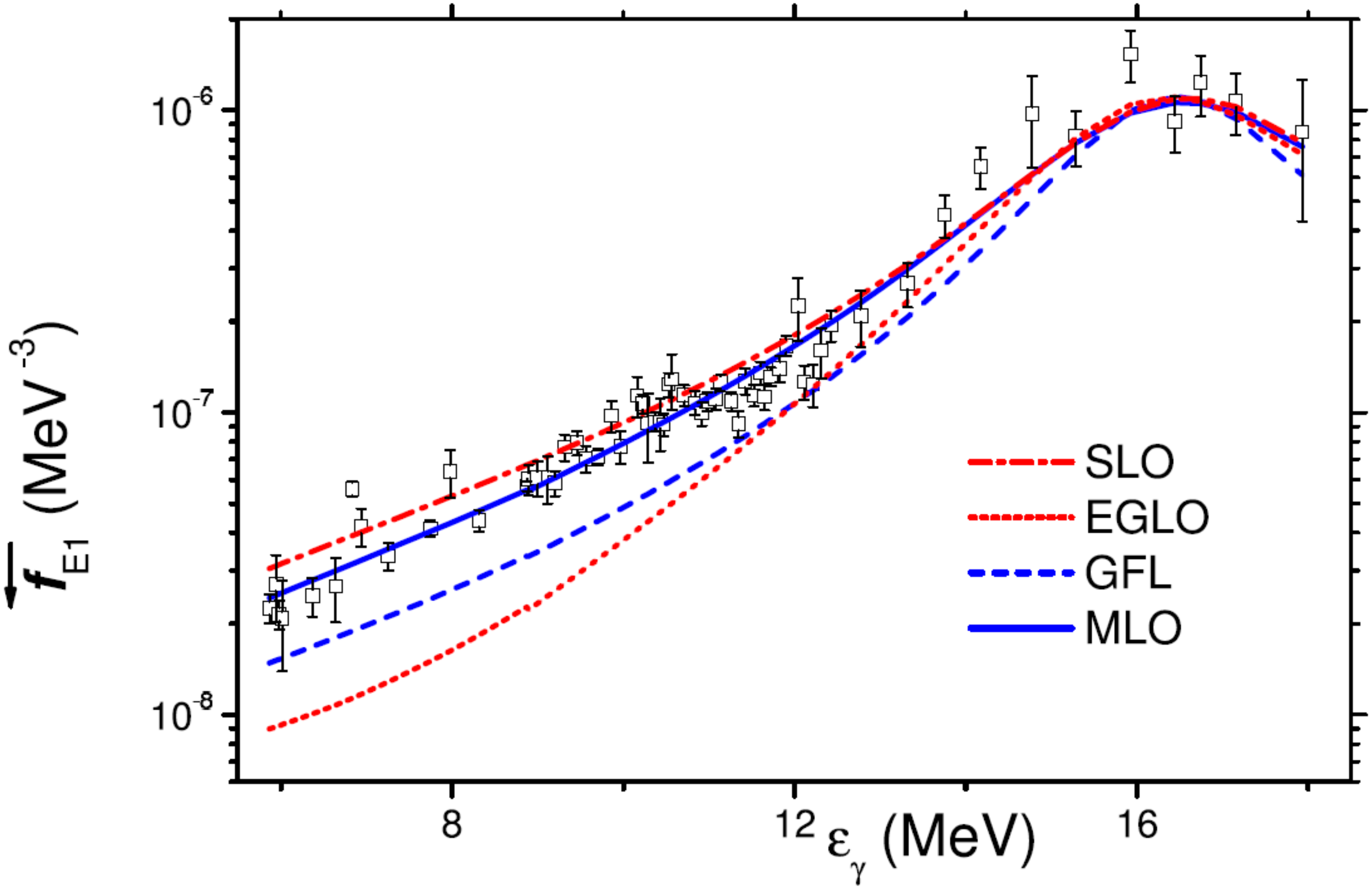


FIG. 42: E1 γ-decay strength function plotted against energy ϵ_γ for ^{90}Zr; experimental data are taken from Ref. [327].

GAMMA-RAY STENGTH
(Analytical expressions)

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)
    - ⇒ Hybrid model of Goriely (1998)
    - ⇒ Generalized Fermi liquid model of Plujko-Kavatsyuk (2003)

- Reconciliation with electromagnetic nuclear response theory
    - ⇒ Modified Lorentzian model of Plujko et al. (2002)
    - ⇒ Simplified Modified Lorentzian model of Plujko et al. (2008)

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

GAMMA-RAY STENGTH
(Analytical expressions summary)

- Standard Lorentzian (E_0, Γ_0, σ_0)
- Lorentzian with *E*-dependent width (e.g McCullagh et al. 1981) $\Gamma = \Gamma_0 \left(\frac{E}{E_0} \right)^{1/2}$
- Generalized Lorentzian with *T*- and *E*-dep. width (e.g Kopecky & Uhl 1990)

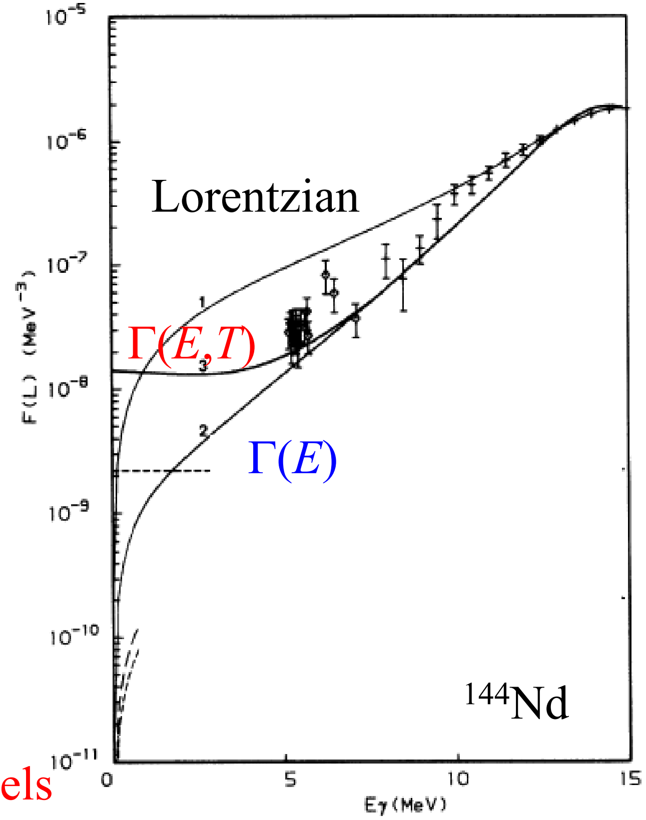
The *E*- and *T*-dependent width is essentially derived from the theory of Fermi liquids (e.g Kadmenski et al. 1983) and also suggested by experimental ARC data

$$G = \frac{G_0}{E_0^2}\left(E^2 + 4p^2T^2\right)$$

decay of p-h states into more complex states

collisions between quasi-particles

At the basis of GLO, EGLO, MLO, SMLO, Hybrid, … models



Kopecky & Uhl (1990)

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 STENGTH
(Microscopic approaches expressions)

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 force for 3317 nuclei performed by Goriely-Khan (2002,2004)

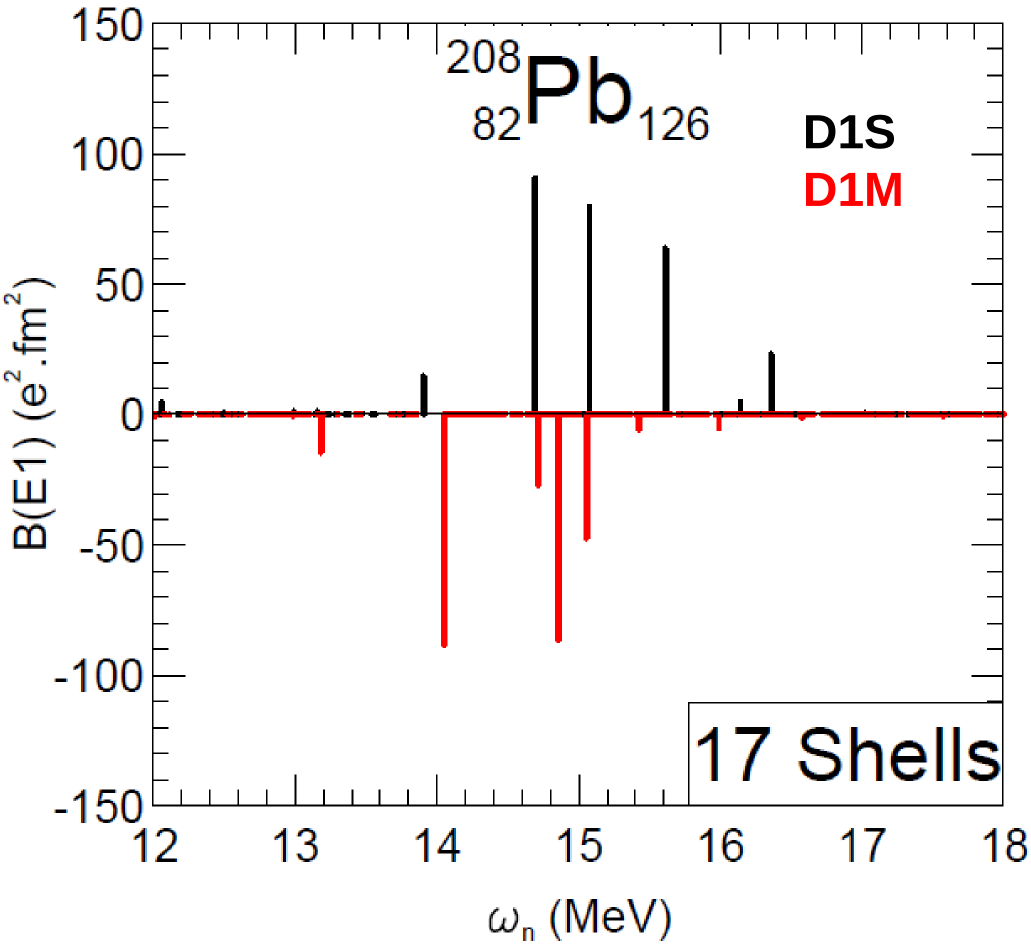
⇒ Systematic QRPA with Gogny force under work (300 Mh!!!)

Local approaches : regional study only

⇒ Shell Model approach

MICROSCOPIC APPROACHES (QRPA)

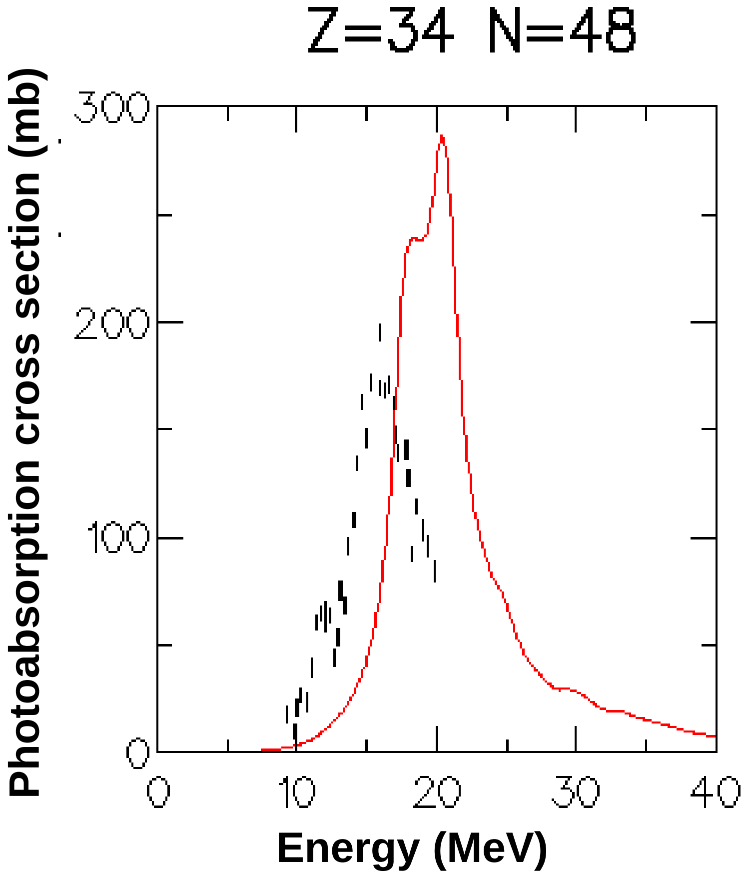
QRPA provides with emission probability between an excited state and the GS



⇒ Broadening necessary to account for damping of collective motion

MICROSCOPIC APPROACHES (QRPA)

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

MICROSCOPIC APPROACHES
(QRPA + Skm force : peak normalization)

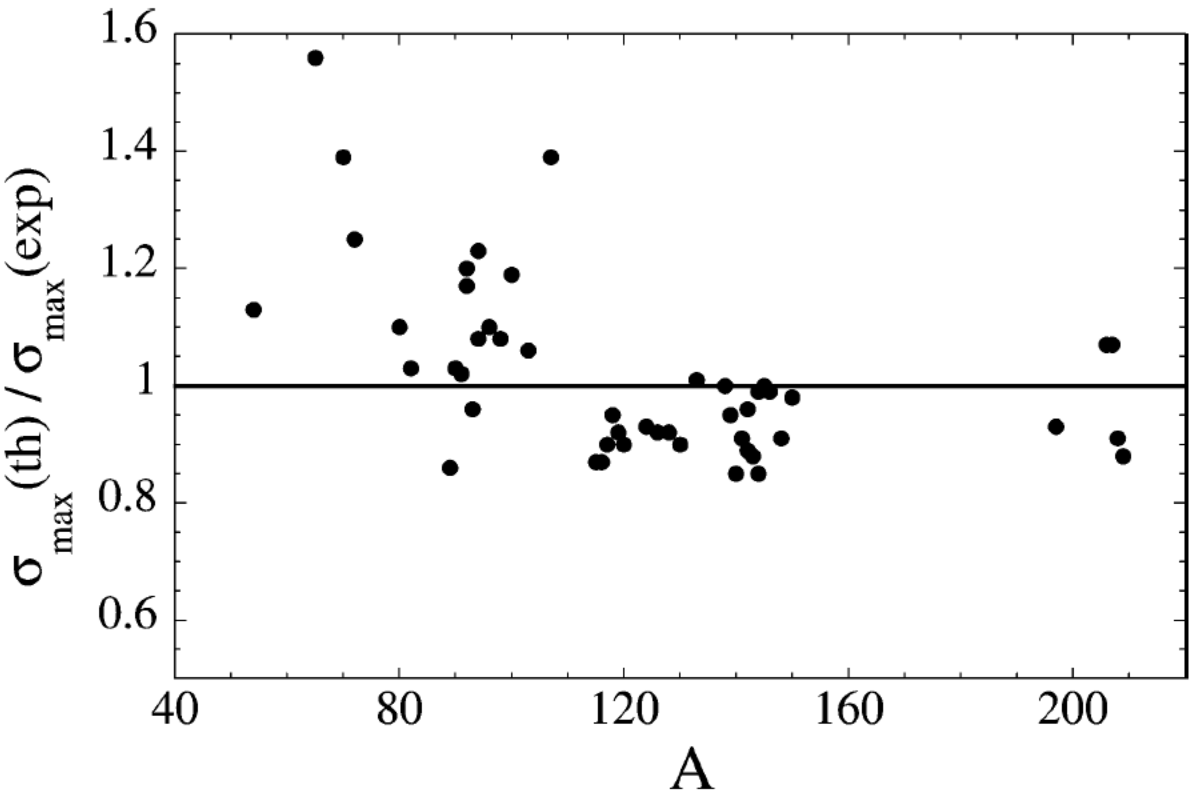
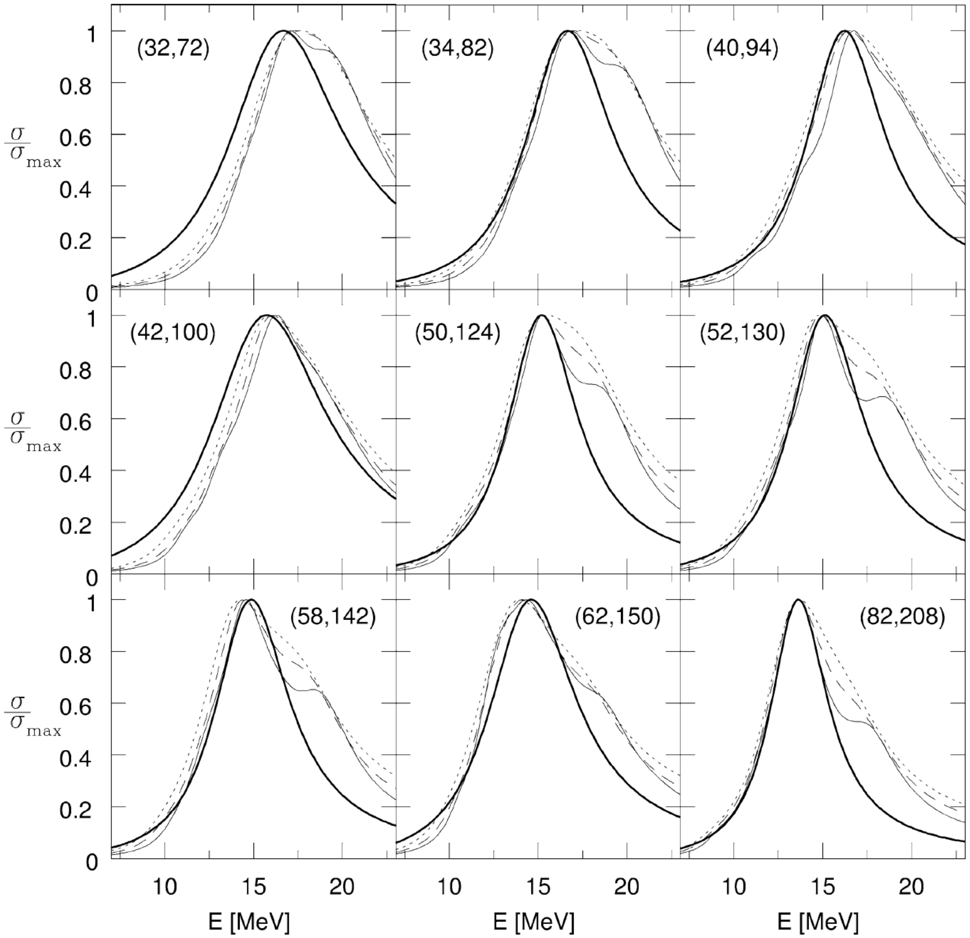


Fig. 4. Ratio of the peak cross section $\sigma_{max}(th)$ estimated within the HFB + QRPA model with the BSk7 Skyrme force to the experimental value $\sigma_{max}(exp)$ for the 48 spherical nuclei as a function of the mass number A.

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

MICROSCOPIC APPROACHES (Skyrme+QRPA after fitting)



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

MICROSCOPIC APPROACHES (QRPA+Skm for deformed nuclei)

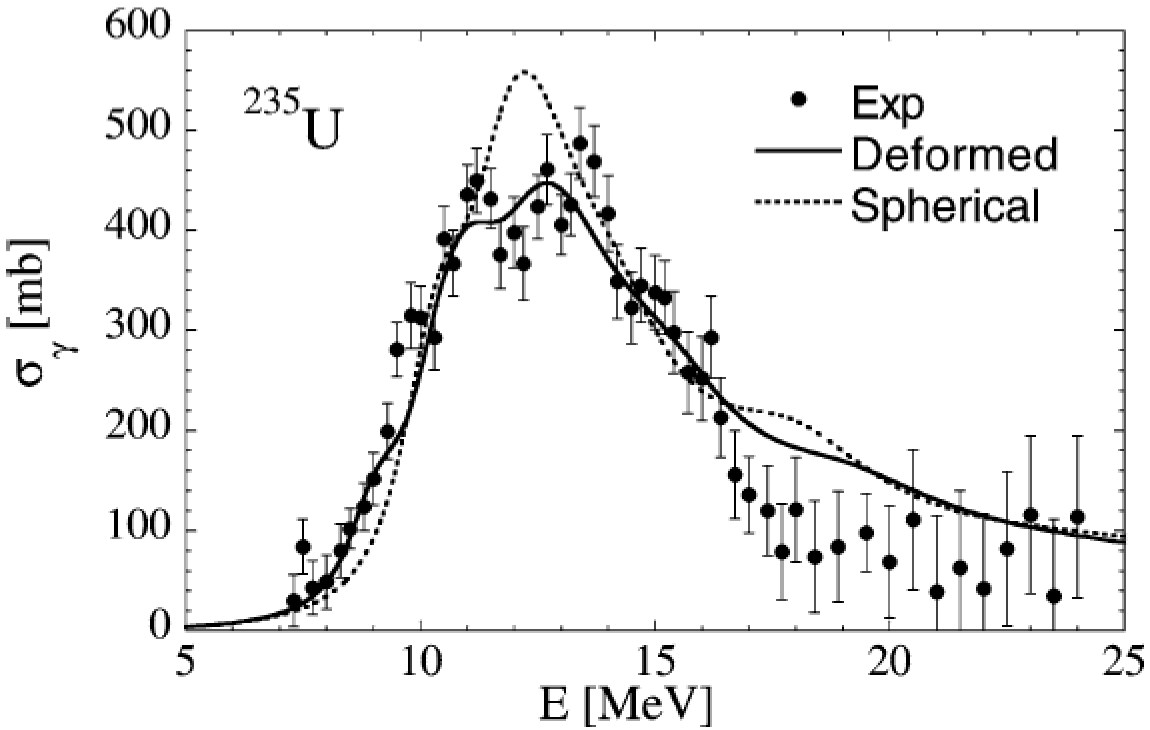
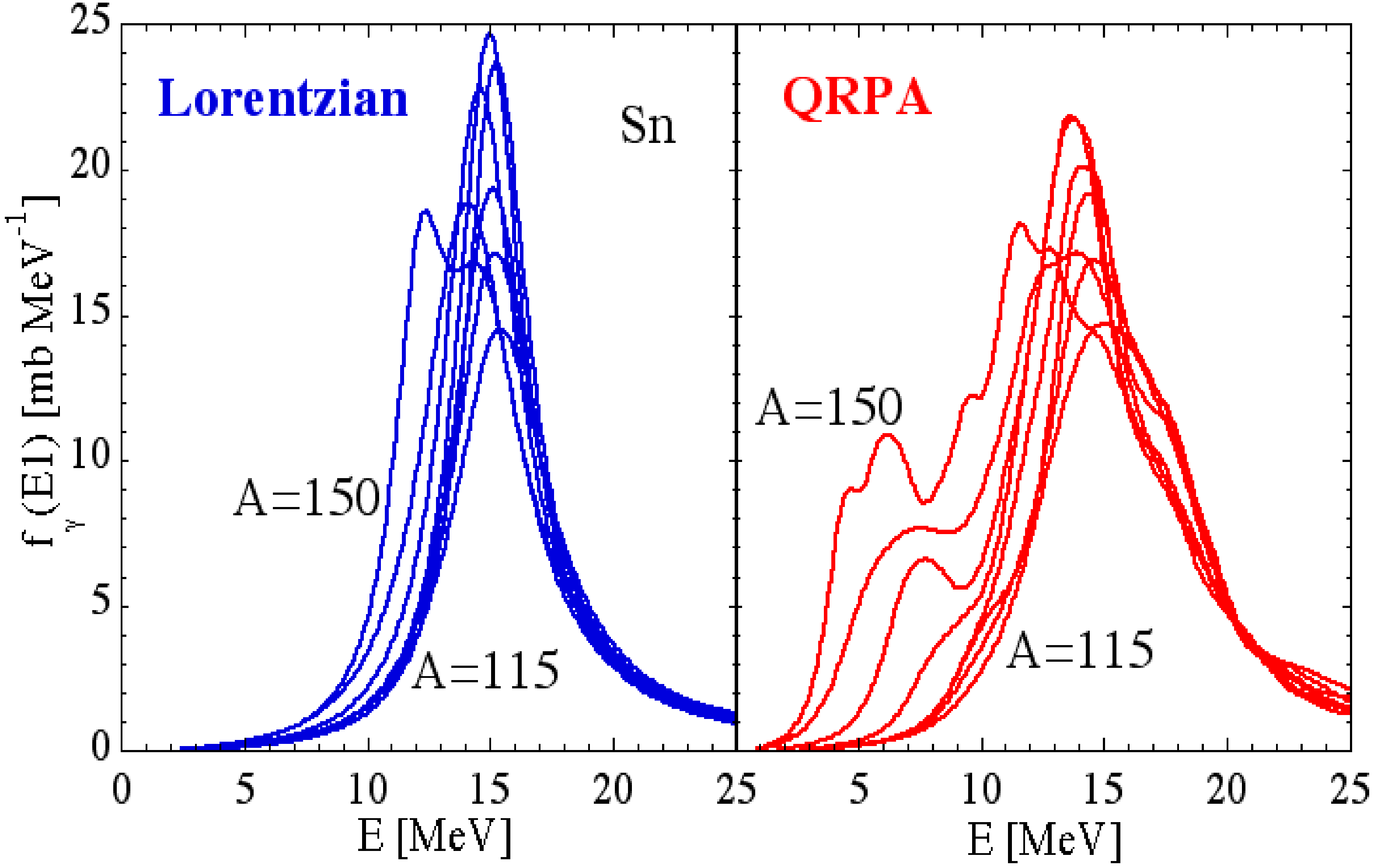


Fig. 5. Photoabsorption cross section for ^{235}U. The dots correspond to experimental data [16]. The dotted line is the HFB + QRPA calculation obtained with the BSk7 force in the spherical approximation (applying the damping method) and the full line when applying in addition our phenomenological procedure 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.

MICROSCOPIC APPROACHES
(QRPA + Skm for exotic nuclei)



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

MICROSCOPIC APPROACHES (QRPA+Skm conclusions)

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 QRPA+Gogny framework but high computational cost

MICROSCOPIC APPROACHES
(QRPA + Gogny force)

QRPA calculations performed to

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

1) perform sensitivity analyses w.r.t :

- **effective interaction (D1S vs D1M)**
- **nuclear deformation**
- **quasiparticle energy cut-off ε_c**
- **number of major shells N_{sh}**

compromise accuracy vs computing time

2) compute QRPA strengths for all nuclei included in the IAEA RIPL-3 database
3) compute low energy collective states

⇒ 25 Mh allocated on the CURIE supercomputer in 2011-2012
⇒ 2 Tb of data produced
⇒ 111 nuclei considered

MICROSCOPIC APPROACHES
(QRPA+Gogny force : adjustment procedure)

folded strength

raw strength

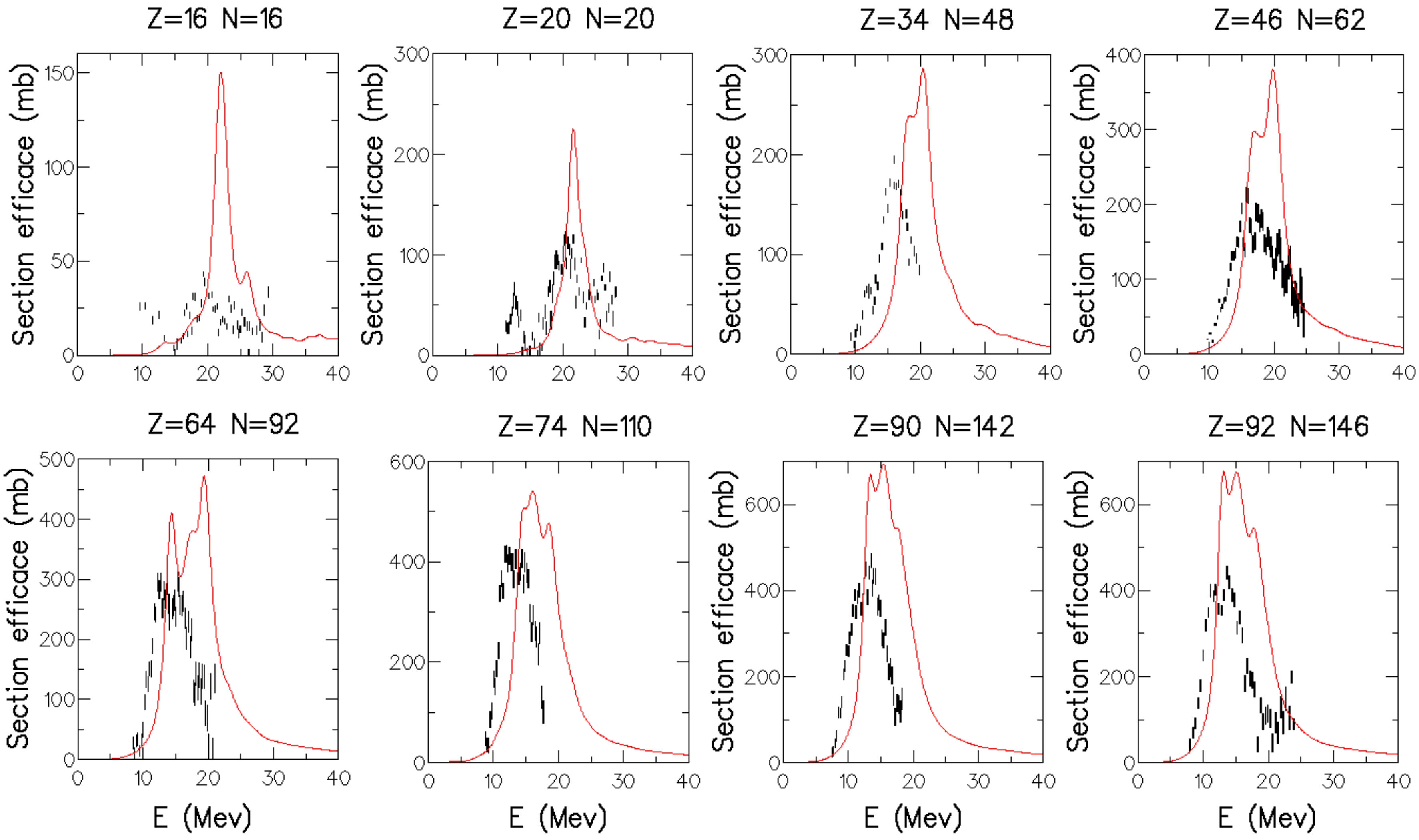
$$S_{E1}(E) = \sum_n L(E, \omega_n) B_{E1}(\omega_n)$$

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

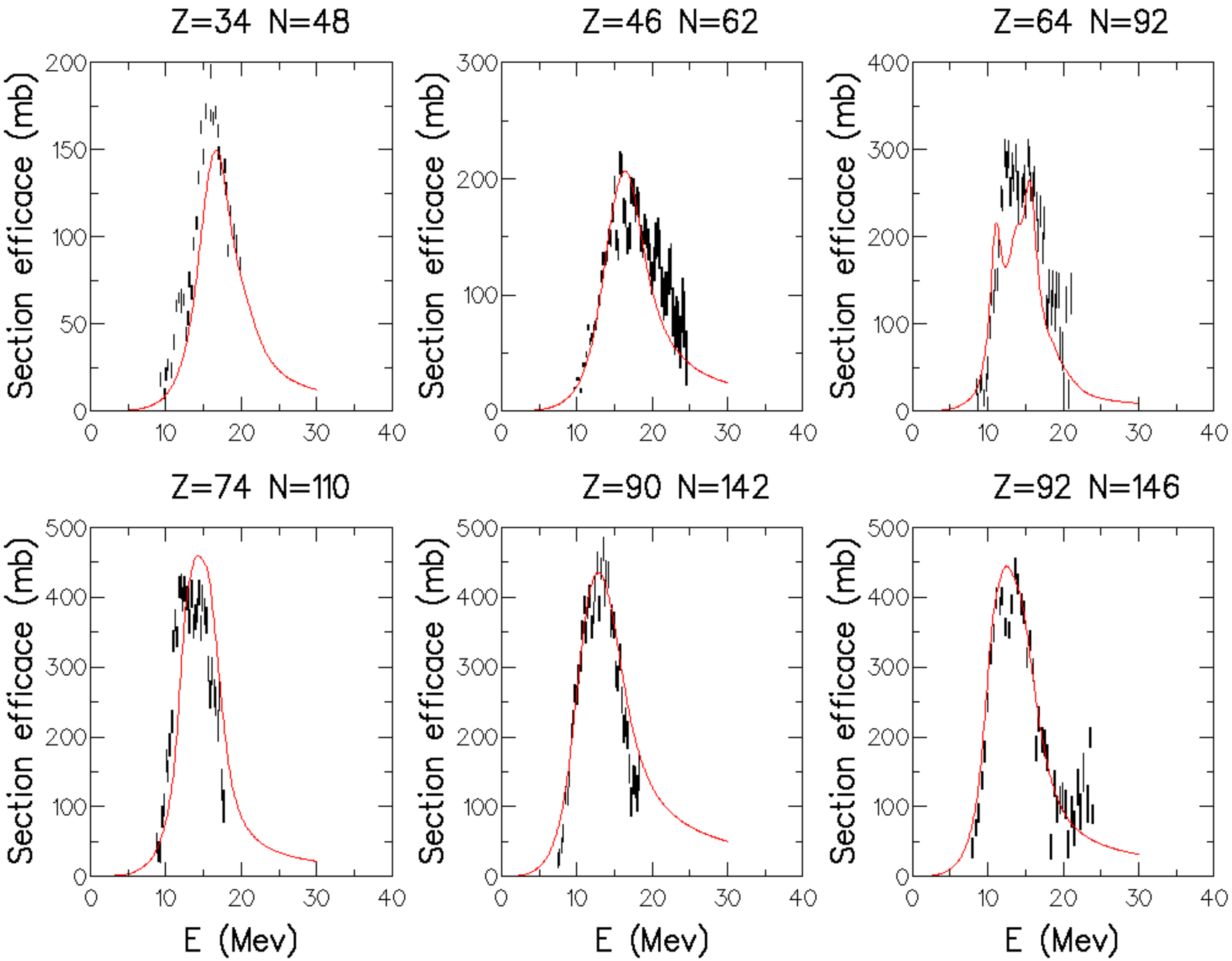
MICROSCOPIC APPROACHES (QRPA+Gogny force : broadening of 2 MeV only)



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

⇒ Peak normalization to improve experimental data fitting

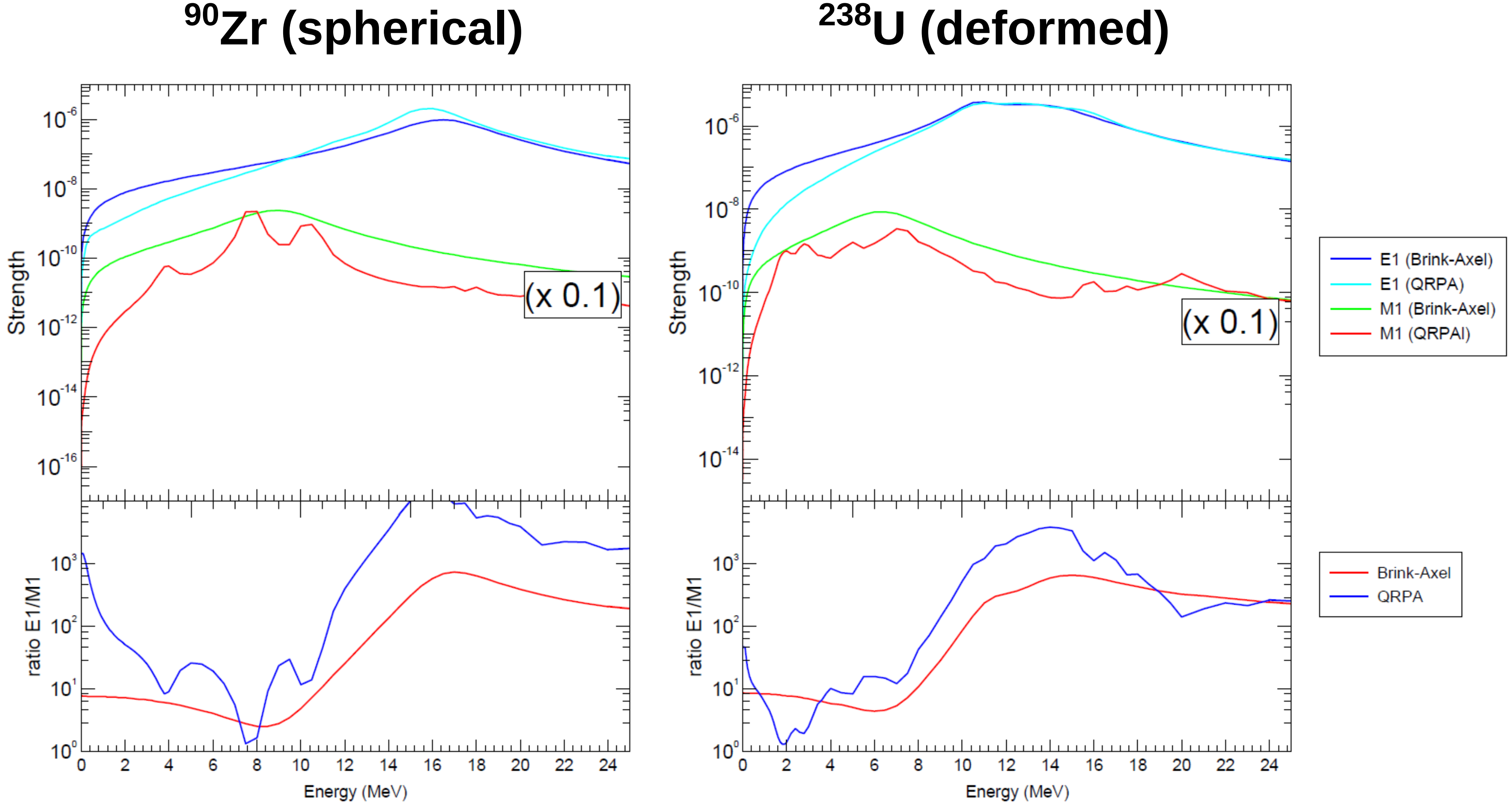
MICROSCOPIC APPROACHES
(QRPA+Gogny force : all parameters being adjusted)



⇒ Good agreement with data

⇒ Systematic predictions can be performed

GAMMA-RAY STENGTH
(QRPA+Gogny force : comparison with Brink-Axel)



^{90}Zr (spherical)

^{238}U (deformed)

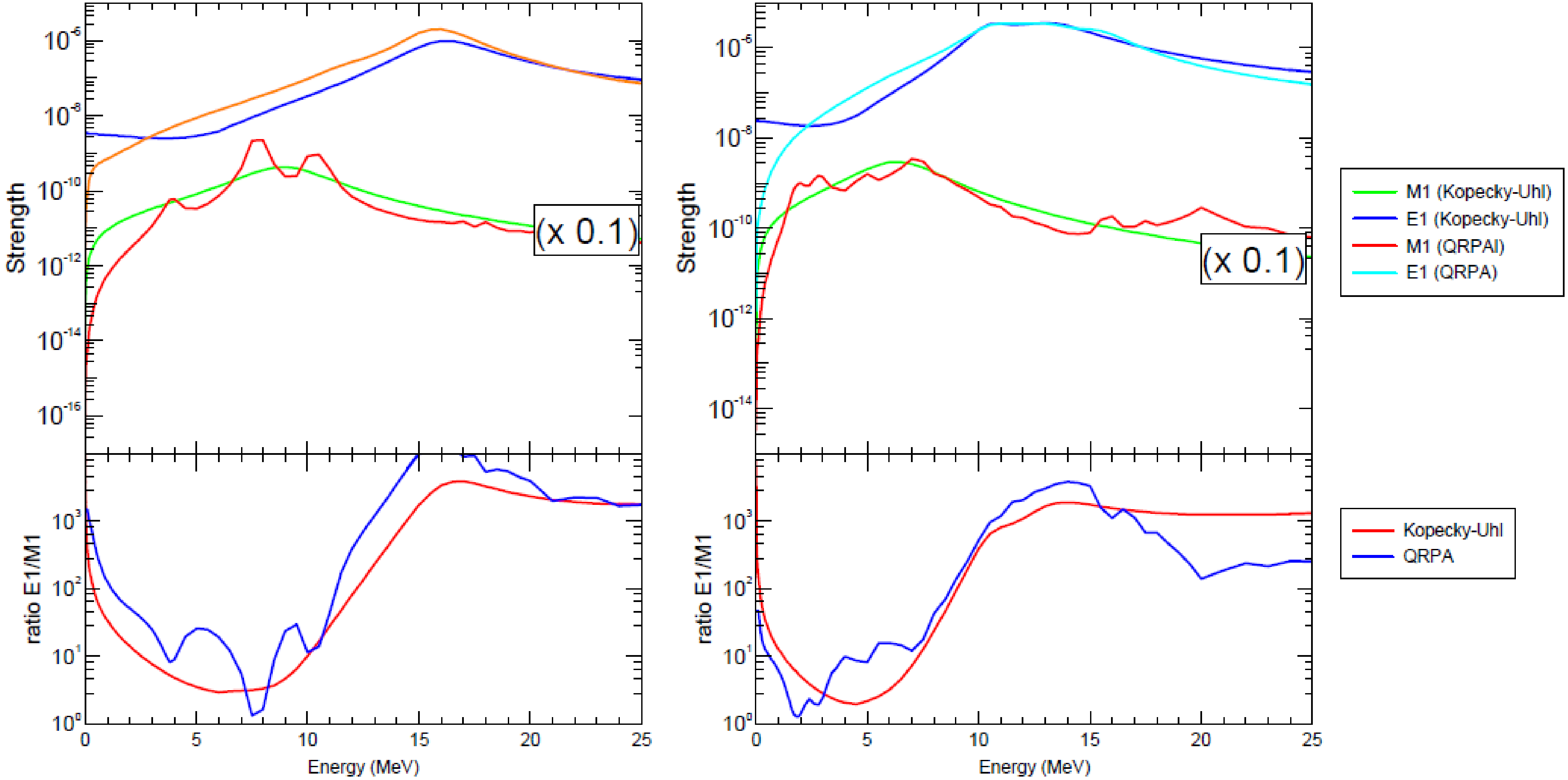
⇒ OK for photoabsorption

⇒ Significant structure for M1 transitions

GAMMA-RAY STENGTH
(QRPA+Gogny force : comparison with Kopecky-Uhl)

^{90}Zr (spherical)

^{238}U (deformed)



⇒ Missing low energy strength for gamma decay
⇒ Significant structure for M1 transitions

MICROSCOPIC APPROACHES
(Shell Model)

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

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

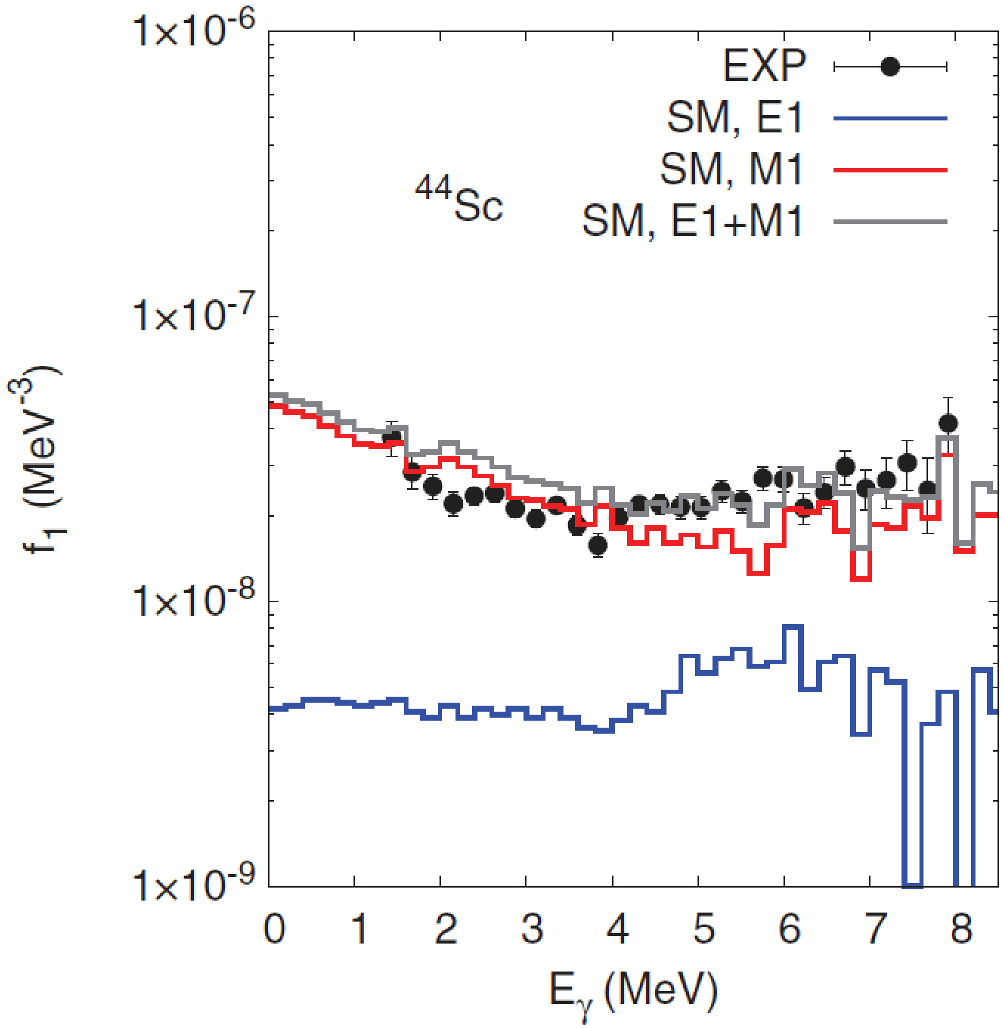
- spectra
- transitions between **any** excited state
- weak decays (beta, double-beta, …)
- pairing, deformation, …

Courtesy K. Sieja

But

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

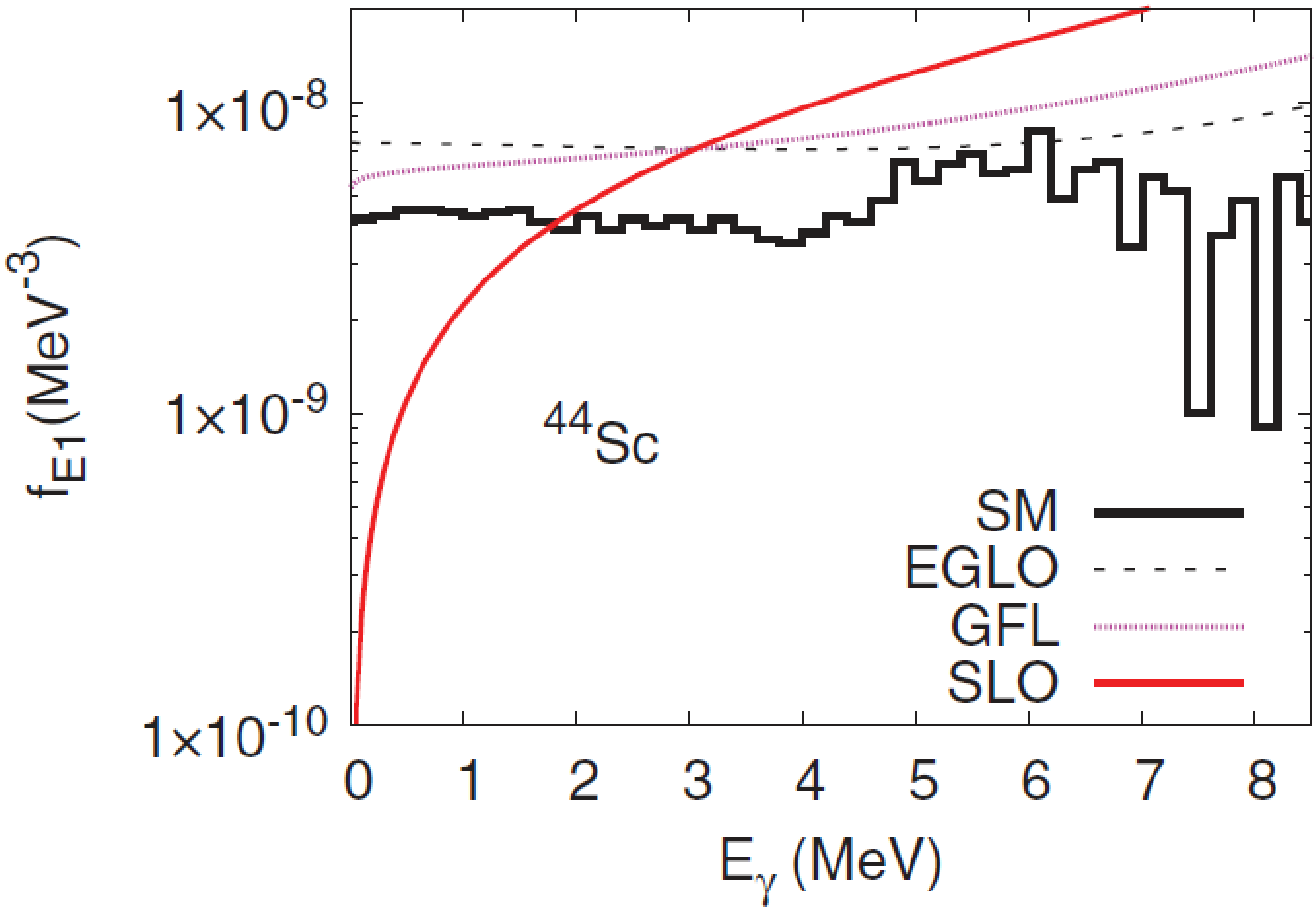
MICROSCOPIC APPROACHES
(Shell Model)



Courtesy K. Sieja

⇒ Shell model : sole microscopic model up to now to agree with low energy experimental data related to gamma decay

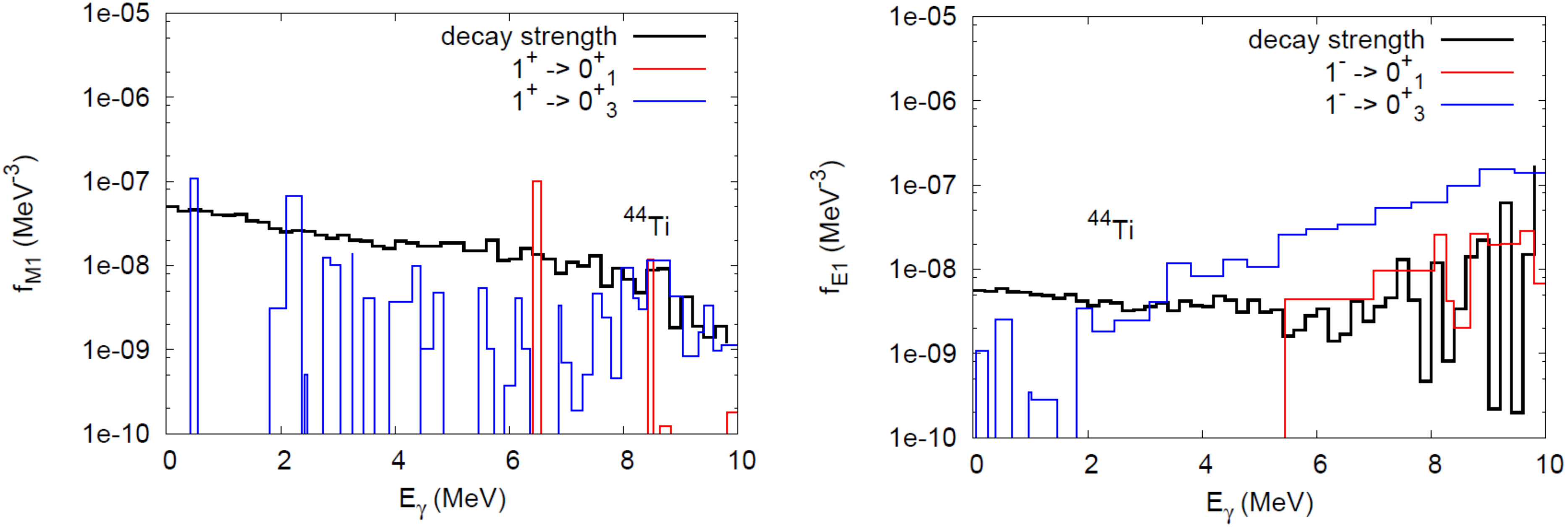
MICROSCOPIC APPROACHES
(Shell Model)



Courtesy K. Sieja

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

MICROSCOPIC APPROACHES
(Shell Model)



⇒ 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

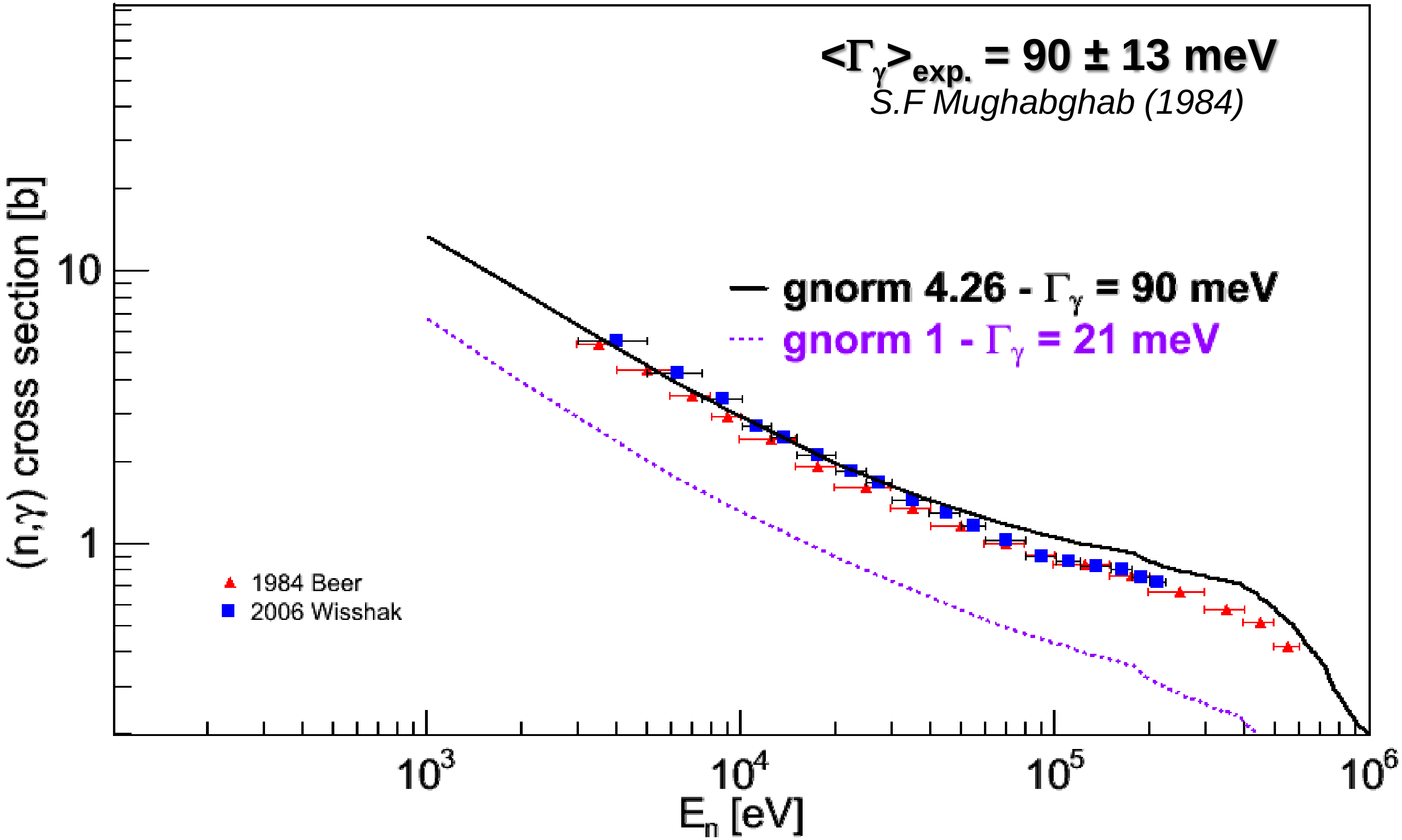
- Normalizations
- Exotic nuclei
- Hot topics

IMPACTS ON CROSS SECTIONS
(Normalizations)

Normalisation method for thermal neutrons

experiment

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

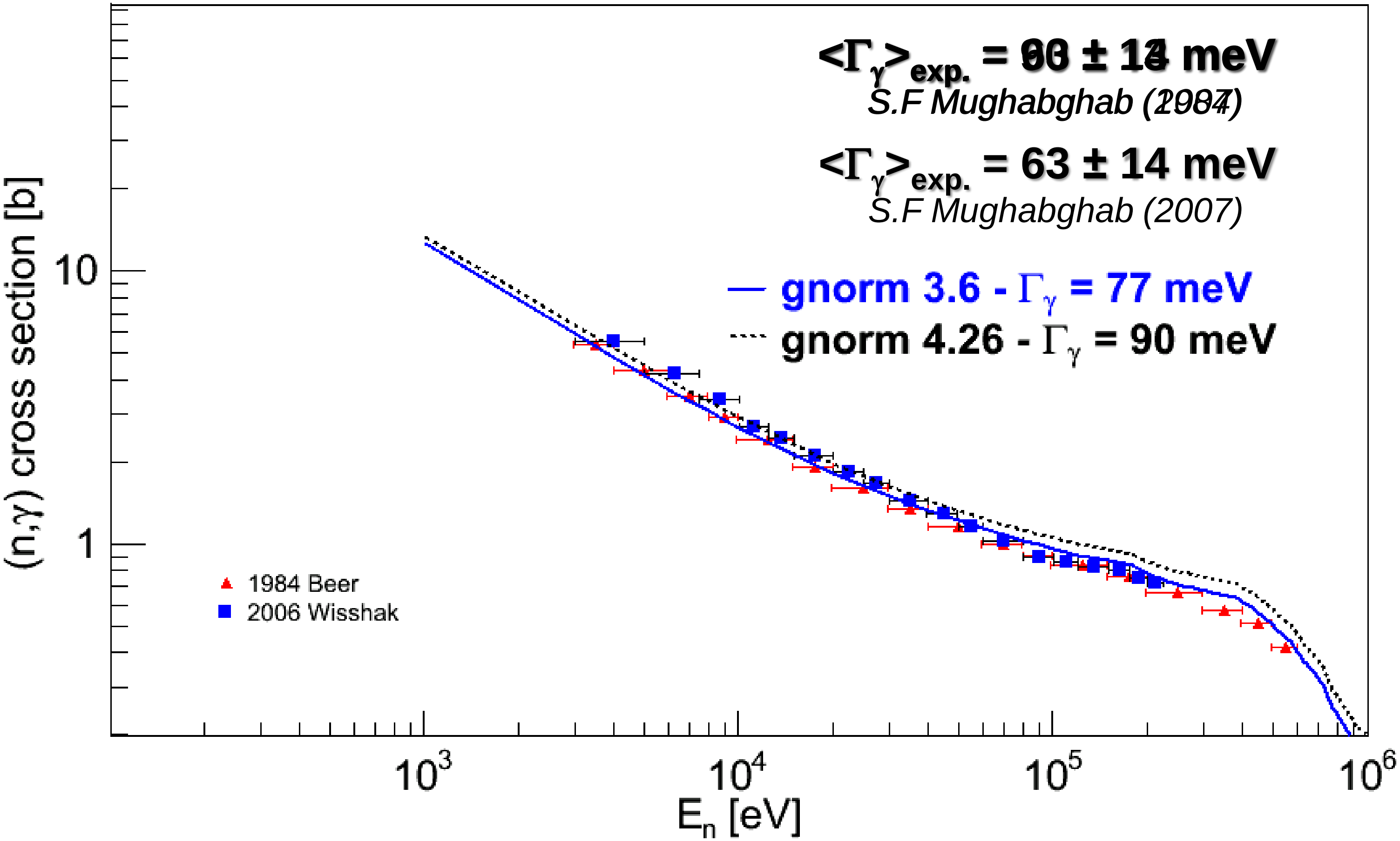


IMPACTS ON CROSS SECTIONS
(Normalizations)

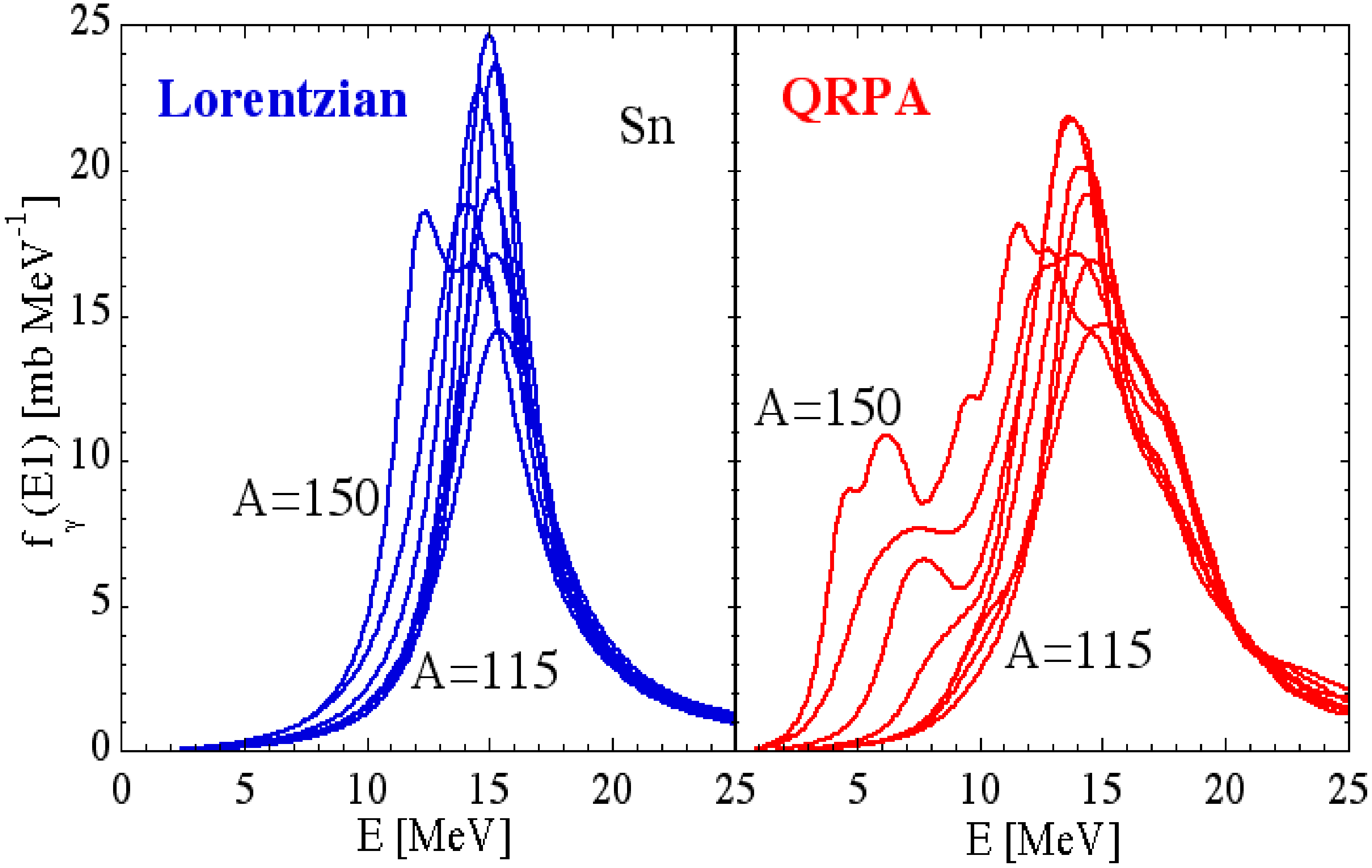
Normalisation method for thermal neutrons

experiment

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

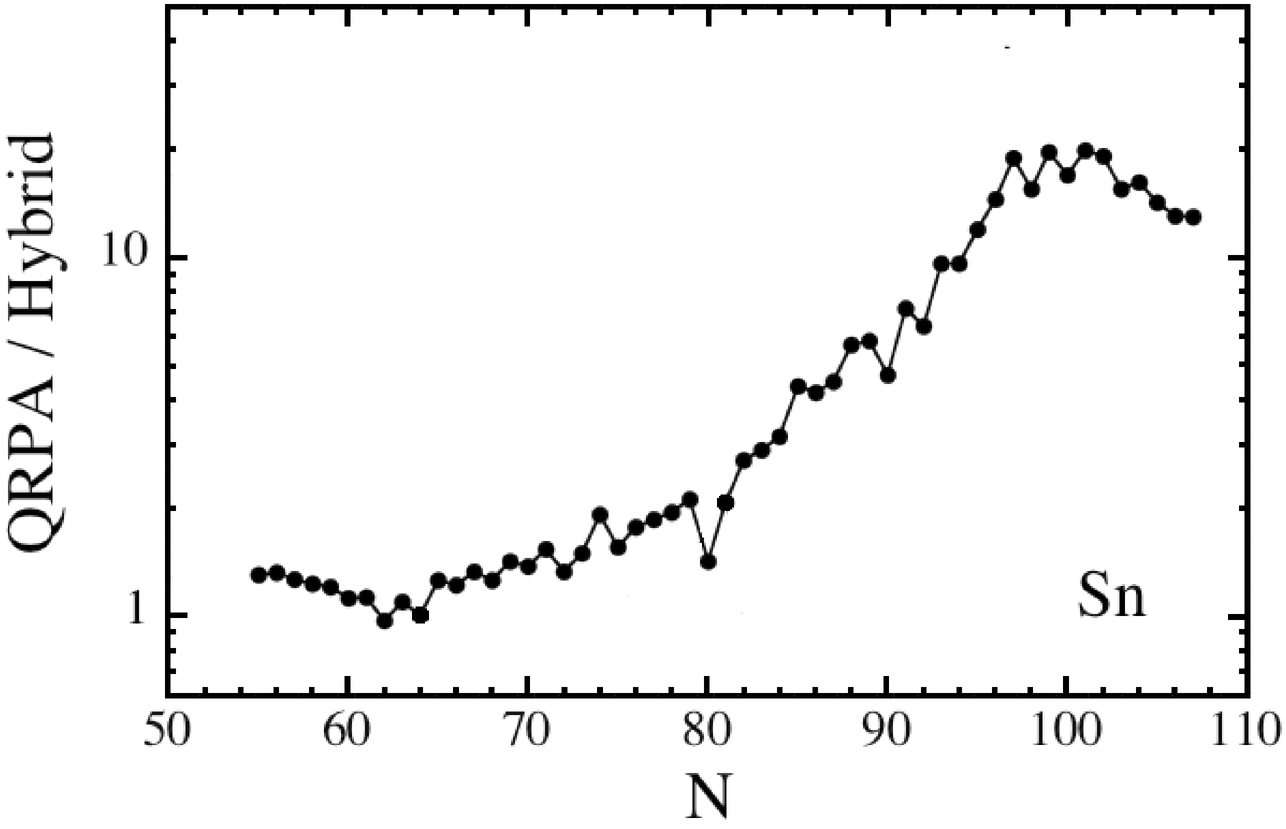


IMPACTS ON CROSS SECTIONS
(Exotic nuclei)



IMPACTS ON CROSS SECTIONS
(Exotic nuclei)

Capture cross section @ E_n=10 MeV for Sn isotopes



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

HOT TOPICS
(Low energy upbend ? M1 or E1 ?)

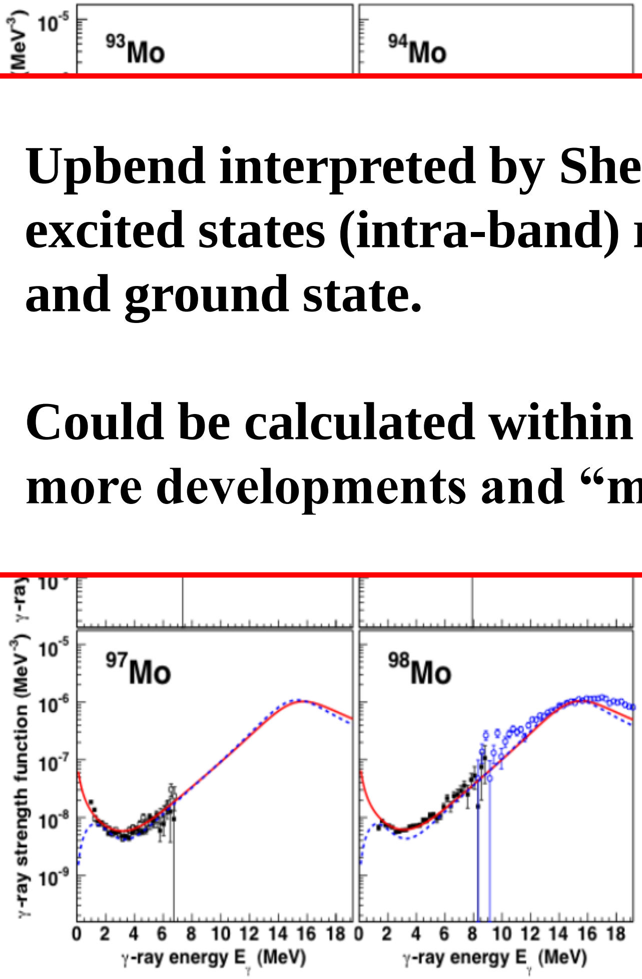
Low energy upbend of gamma-ray strength observed in several experiment

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

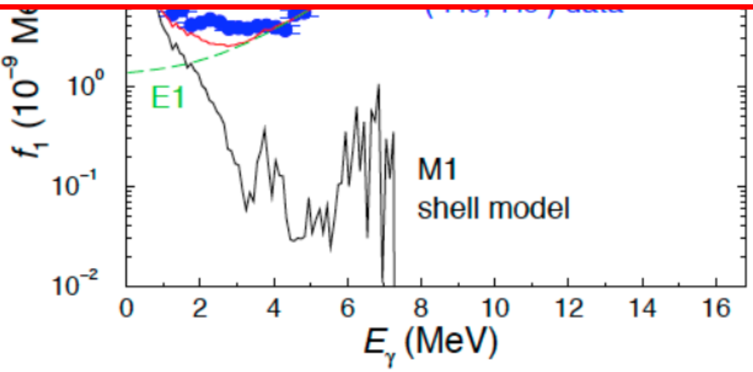
Upbend observed for ^{44,45}Sc, ^{50,51}V, ^{56,57}Fe, $^{73\text{-}74}$Ge, $^{93\text{-}98}$Mo, Sm but not (yet) for Sn,

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”



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



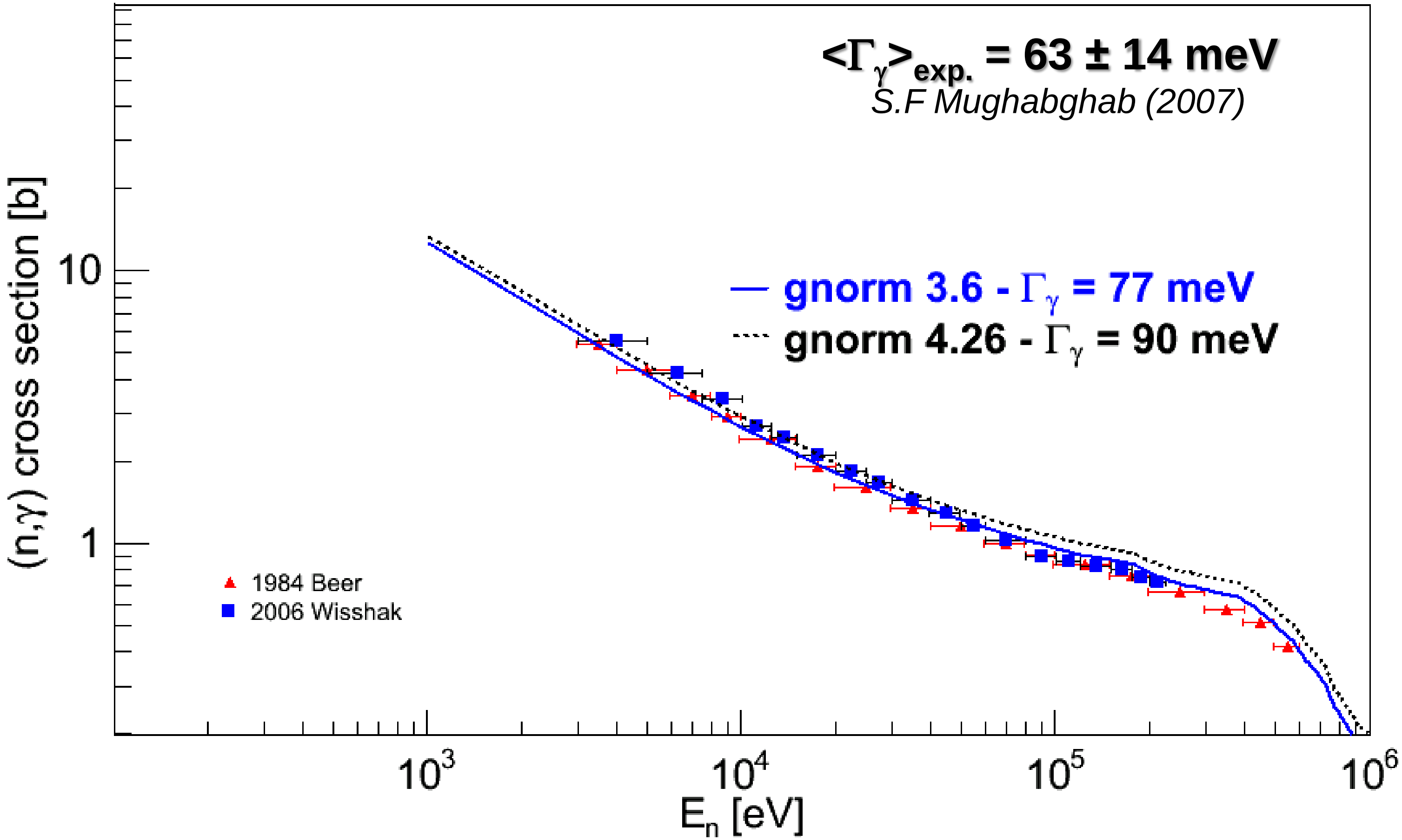
R. Schwengner et al. (2013); Brown & Larsen (2014); Sieja (2016)

HOT TOPICS
(Impact of low energy extra strength ?)

Normalisation method for thermal neutrons

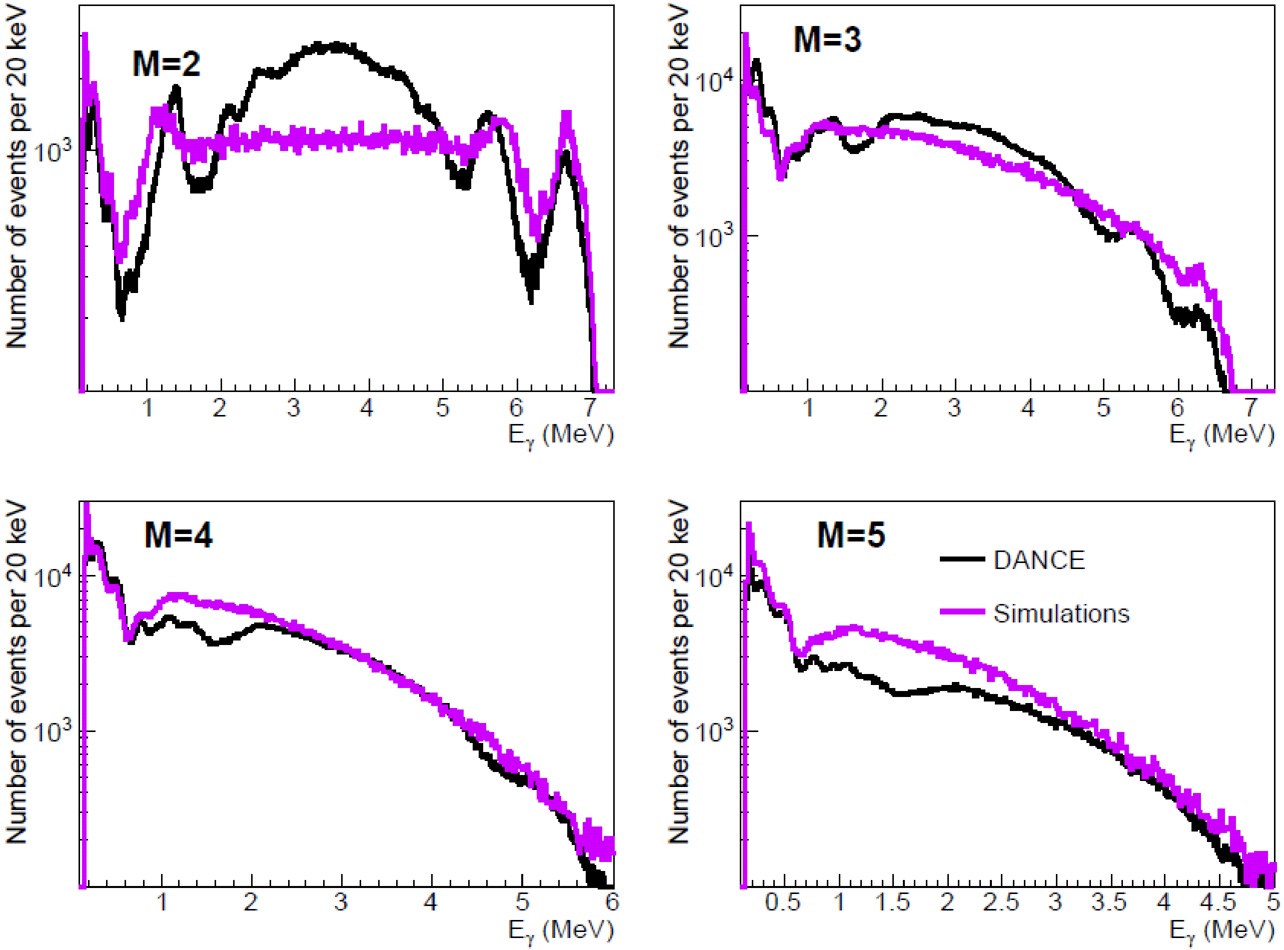
experiment

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



HOT TOPICS
(Impact of low energy extra strength ?)

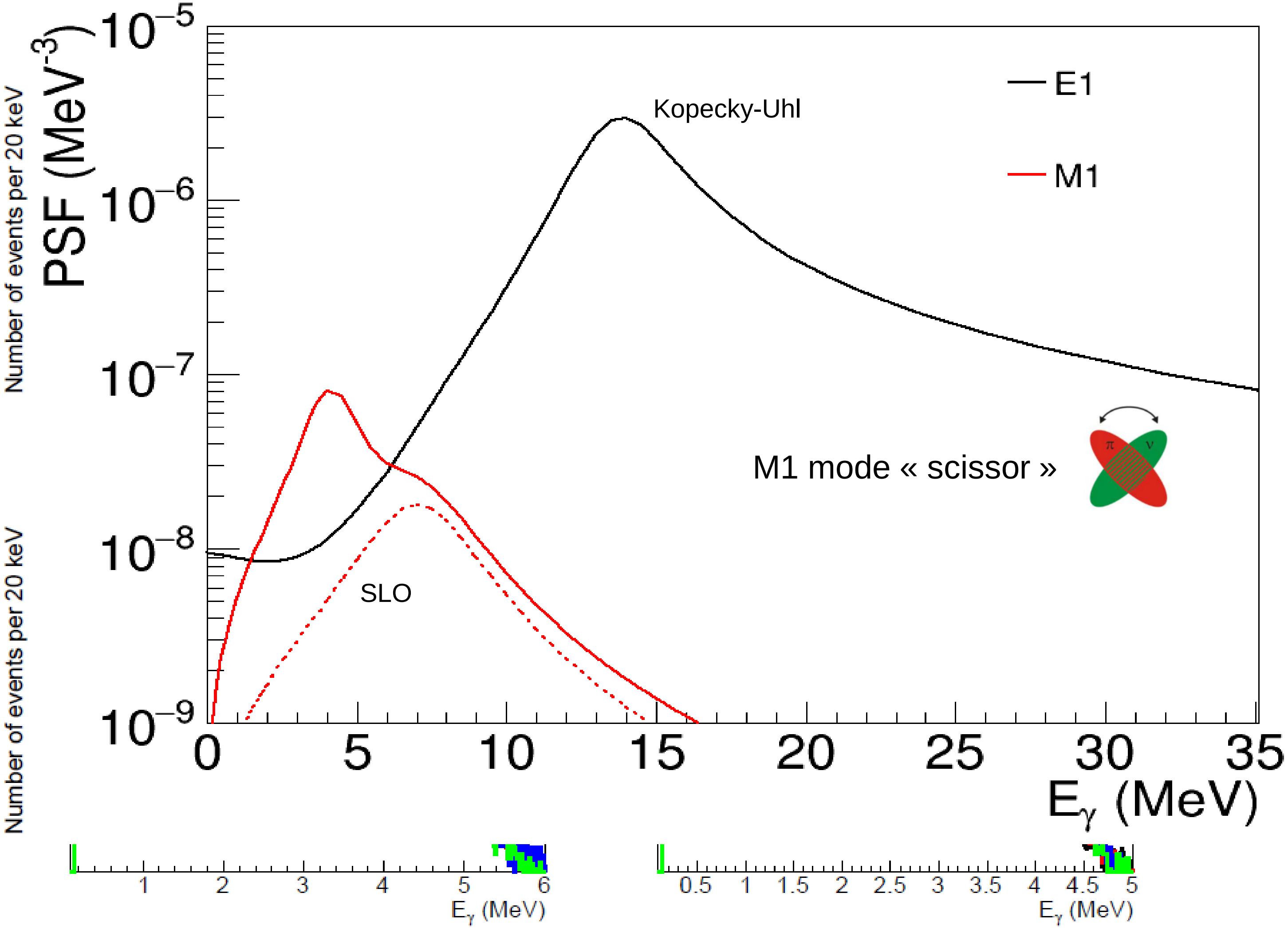
Capture cross section OK but gamma spectra constrained by multiplicity not reproduced !



HOT TOPICS
(Impact of low energy extra strength ?)

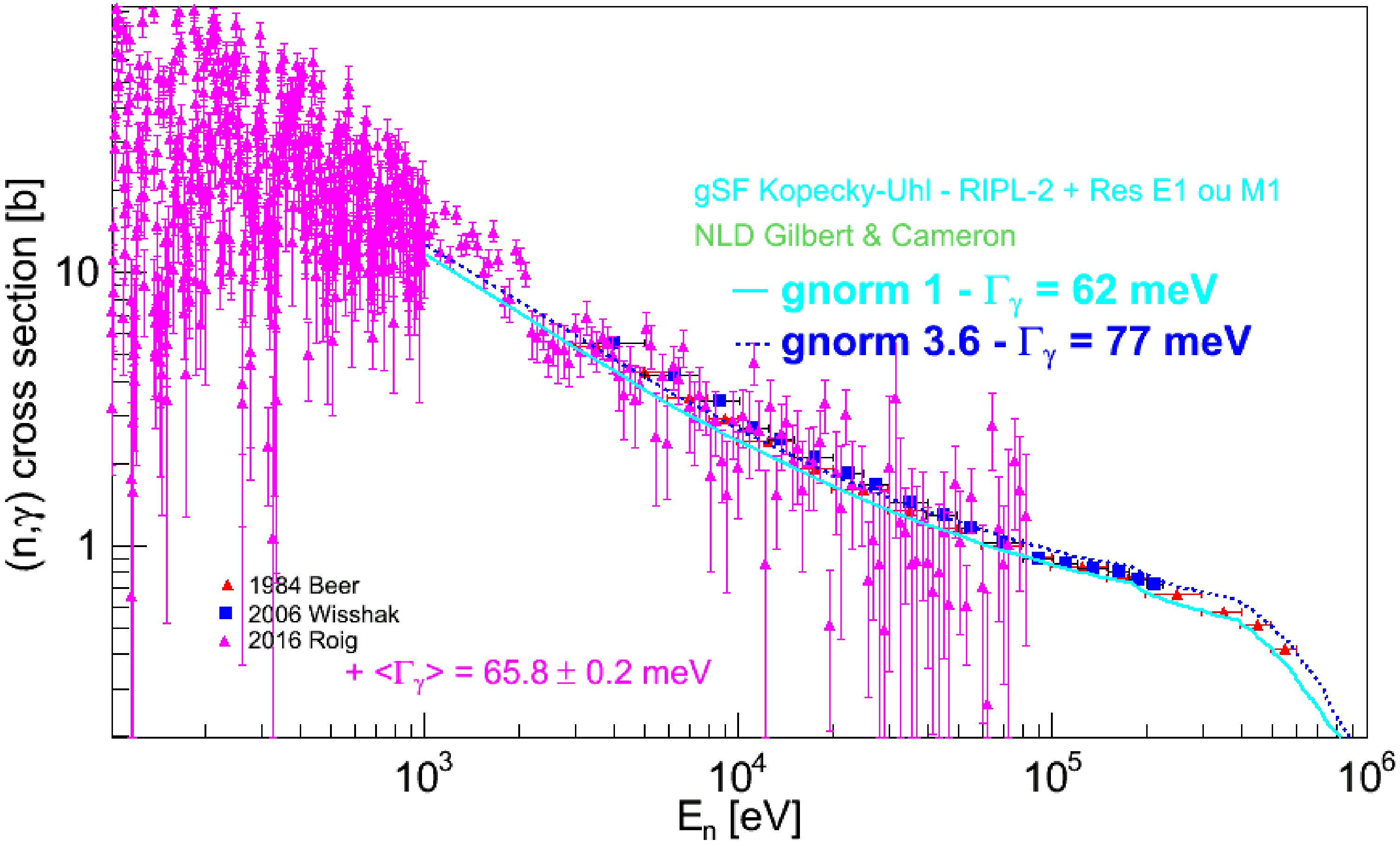
Capture cross section OK but gamma spectra constrained by multiplicity not reproduced

⇒ Much better agreement introducing a new resonance at energies around 4 MeV



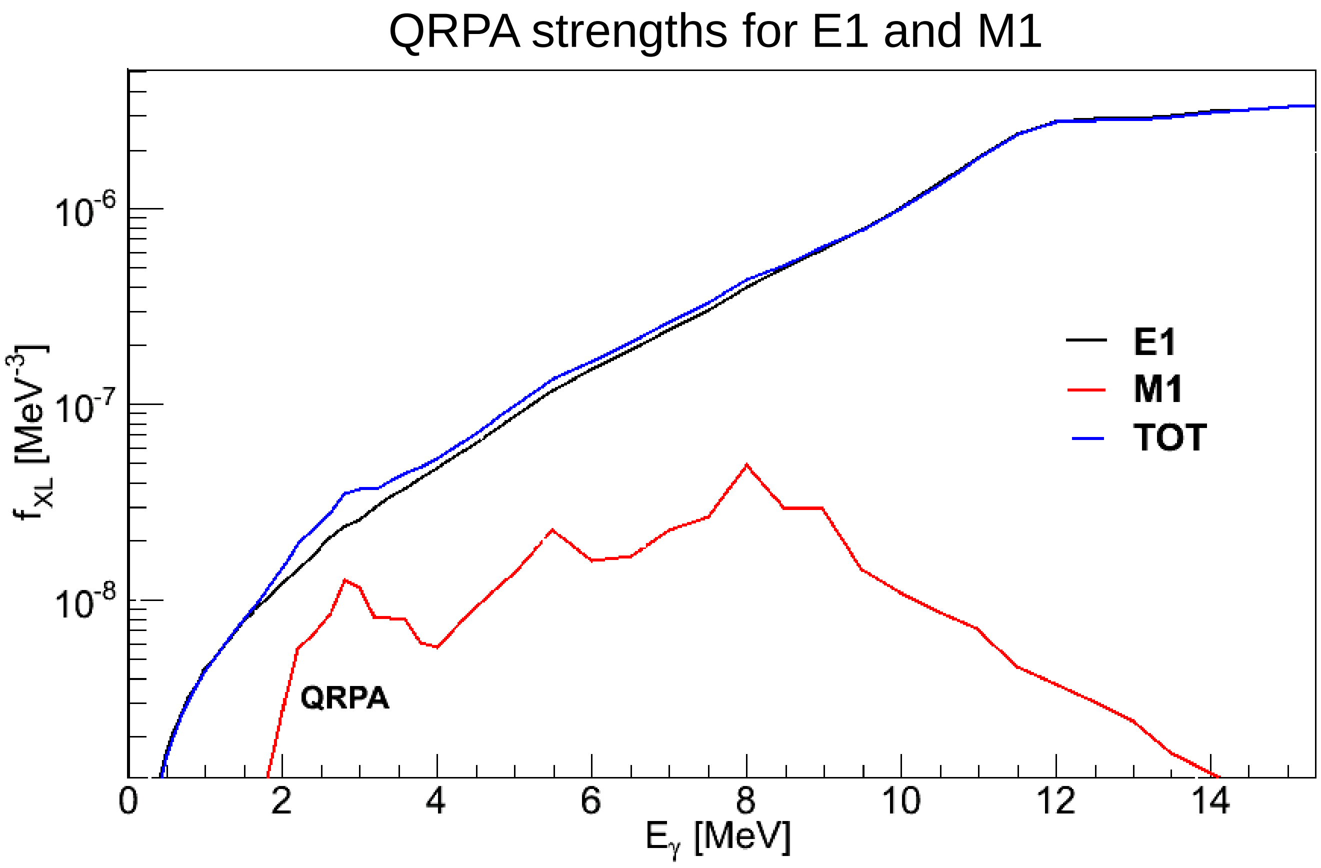
HOT TOPICS
(Impact of low energy extra strength ?)

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



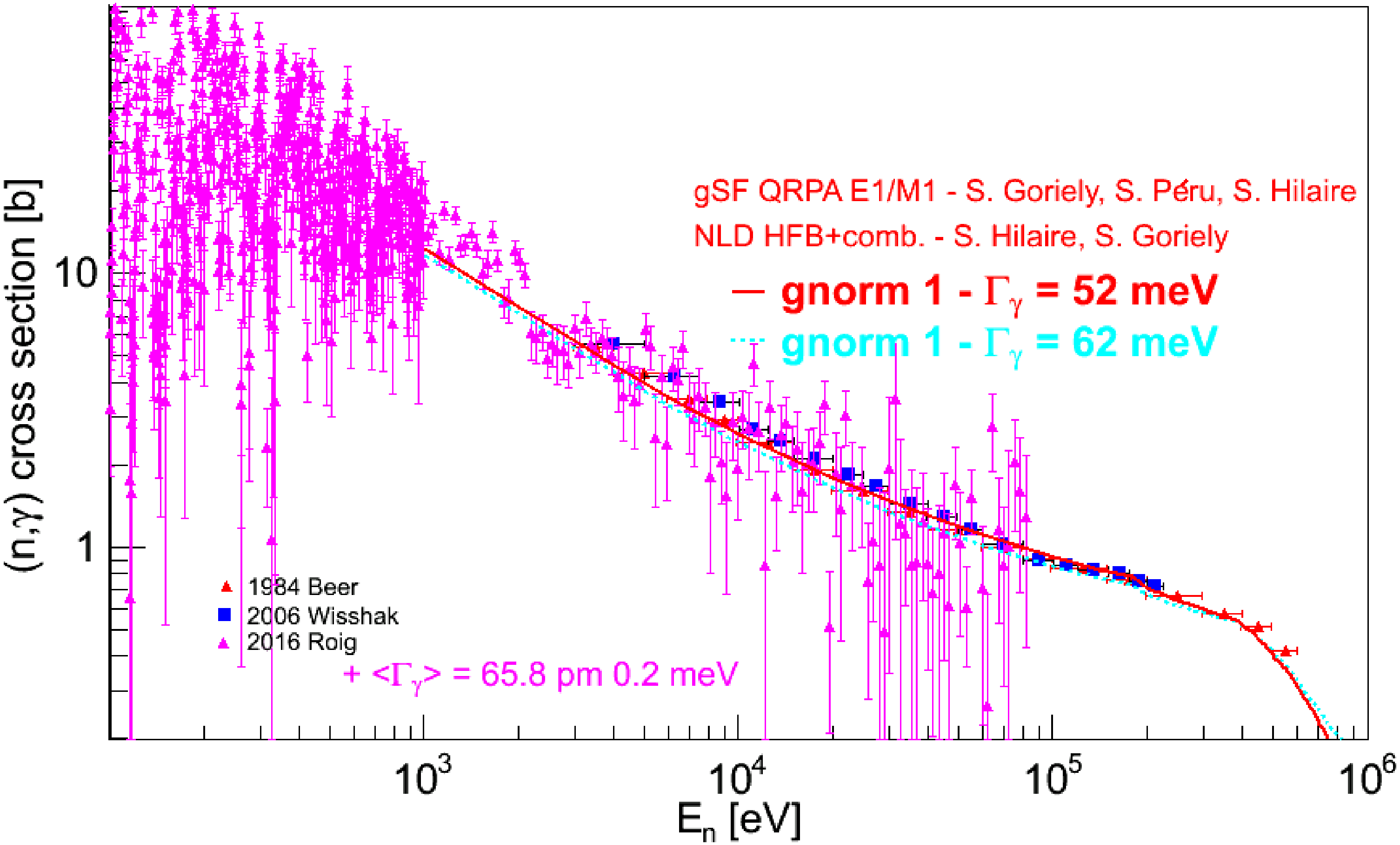
HOT TOPICS
(Impact of low energy extra strength)

What about QRPA ?

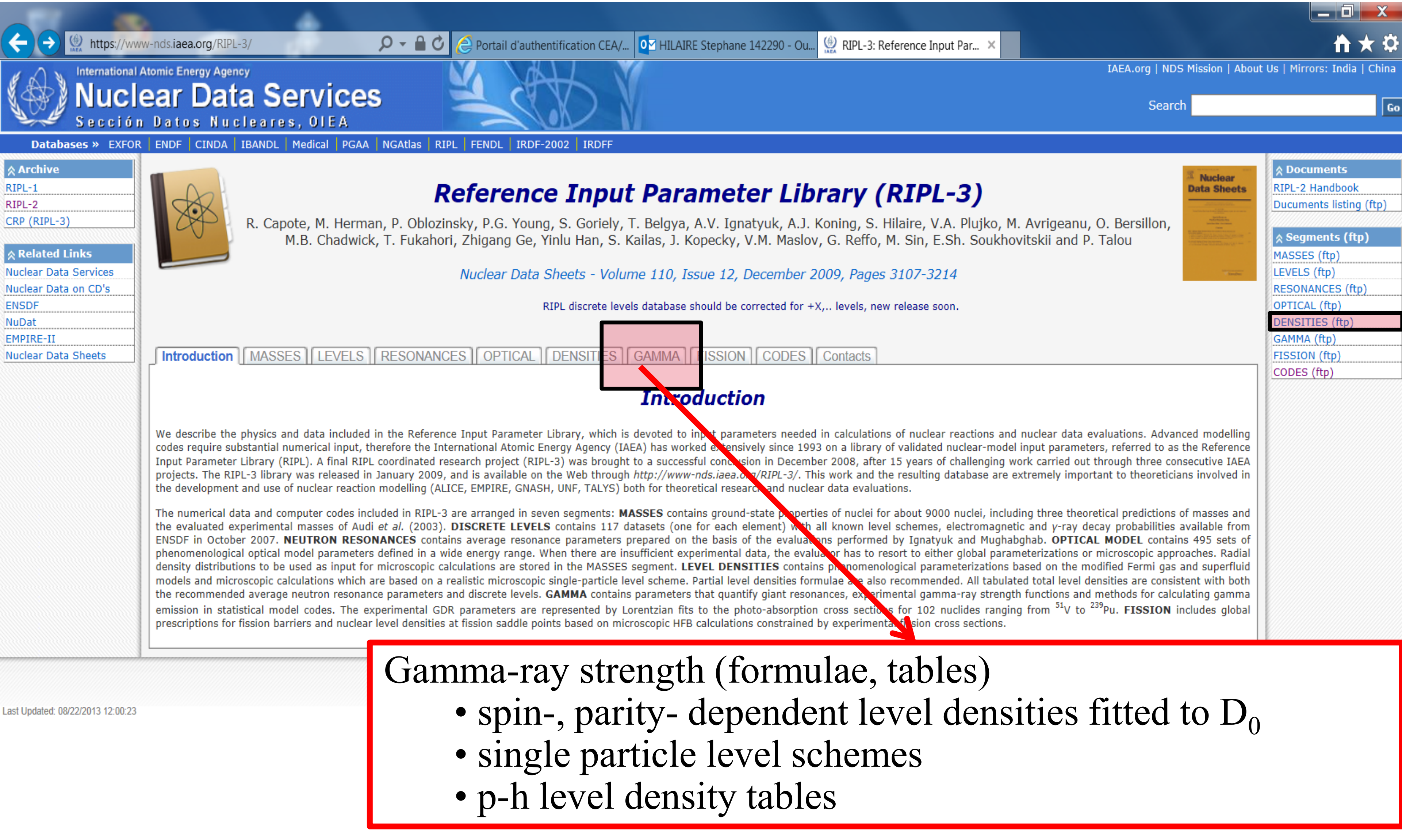


HOT TOPICS
(Impact of low energy extra strength : what about QRPA ?)

What about QRPA ?



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



Reference Input Parameter Library (RIPL-3)

R. Capote, M. Herman, P. Oblozinsky, P.G. Young, S. Goriely, T. Belgya, A.V. Ignatyuk, A.J. Koning, S. Hilaire, V.A. Plujko, M. Avrigeanu, O. Bersillon, M.B. Chadwick, T. Fukahori, Zhigang Ge, Yinlu Han, S. Kailas, J. Kopecky, V.M. Maslov, G. Reffo, M. Sin, E.Sh. Soukhovitskii and P. Talou

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

RIPL discrete levels database should be corrected for +X,.. levels, new release soon.

Introduction

We describe the physics and data included in the Reference Input Parameter Library, which is devoted to input parameters needed in calculations of nuclear reactions and nuclear data evaluations. Advanced modelling codes require substantial numerical input, therefore the International Atomic Energy Agency (IAEA) has worked extensively since 1993 on a library of validated nuclear-model input parameters, referred to as the Reference Input Parameter Library (RIPL). A final RIPL coordinated research project (RIPL-3) was brought to a successful conclusion in December 2008, after 15 years of challenging work carried out through three consecutive IAEA projects. The RIPL-3 library was released in January 2009, and is available on the Web through *http://www-nds.iaea.org/RIPL-3/*. This work and the resulting database are extremely important to theoreticians involved in the development and use of nuclear reaction modelling (ALICE, EMPIRE, GNASH, UNF, TALYS) both for theoretical research and nuclear data evaluations.

The numerical data and computer codes included in RIPL-3 are arranged in seven segments: **MASSES** contains ground-state properties of nuclei for about 9000 nuclei, including three theoretical predictions of masses and the evaluated experimental masses of Audi *et al.* (2003). **DISCRETE LEVELS** contains 117 datasets (one for each element) with all known level schemes, electromagnetic and γ-ray decay probabilities available from ENSDF in October 2007. **NEUTRON RESONANCES** contains average resonance parameters prepared on the basis of the evaluations performed by Ignatyuk and Mughabghab. **OPTICAL MODEL** contains 495 sets of phenomenological optical model parameters defined in a wide energy range. When there are insufficient experimental data, the evaluator has to resort to either global parameterizations or microscopic approaches. Radial density distributions to be used as input for microscopic calculations are stored in the MASSES segment. **LEVEL DENSITIES** contains phenomenological parameterizations based on the modified Fermi gas and superfluid models and microscopic calculations which are based on a realistic microscopic single-particle level scheme. Partial level densities formulae are also recommended. All tabulated total level densities are consistent with both the recommended average neutron resonance parameters and discrete levels. **GAMMA** contains parameters that quantify giant resonances, experimental gamma-ray strength functions and methods for calculating gamma emission in statistical model codes. The experimental GDR parameters are represented by Lorentzian fits to the photo-absorption cross sections for 102 nuclides ranging from ^{51}V to ^{239}Pu. **FISSION** includes global prescriptions for fission barriers and nuclear level densities at fission saddle points based on microscopic HFB calculations constrained by experimental fission cross sections.

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Gamma-ray strength (formulae, tables)

- spin-, parity- dependent level densities fitted to D_0
- single particle level schemes
- p-h level density tables

FISSION TRANSMISSION COEFFICIENTS

To be discussed tomorrow !