DE LA RECHERCHE À L'INDUSTRIE

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Statistical Theory of Nuclear Reactions, Channel Widths and Level Densities

S. Hilaire - CEA,DAM,DIF

Content

TODAY

- **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
  - Miscellaneous : level densities, fission, capture
- **From in depth analysis to large scale production with TALYS**
  - General features about TALYS
  - Fine tuning and accuracy
  - Global systematic approaches
- **What remains to be done ?**

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TOMORROW

INTRODUCTION

The bible today

Available online at www.sciencedirect.com

ScienceDirect

Nuclear Data Sheets 110 (2009) 3107–3214

Nuclear Data Sheets

www.elsevier.com/locate/nds

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

R. Capote,[1]* M. Herman,[1,2] P. Obložinský,[1,2] P.G. Young,[3] S. Goriely,[4] T. Belgya,[5] A.V. Ignatyuk,[6]
A.J. Koning,[7] S. Hilaire,[8] V.A. Plujko,[9] M. Avrigeanu,[10] O. Bersillon,[8] M.B. Chadwick,[3] T. Fukahori,[11]
Zhigang Ge,[12] Yinlu Han,[12] S. Kailas,[13] J. Kopecky,[14]
V.M. Maslov,[15] G. Reffo,[16] M. Sin,[17] E.Sh. Soukhovitskii,[15] P. Talou[3]

[1] *NAPC–Nuclear Data Section, International Atomic Energy Agency, A-1400 Vienna, Austria*
[2] *National Nuclear Data Center, Brookhaven National Laboratory, Upton, NY 11973, USA*
[3] *Los Alamos National Laboratory, Los Alamos, NM 87544, USA*
[4] *Université Libre de Bruxelles, BE 1050 Brussels, Belgium*
[5] *Institute of Isotope and Surface Chemistry, Chemical Research Center, H-1525 Budapest, Hungary*
[6] *Institute of Physics and Power Engineering, 249033 Obninsk, Russia*
[7] *Fuels Actinides and Isotopes NRG Nuclear Research and Consultance Group, NL-1755 Petten, The Netherlands*
[8] *CEA, DAM, DIF, F-91297 Arpajon, France*
[9] *Taras Shevchenko National University, 03022 Kiev, Ukraine*
[10] *National Institute of Physics and Nuclear Engineering "Horia Hulubei", 077125 Bucharest-Magurele, Romania*
[11] *Japan Atomic Energy Agency, Tokai-mura, Naka-gun, Ibaraki-ken, 319-1195 Japan*
[12] *China Institute of Atomic Energy, Beijing 102413 China*
[13] *Bhabha Atomic Research Center, Trombay, 400085 Mumbai, India*
[14] *JUKO Research, NL-1817 Alkmaar, The Netherlands*
[15] *Joint Institute for Power and Nuclear Research – Sosny, BY-220109 Minsk, Belarus*
[16] *Retired in 1998, Ente Nuove Tecnologie, Energia e Ambiente (ENEA), 40129 Bologna, Italy and*
[17] *Nuclear Physics Department, Bucharest University, 077125 Bucharest-Magurele, Romania*

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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

Why do we need nuclear data and how much accurate ?

Nuclear data needed for

Understanding basic reaction mechanism between particles and nuclei

Good accuracy if possible ⇒ good understanding or room for improvements

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Astrophysical applications (Age of the Galaxy, element abundances …)

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Predictive power important ⇒ sound physics (first principles)

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Understanding basic reaction mechanism between particles and nuclei

Astrophysical applications (Age of the Galaxy, element abundances …)

Existing or future nuclear reactor simulations

Good (Excellent) accuracy required ⇒ reproduction of data, safety

Predictive power less important ⇒ Reproductive power

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Medical applications, oil well logging, waste transmutation, fusion, …

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Astrophysical applications (Age of the Galaxy, element abundances …)

Existing or future nuclear reactor simulations

Medical applications, oil well logging, waste transmutation, fusion, …

But

Finite number of experimental data (price, safety or counting rates)

Complete measurements restricted to low energies (< 1 MeV)
to scarce nuclei

➡ **Predictive & Robust Nuclear models (codes) are essential**

GENERAL FEATURES ABOUT NUCLEAR REACTIONS

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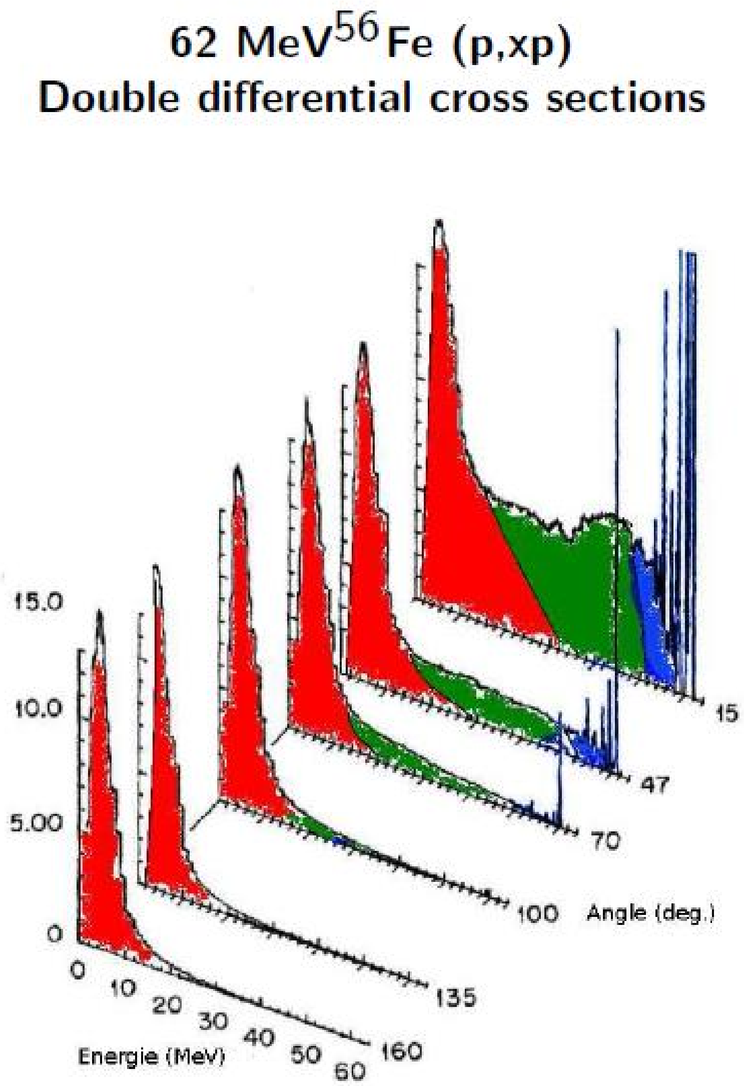
  - Fine tuning and accuracy
  - Global systematic approaches

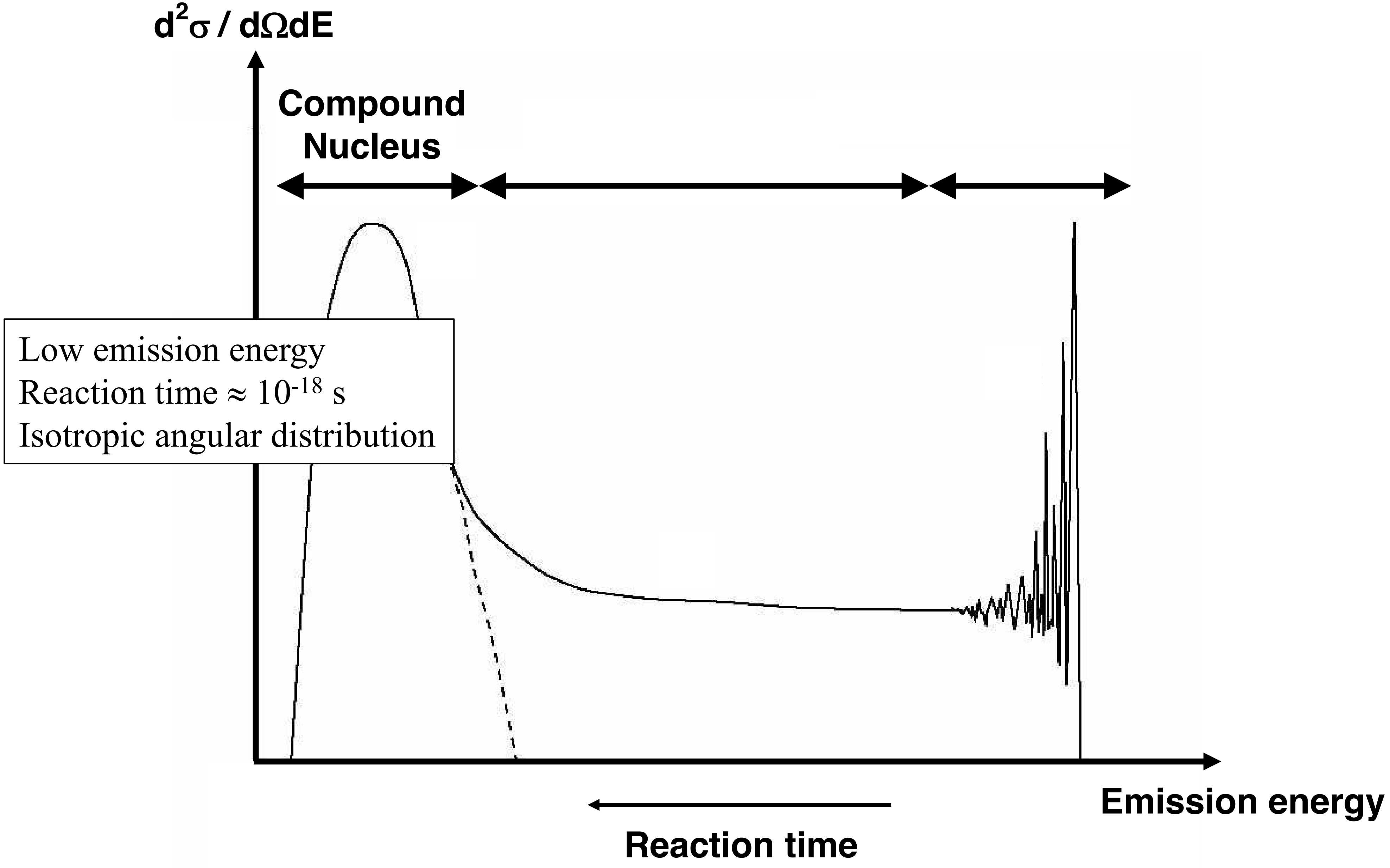
- What remains to be done ?

TIME SCALES AND ASSOCIATED MODELS (1/4)
Typical spectrum shape


62 MeV ^{56}Fe (p,xp)
Double differential cross sections

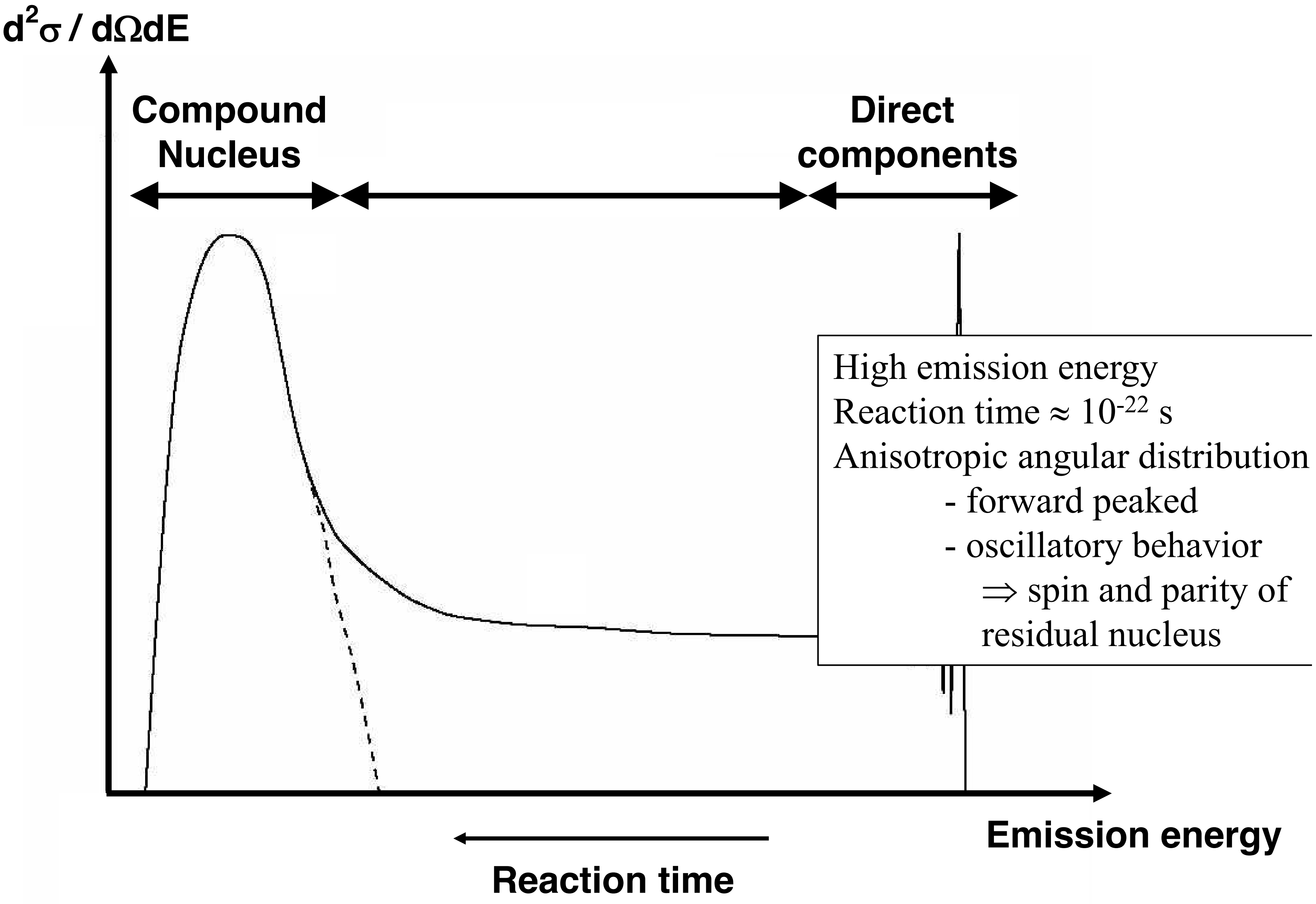
- Always evaporation peak
- Discrete peaks at forward angles
- Flat intermediate region

TIME SCALES AND ASSOCIATED MODELS (2/4)



Low emission energy
Reaction time ≈ 10^{-18} s
Isotropic angular distribution

TIME SCALES AND ASSOCIATED MODELS (2/4)



High emission energy

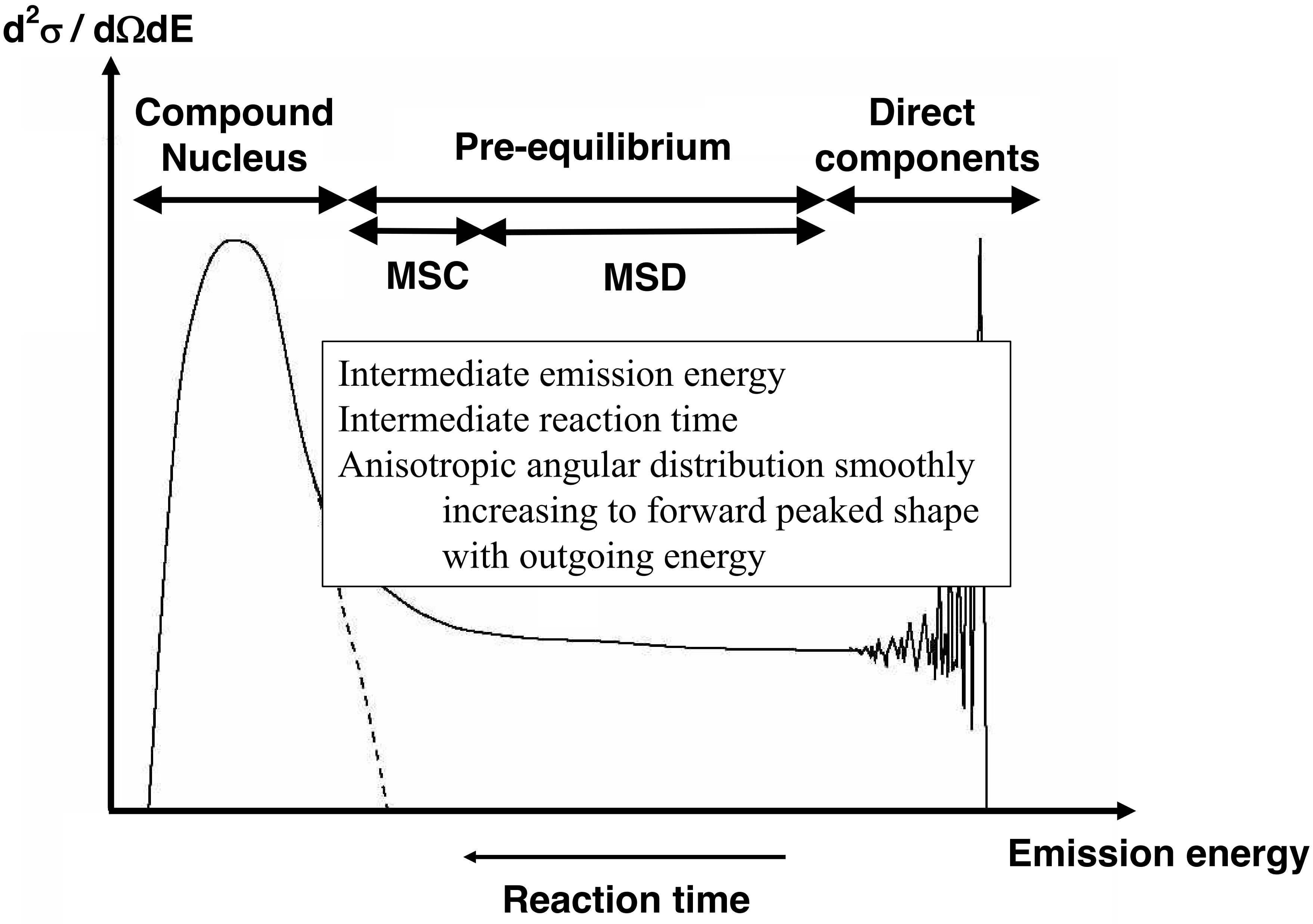
Reaction time ≈ 10^{-22} s

Anisotropic angular distribution

- forward peaked
- oscillatory behavior

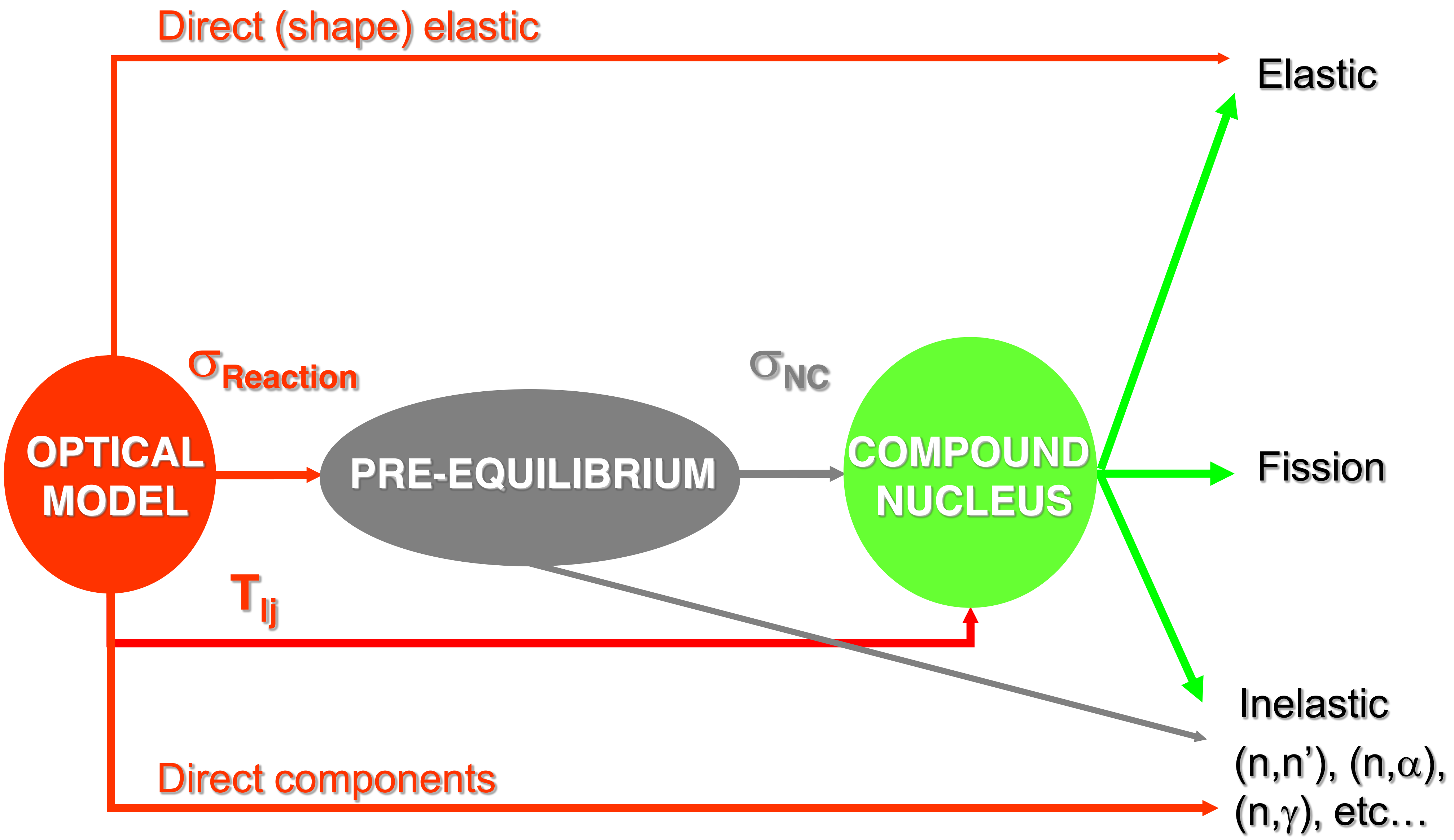
$\Rightarrow$ spin and parity of residual nucleus

TIME SCALES AND ASSOCIATED MODELS (2/4)



Intermediate emission energy
Intermediate reaction time
Anisotropic angular distribution smoothly increasing to forward peaked shape with outgoing energy

TIME SCALES AND ASSOCIATED MODELS (3/4)



Direct (shape) elastic

Elastic

$\sigma_{\mathrm{Reaction}}$

σ_{NC}

OPTICAL MODEL

PRE-EQUILIBRIUM

COMPOUND NUCLEUS

Fission

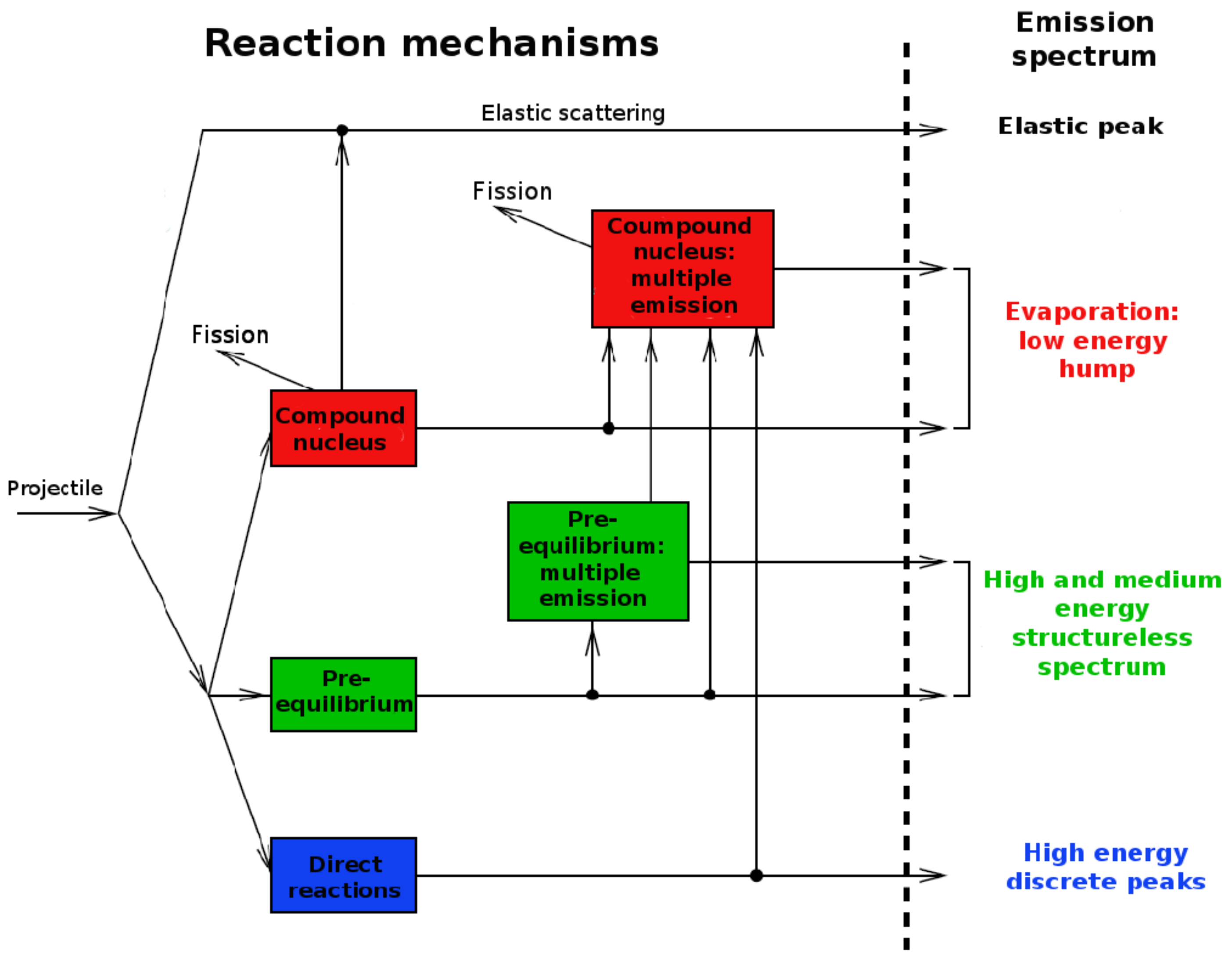
T_{lj}

Inelastic

(n,n'), (n,α), (n,γ), etc…

Direct components

TIME SCALES AND ASSOCIATED MODELS (4/4)



Reaction mechanisms

Emission spectrum

Projectile

Elastic scattering

Elastic peak

Fission

Compound nucleus

Fission

Coumpound nucleus: multiple emission

Evaporation: low energy hump

Pre-equilibrium

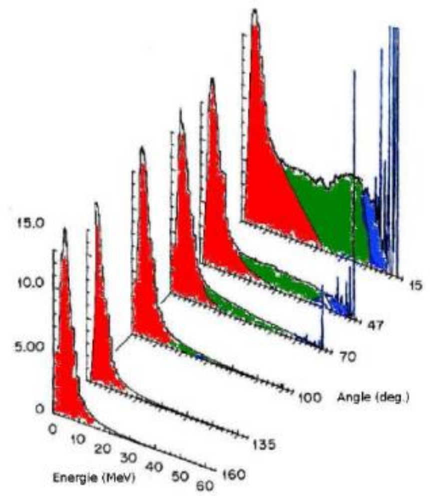
Pre-equilibrium: multiple emission

High and medium energy structureless spectrum

Direct reactions

High energy discrete peaks

62 MeV^{56}Fe (p,xp)
Double differential cross sections



TYPES OF DATA NEEDED

Cross sections :

total, reaction, elastic (shape & compound), non-elastic, inelastic (discrete levels & total)
total particle (residual) production
all exclusive reactions (n,nd2a)
all exclusive isomer production
all exclusive discrete and continuum γ-ray production

Spectra :

elastic and inelastic angular distribution or energy spectra
all exclusive double-differential spectra
total particle production spectra
compound and pre-equilibrium spectra per reaction stage.

Fission observables :

cross sections (total, per chance)
fission fragment mass and isotopic yields
fission neutrons (multiplicities, spectra)

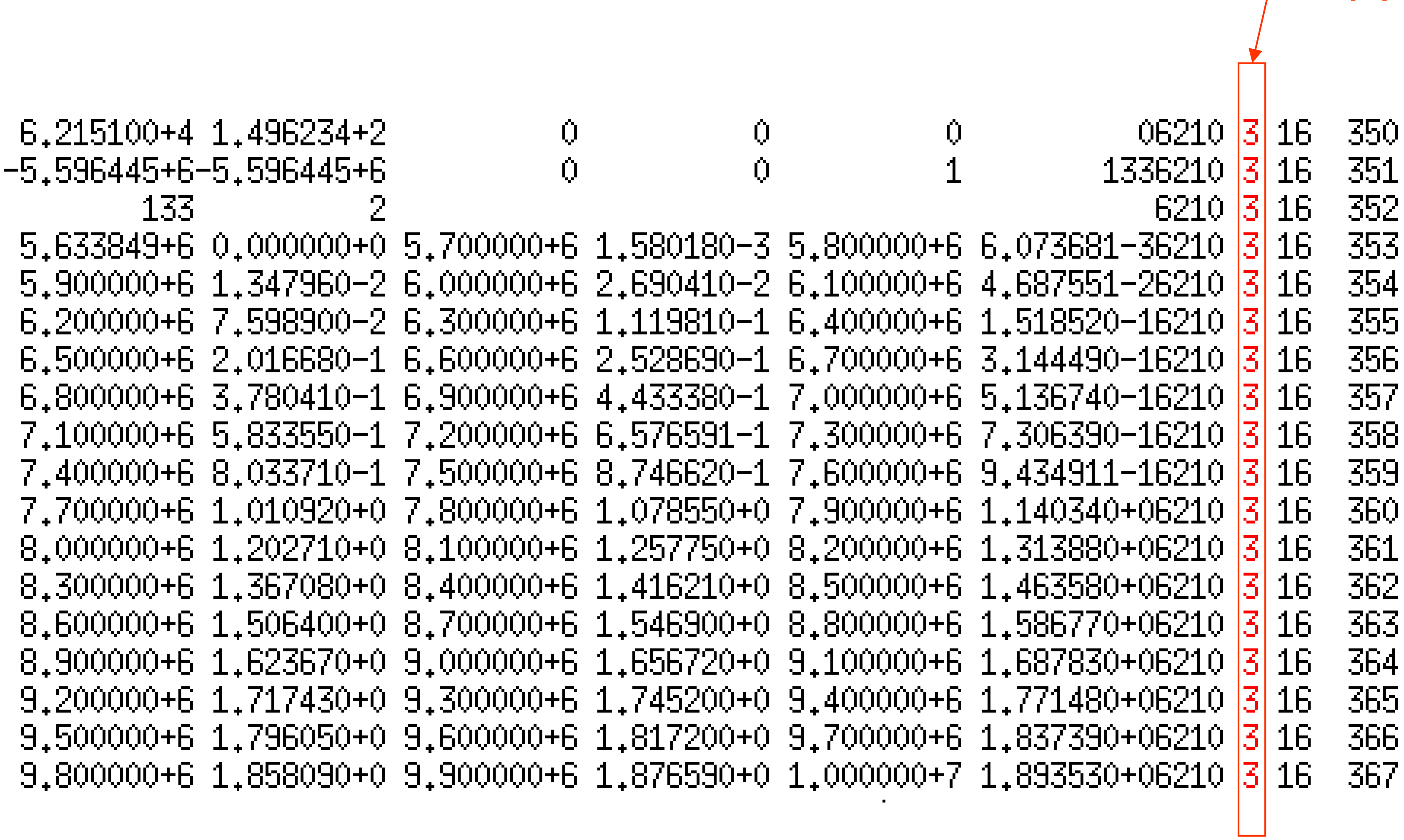
Miscellaneous :

recoil cross sections and ddx
particle multiplicities
astrophysical reaction rates
covariances informations

DATA FORMAT

- Trivial for basic nuclear science : x,y,(z) file
- Complicated (even crazy) for data production issues : ENDF file

DATA FORMAT : ENDF file



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        133          2                                            6210 3 16  352
 5.633849+6 0.000000+0 5.700000+6 1.580180-3 5.800000+6 6.073681-36210 3 16  353
 5.900000+6 1.347960-2 6.000000+6 2.690410-2 6.100000+6 4.687551-26210 3 16  354
 6.200000+6 7.598900-2 6.300000+6 1.119810-1 6.400000+6 1.518520-16210 3 16  355
 6.500000+6 2.016680-1 6.600000+6 2.528690-1 6.700000+6 3.144490-16210 3 16  356
 6.800000+6 3.780410-1 6.900000+6 4.433380-1 7.000000+6 5.136740-16210 3 16  357
 7.100000+6 5.833550-1 7.200000+6 6.576591-1 7.300000+6 7.306390-16210 3 16  358
 7.400000+6 8.033710-1 7.500000+6 8.746620-1 7.600000+6 9.434911-16210 3 16  359
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 9.500000+6 1.796050+0 9.600000+6 1.817200+0 9.700000+6 1.837390+06210 3 16  366
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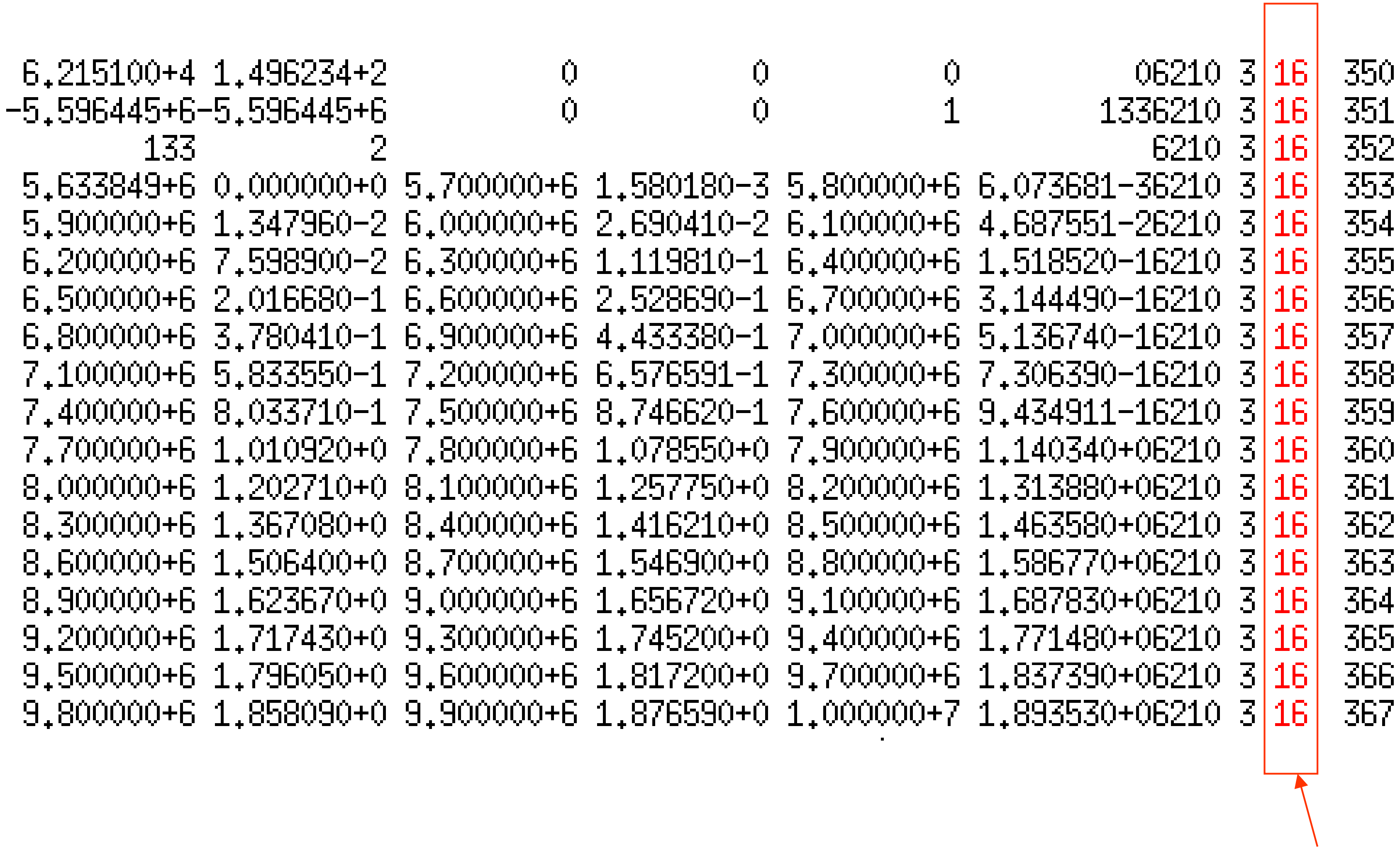

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Content type (n,2n)

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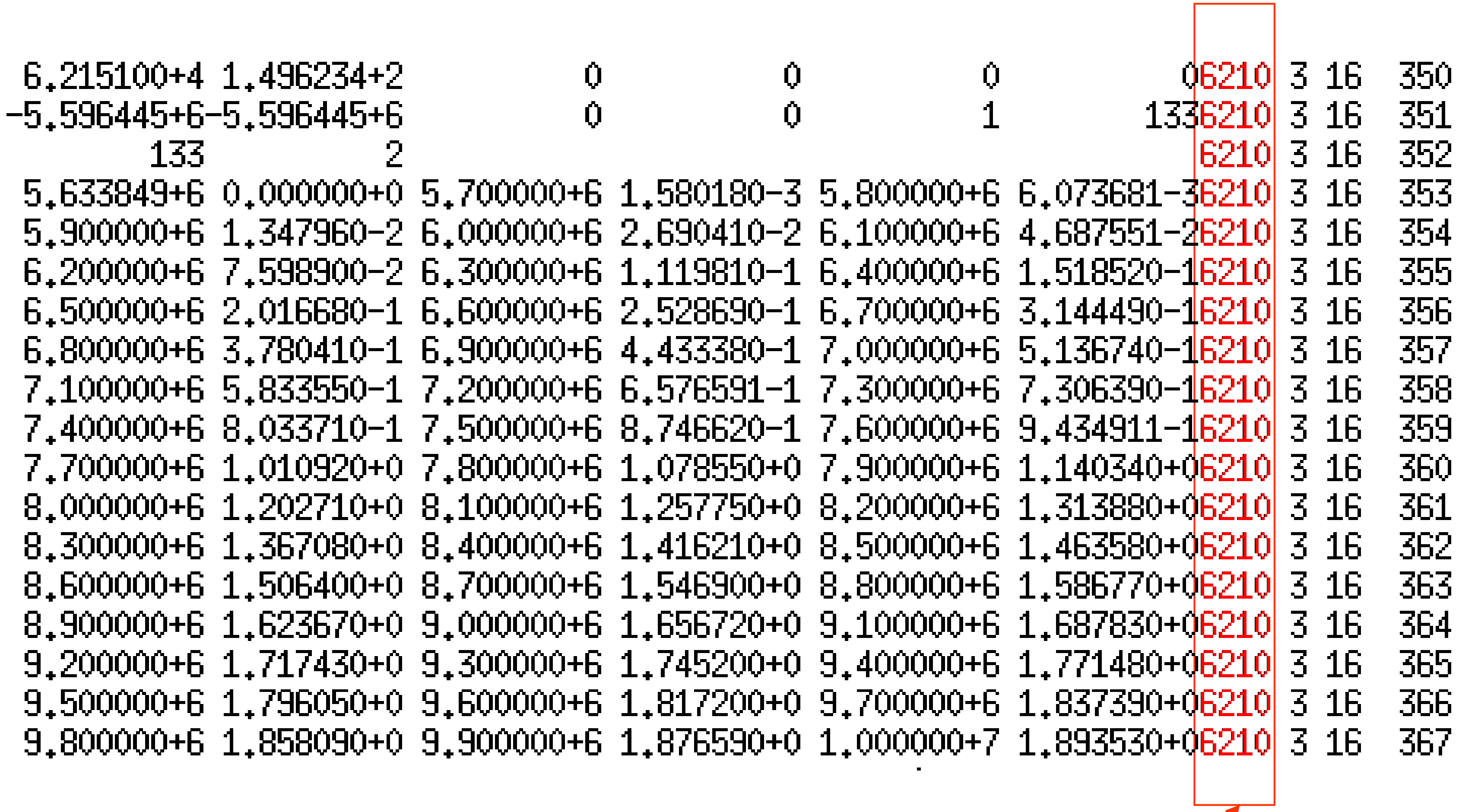

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 9.800000+6 1.858090+0 9.900000+6 1.876590+0 1.000000+7 1.893530+06210 3 16  367
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Material number

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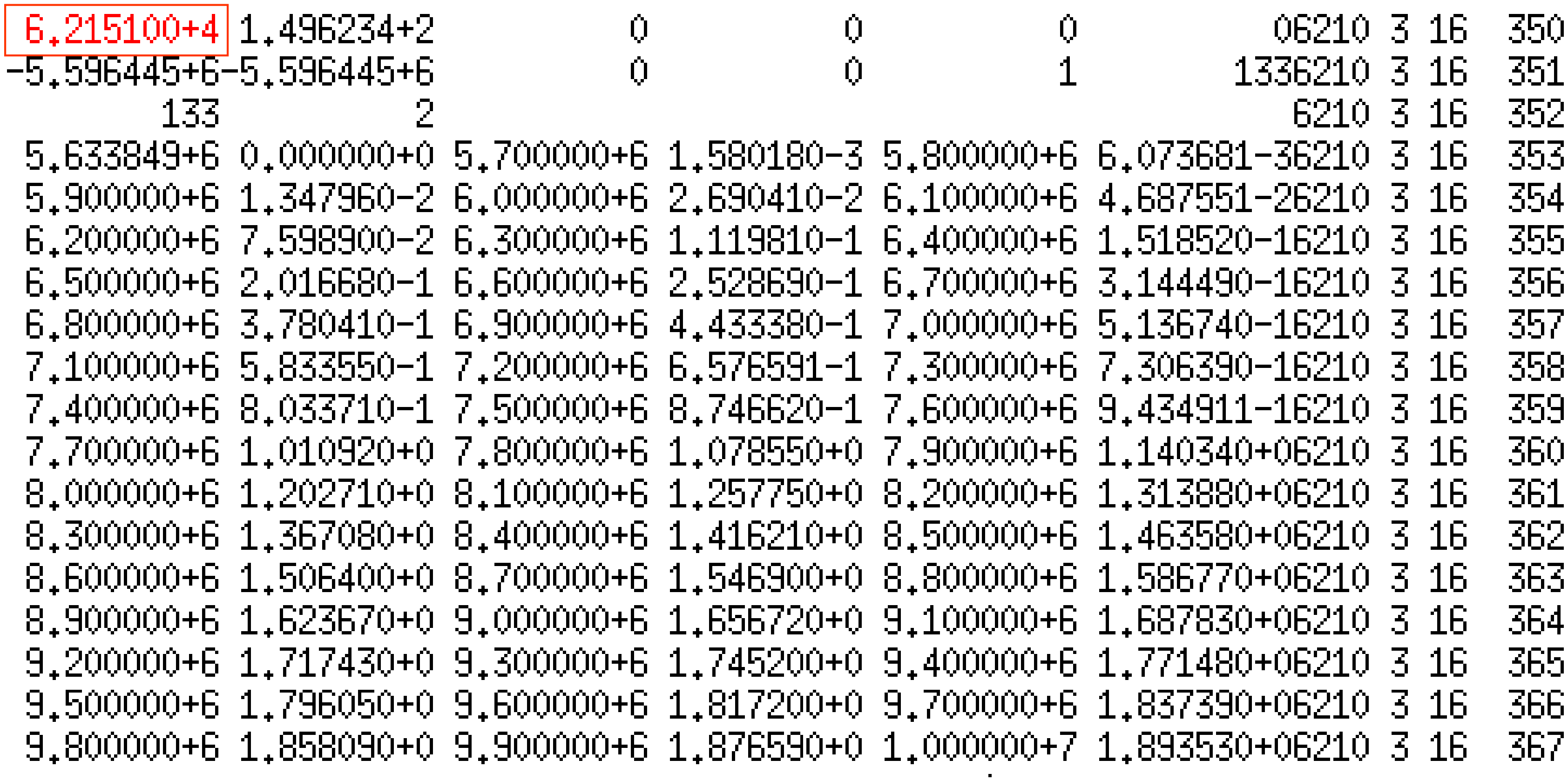
Target identification (^{151}Sm)



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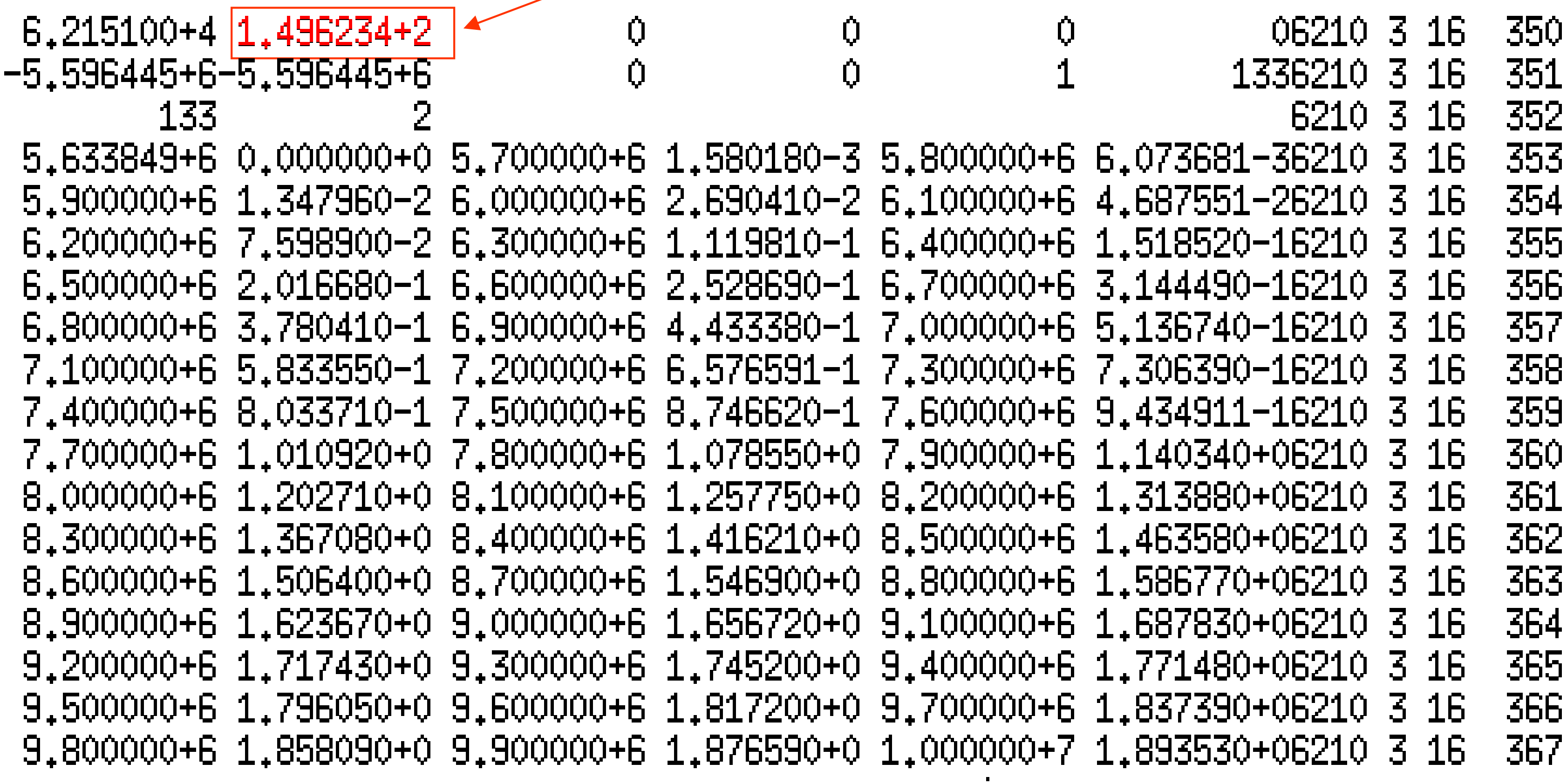

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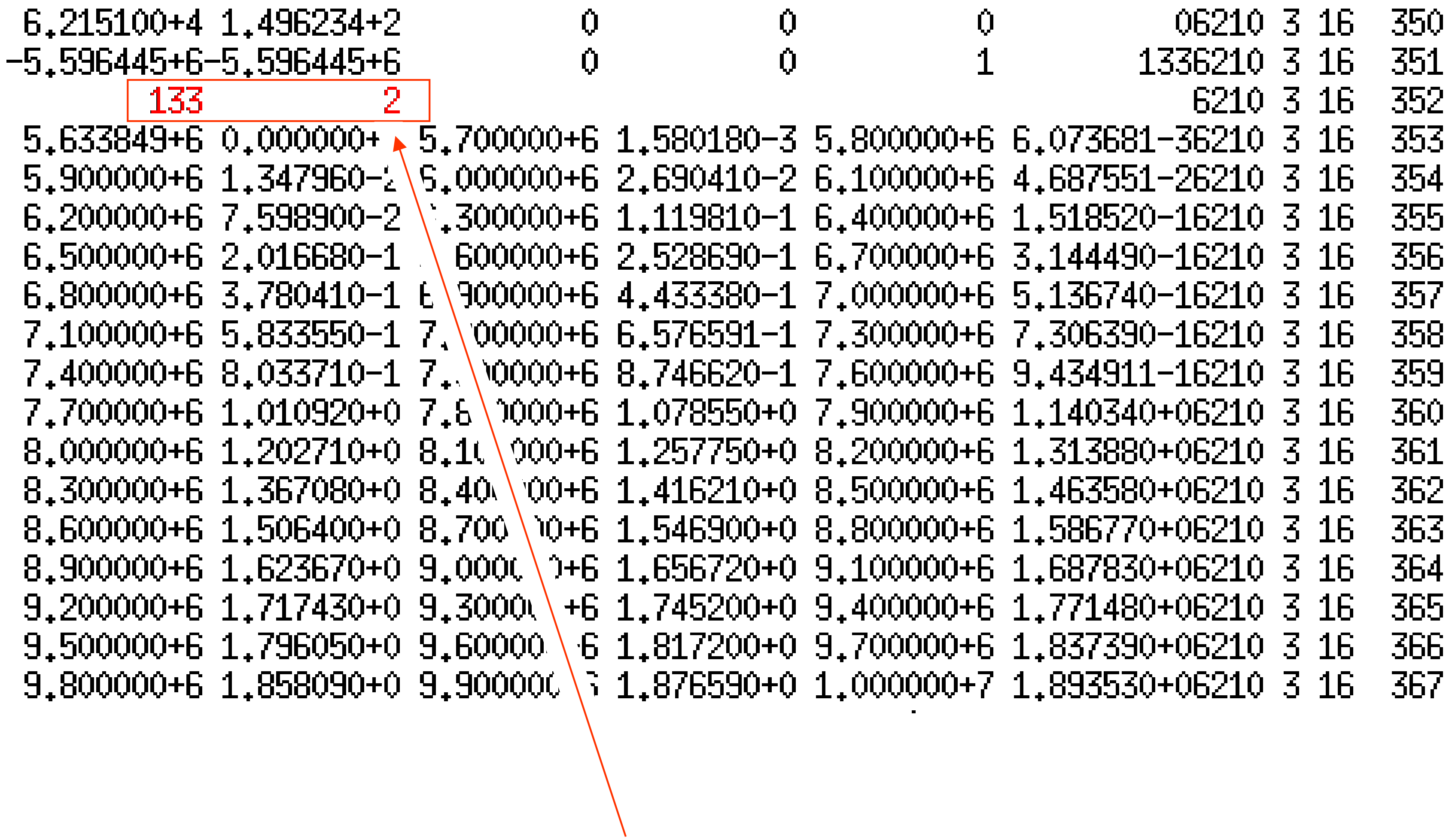

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 8.300000+6 1.367080+0 8.400000+6 1.416210+0 8.500000+6 1.463580+06210 3 16  362
 8.600000+6 1.506400+0 8.700000+6 1.546900+0 8.800000+6 1.586770+06210 3 16  363
 8.900000+6 1.623670+0 9.000000+6 1.656720+0 9.100000+6 1.687830+06210 3 16  364
 9.200000+6 1.717430+0 9.300000+6 1.745200+0 9.400000+6 1.771480+06210 3 16  365
 9.500000+6 1.796050+0 9.600000+6 1.817200+0 9.700000+6 1.837390+06210 3 16  366
 9.800000+6 1.858090+0 9.900000+6 1.876590+0 1.000000+7 1.893530+06210 3 16  367
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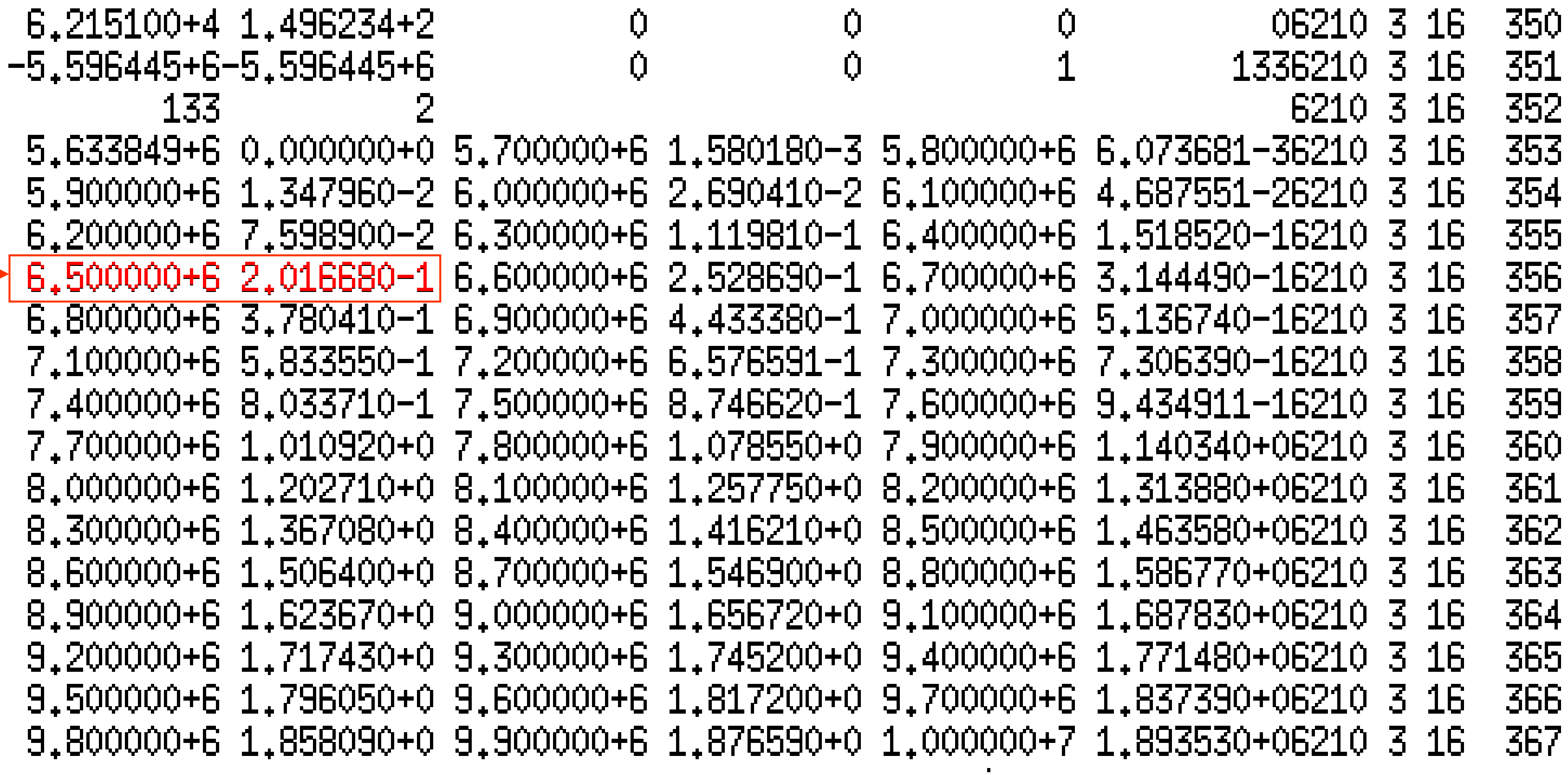
Number of values

DATA FORMAT : ENDF file



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-5.596445+6-5.596445+6          0          0          1        1336210 3 16  351
        133          2                                            6210 3 16  352
 5.633849+6 0.000000+0 5.700000+6 1.580180-3 5.800000+6 6.073681-36210 3 16  353
 5.900000+6 1.347960-2 6.000000+6 2.690410-2 6.100000+6 4.687551-26210 3 16  354
 6.200000+6 7.598900-2 6.300000+6 1.119810-1 6.400000+6 1.518520-16210 3 16  355
 6.500000+6 2.016680-1 6.600000+6 2.528690-1 6.700000+6 3.144490-16210 3 16  356
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 7.700000+6 1.010920+0 7.800000+6 1.078550+0 7.900000+6 1.140340+06210 3 16  360
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 9.800000+6 1.858090+0 9.900000+6 1.876590+0 1.000000+7 1.893530+06210 3 16  367
```

Values

NUCLEAR MODELS

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
  - Miscellaneous : level densities, fission, capture
- From in depth analysis to large scale production with TALYS
  - General features about TALYS
  - Fine tuning and accuracy
  - Global systematic approaches

- What remains to be done ?

BASIC STRUCTURE PROPERTIES (1/5)

What is needed

Nuclear Masses :

⇒ basic information to determine reaction threshold

Excited levels :

⇒ Angular distributions (depend on spin and parities)

⇒ Decay properties (branching ratios)

⇒ Excitation energies (reaction thresholds)

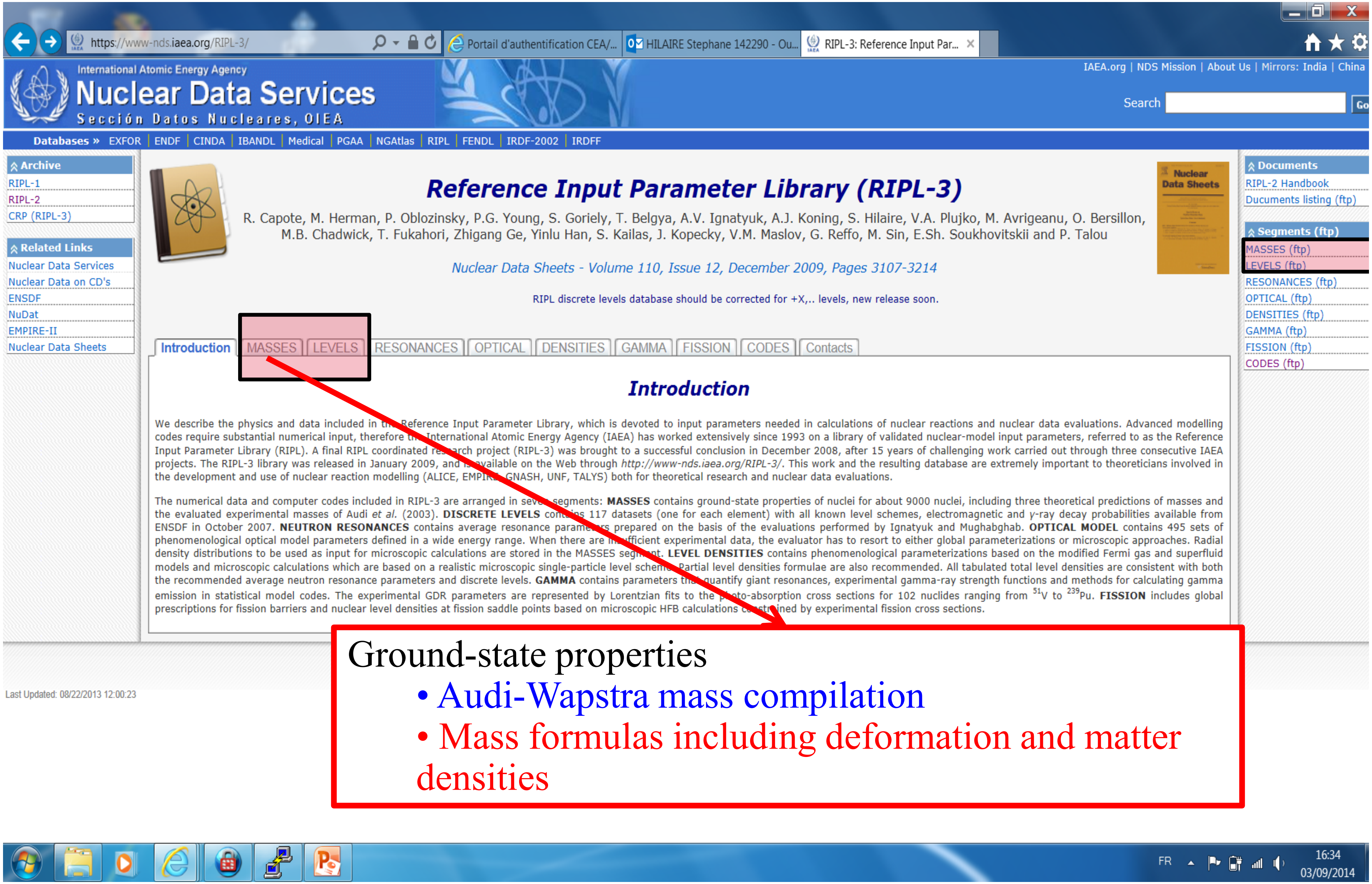
Target levels' deformations :

⇒ Required to select appropriate optical model

⇒ Required to select appropriate coupling scheme

Many different theoretical approaches if experimental data is missing

Recommended databases (RIPL !)



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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

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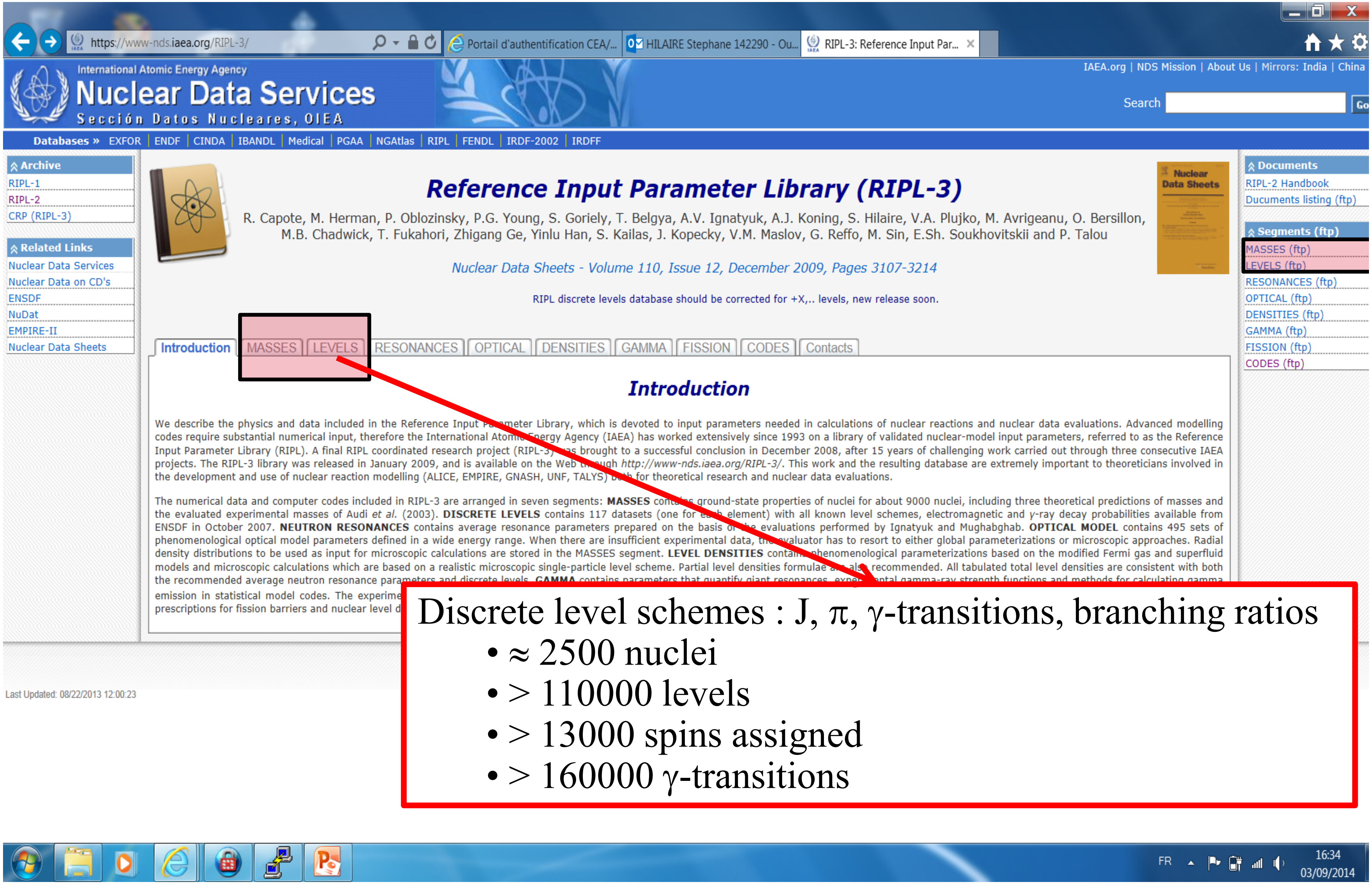
Ground-state properties

- Audi-Wapstra mass compilation
- Mass formulas including deformation and matter densities



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prescriptions for fission barriers and nuclear level d

Discrete level schemes : J, π, γ-transitions, branching ratios

- ≈ 2500 nuclei
- \> 110000 levels
- \> 13000 spins assigned
- \> 160000 γ-transitions

BASIC STRUCTURE PROPERTIES (2/5)

Mass models

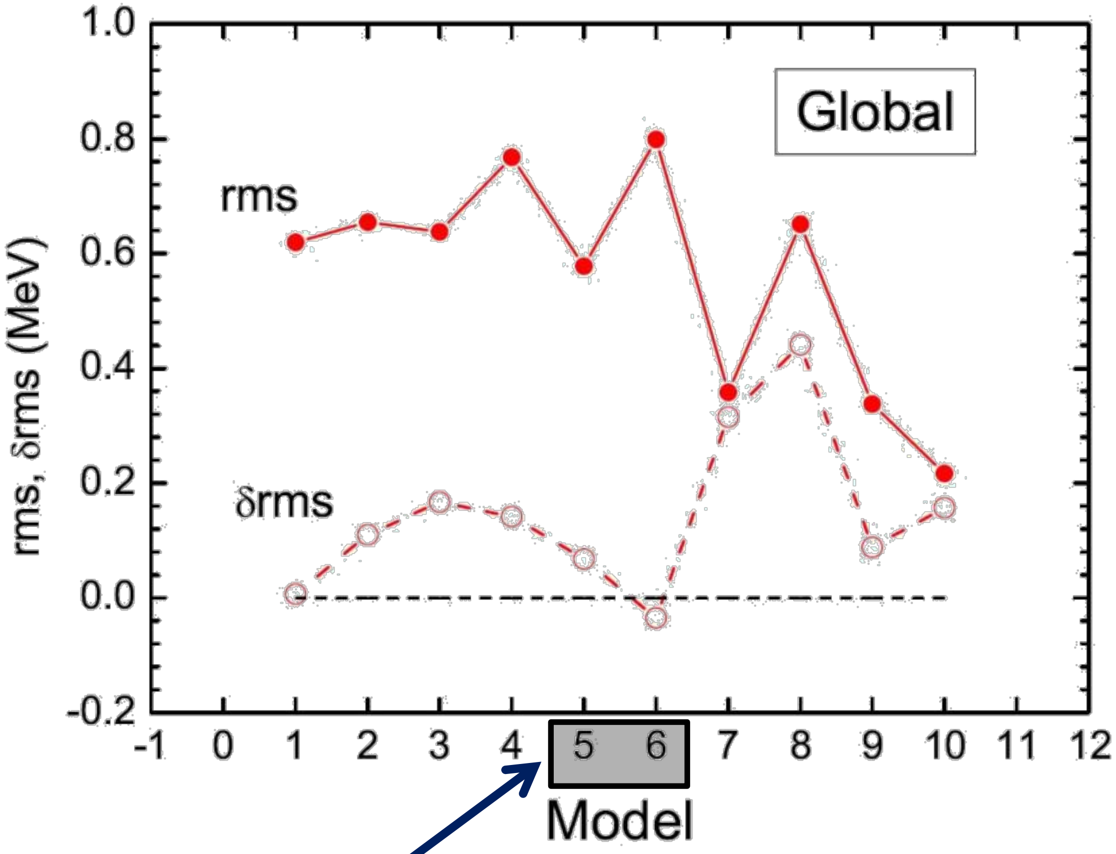
	Reliability	Accuracy
• Macroscopic-Microscopic Approaches		
Liquid drop model (Myers & Swiateki 1966)	– –	+ +
Droplet model (Hilf et al. 1976)	– –	+ +
FRDM model (Moller et al. 1995)	+ –	+ +
KUTY model (Koura et al. 2000)	+ –	+ +
• Approximation to Microscopic models		
Shell model (Duflo & Zuker 1995)	+	+++
ETFSI model (Aboussir et al. 1995)	+	+ +
• Mean Field Model		
Hartree-Fock-BCS model	+ +	+ +
Hartree-Fock-Bogolyubov model	+ + +	+ +
EDF, RHB, Shell model	+ + +	– –

Typical deviations for the best mass formulas:

rms(M) = 600-700 keV on 2149 ($Z \geq 8$) experimental masses

BASIC STRUCTURE PROPERTIES (3/5)
Mass models predictive power

Comparison between several mass models adjusted with 2003 exp and tested with 2012 exp masses



Microscopic models

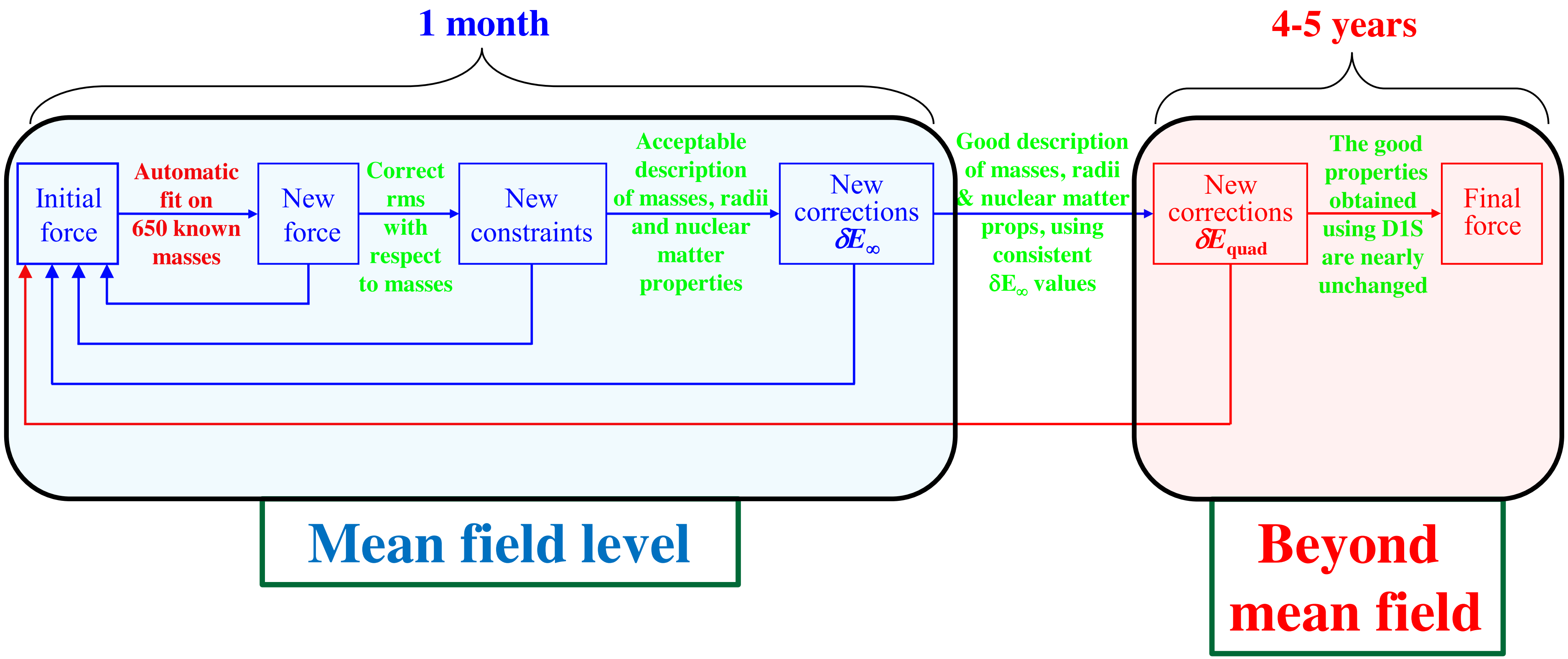
Current status

- **rms < 1 MeV (masses ≈ GeV)**
- **micro ~ macro**
- **micro more predictive**

BASIC STRUCTURE PROPERTIES (4/5)
HFB Mass models

Most advanced theoretical approach = multireference level

- Methodology : $E = E_{mf} + \delta E_{\infty} + \delta E_{bmf}$



* Additional filters

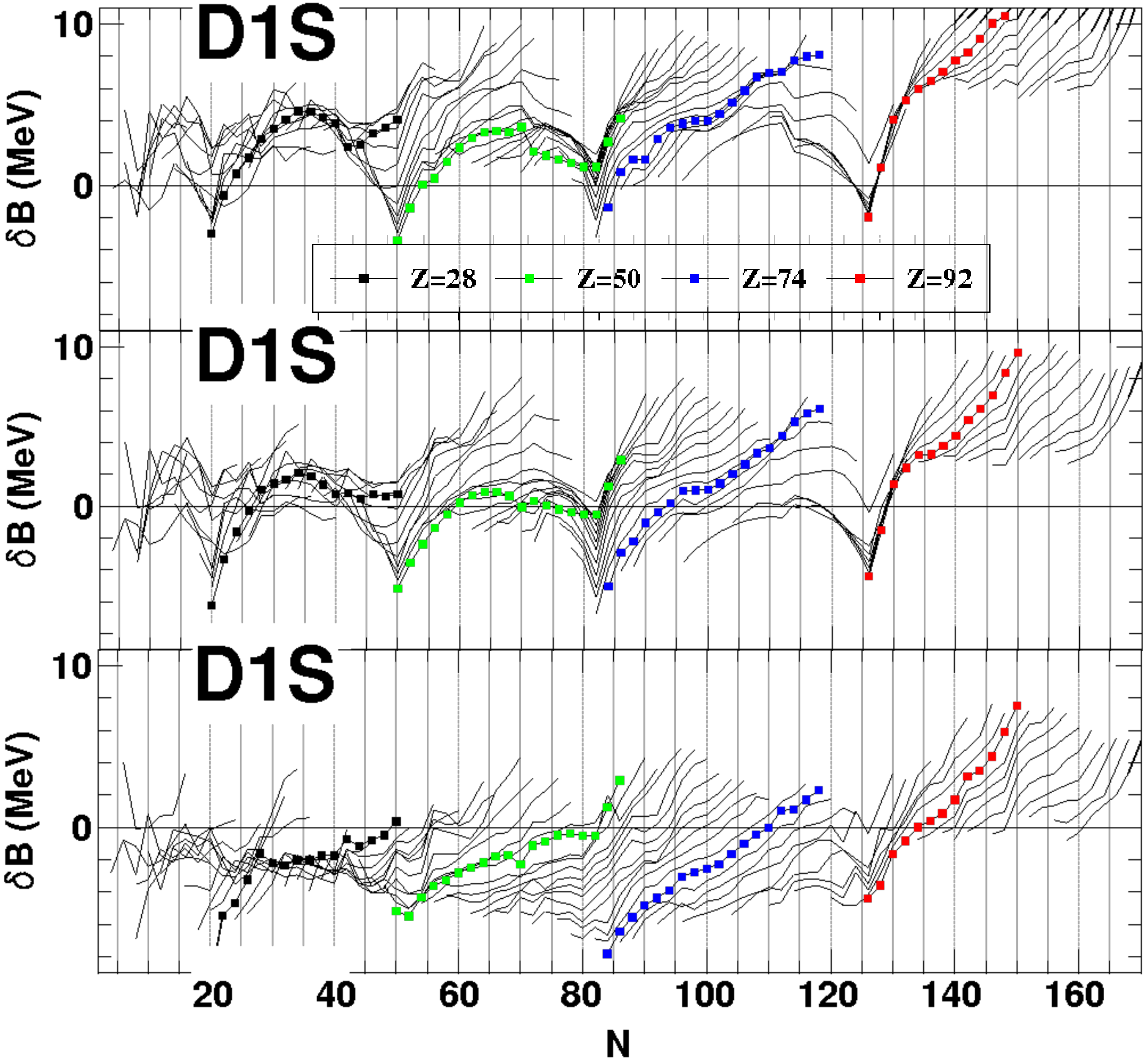
- Collective properties (0+,2+, BE2), RPA modes, backbending properties, pairing properties, fission properties, gamma strength functions, level densities

BASIC STRUCTURE PROPERTIES (5/5)

HFB-Gogny Mass model

D1S

Comparison with 2149 Exp. Masses



- $E_{th} = E_{HFB}$

r.m.s ~ 4.4 MeV

- $E_{th} = E_{HFB} - \Delta_\infty$

r.m.s ~ 2.6 MeV

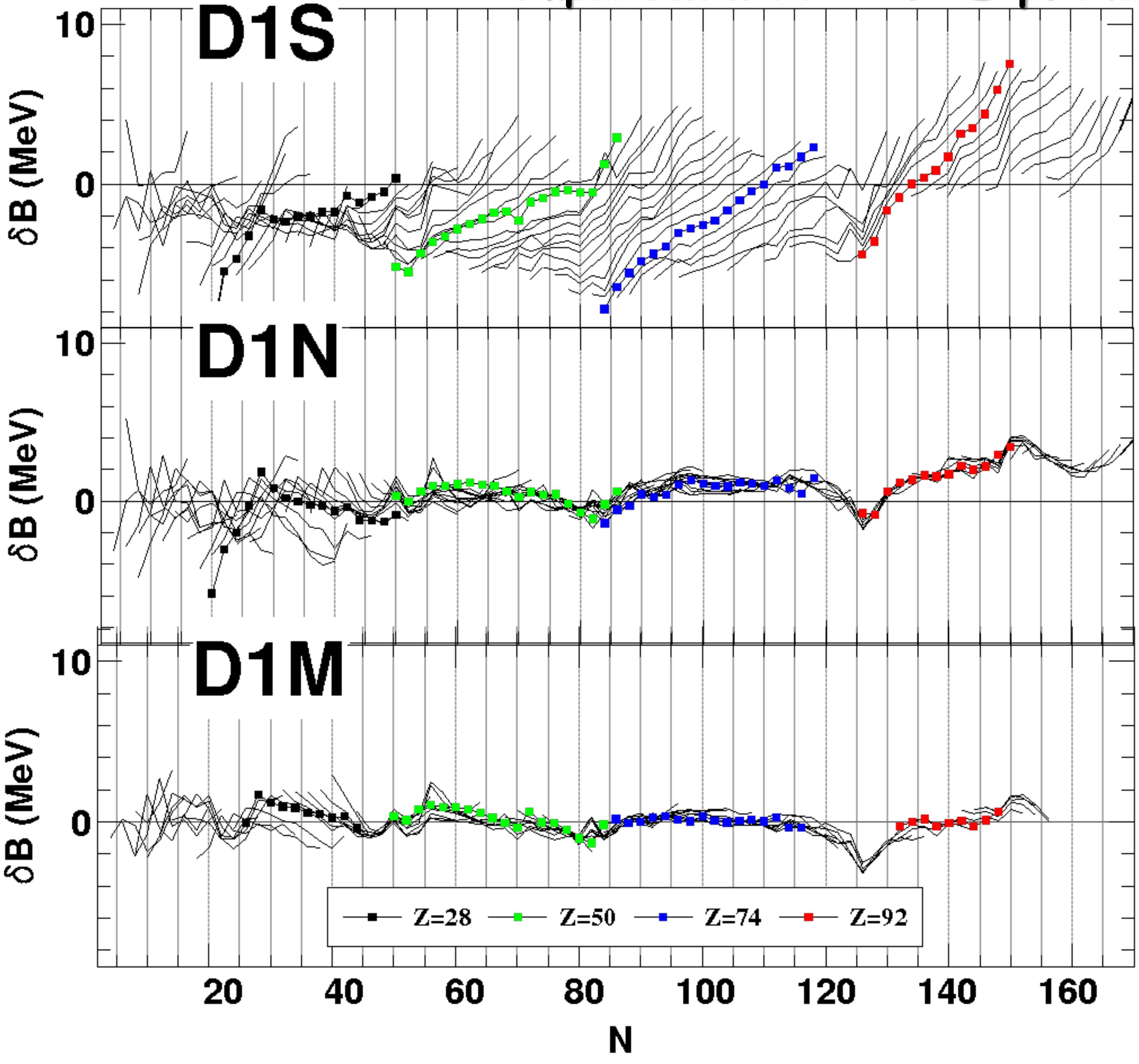
- $E_{th} = E_{HFB} - \Delta_\infty - \Delta_{quad}$

r.m.s ~ 2.9 MeV

BASIC STRUCTURE PROPERTIES (5/5)

HFB-Gogny Mass model

Comparison with 2149 Exp. Masses



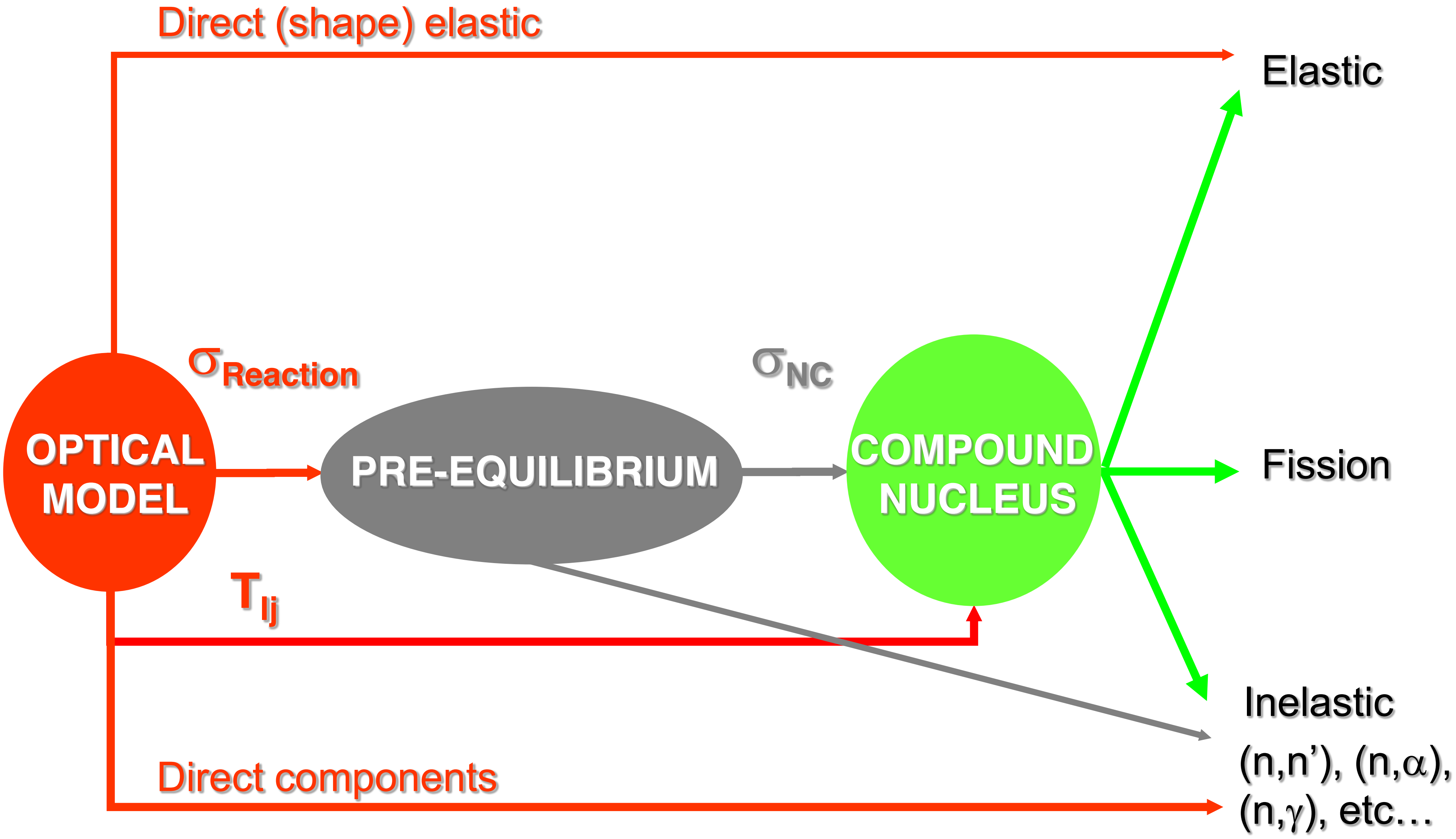
r.m.s ~ 2.5 MeV

r.m.s ~ 0.95 MeV

ε = 0.126 MeV

r.m.s = 0.798 MeV

THE OPTICAL MODEL



Direct (shape) elastic

Elastic

σ_{Reaction}

σ_{NC}

OPTICAL MODEL

PRE-EQUILIBRIUM

COMPOUND NUCLEUS

Fission

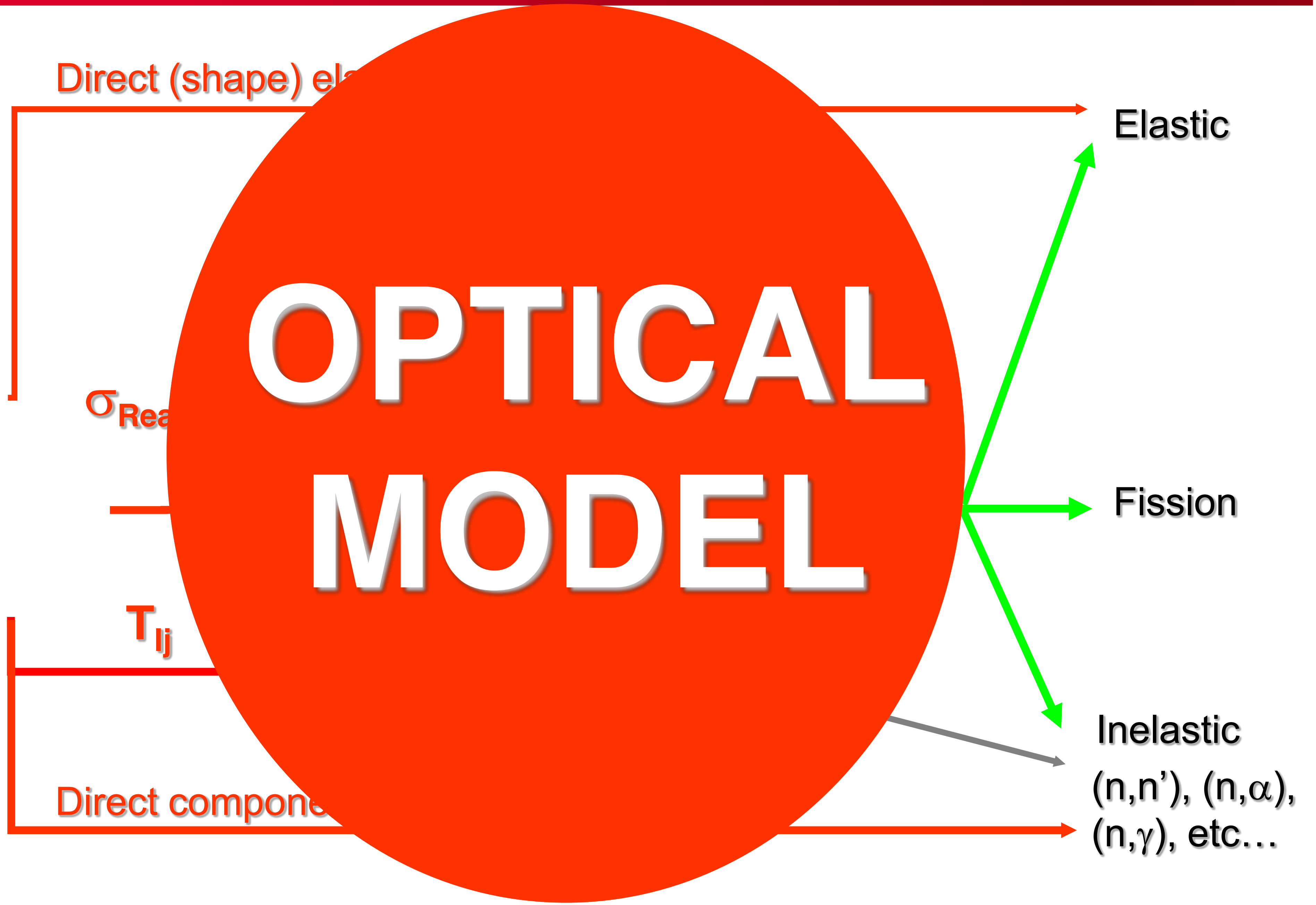
T_{lj}

Inelastic

(n,n'), (n,α), (n,γ), etc…

Direct components

THE OPTICAL MODEL



Direct (shape) ela

σ_{Rea}

T_{lj}

Direct compone

OPTICAL MODEL

Elastic

Fission

Inelastic

(n,n’), (n,α), (n,γ), etc…

THE OPTICAL MODEL

Direct interaction of a projectile with a target nucleus considered as a whole
Quantum model → Schrödinger equation

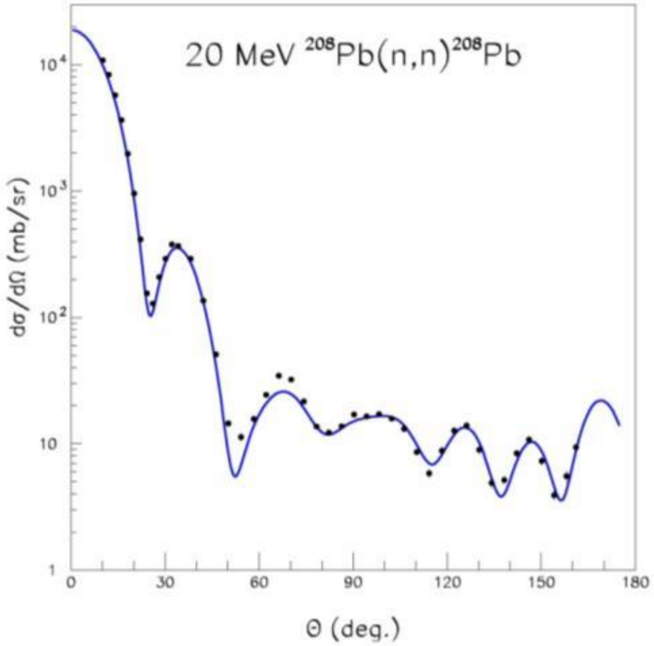
$$\left(-\frac{\hbar^2}{2\mu}\nabla^2 + U - E\right)\Psi = 0$$

Complex potential:

$$U = V + iW$$

Refraction

Absorption



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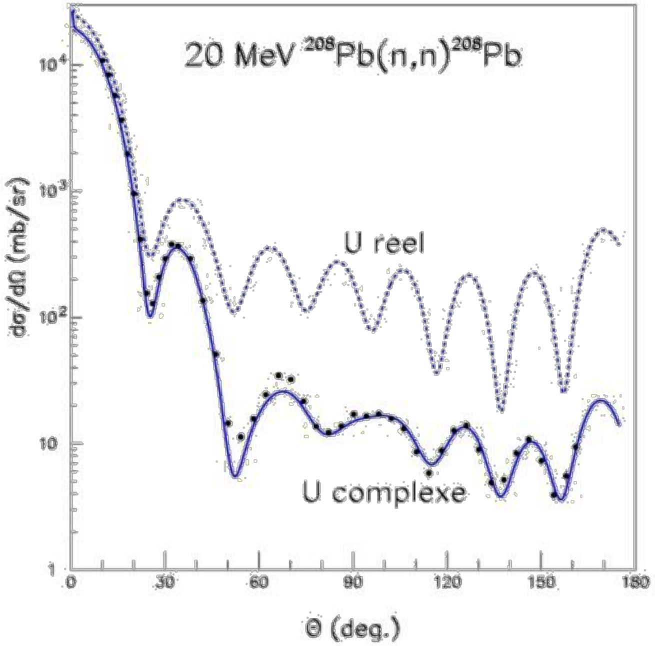
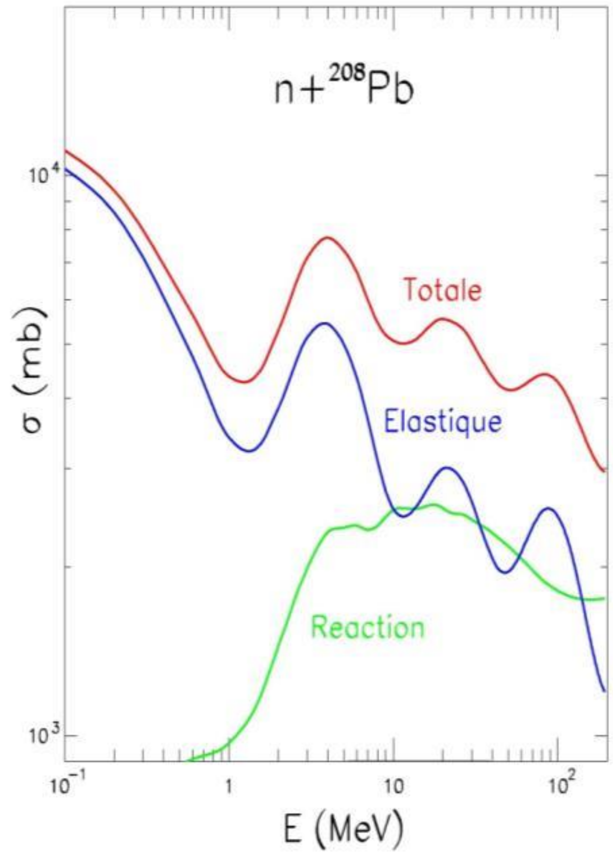


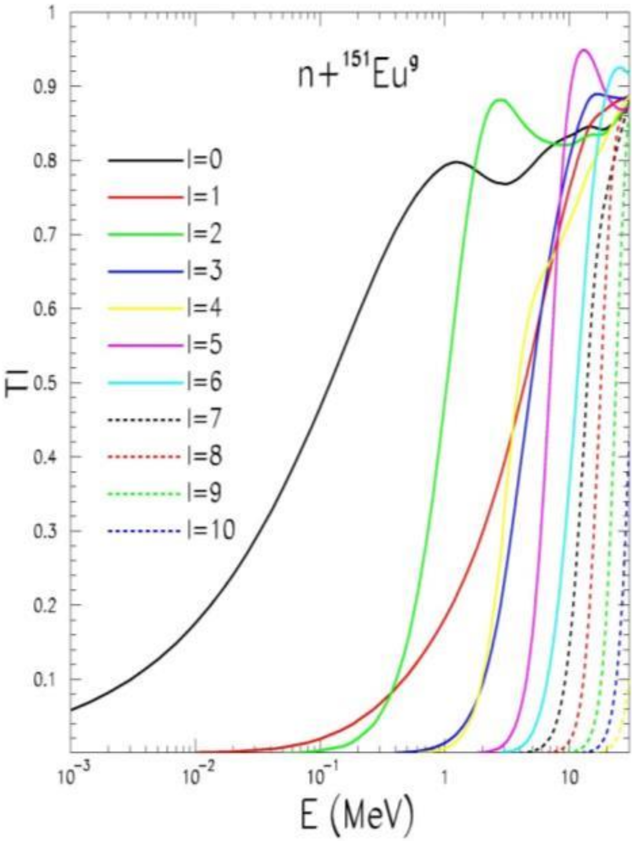
THE OPTICAL MODEL

The optical model yields :

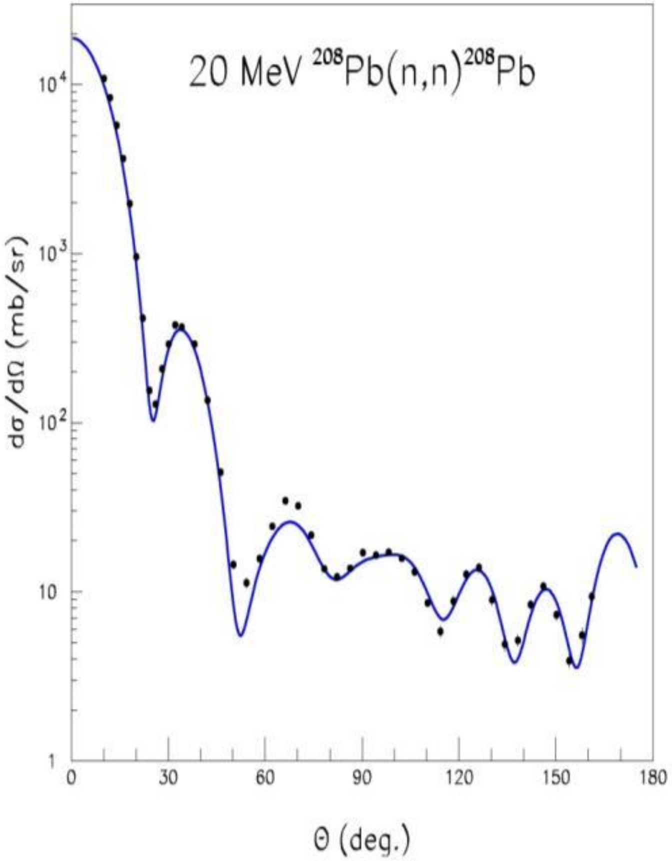
Integrated cross sections



Transmission coefficients



Angular distributions



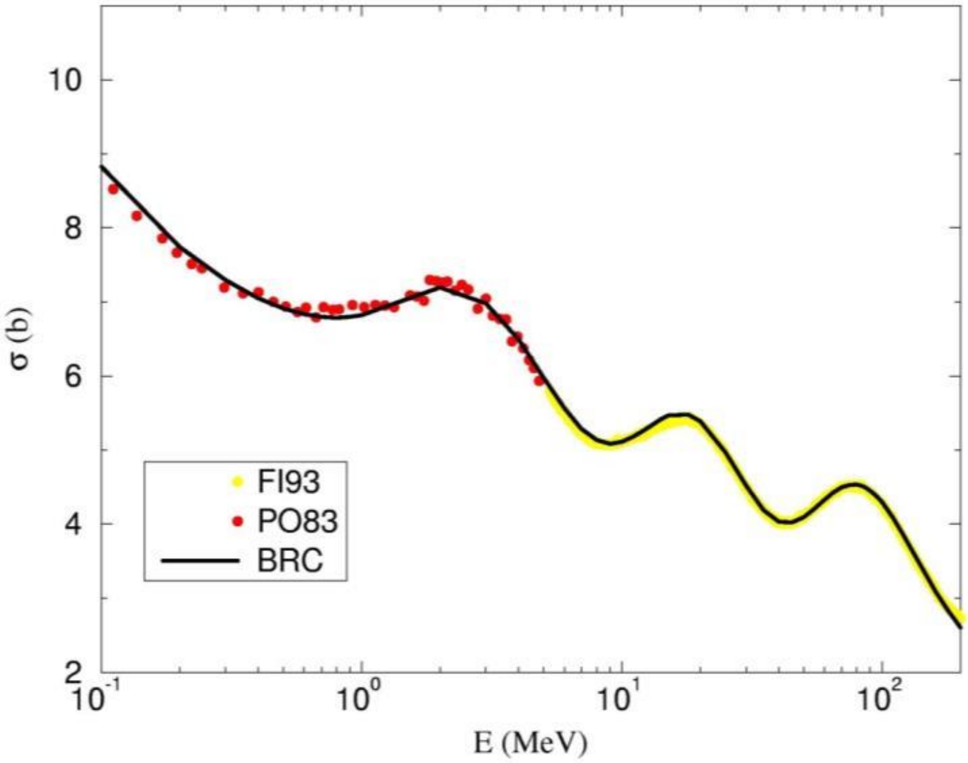
TWO TYPES OF APPROACHES

Phenomenological

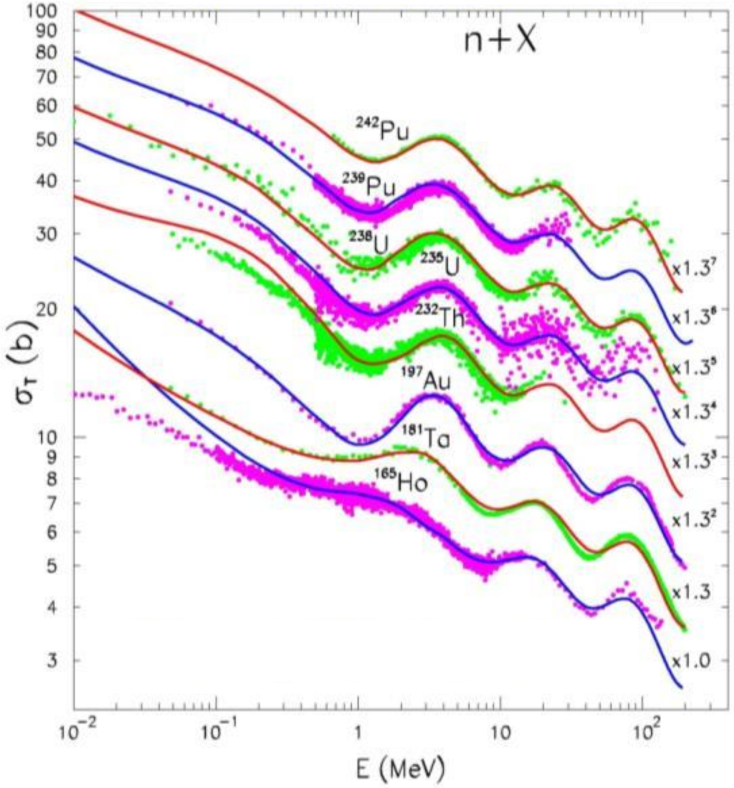
Adjusted parameters
Weak predictive power
Very precise (≈ 1%)
Important work

(Semi-)microscopic

No adjustable parameters
Usable without exp. data
Less precise (≈ 5-10 %)
Quasi-automated

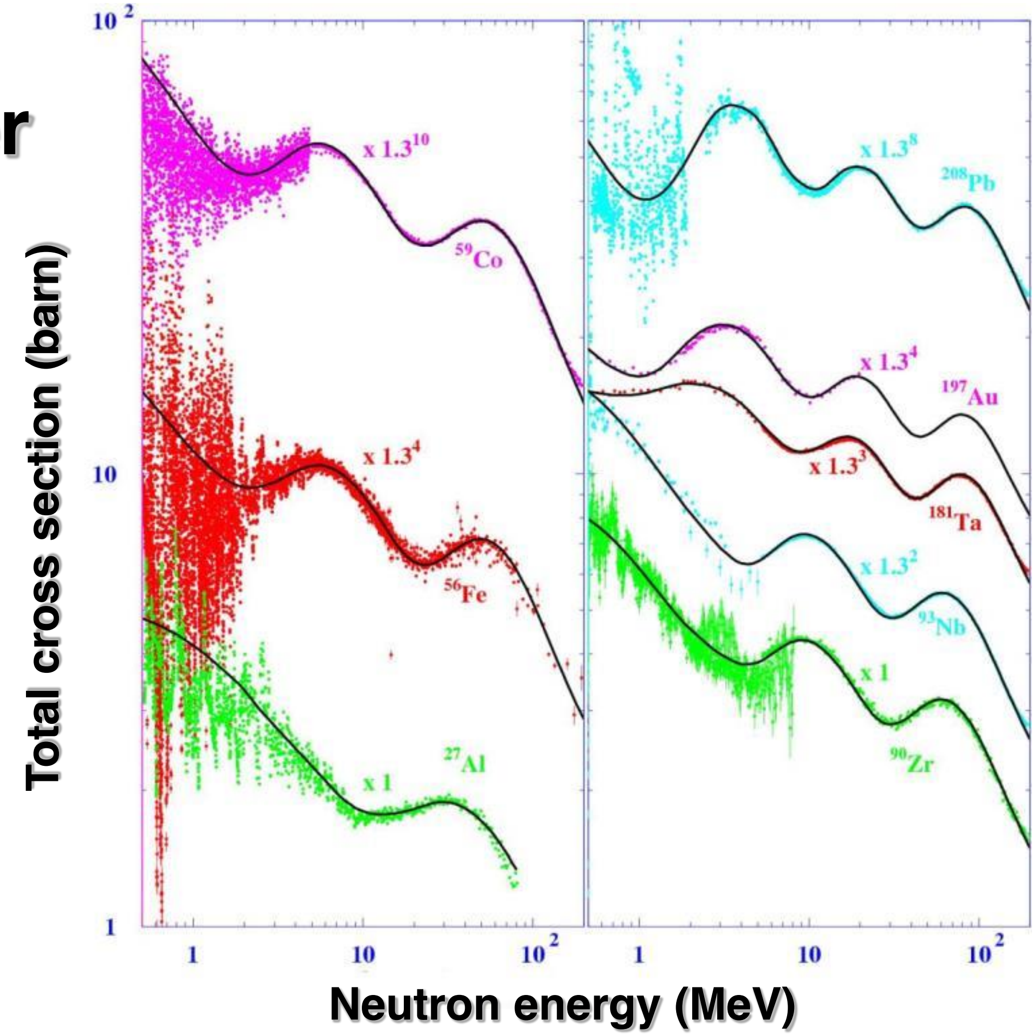


Total cross sections

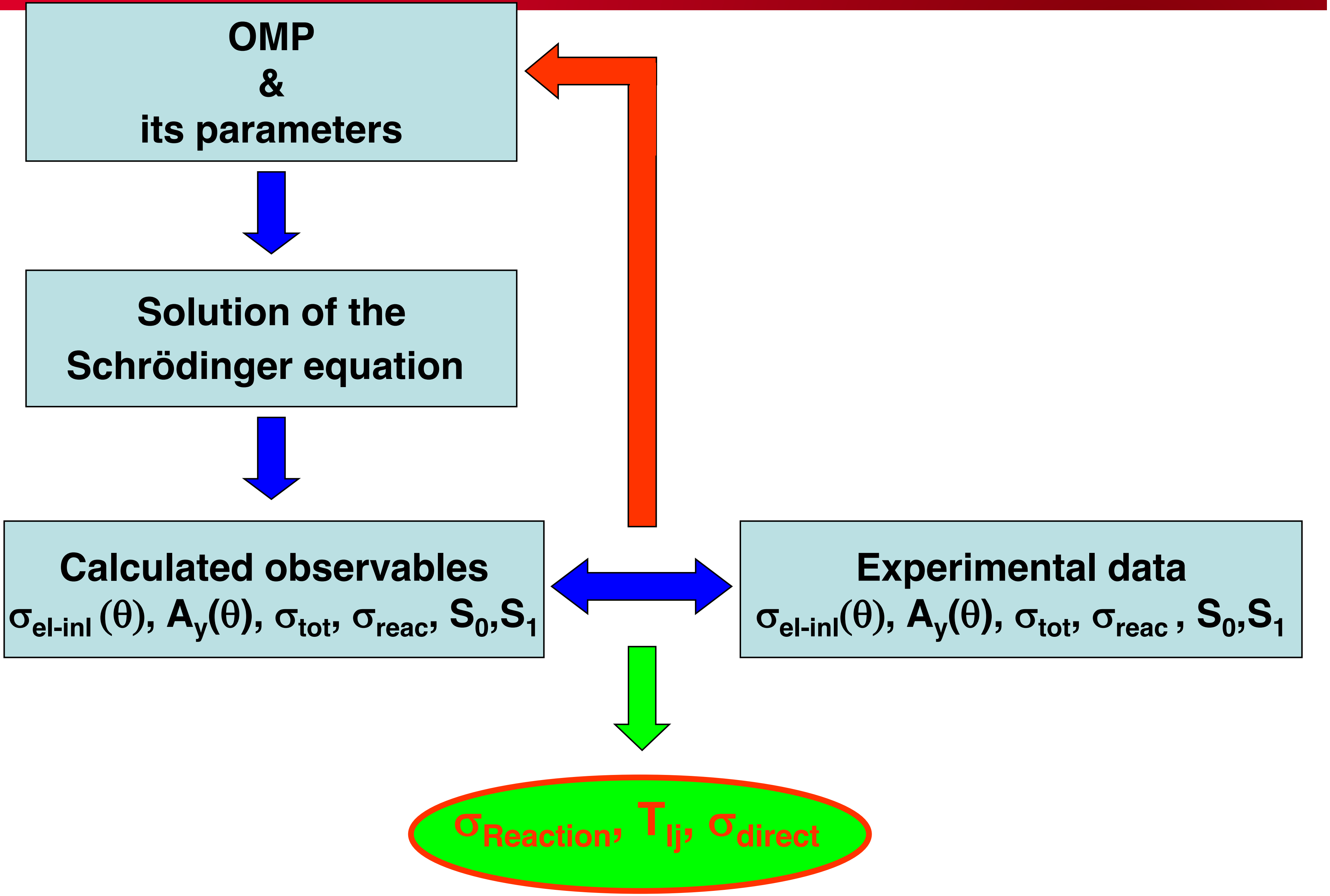


PHENOMENOLOGICAL OPTICAL MODEL

- ≈ 20 adjusted parameters
- Very precise (1%)
- Weak predictive power



PHENOMENOLOGICAL OPTICAL MODEL



OMP
&
its parameters

Solution of the Schrödinger equation

Calculated observables
$\sigma_{el\text{-}inl}(\theta)$, $A_y(\theta)$, σ_{tot}, σ_{reac}, S_0,S_1

Experimental data
$\sigma_{el\text{-}inl}(\theta)$, $A_y(\theta)$, σ_{tot}, σ_{reac} , S_0,S_1

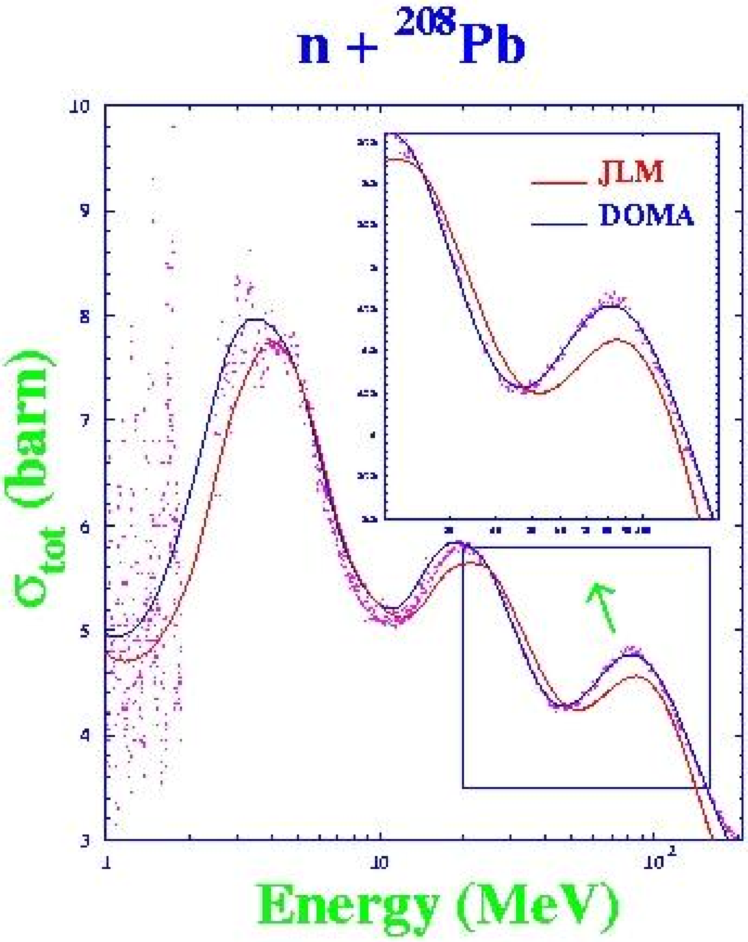
$\sigma_{Reaction}$, T_{lj}, σ_{direct}

SEMI-MICROSCOPIC OPTICAL MODEL

- No adjustable parameters
- Based on nuclear structure properties

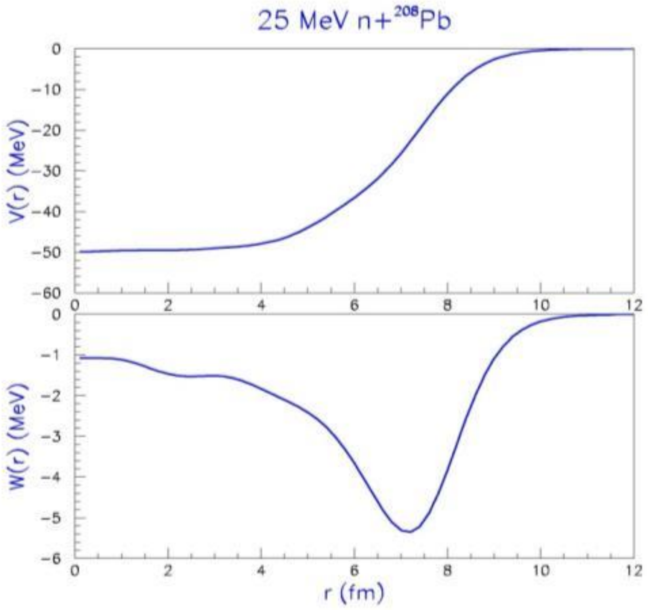
⇒ usable for any nucleus

- Less precise than the phenomenological approach



SEMI-MICROSCOPIC OPTICAL MODEL

Optical potential = Effective Interaction ⊗ Radial densities



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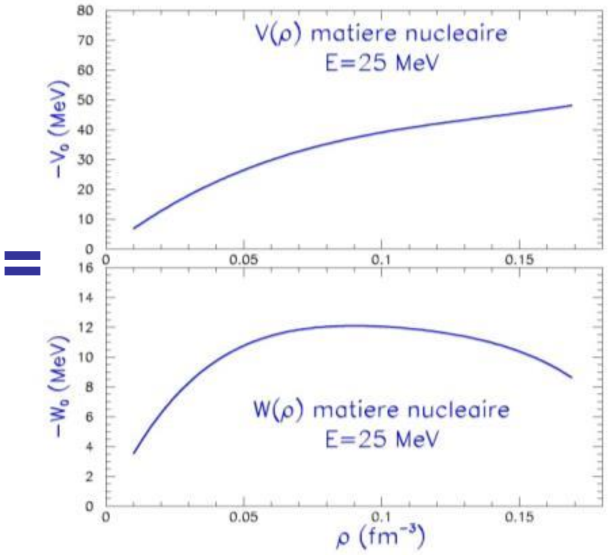

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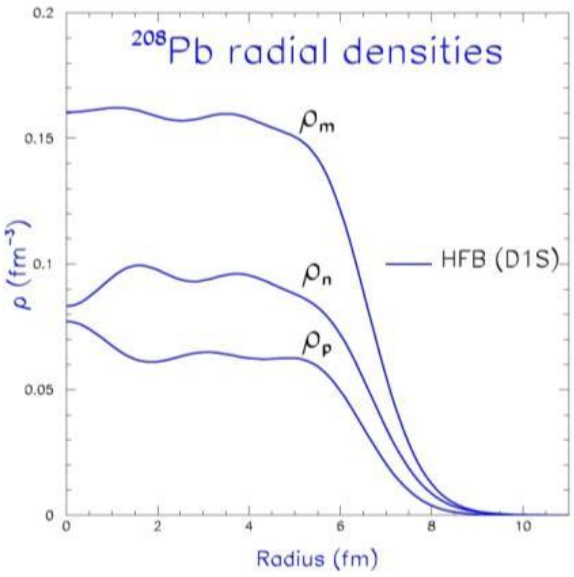


$$U(r,E) = \frac{U(\rho(r'),E)}{\rho(r')} \otimes \rho(r)$$

Depends on the nucleus

Independent of the nucleus

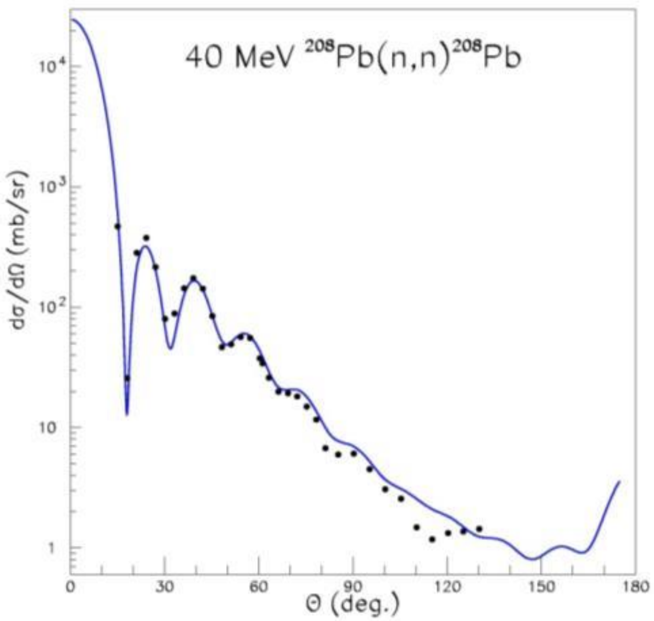
Depends on the nucleus

SEMI-MICROSCOPIC OPTICAL MODEL

Unique description of elastic scattering

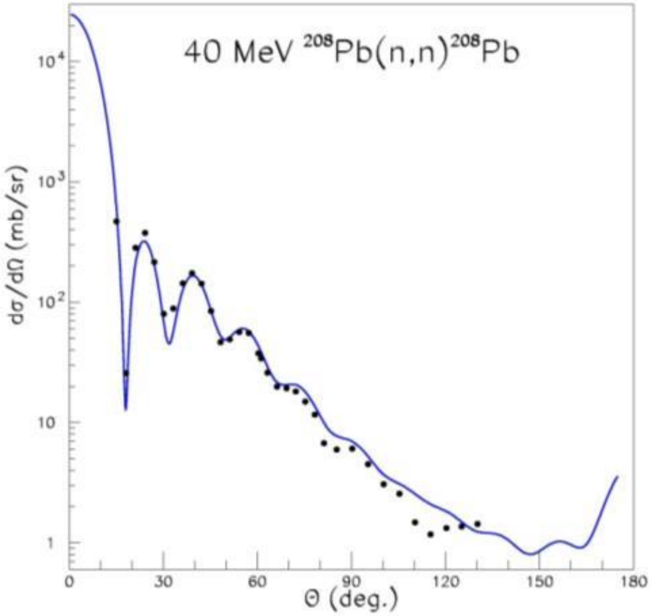
SEMI-MICROSCOPIC OPTICAL MODEL

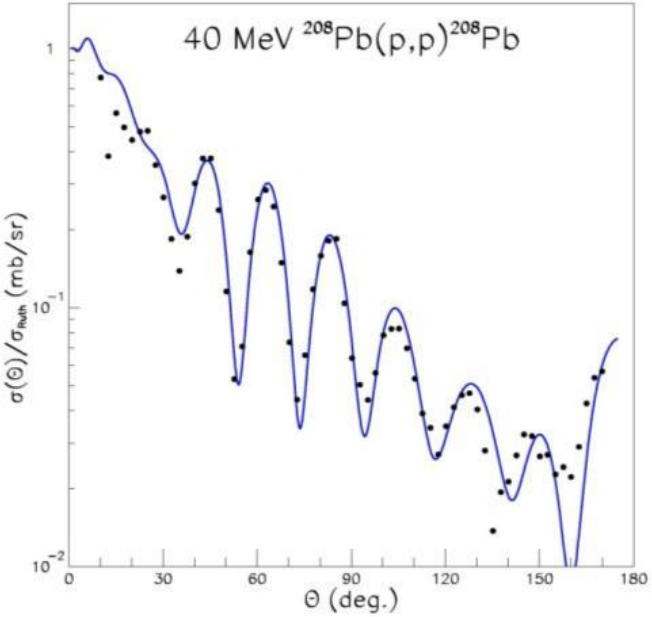
Unique description of elastic scattering (n,n)



SEMI-MICROSCOPIC OPTICAL MODEL

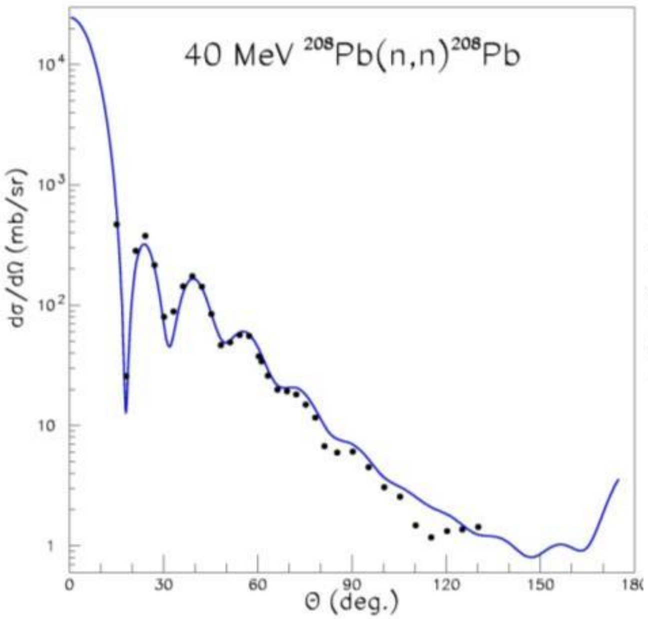
Unique description of elastic scattering (n,n), (p,p)

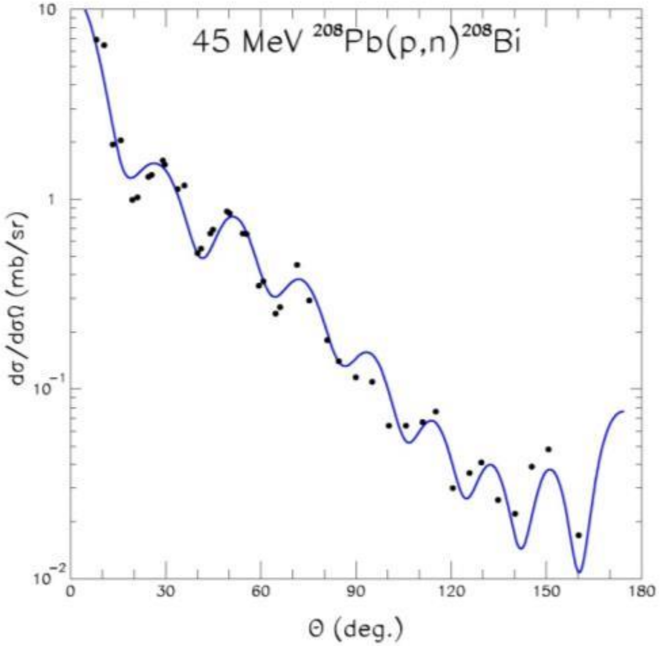


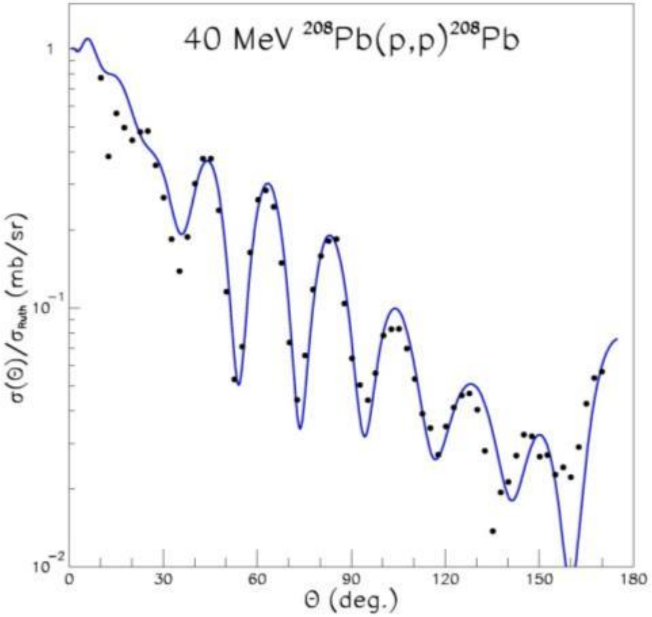


SEMI-MICROSCOPIC OPTICAL MODEL

Unique description of elastic scattering (n,n), (p,p) and (p,n)

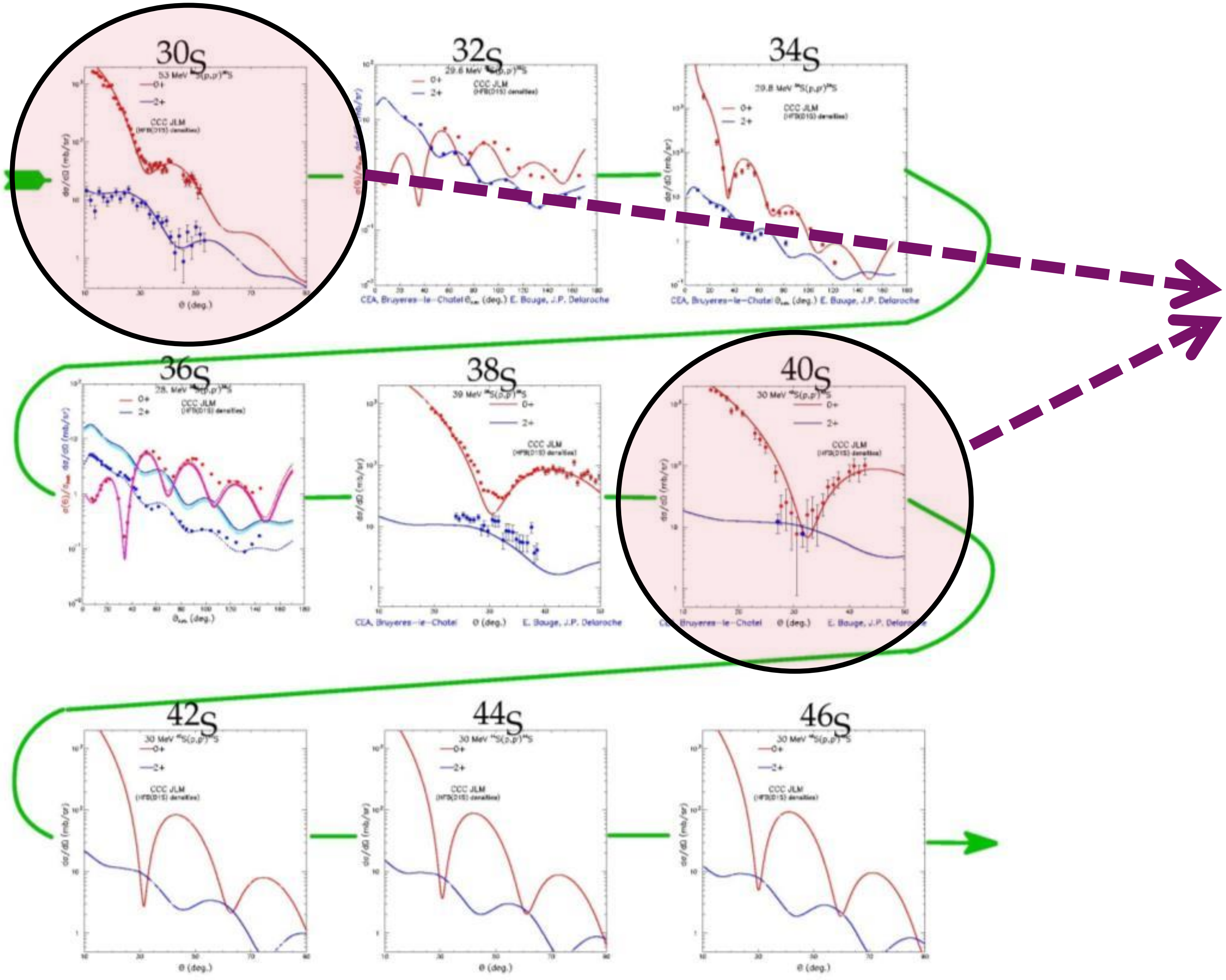




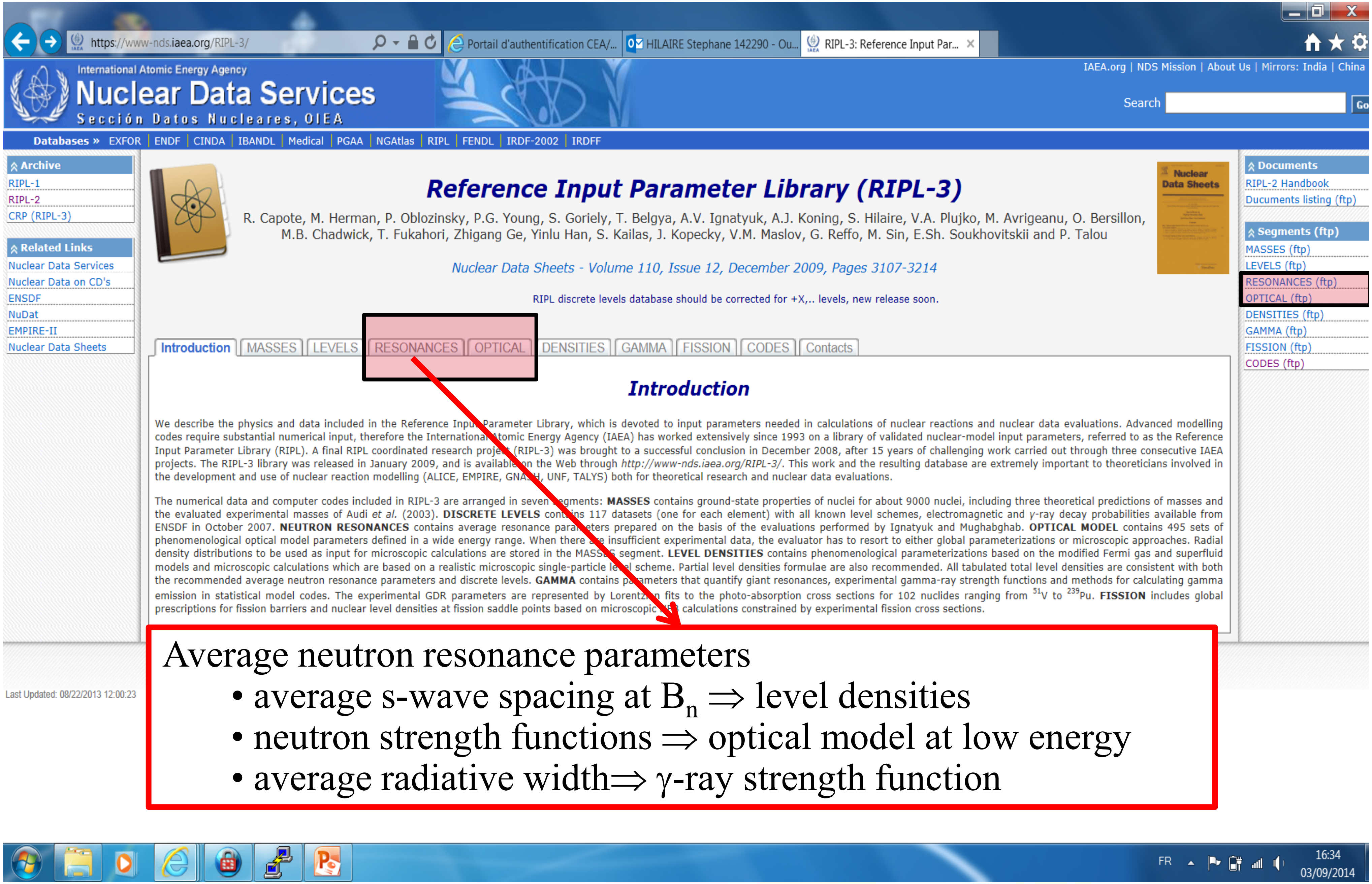


SEMI-MICROSCOPIC OPTICAL MODEL

Enables to give predictions for very exotic nuclei for which there exist no experimental data



Experiment performed after calculation



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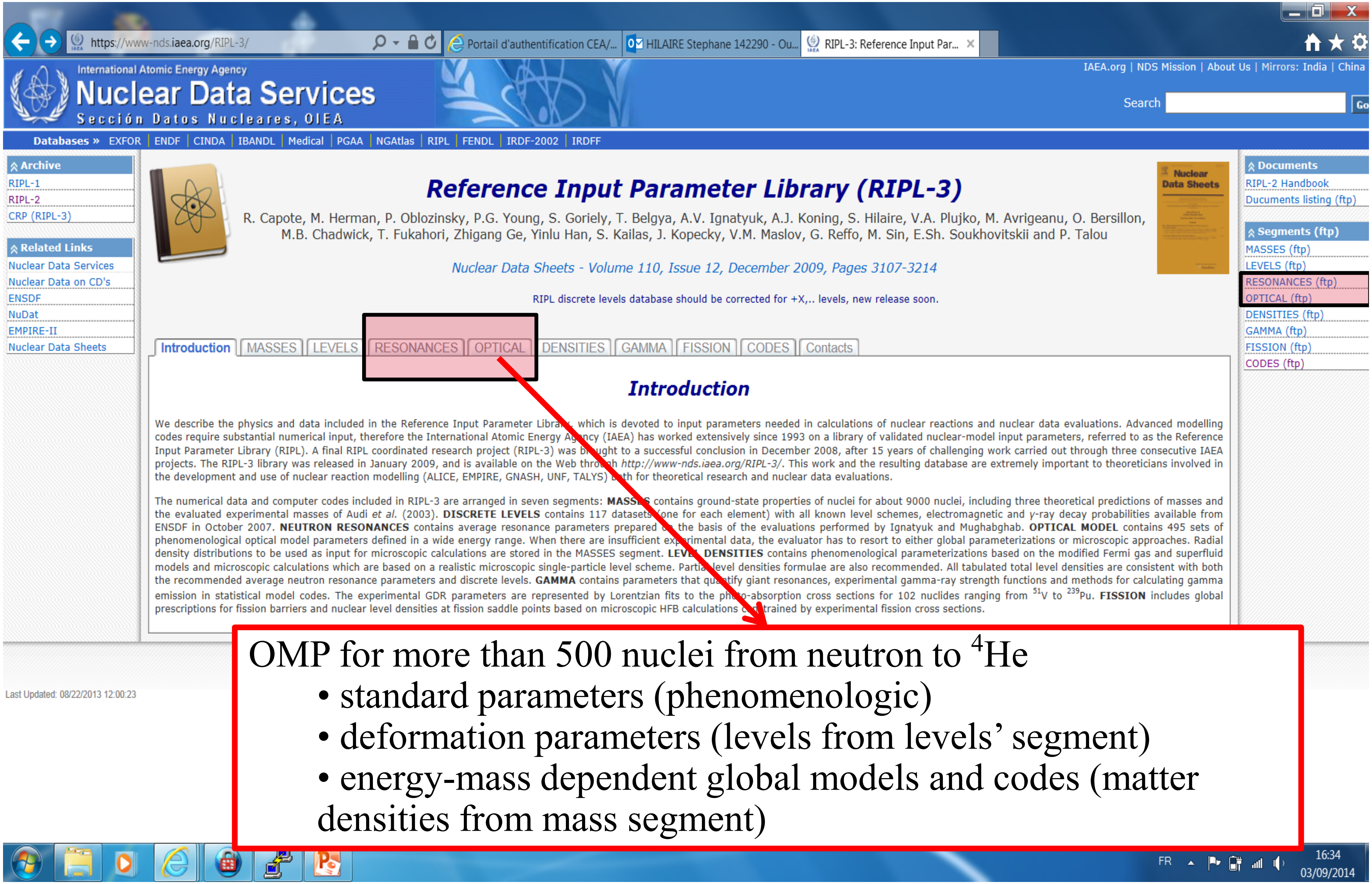
Average neutron resonance parameters

- average s-wave spacing at $B_n \Rightarrow$ level densities
- neutron strength functions $\Rightarrow$ optical model at low energy
- average radiative width$\Rightarrow$ γ-ray strength function



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

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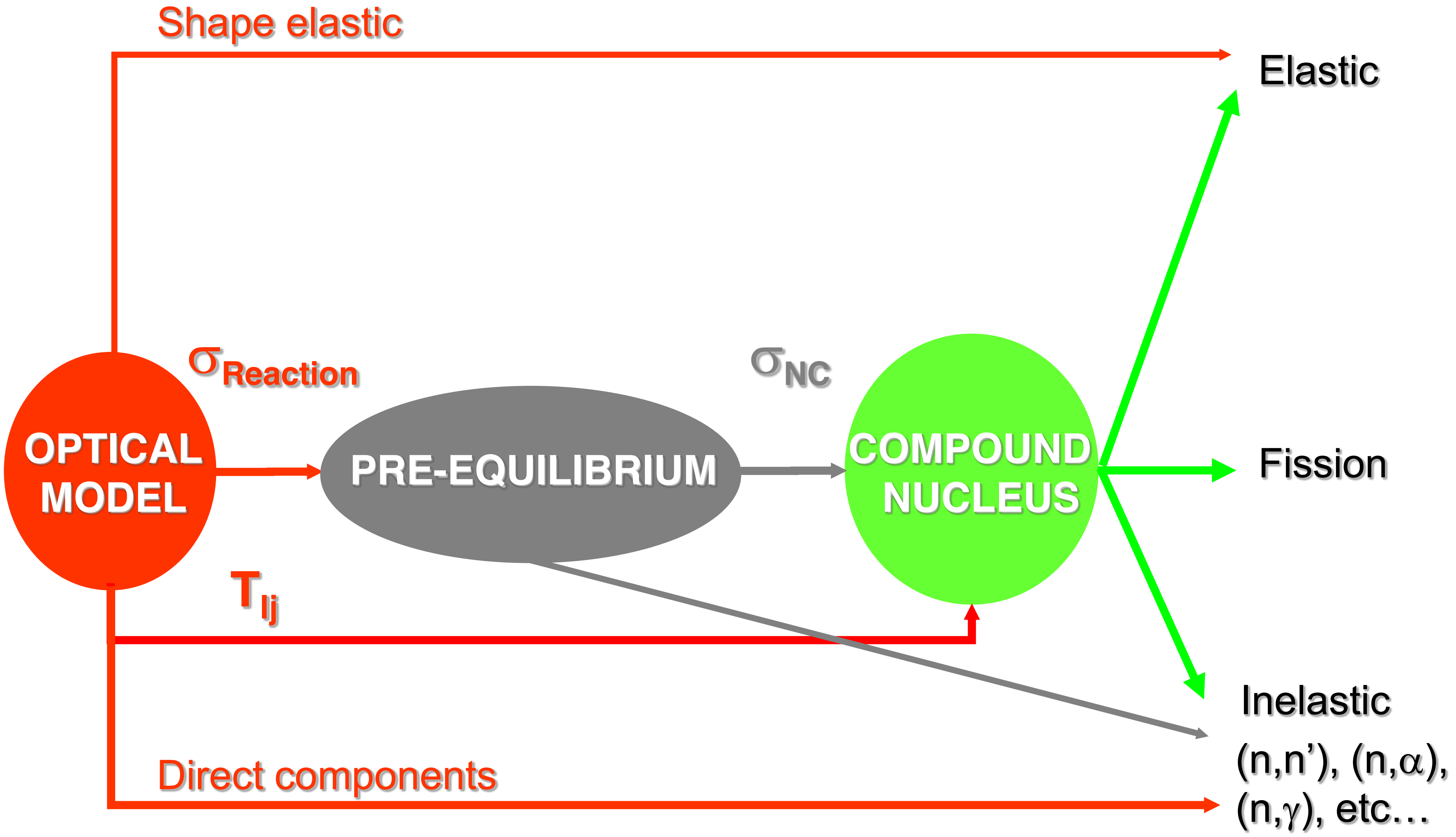
OMP for more than 500 nuclei from neutron to ^{4}He
- standard parameters (phenomenologic)
- deformation parameters (levels from levels' segment)
- energy-mass dependent global models and codes (matter densities from mass segment)

THE PRE-EQUILIBRIUM MODEL



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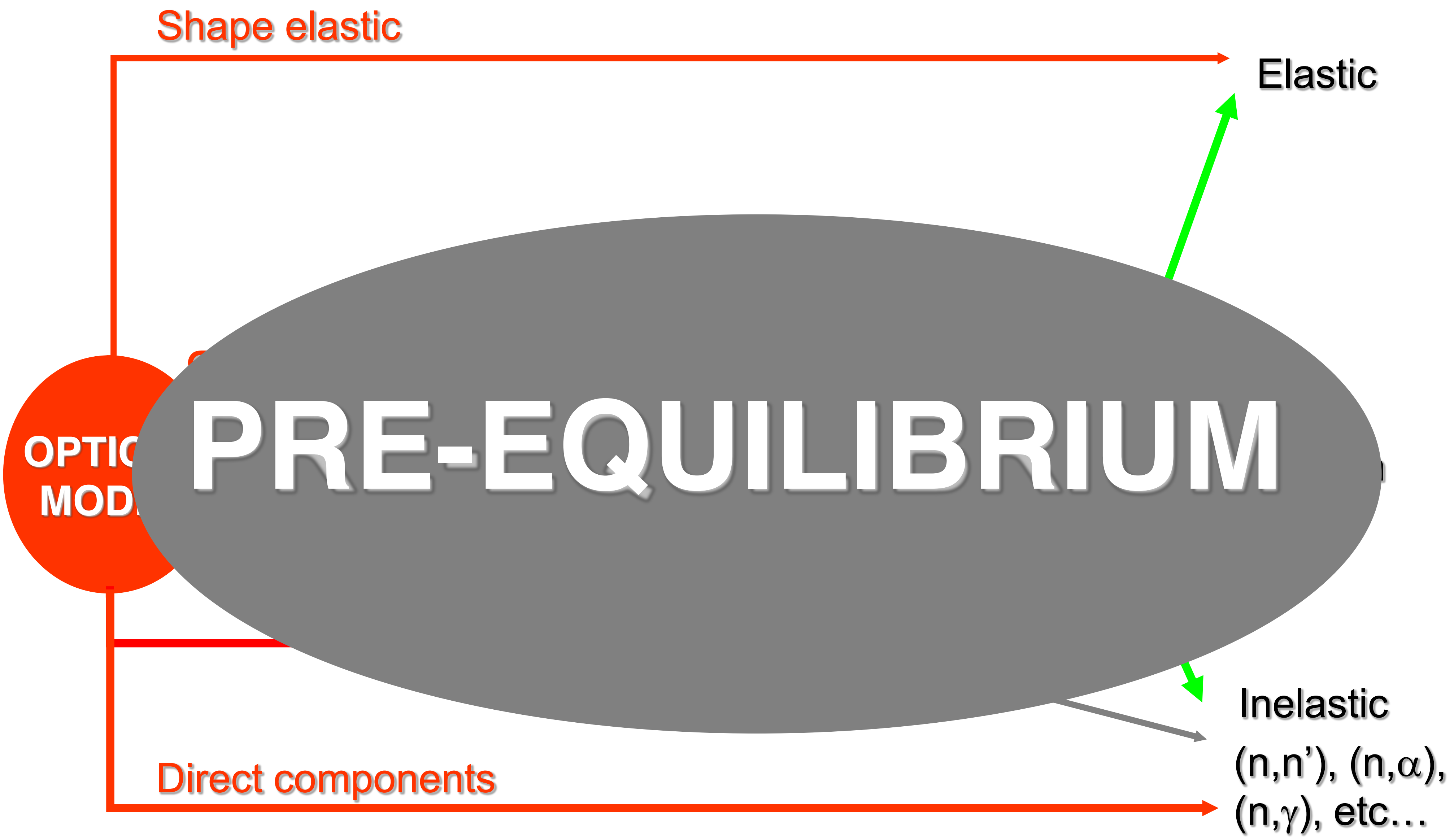


Shape elastic

Elastic

OPTIC
MOD

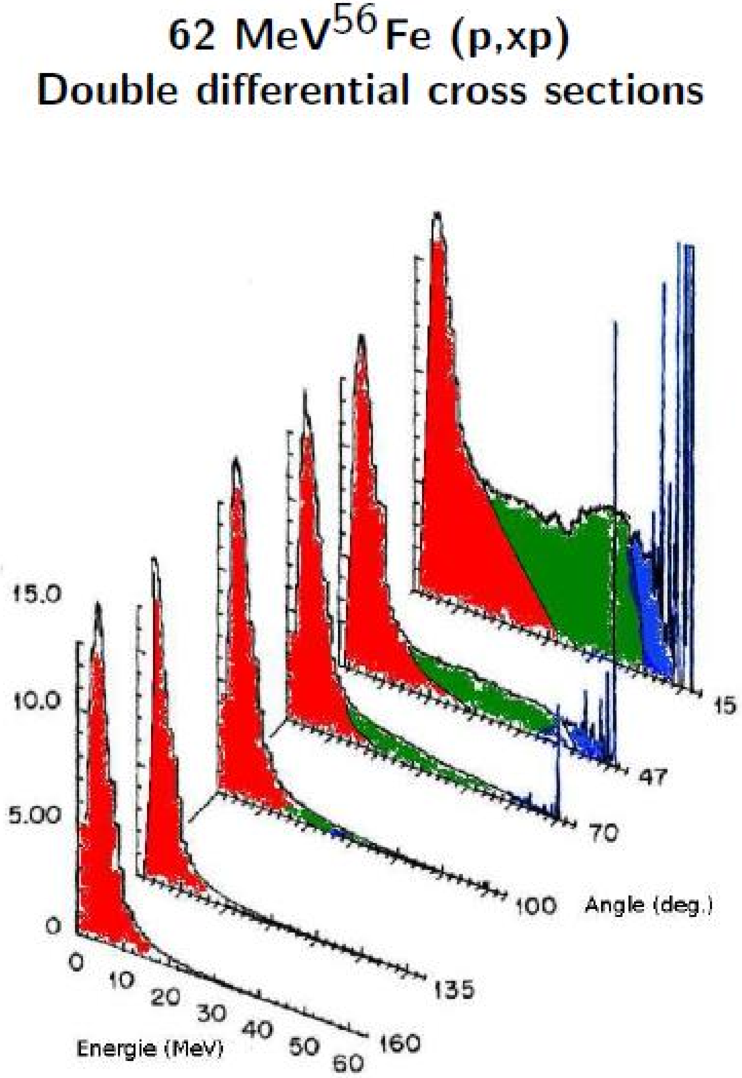
PRE-EQUILIBRIUM

Inelastic

(n,n'), (n,α),
(n,γ), etc…

Direct components

TIME SCALES AND ASSOCIATED MODELS (1/4)
Typical spectrum shape



- Always evaporation peak
- Discrete peaks at forward angles
- **Flat intermediate region**

THE PRE-EQUILIBRIUM MODEL
(quantum vs semi-classical approaches)

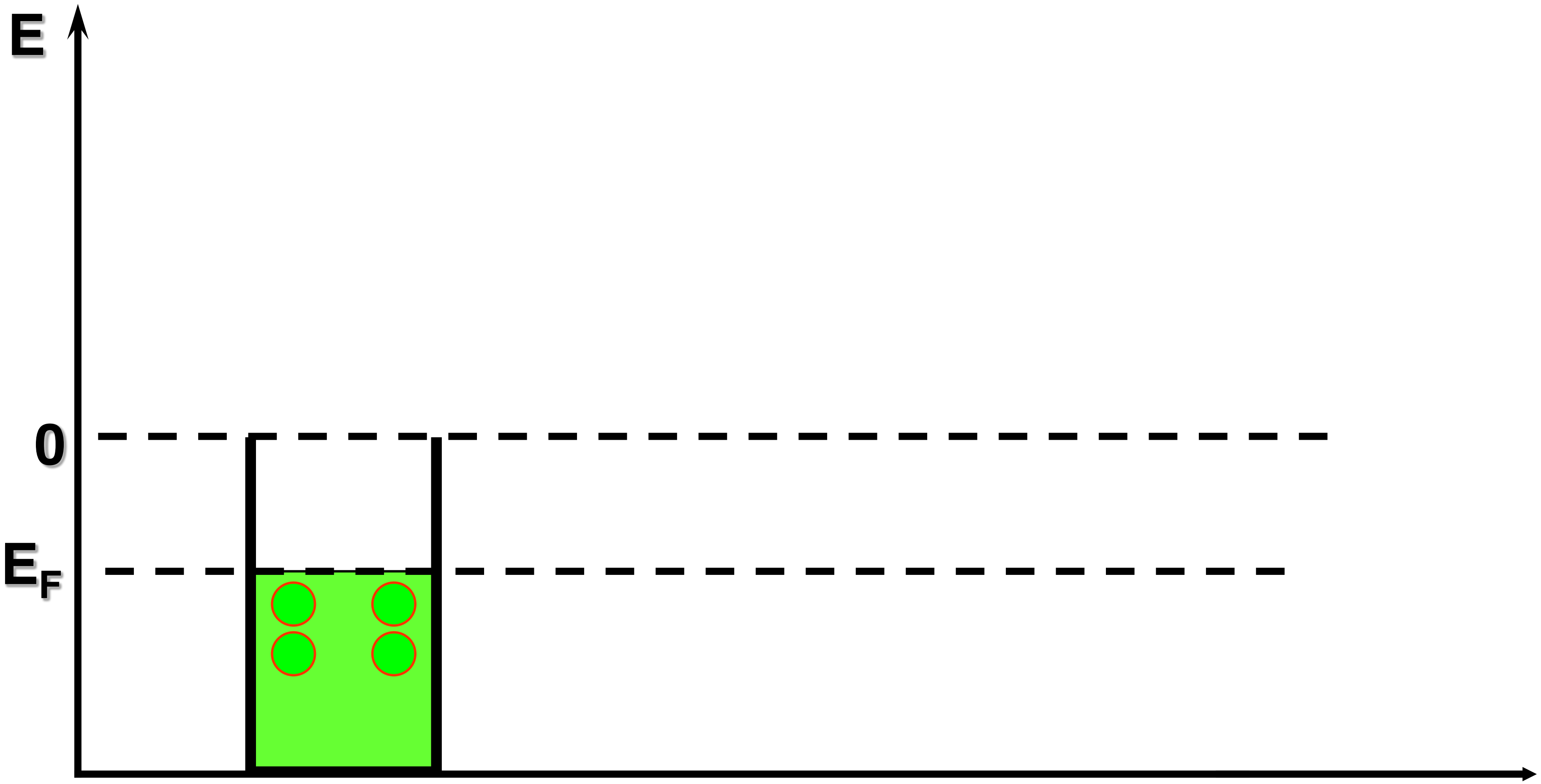
Semi-classical approaches

- called « exciton model »
- « simple » to implement
- initially only able to describe angle integrated spectra (1966 & 1970)
- extended to ddx spectra in 1976
- link with Compound Nucleus established in 1987
- systematical underestimation of ddx spectra at backward angles
- complemented by Kalbach systematics (1988) to improve ddx description
- link with OMP imaginary performed in 2004

Quantum mechanical approaches

- distinction between MSC and MSD processes
  - MSC = bound p-h excitations, symetrical angular distributions
  - MSD = unbound configuration, smooth forward peaked ang. dis.
- MSD dominates pre-equ xs above 20 MeV
- 3 approaches : FKK (1980)
  TUL (1982)
  NWY (1986)
- ddx spectra described as well as with Kalbach systematics

THE PRE-EQUILIBRIUM MODEL
(Exciton model principle)



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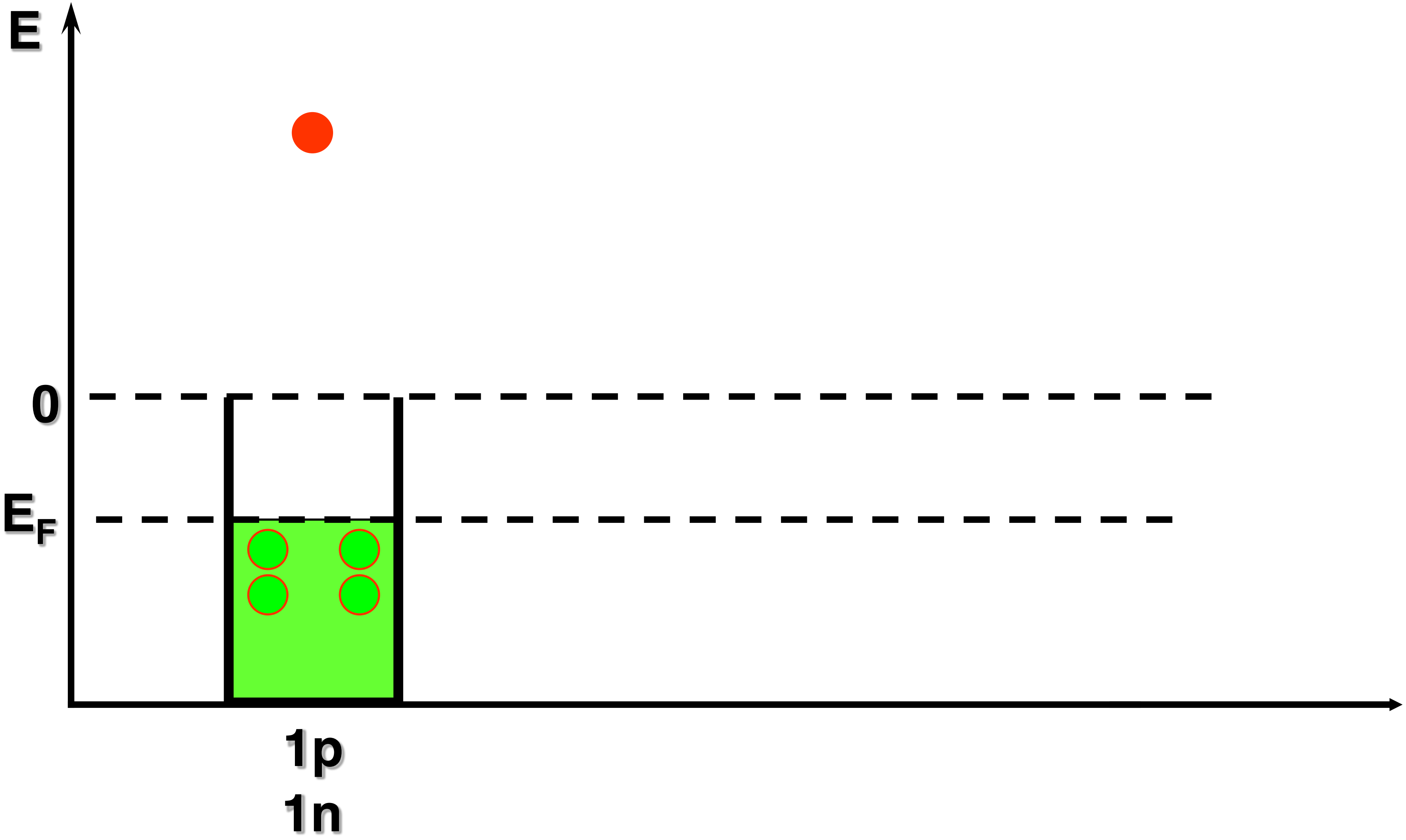

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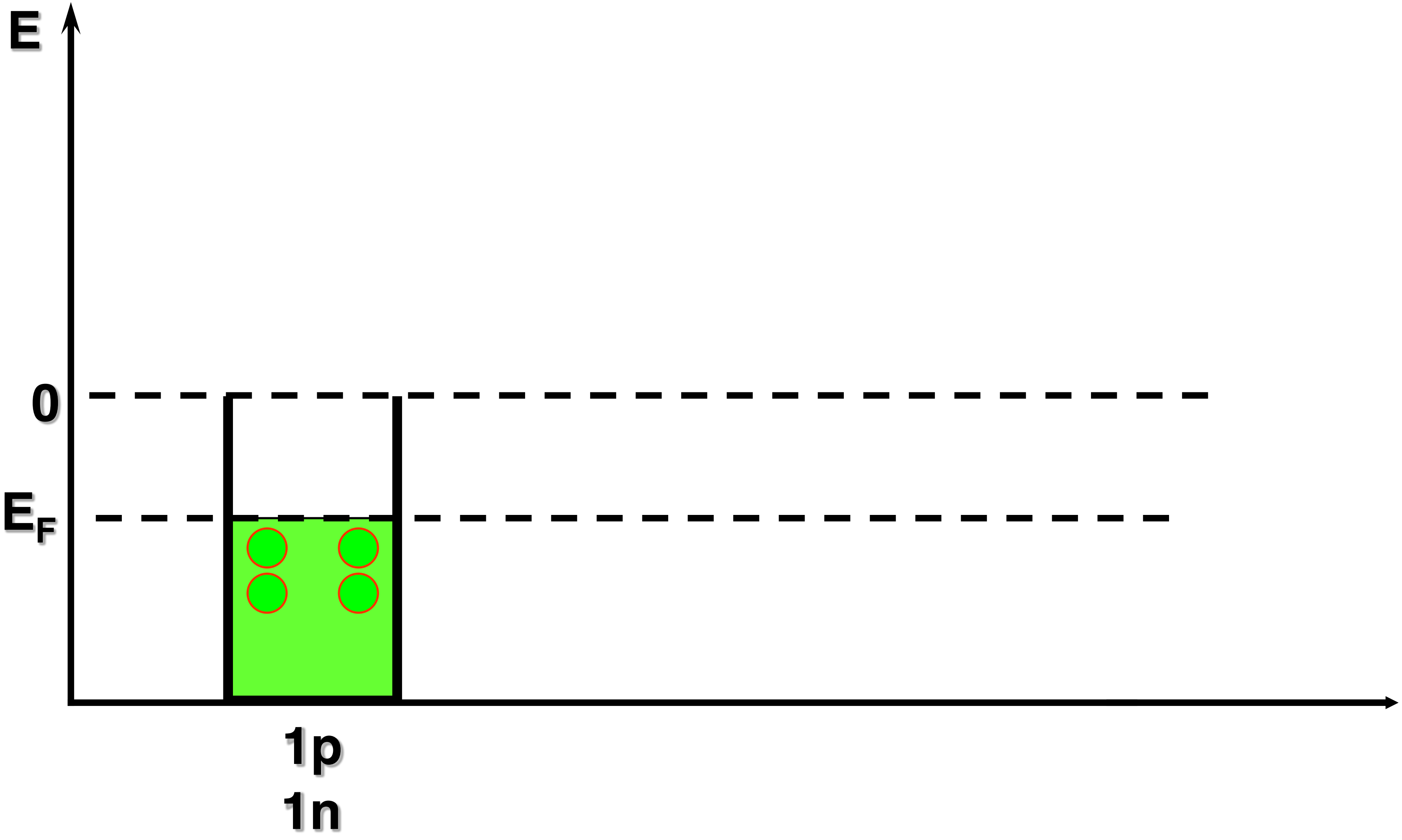

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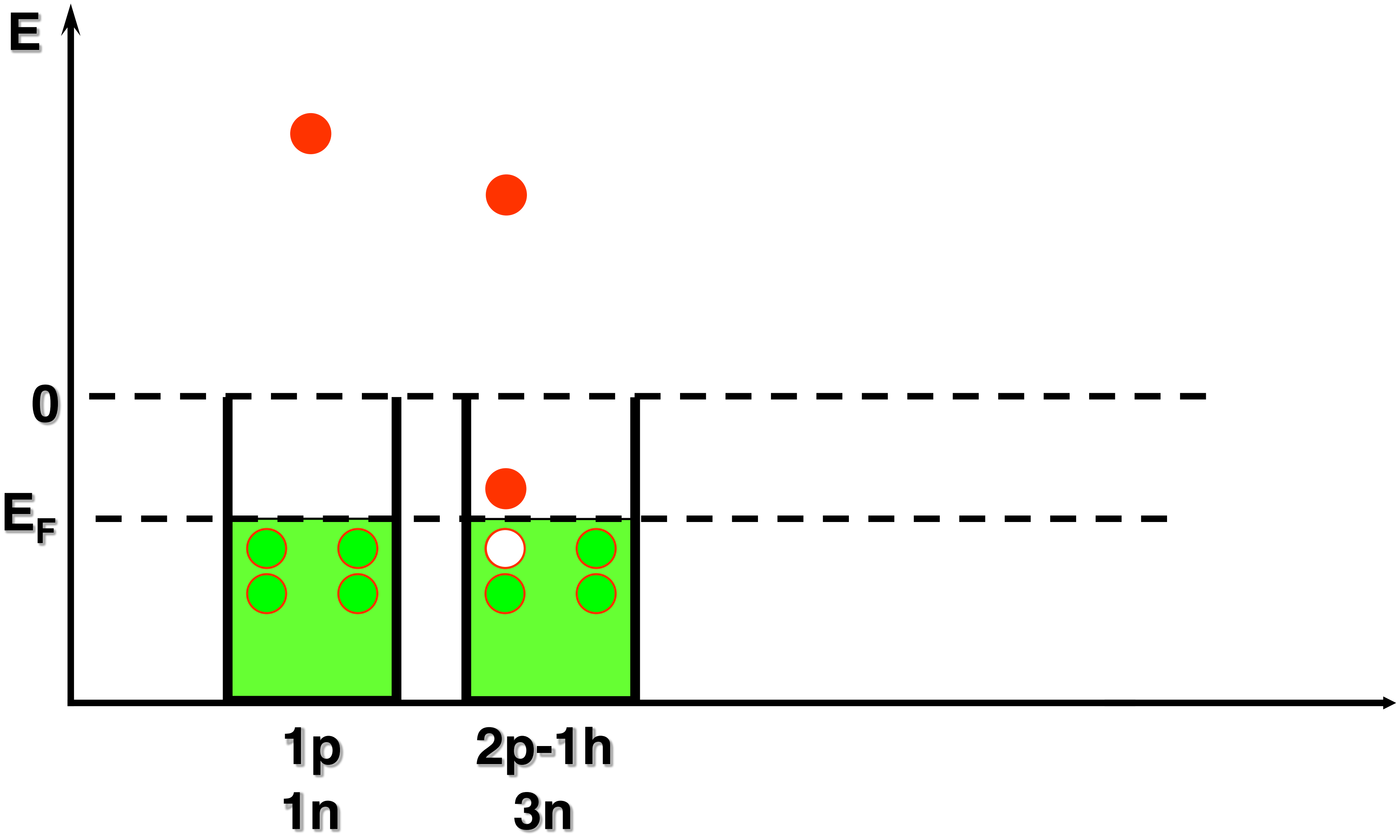

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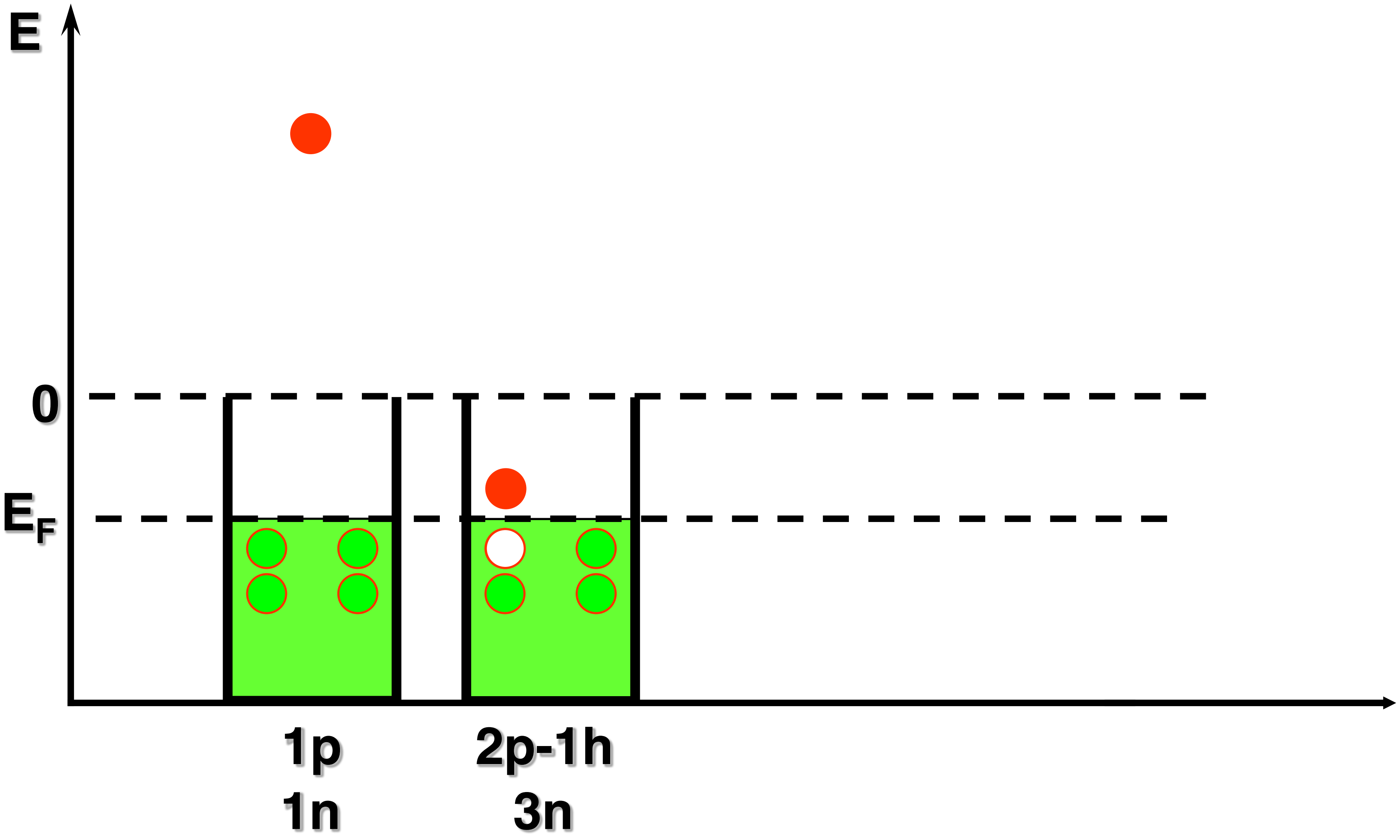

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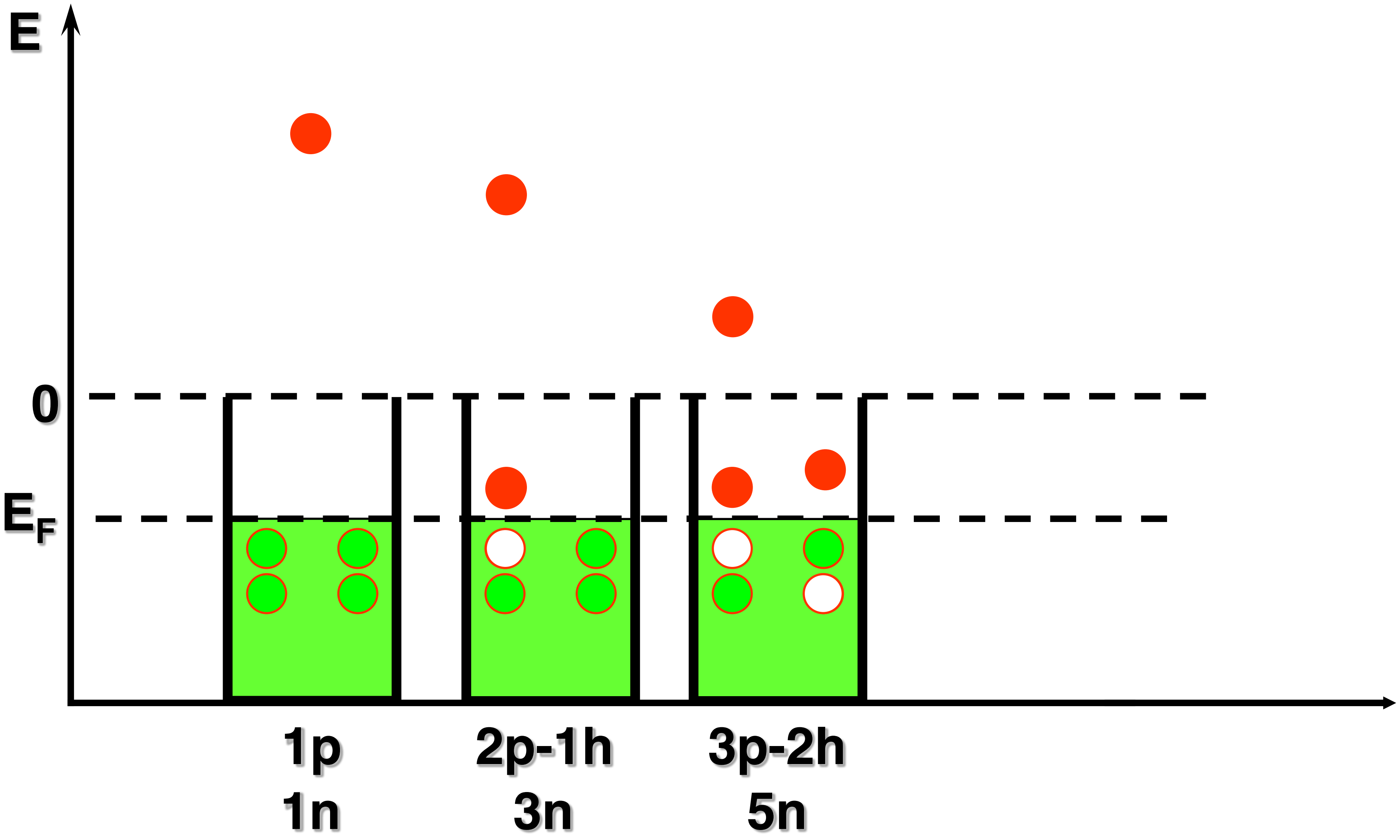

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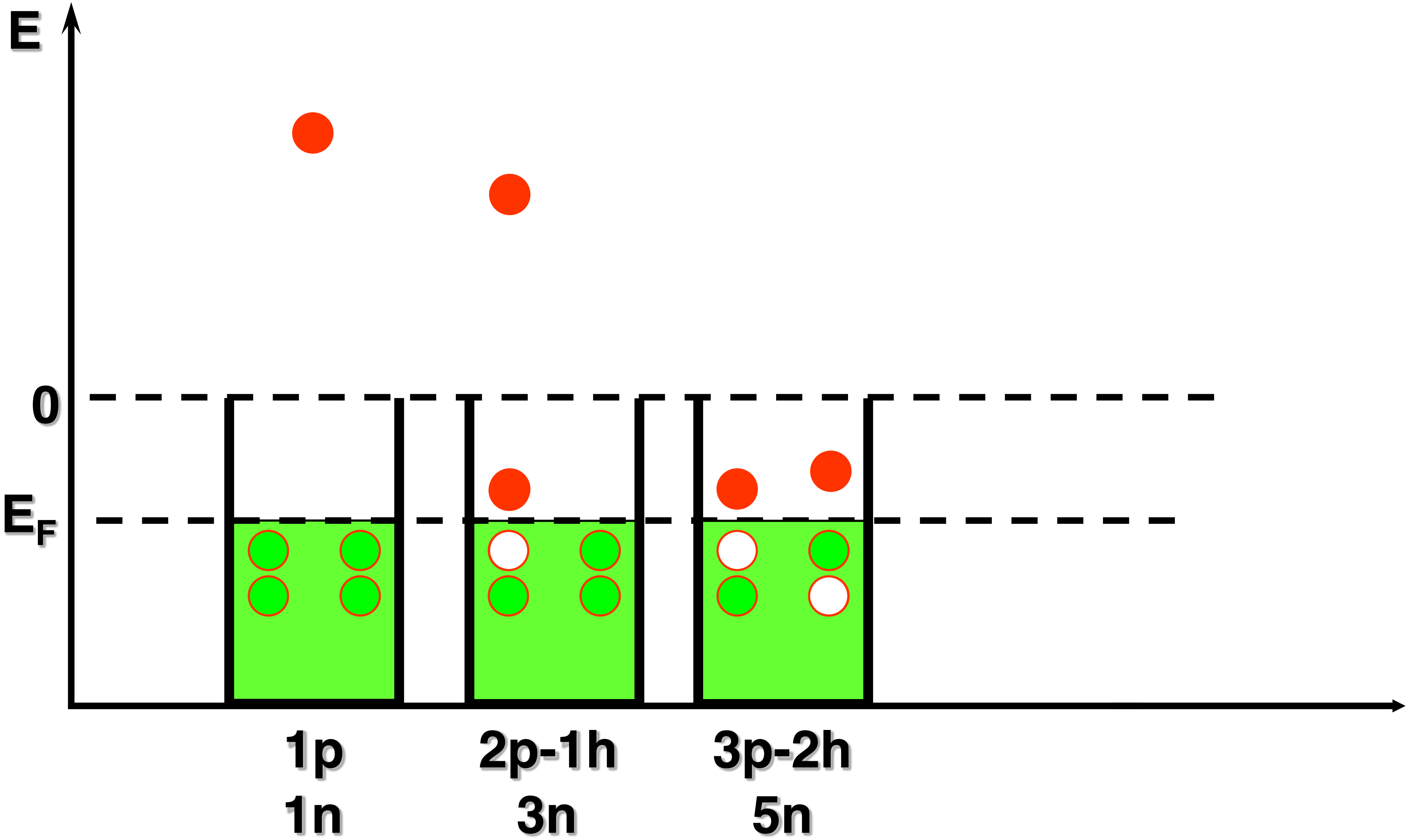

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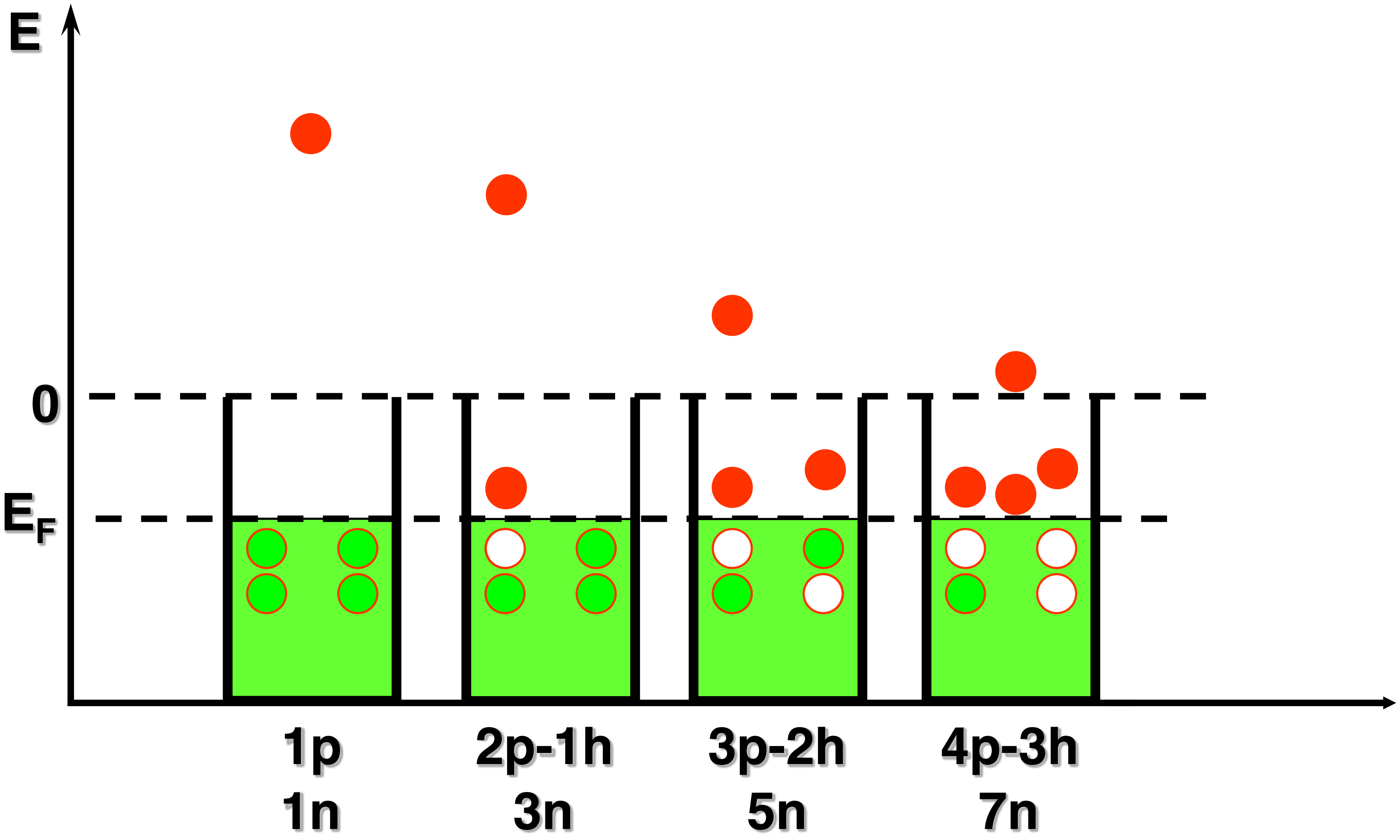

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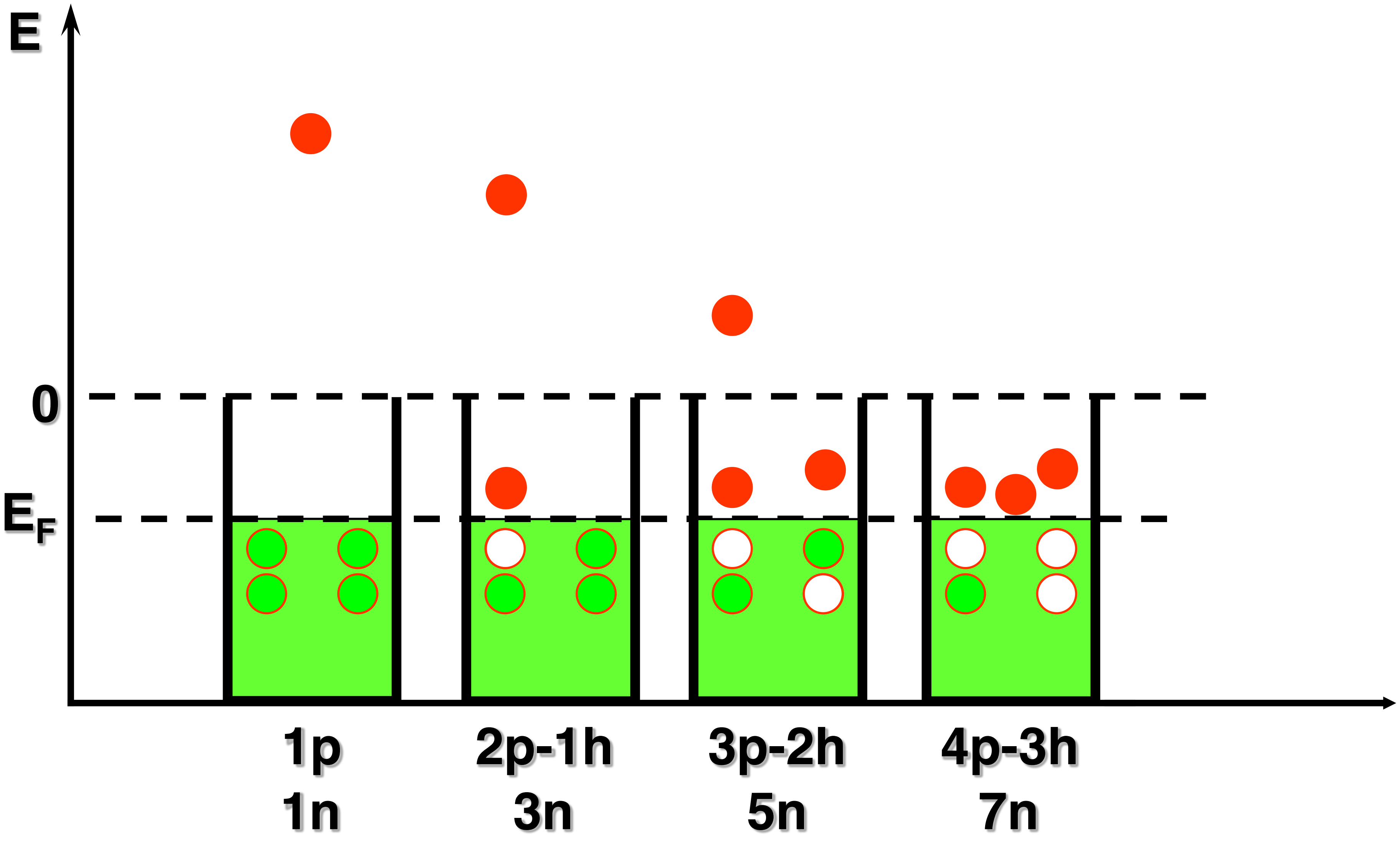

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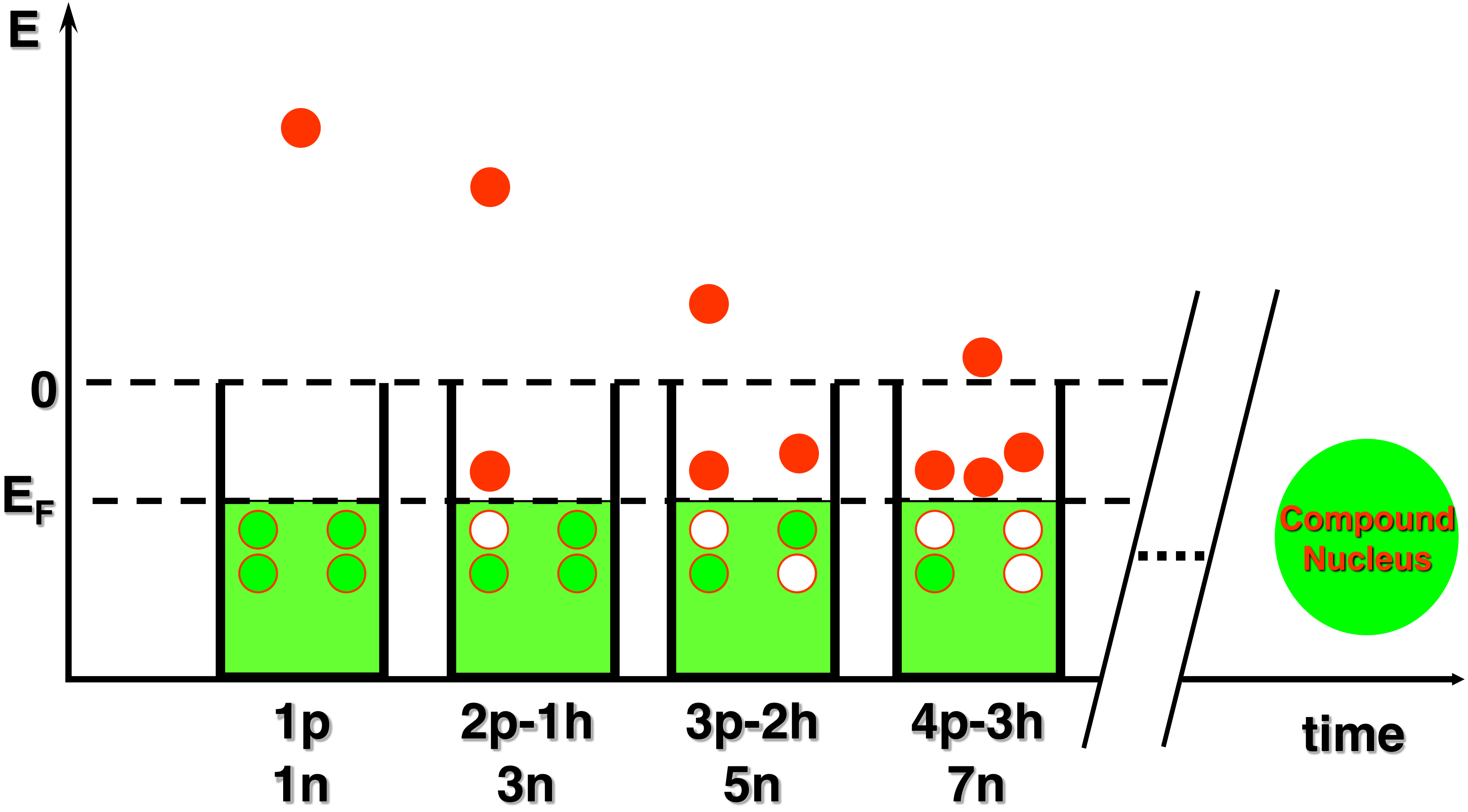

THE PRE-EQUILIBRIUM MODEL
(Master equation exciton model)

$P(n,E,t)$ = 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.

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Evolution equation

$$\frac{dP(n,E,t)}{dt} = \text{Apparition}$$

$$- \quad \text{Disparition}$$

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Evolution equation

$$\frac{dP(n,E,t)}{dt} = P(n-2, E, t)\,\lambda_{n-2,\,n}(E) + P(n+2, E, t)\,\lambda_{n+2,\,n}(E)$$

\- Disparition

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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)

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Initialisation

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

Transition rates

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

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

Original formulation

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Corrections for
proton-neutron
distinguishability
&
complex particle
emission

DE LA RECHERCHE À L'INDUSTRIE

cea

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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

THE PRE-EQUILIBRIUM MODEL
(State 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

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

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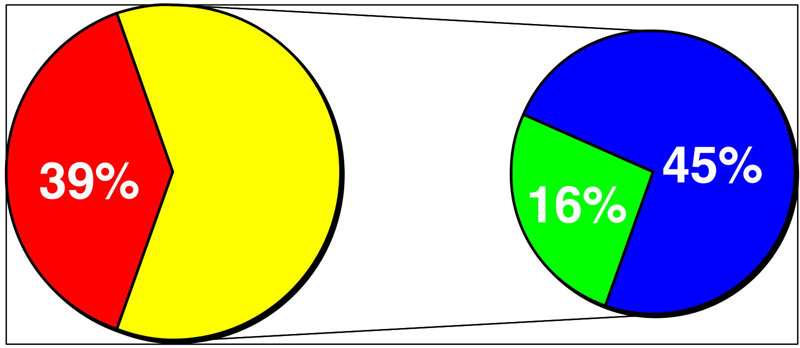
- **Běták and Doběs 1976 : account for finite number of holes' states**
- **Obložinský 1986 : account for finite number of particles' states (MSC)**
- **Anzaldo-Meneses 1995 : first order corrections for increasing number of p-h**
- **Hilaire and Koning 1998 : generalized expression in ESM**

DE LA RECHERCHE À L'INDUSTRIE

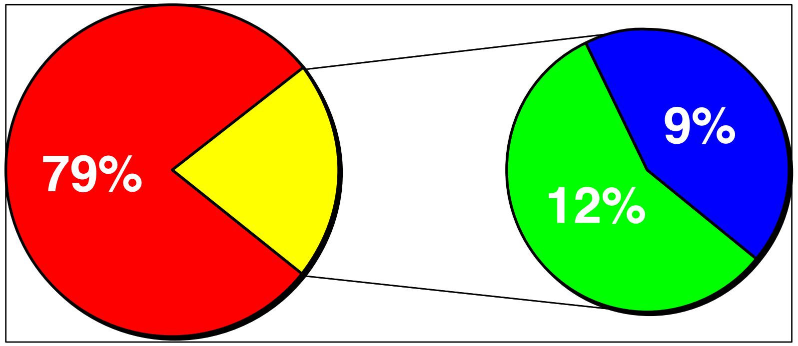
THE PRE-EQUILIBRIUM MODEL

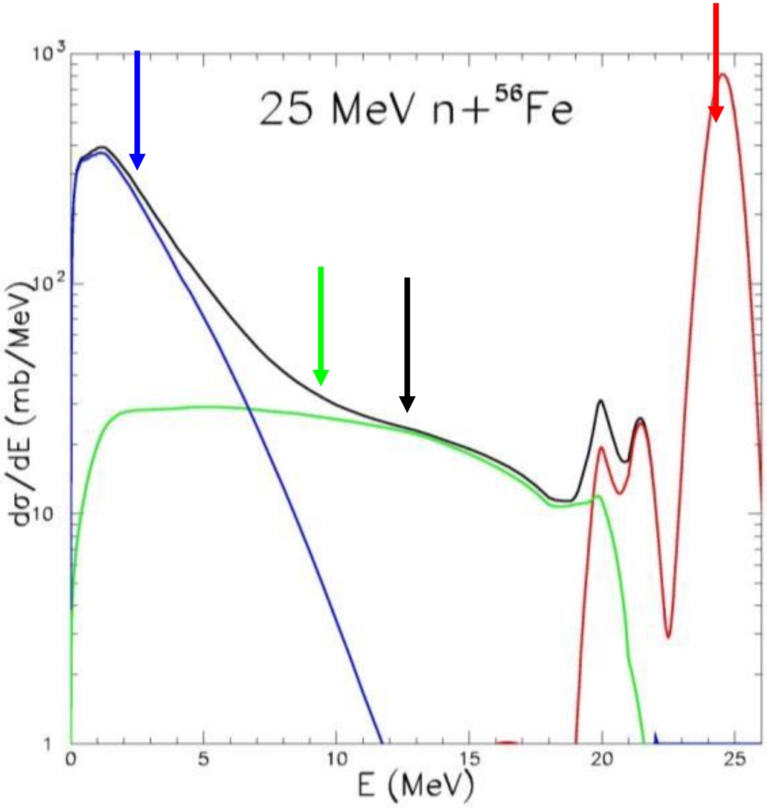
Cross section



Total
Direct
Pre-equilibrium
Statistical

Outgoing energy





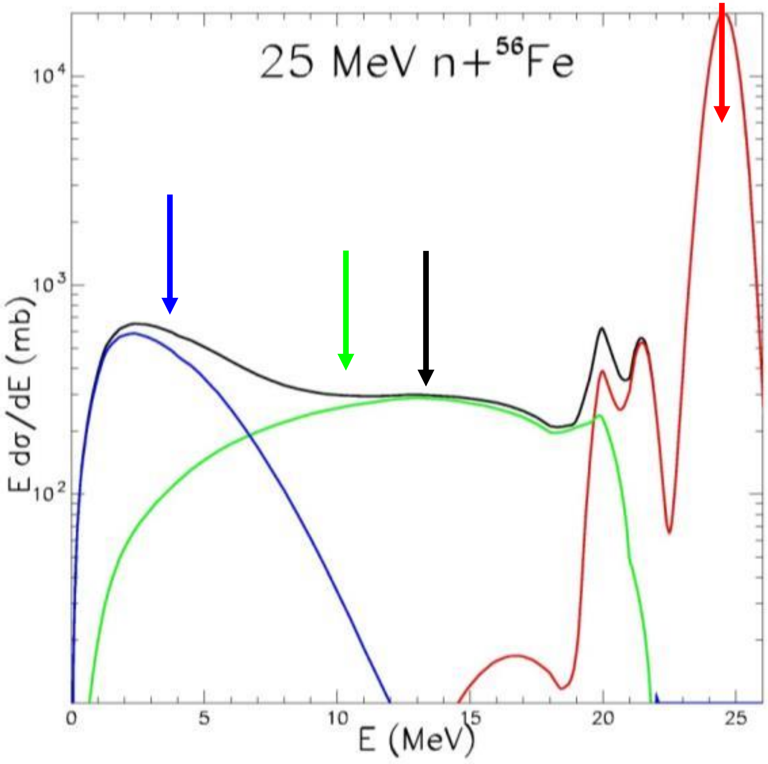
$\langle E_{Tot} \rangle = 12.1$

$\langle E_{Dir} \rangle = 24.3$

$\langle E_{PE} \rangle = 9.32$

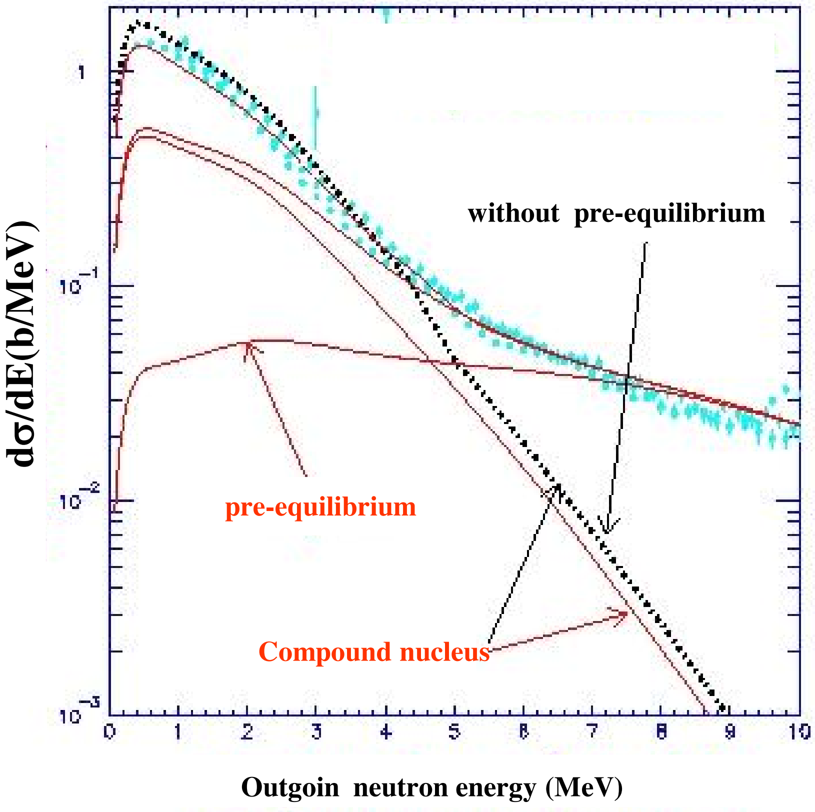
$\langle E_{Sta} \rangle = 2.5$

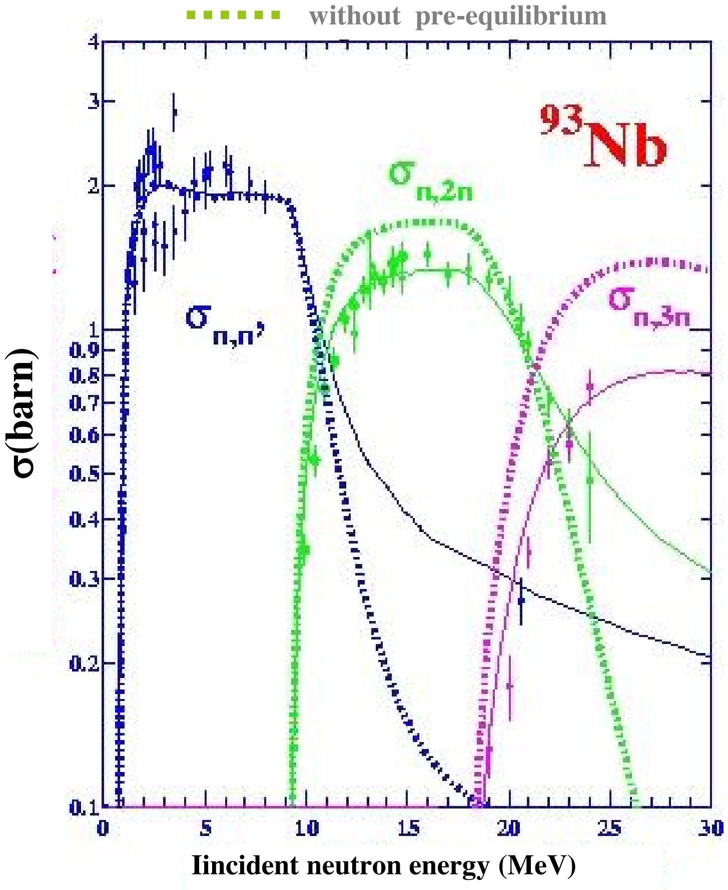
(MeV)

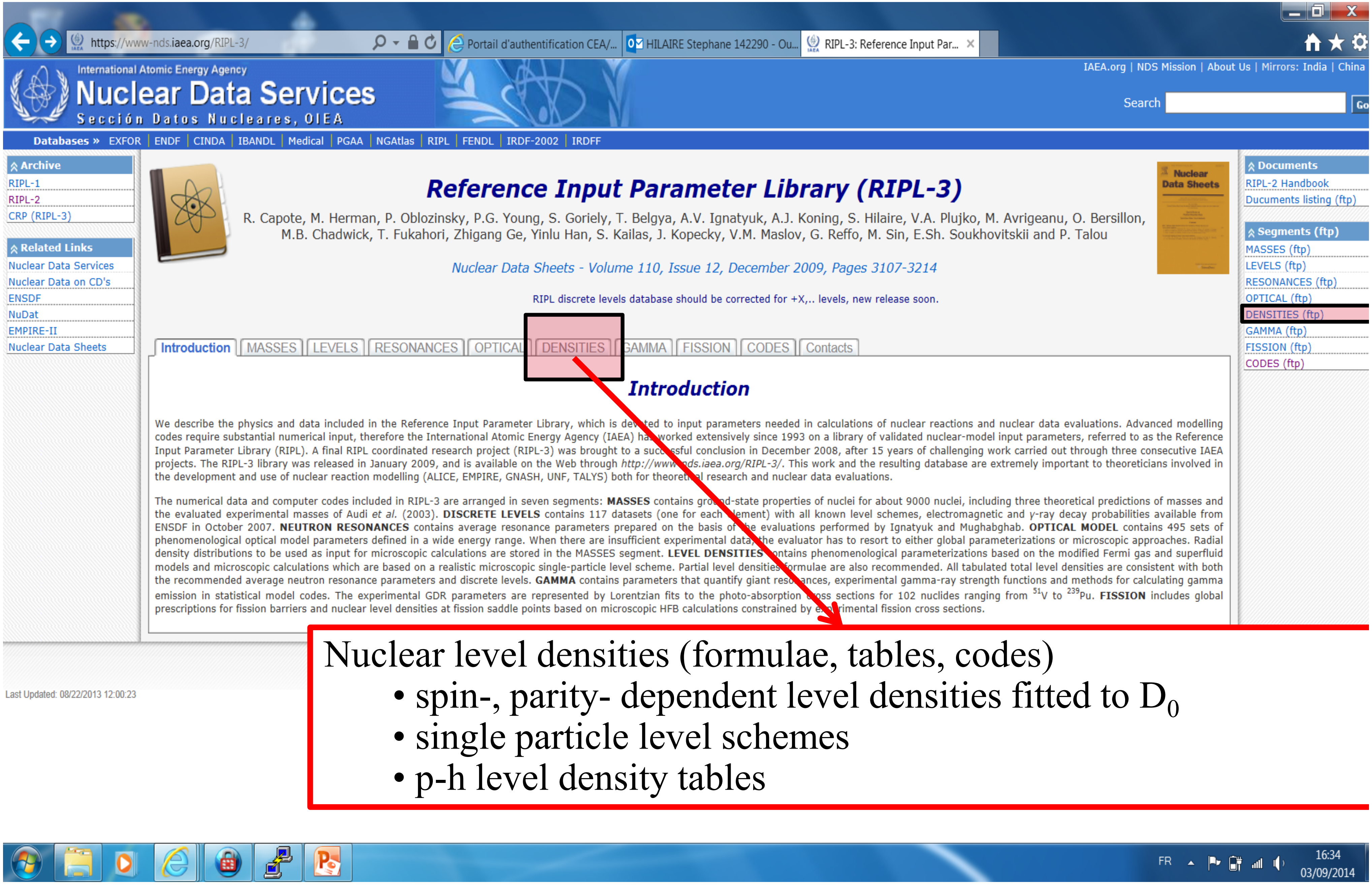


THE PRE-EQUILIBRIUM MODEL

14 MeV neutron + ^{93} Nb







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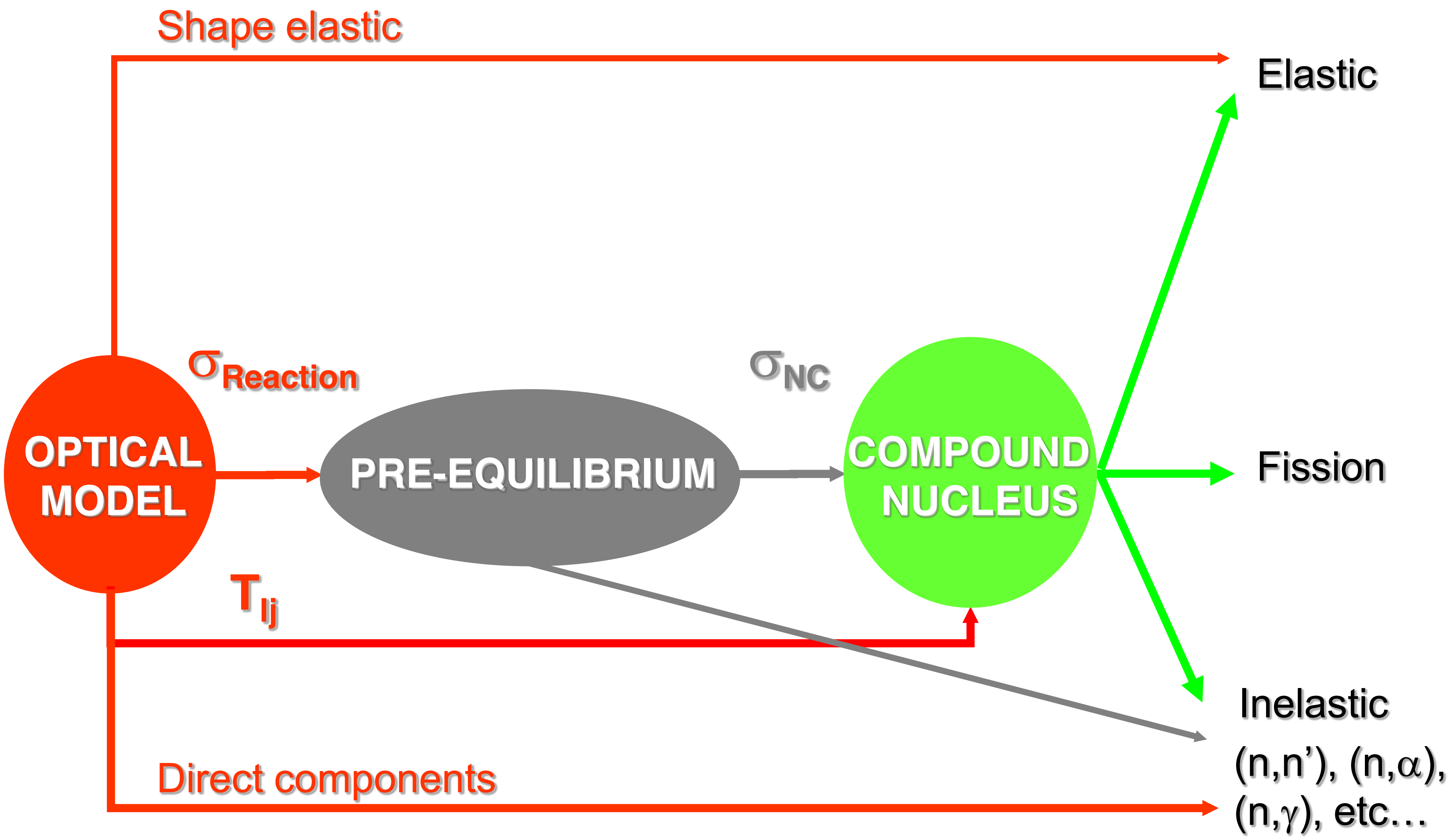
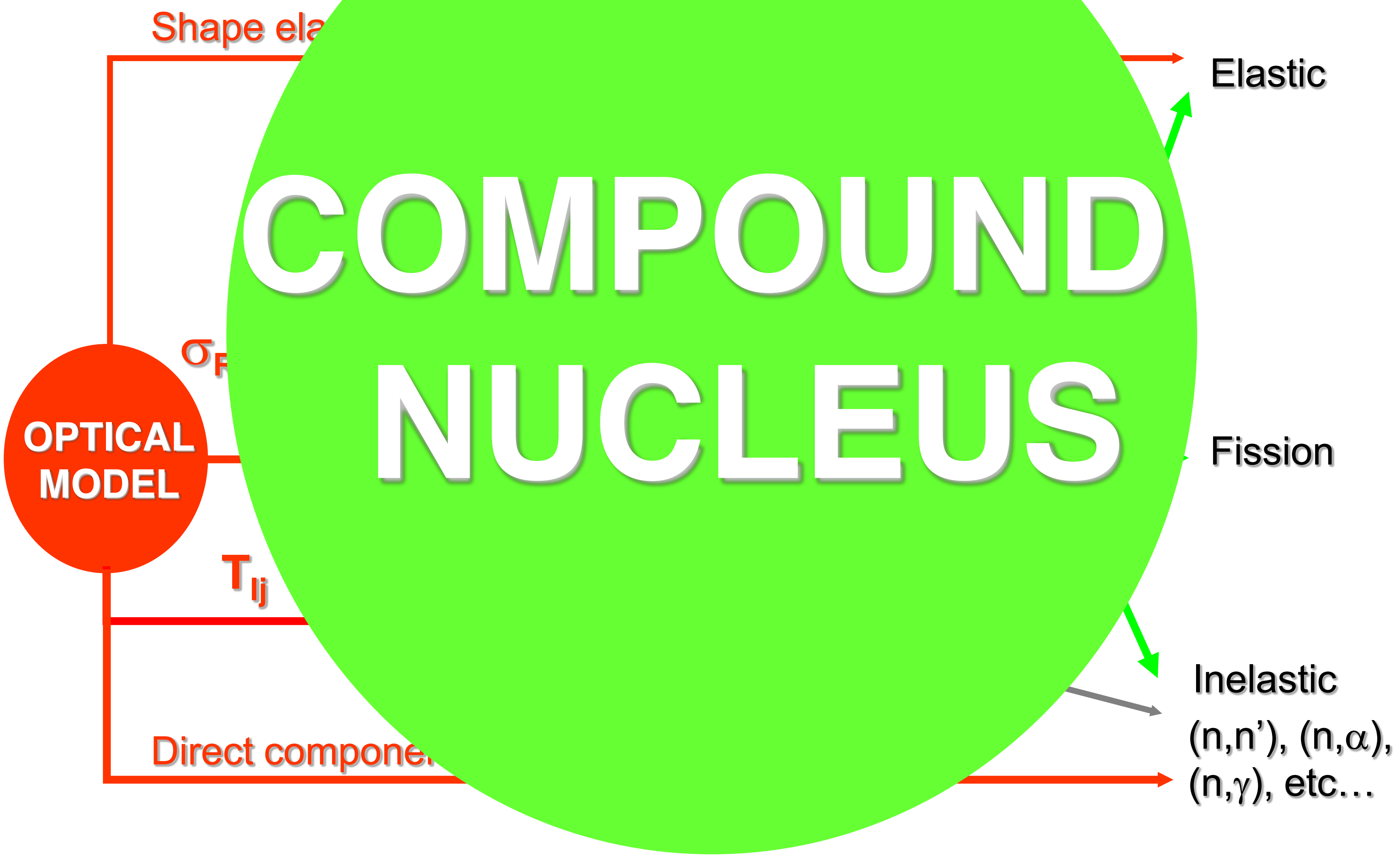
Nuclear level densities (formulae, tables, codes)
- spin-, parity- dependent level densities fitted to D_0
- single particle level schemes
- p-h level density tables

THE COMPOUND NUCLEUS MODEL



THE CO MODEL



Shape ela

Elastic

σ_R

OPTICAL MODEL

COMPOUND NUCLEUS

Fission

T_{lj}

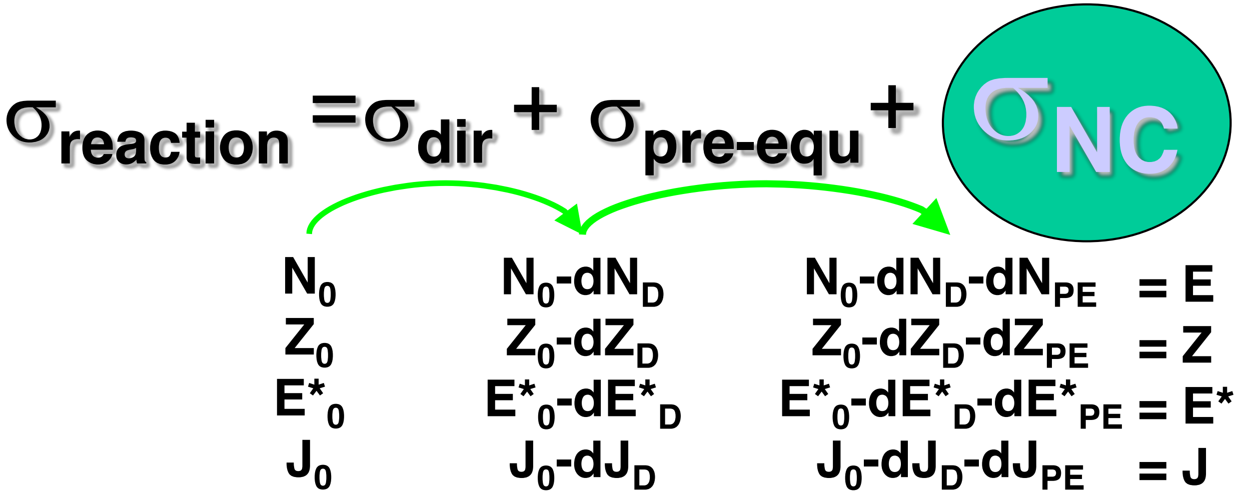
Inelastic

(n,n'), (n,α), (n,γ), etc…

Direct compone

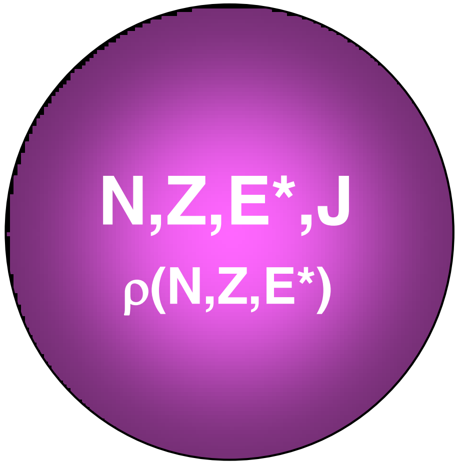
THE COMPOUND NUCLEUS MODEL
(initial population)

After direct and pre-equilibrium emission



$$\sigma_{reaction} = \sigma_{dir} + \sigma_{pre\text{-}equ} + \boxed{\sigma_{NC}}$$

$$\begin{array}{ccc} N_0 & N_0\text{-}dN_D & N_0\text{-}dN_D\text{-}dN_{PE} = E \\ Z_0 & Z_0\text{-}dZ_D & Z_0\text{-}dZ_D\text{-}dZ_{PE} = Z \\ E^*_0 & E^*_0\text{-}dE^*_D & E^*_0\text{-}dE^*_D\text{-}dE^*_{PE} = E^* \\ J_0 & J_0\text{-}dJ_D & J_0\text{-}dJ_D\text{-}dJ_{PE} = J \end{array}$$



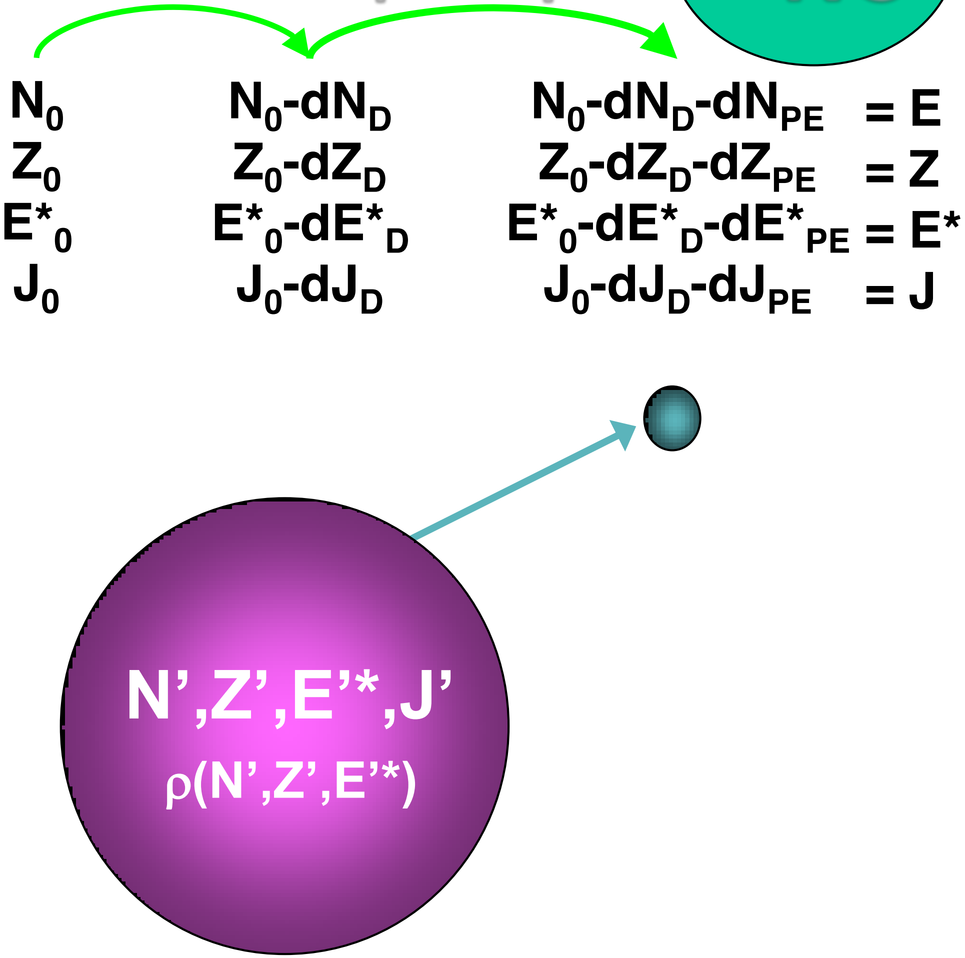
N,Z,E*,J

$\rho(N,Z,E^*)$

THE COMPOUND NUCLEUS MODEL
(initial population)

After direct and pre-equilibrium emission

$$\sigma_{\text{reaction}} = \sigma_{\text{dir}} + \sigma_{\text{pre-equ}} + \boxed{\sigma_{\text{NC}}}$$



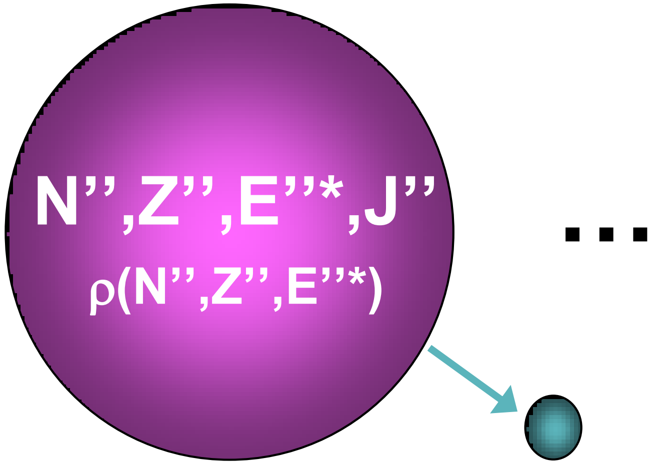
N_0	N_0-dN_D	$N_0-dN_D-dN_{PE}$	$= E$
Z_0	Z_0-dZ_D	$Z_0-dZ_D-dZ_{PE}$	$= Z$
E^*_0	$E^*_0-dE^*_D$	$E^*_0-dE^*_D-dE^*_{PE}$	$= E^*$
J_0	J_0-dJ_D	$J_0-dJ_D-dJ_{PE}$	$= J$

THE COMPOUND NUCLEUS MODEL
(initial population)

After direct and pre-equilibrium emission

$$\sigma_{reaction} = \sigma_{dir} + \sigma_{pre\text{-}equ} + \boxed{\sigma_{NC}}$$

$$\begin{array}{cccc}
N_0 & N_0\text{-}dN_D & N_0\text{-}dN_D\text{-}dN_{PE} & = E \\
Z_0 & Z_0\text{-}dZ_D & Z_0\text{-}dZ_D\text{-}dZ_{PE} & = Z \\
E^*{}_0 & E^*{}_0\text{-}dE^*{}_D & E^*{}_0\text{-}dE^*{}_D\text{-}dE^*{}_{PE} & = E^* \\
J_0 & J_0\text{-}dJ_D & J_0\text{-}dJ_D\text{-}dJ_{PE} & = J
\end{array}$$



THE COMPOUND NUCLEUS MODEL
(basic formalism)

Compound nucleus hypothesys

- Continuum of excited levels
- Independence between incoming channel a and outgoing channel b

$$\sigma_{ab} = \sigma_a^{(CN)} P_b$$

$$\sigma_a^{(CN)} = \frac{\pi}{k_a^2} T_a$$

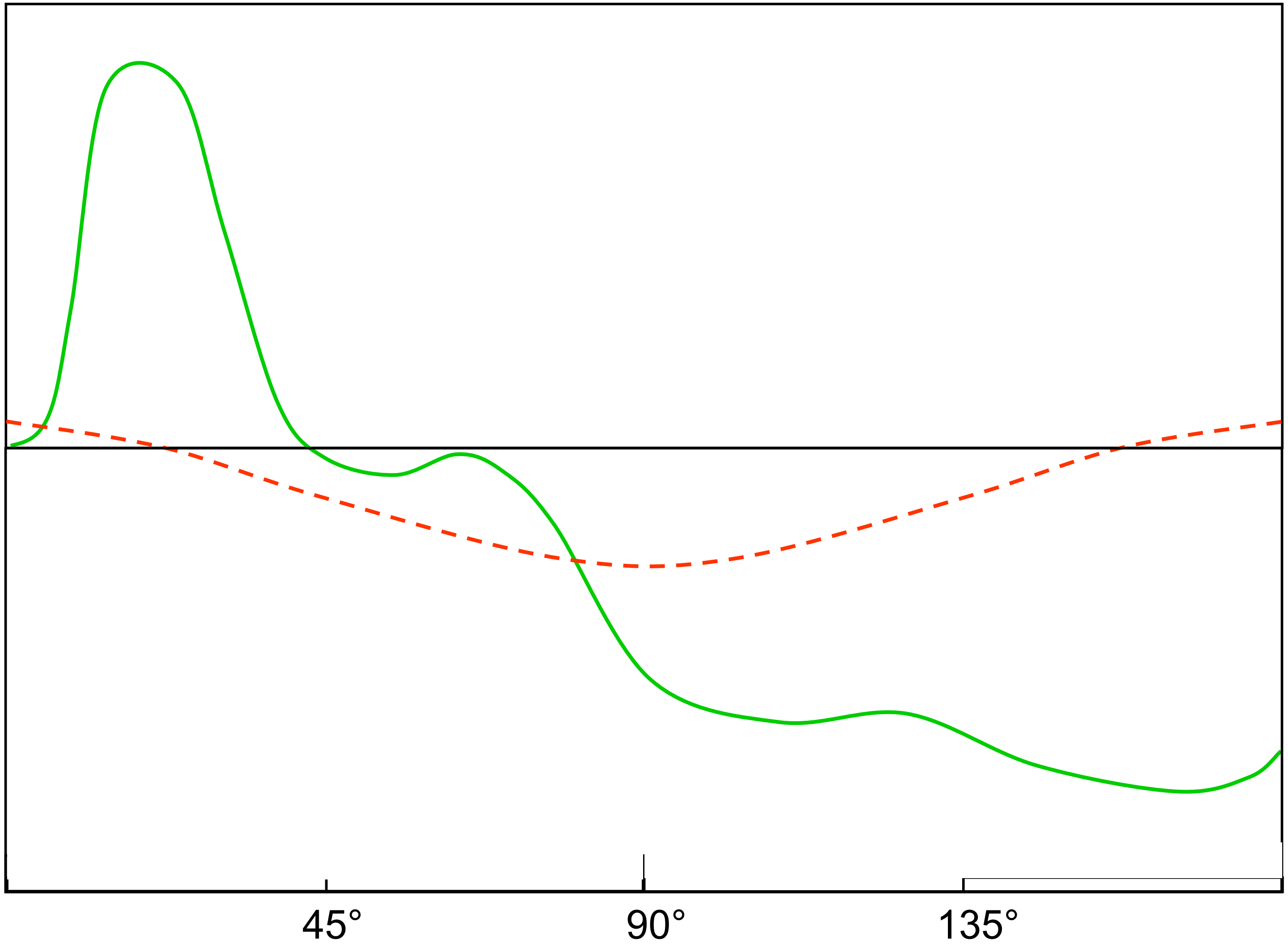
$$P_b = \frac{T_b}{\sum_c T_c}$$

$\Rightarrow$ Hauser- Feshbach formula

$$\sigma_{ab} = \frac{\pi}{k_a^2} \frac{T_a T_b}{\sum_c T_c}$$

THE COMPOUND NUCLEUS MODEL
(qualitative feature)

Compound angular distribution & direct angular distributions



THE COMPOUND NUCLEUS MODEL
(complete channel definition)

Channel Definition

$$a + A \rightarrow (CN)^* \rightarrow b+B$$

Incident channel $a = (\vec{l}_a, \vec{j}_a=\vec{l}_a+\vec{s}_a, \vec{J}_A, \pi_A, E_A, E_a)$

Conservation equations

- Total energy : $E_a + E_A = E_{CN} = E_b + E_B$
- Total momentum : $\vec{p}_a + \vec{p}_A = \vec{p}_{CN} = \vec{p}_b + \vec{p}_B$
- Total angular momentum : $\vec{l}_a + \vec{s}_a + \vec{J}_A = \vec{J}_{CN} = \vec{l}_b + \vec{s}_b + \vec{J}_B$
- Total parity : $\pi_A\ (-1)^{l_a} = \pi_{CN} = \pi_B\ (-1)^{l_b}$

THE COMPOUND NUCLEUS MODEL
(loops over all quantum numbers)

In realistic calculations, all possible quantum number combinations have to be considered

Given by OMP

$$\sigma_{ab} = \frac{\pi}{k_a^2} \sum_{J=|I_A - s_a|}^{I_A + s_a + l_a^{max}} \sum_{\pi = \pm} \frac{(2J+1)}{(2I_A+1)\,(2s_a+1)}$$

THE COMPOUND NUCLEUS MODEL
(loops over all quantum numbers)

In realistic calculations, all possible quantum number combinations have to be considered

$$\sigma_{ab} = \frac{\pi}{k_a^2} \sum_{J=|I_A-s_a|}^{I_A+s_a+l_a^{max}} \sum_{\pi=\pm} \frac{(2J+1)}{(2I_A+1)\,(2s_a+1)}$$

$$\sum_{j_a=|J-I_A|}^{J+I_A} \sum_{l_a=|j_a-s_a|}^{j_a+s_a} \sum_{j_b=|J-I_B|}^{J+I_B} \sum_{l_b=|j_b-s_b|}^{j_b+s_b}$$

Parity selection rules

$$\delta_\pi(a)\,\delta_\pi(b)\,\frac{T^{J\pi}_{a,l_a,j_a}\; T^{J\pi}_{b,l_b,j_b}}{\sum_{c} T^{J\pi}_{c,l_c,j_c}}$$

THE COMPOUND NUCLEUS MODEL
(loops over all quantum numbers)

In realistic calculations, all possible quantum number combinations have to be considered

$$\sigma_{ab} = \frac{\pi}{k_a^2} \sum_{J=|I_A-s_a|}^{I_A+s_a+l_a^{max}} \sum_{\pi=\pm} \frac{(2J+1)}{(2I_A+1)\,(2s_a+1)}$$

$$\sum_{j_a=|J-I_A|} \quad \sum_{l_a=|j_a-s_a|} \quad \sum_{j_b} \quad \sum_{l_b=|j_b-s_b|}$$

$$\delta_\pi(a)\,\delta_\pi(b)\,\frac{T^{J\pi}_{a,l_a,j_a}\;T^{J\pi}_{b,l_b,j_b}}{\sum_{c} T^{J\pi}_{c,l_c,j_c}}\;W^{J\pi}_{a,l_a,j_a,b,l_b,j_b}$$

Width fluctuation correction factor to account for deviations from independance hypothesis

THE COMPOUND NUCLEUS MODEL
(width fluctuation correction factor)

Breit-Wigner resonance integrated and averaged over an energy width Corresponding to the incident beam dispersion

$$\langle \sigma_{ab} \rangle = \frac{\pi}{k_a^2} \frac{2\pi}{D} \left\langle \frac{\Gamma_a \Gamma_b}{\Gamma_{tot}} \right\rangle$$

Since $T_\alpha \approx \frac{2\pi \langle \Gamma_\alpha \rangle}{D}$

$$\Rightarrow \begin{cases} \langle \sigma_{ab} \rangle = \frac{\pi}{k_a^2} \frac{T_a \; T_b}{\sum_c T_c} W_{ab} \\ \text{with} \quad W_{ab} = \left\langle \frac{\Gamma_a \Gamma_b}{\Gamma_{tot}} \right\rangle \Big/ \frac{\langle \Gamma_a \rangle \langle \Gamma_b \rangle}{\langle \Gamma_{tot} \rangle} \end{cases}$$

THE COMPOUND NUCLEUS MODEL
(main methods to calculate WFCF)

- Tepel method

  Simplified iterative method

- Moldauer method

  Simple integral

- GOE triple integral

  « exact » result

Elastic enhancement with respect to the other channels
Inelastic enhancement sometimes in very particular situations ?

THE COMPOUND NUCLEUS MODEL
(the GOE triple integral)

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

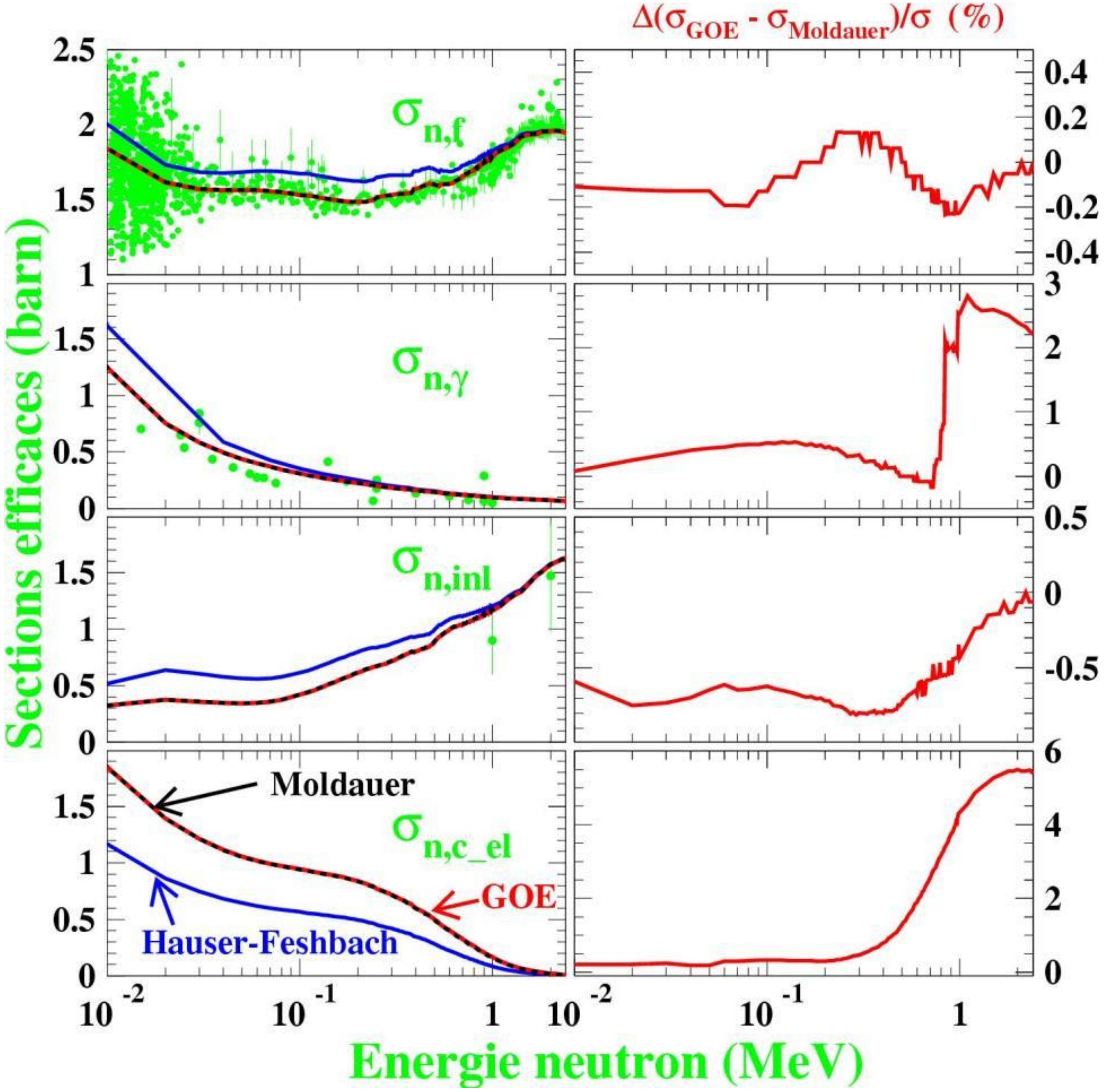
$$\prod_c \frac{(1-\lambda\, T^J_{c,l_c,j_c})}{\sqrt{(1+\lambda_1\, T^J_{c,l_c,j_c})(1+\lambda_2\, T^J_{c,l_c,j_c})}} \quad \Bigg\{ \delta_{ab}(1- \; T^J_{a,l_a,j_a})$$

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

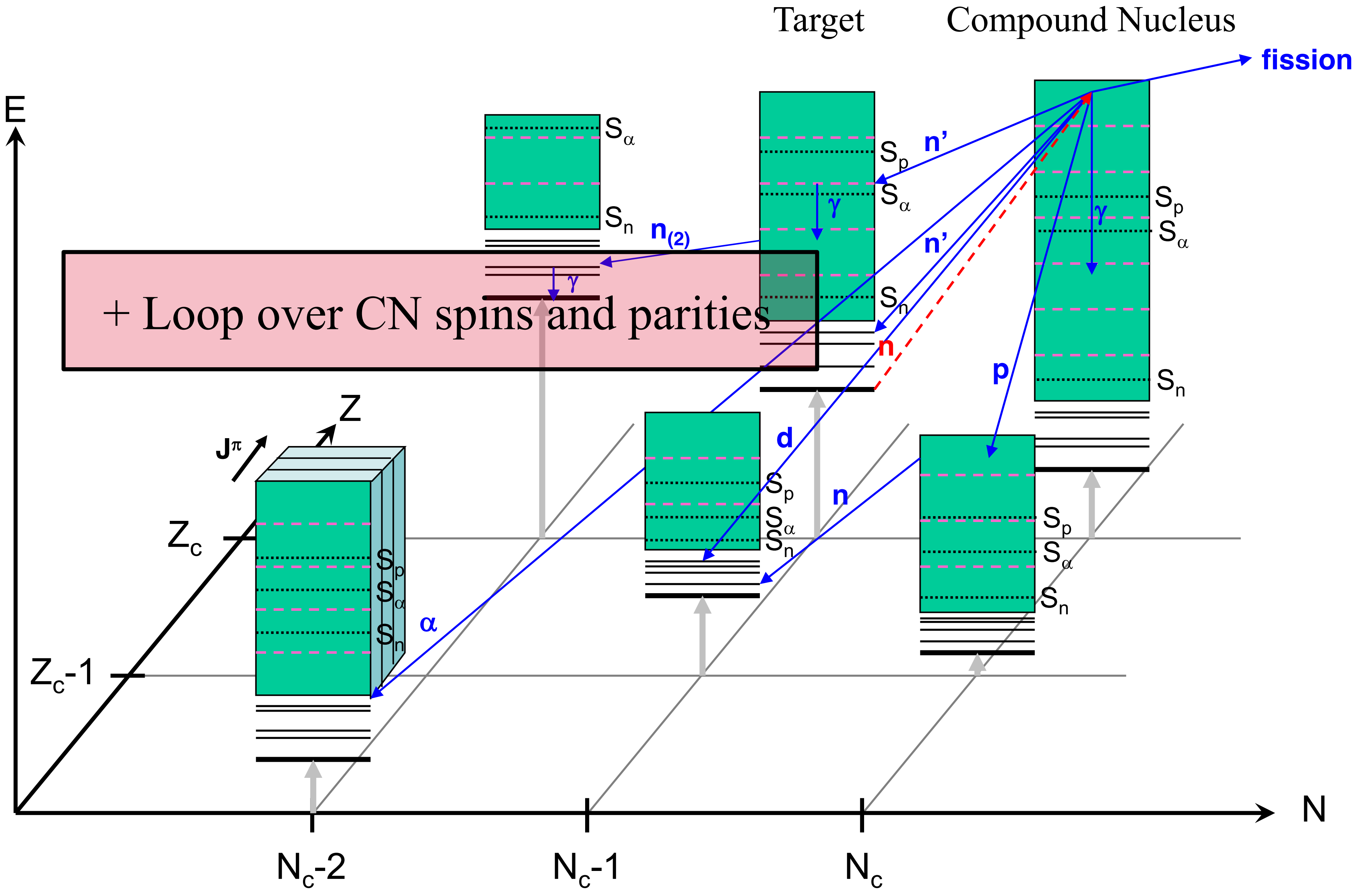
$$\left[\frac{\lambda_1(1+\lambda_1)}{(1+\lambda_1\, T^J_{a,l_a,j_a})(1+\lambda_1\, T_{b,l_b,j_b})} + \frac{\lambda_2(1+\lambda_2)}{(1+\lambda_2\, T^J_{a,l_a,j_a})(1+\lambda_2\, T_{b,l_b,j_b})}\right.$$

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

THE COMPOUND NUCLEUS MODEL
(flux redistribution illustration)

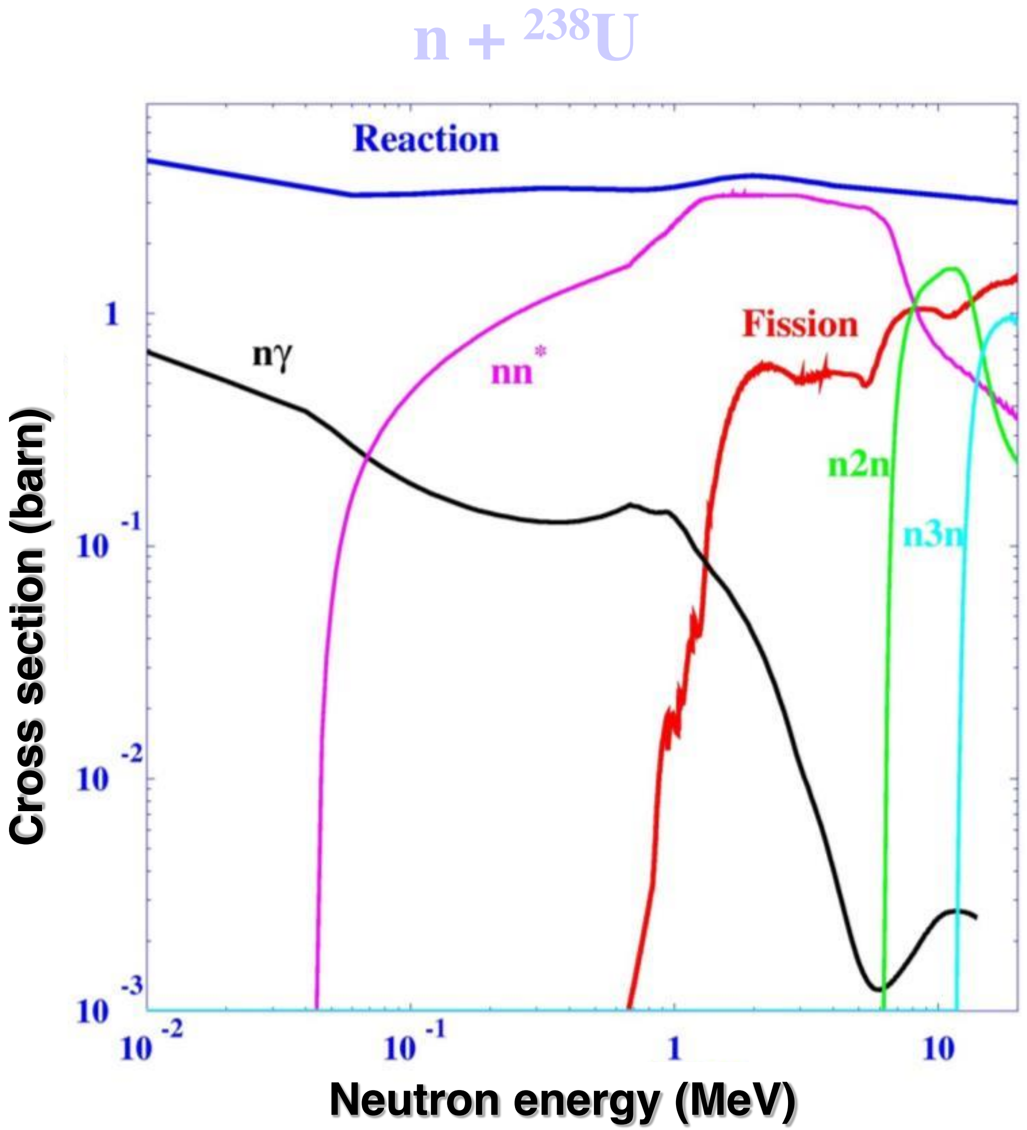


THE COMPOUND NUCLEUS MODEL
(multiple emission)



+ Loop over CN spins and parities

REACTION MODELS & REACTION CHANNELS



Optical model

+

Statistical model

+

Pre-equilibrium model

$$\sigma_R = \sigma_d + \sigma_{PE} + \sigma_{CN}$$

$$= \sigma_{nn'} + \sigma_{nf} + \sigma_{n\gamma} + \ldots$$

THE COMPOUND NUCLEUS MODEL
(compact expression)

$$\sigma_{NC} = \sum_{b} \sigma_{ab}$$ où 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

MISCELLANEOUS : THE PHOTON EMISSION
(strength function and selection rules)

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

Standard Lorentzian (SLO)

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

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

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(strength function and selection rules)

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Spacing of states from which the decay occurs

BUT

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MISCELLANEOUS : THE PHOTON EMISSION
(strength function 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 EM (E ou M)

λ : transition multipolarity

ε_γ : outgoing gamma energy

$f(k,\lambda,\varepsilon_\gamma)$: gamma strength function (several models)

Decay selection rules from a level $J_i^{\pi i}$ to a level $J_f^{\pi f}$:

Pour **Eλ**: $\pi_f=(-1)^{\lambda}\,\pi_i$

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

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

(E1 ≈ 10^2 M1)
(XL ≈ 10^{-3} XL-1)

Renormalisation method for thermal neutrons

$$\langle T_\gamma\rangle = \sum_{J_i,\pi_i}\sum_{k\lambda}\sum_{J_f,\pi_f}\int_{0}^{B_n} T^{k\lambda}(\varepsilon)\,\rho(B_n-\varepsilon,J_f,\pi_f)\,S(\lambda,J_i,\pi_i,J_i,\pi_f)\,d\varepsilon = 2\pi\,\langle\Gamma_\gamma\rangle\,\rho(B_n)$$

MISCELLANEOUS : THE PHOTON EMISSION
(strength function and selection rules)

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

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(E1 ≈ 10^2 M1)
(XL ≈ 10^{-3} XL-1)

Renormalisation method for thermal neutrons

experiment

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

MISCELLANEOUS : THE PHOTON EMISSION
(strength function and selection rules)

Improved analytical expressions :

- 2 Lorentzians for deformed nuclei

- Account for low energy deviations from standard Lorentzians for E1
  - . Kadmenskij-Markushef-Furman model (1983)
    - $\Rightarrow$ Enhanced Generalized Lorentzian model of Kopecky-Uhl (1990)
    - $\Rightarrow$ Hybrid model of Goriely (1998)
    - $\Rightarrow$ Generalized Fermi liquid model of Plujko-Kavatsyuk (2003)

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

MISCELLANEOUS : THE PHOTON EMISSION (strength function and selection rules)

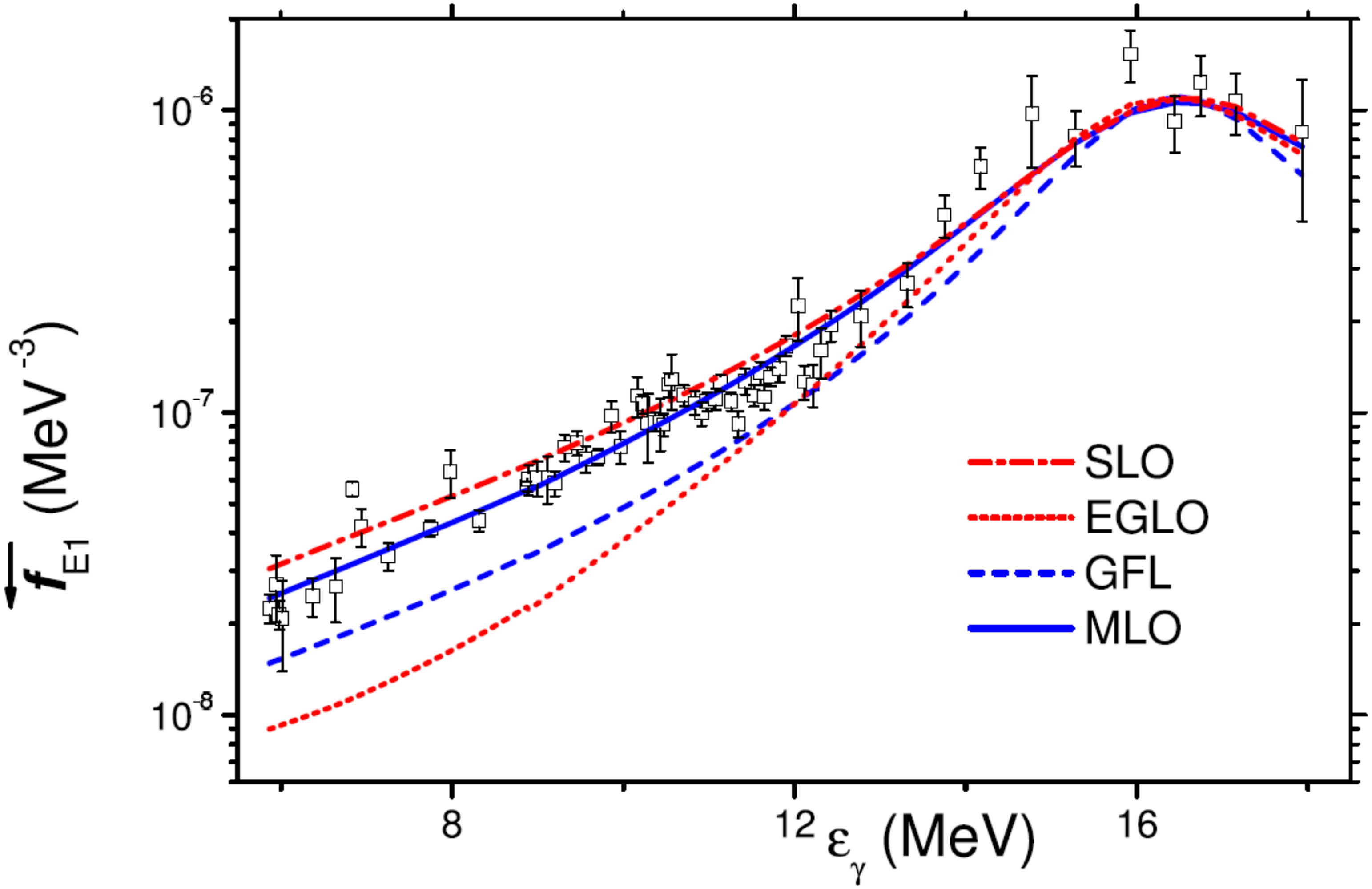

FIG. 42: E1 γ-decay strength function plotted against energy ϵ_γ for ^{90}Zr; experimental data are taken from Ref. [327].

MISCELLANEOUS : THE PHOTON EMISSION
(strength function and selection rules)

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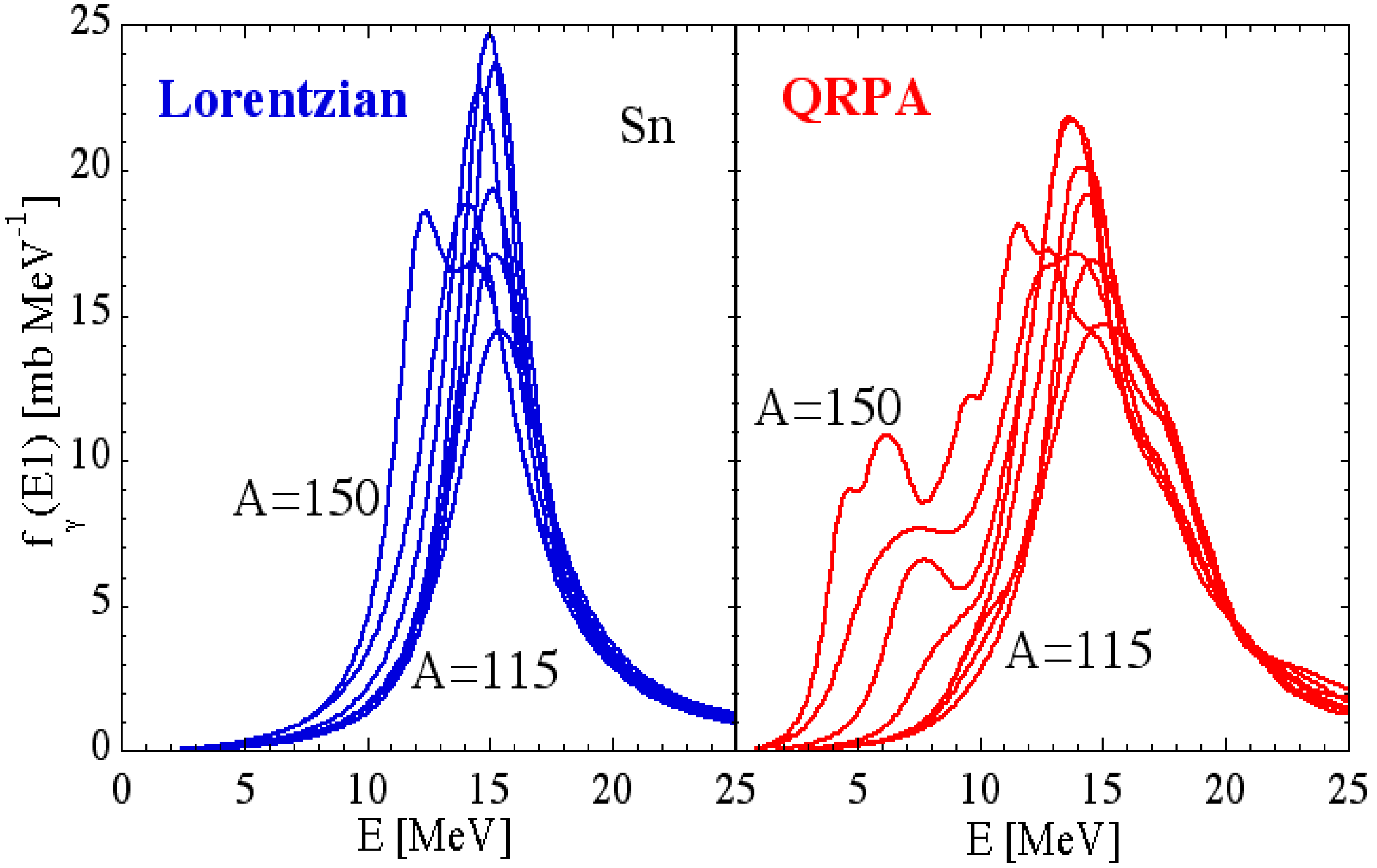
Microscopic approaches : RPA, QRPA

« *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!!!)

MISCELLANEOUS : THE PHOTON EMISSION (phenomenology vs microscopic)

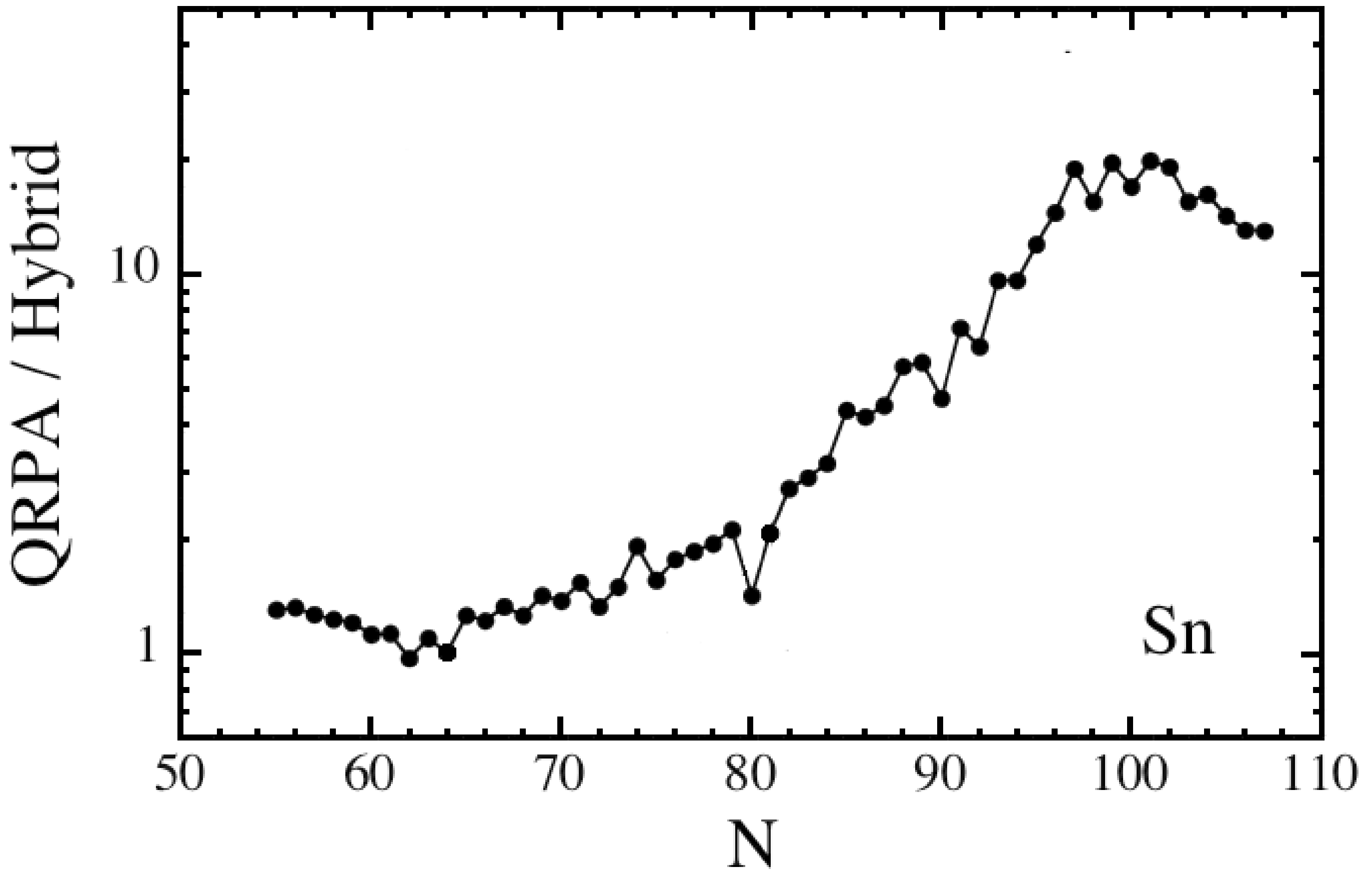


See S. Goriely & E. Khan, NPA 706 (2002) 217.

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

MISCELLANEOUS : THE PHOTON EMISSION (phenomenology vs microscopic)

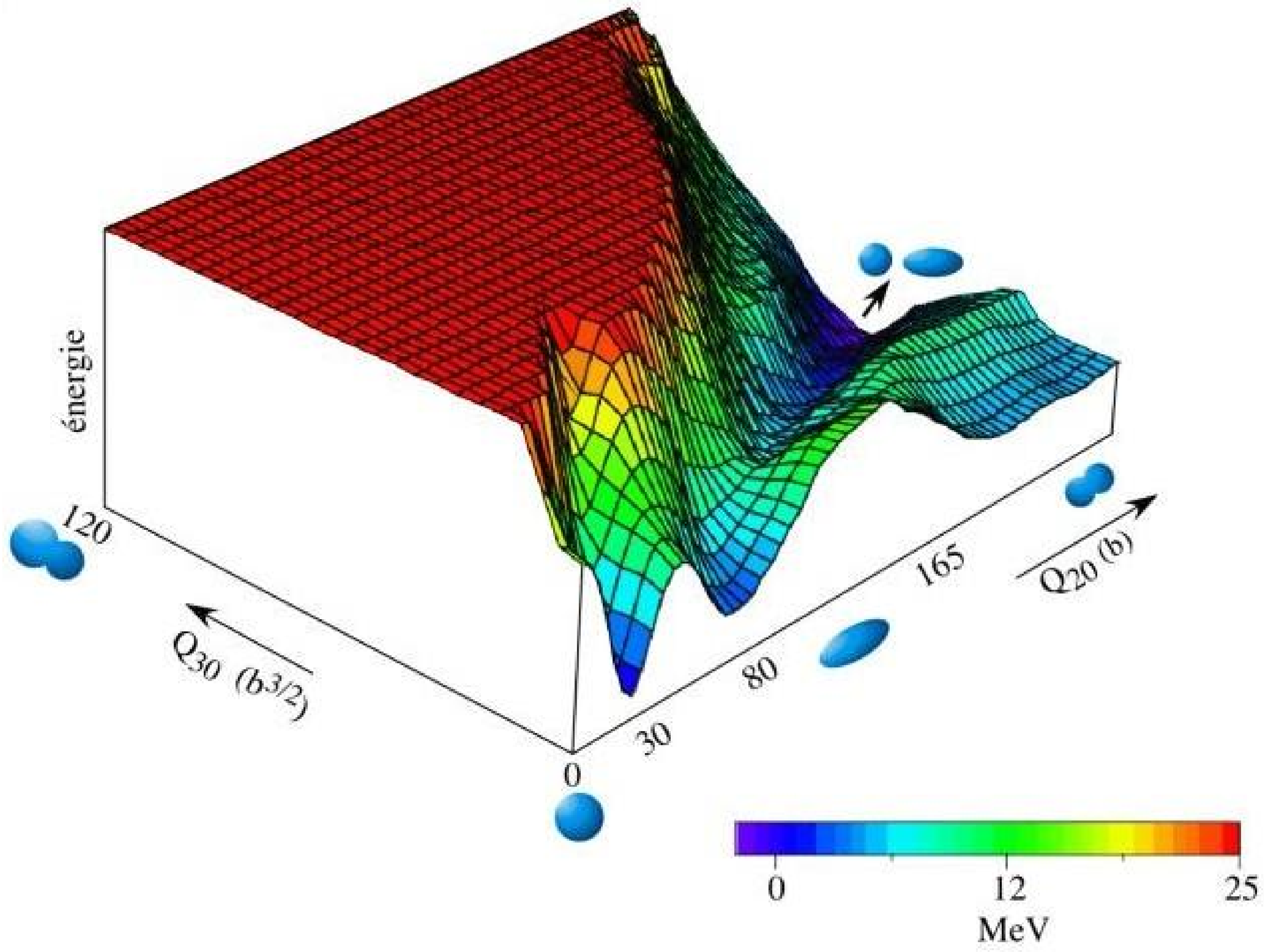
Capture cross section @ E_n=10 MeV for Sn isotopes



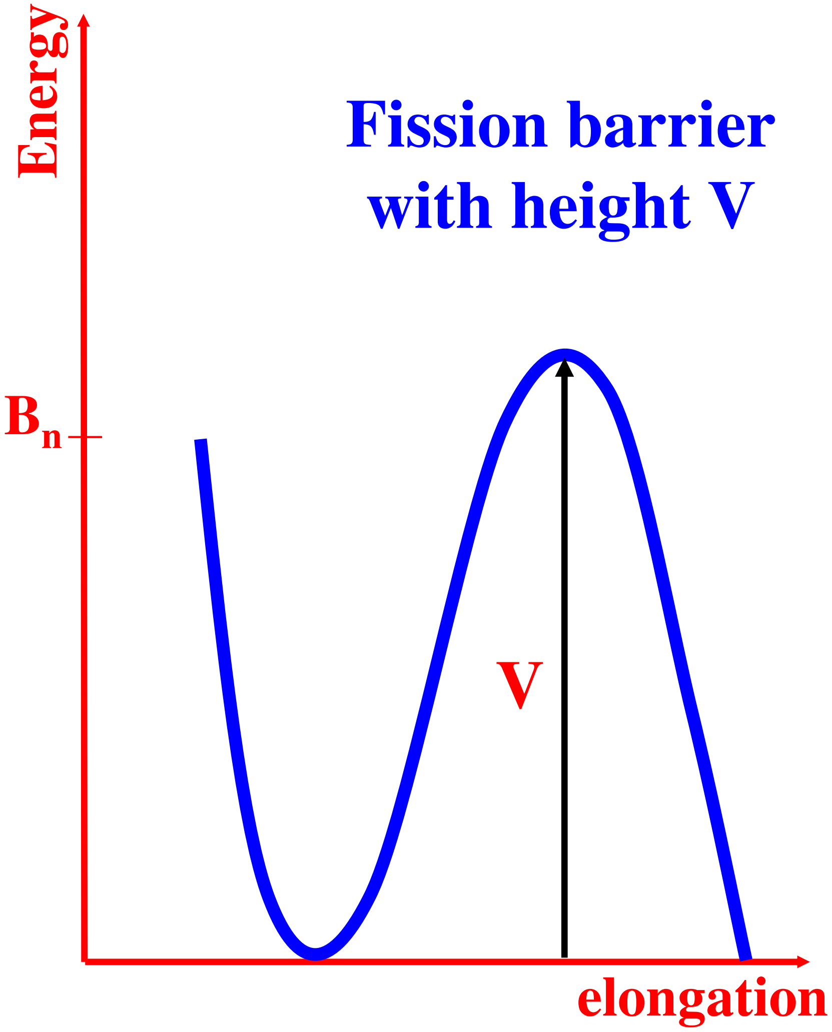
⇒ **Weak impact close to stability but large for exotic nuclei**

MISCELLANEOUS : THE FISSION PROCESS
(static picture exhibiting fission barriers)

Surface ^{238}U

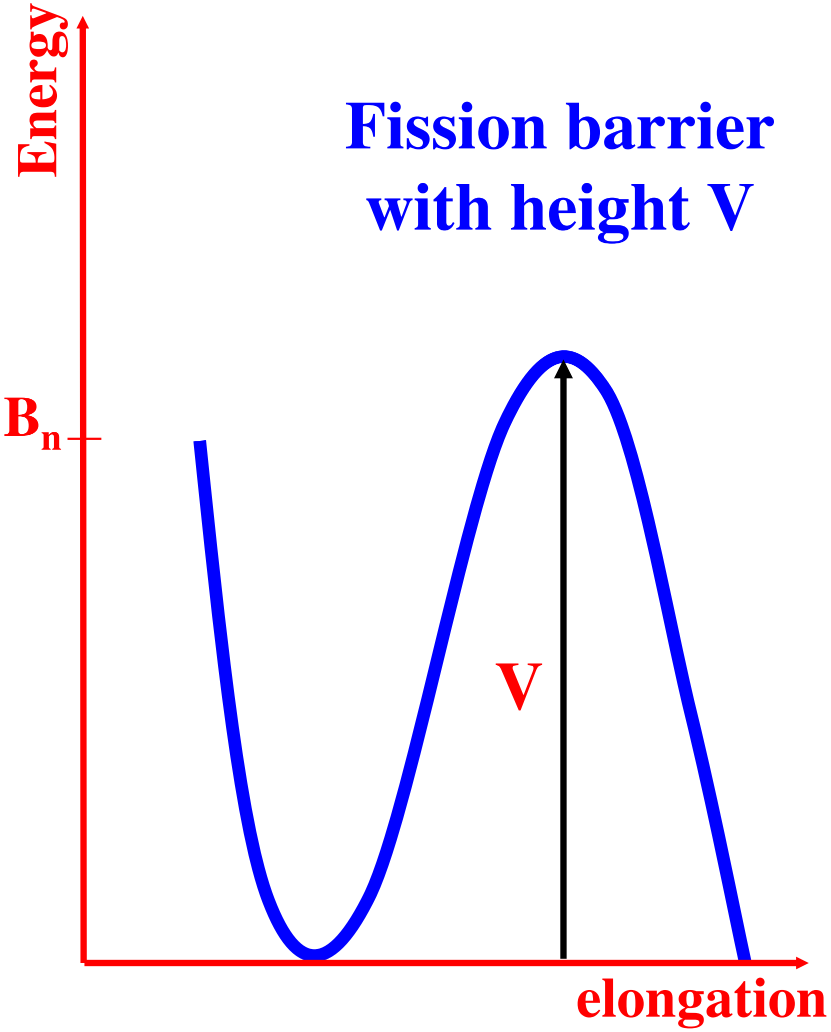


MISCELLANEOUS : THE FISSION PROCESS
(fissile or fertile ?)



$B_n < V$

Fertile target (^{238}U)



MISCELLANEOUS : THE FISSION PROCESS
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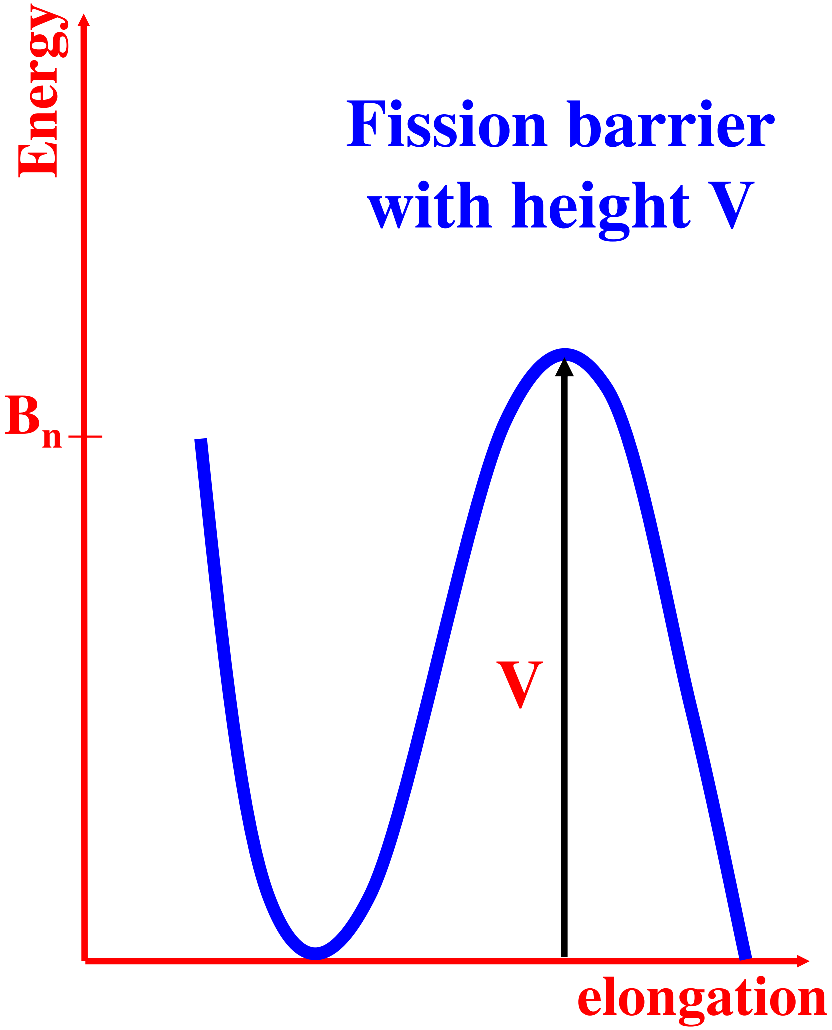
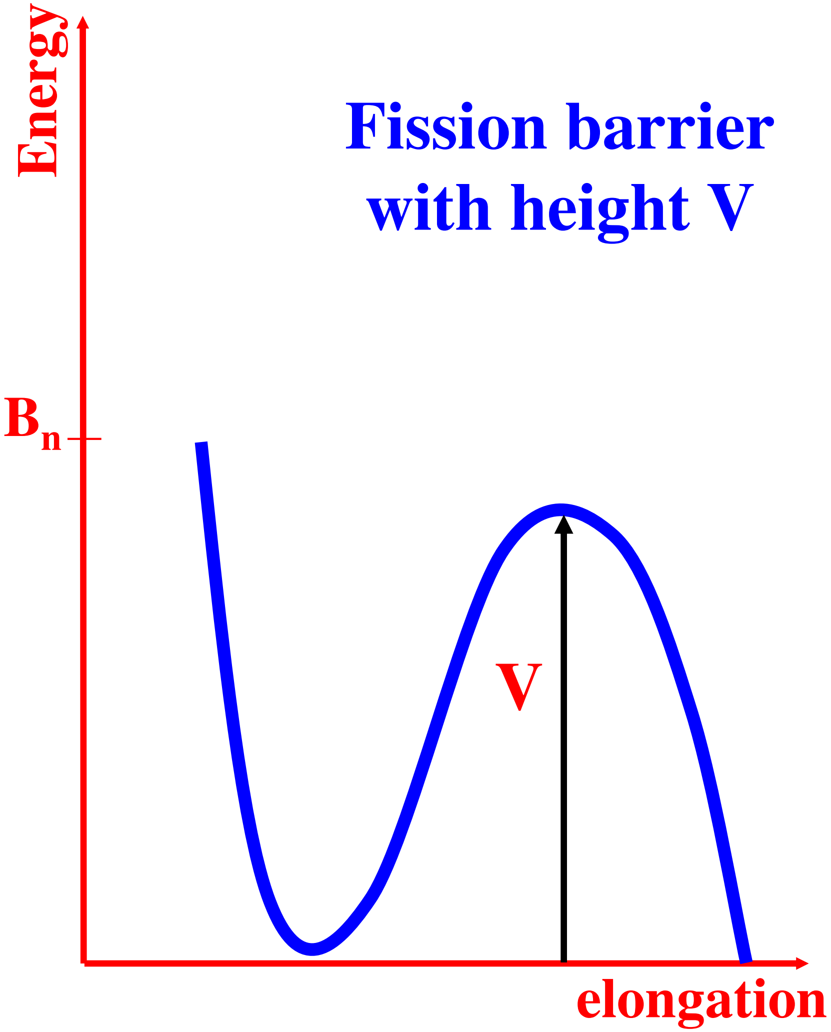


$B_n < V$

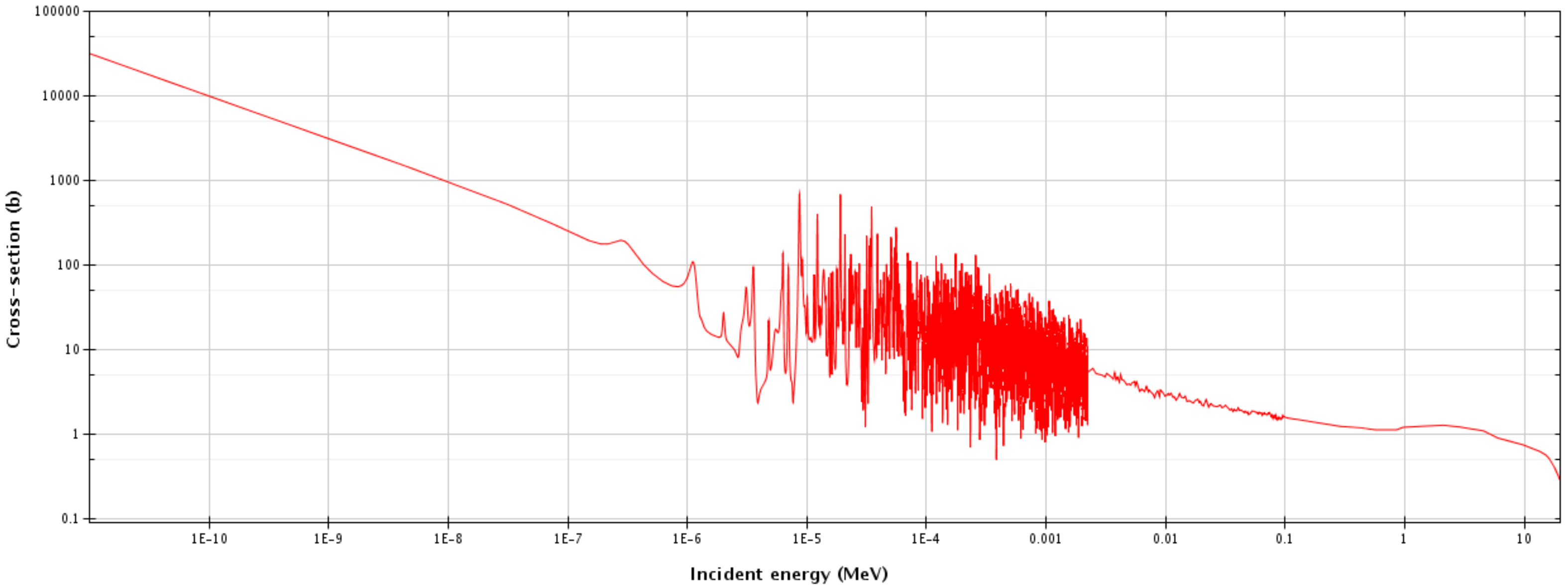
Fertile target (^{238}U)



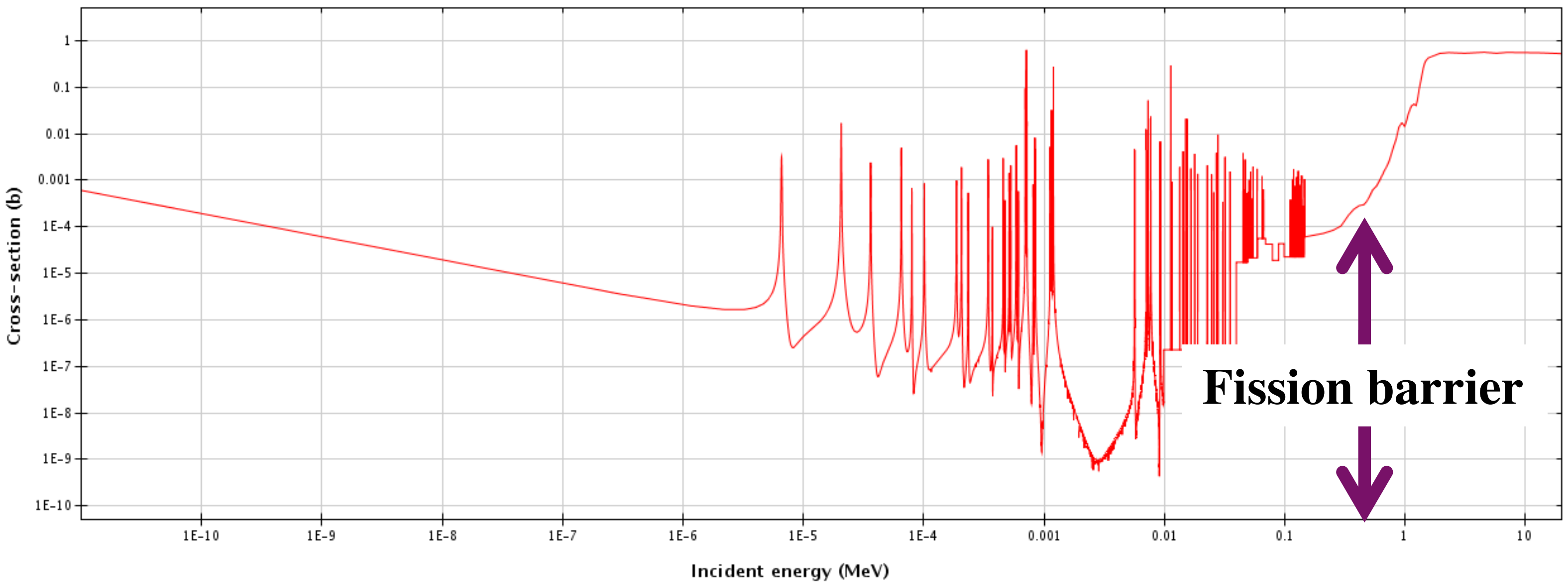
$B_n > V$

Fissile target (^{235}U)

MISCELLANEOUS : THE FISSION PROCESS
(fissile or fertile ?)



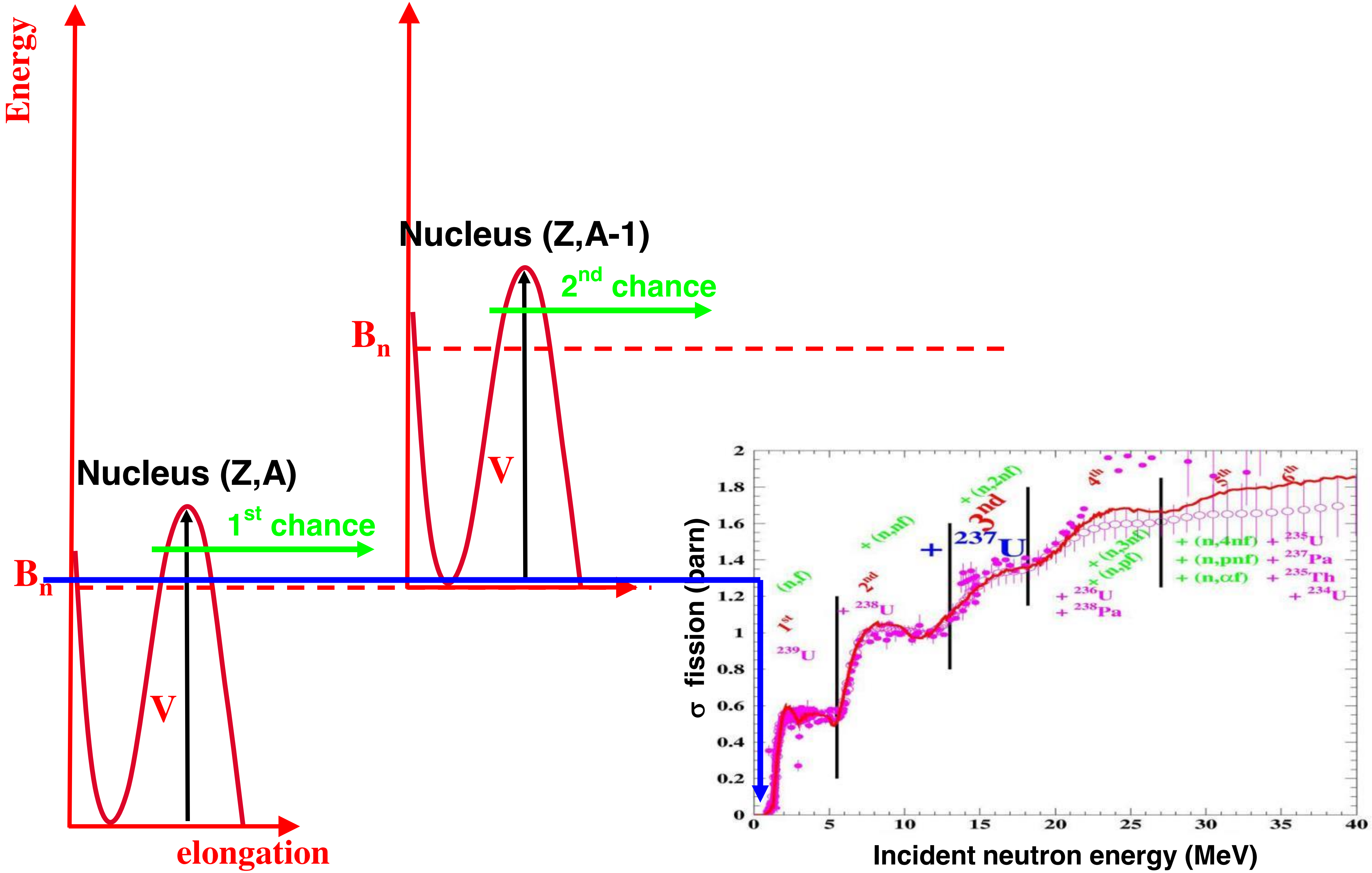
Incident neutron data / ENDF/B-VI.8 / U235 / MT=19 : (n,f) / Cross section



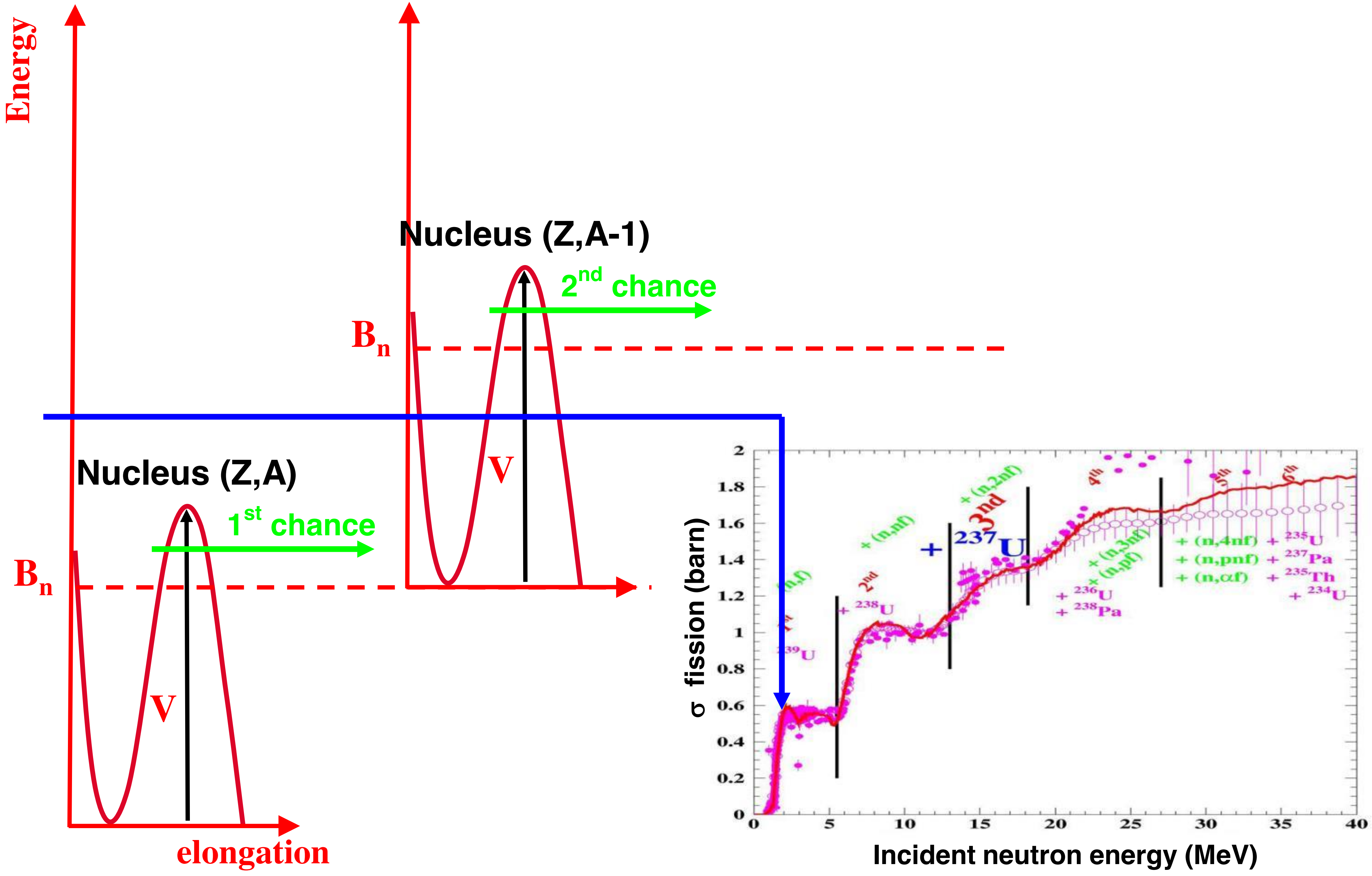
Incident neutron data / ENDF/B-VI.8 / U238 / MT=19 : (n,f) / Cross section

Fission barrier

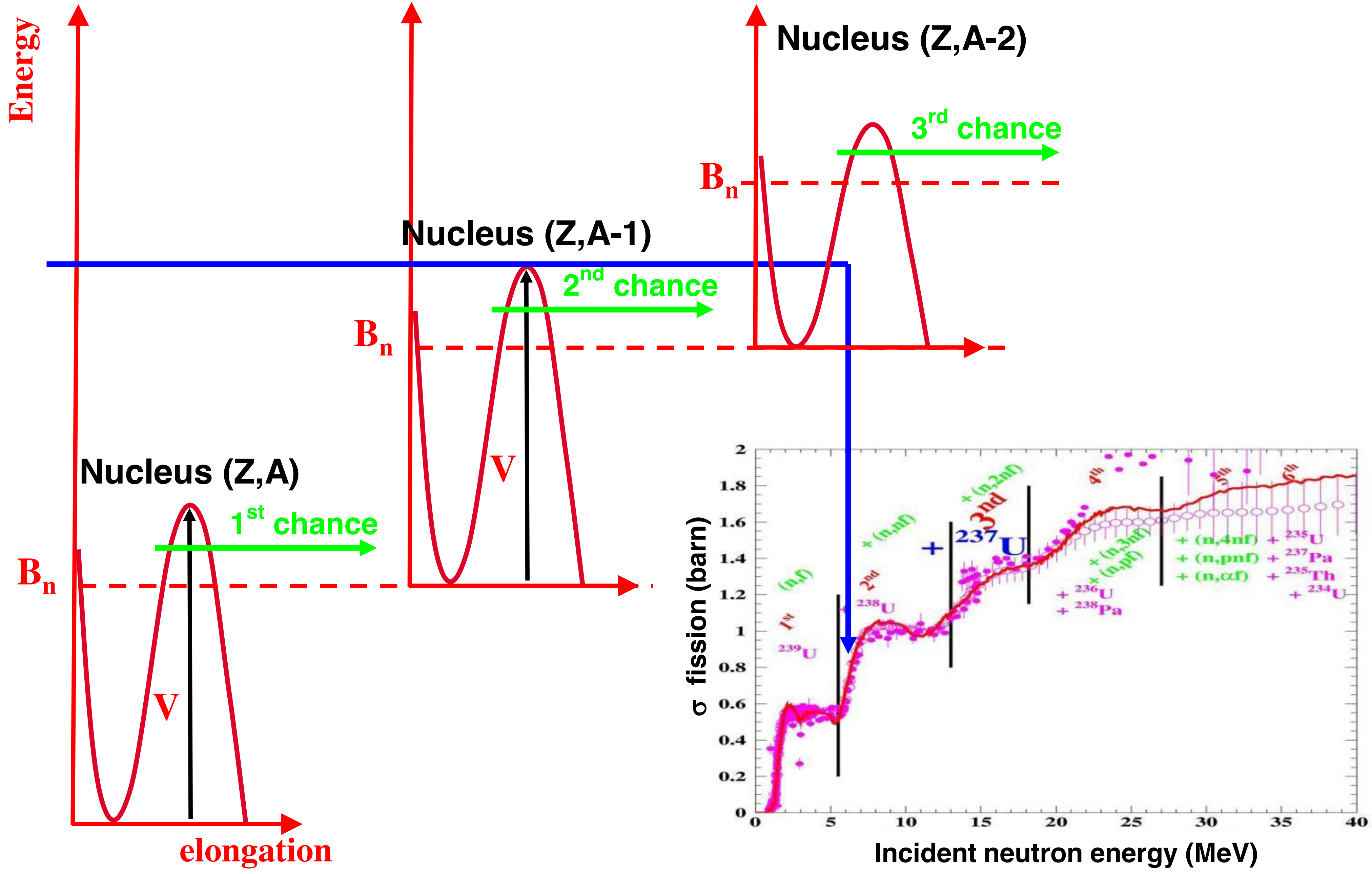
MISCELLANEOUS : THE FISSION PROCESS (multiple chances)



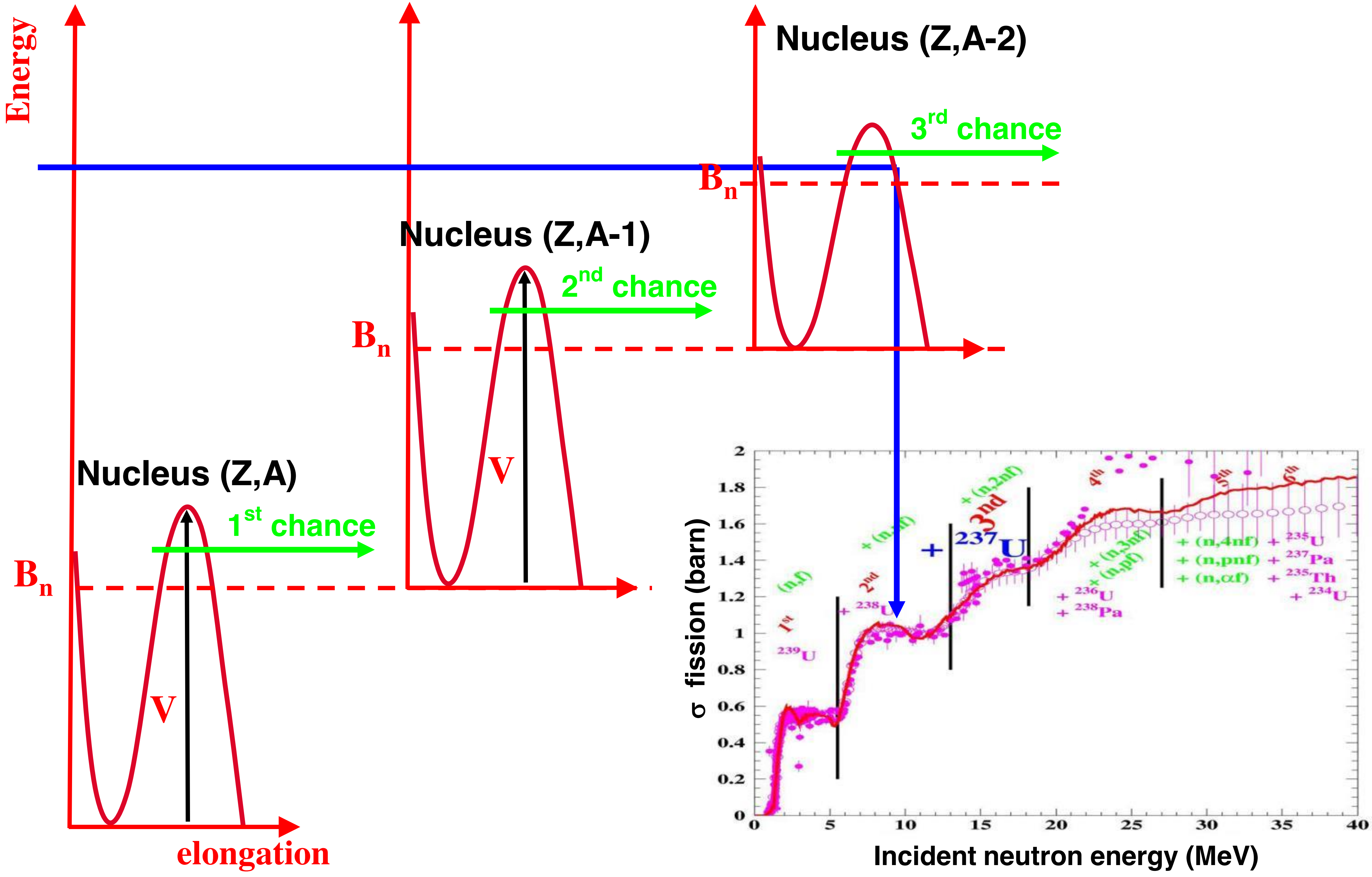
MISCELLANEOUS : THE FISSION PROCESS
(multiple chances)



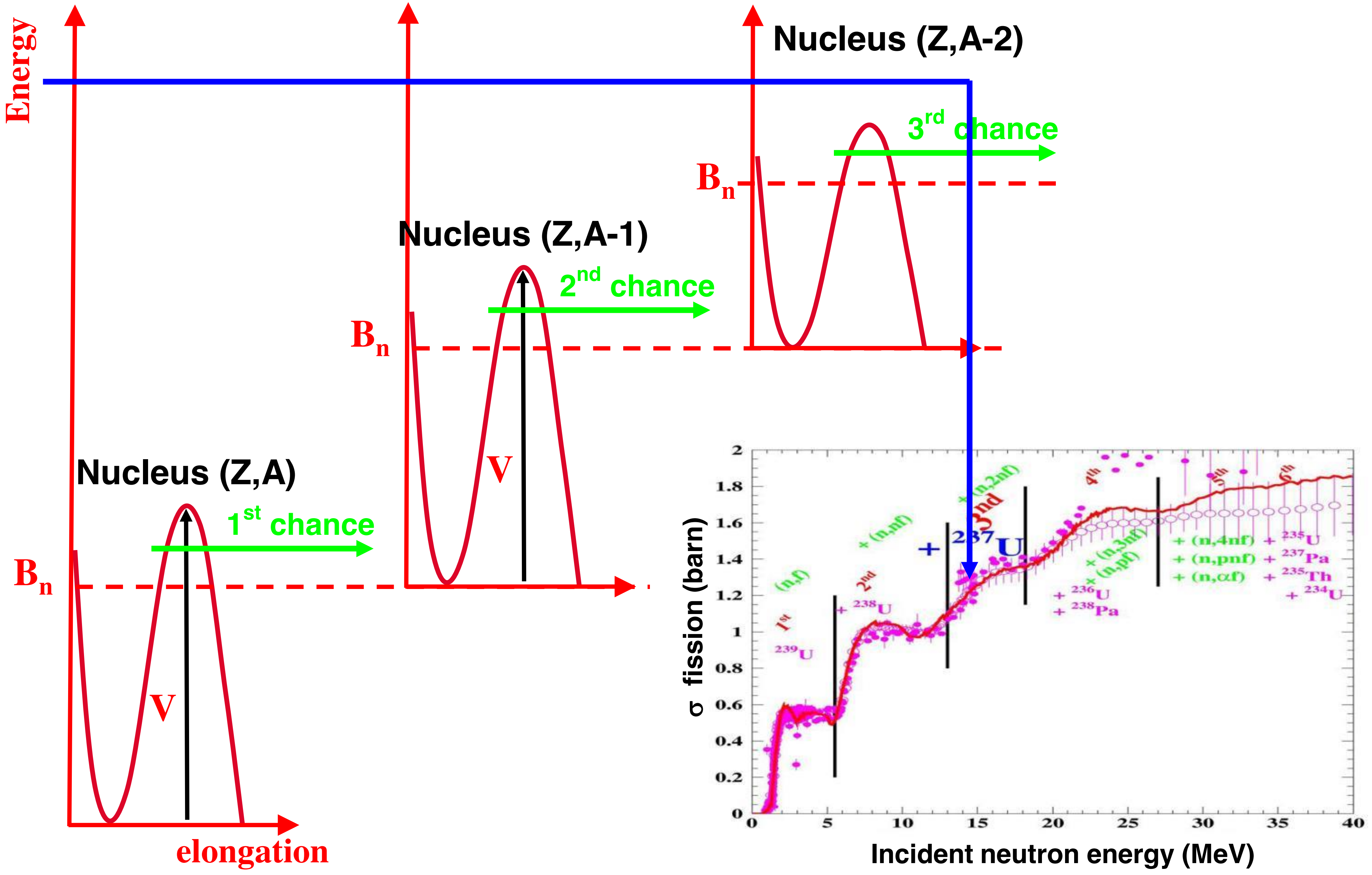
MISCELLANEOUS : THE FISSION PROCESS
(multiple chances)



MISCELLANEOUS : THE FISSION PROCESS
(multiple chances)



MISCELLANEOUS : THE FISSION PROCESS
(multiple chances)



MISCELLANEOUS : THE FISSION PROCESS
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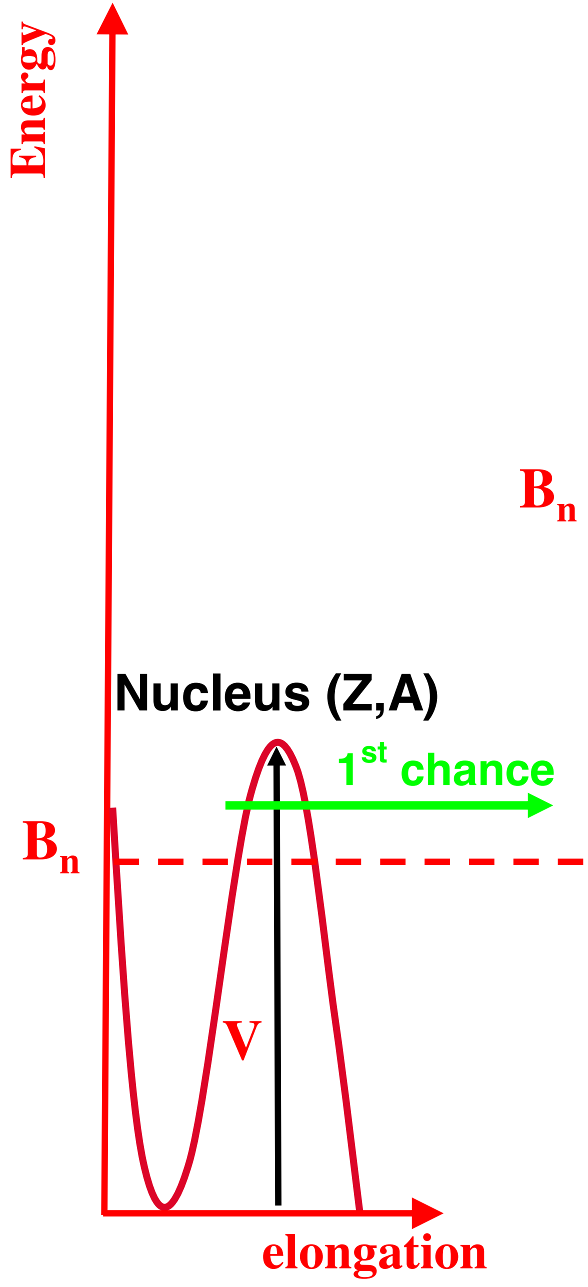
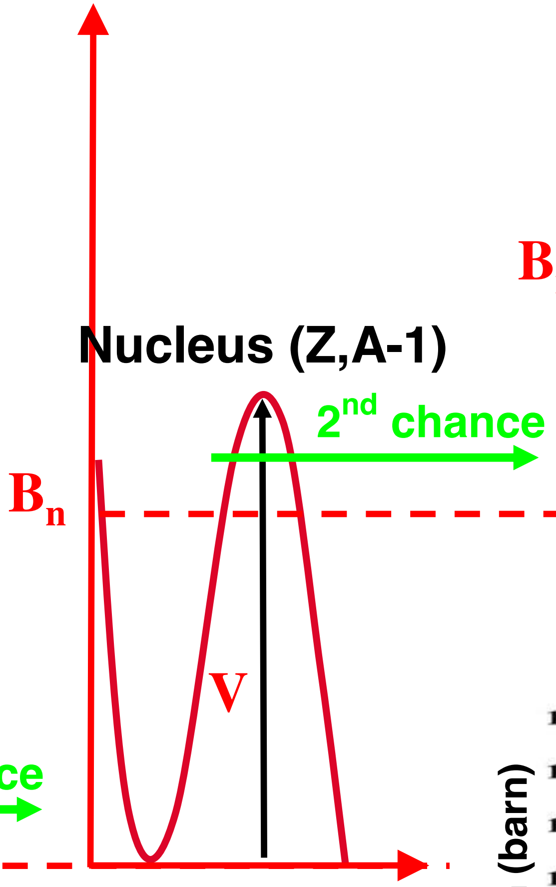
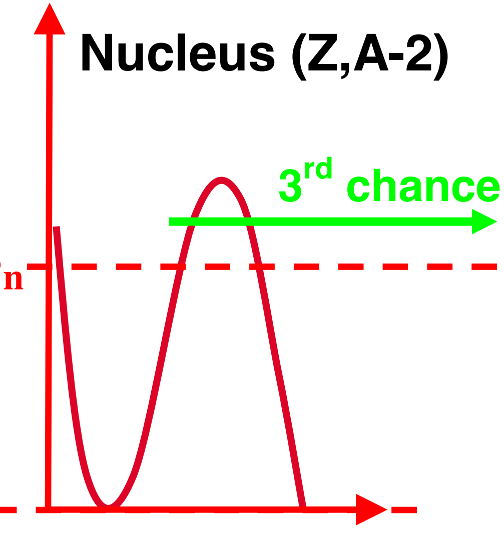
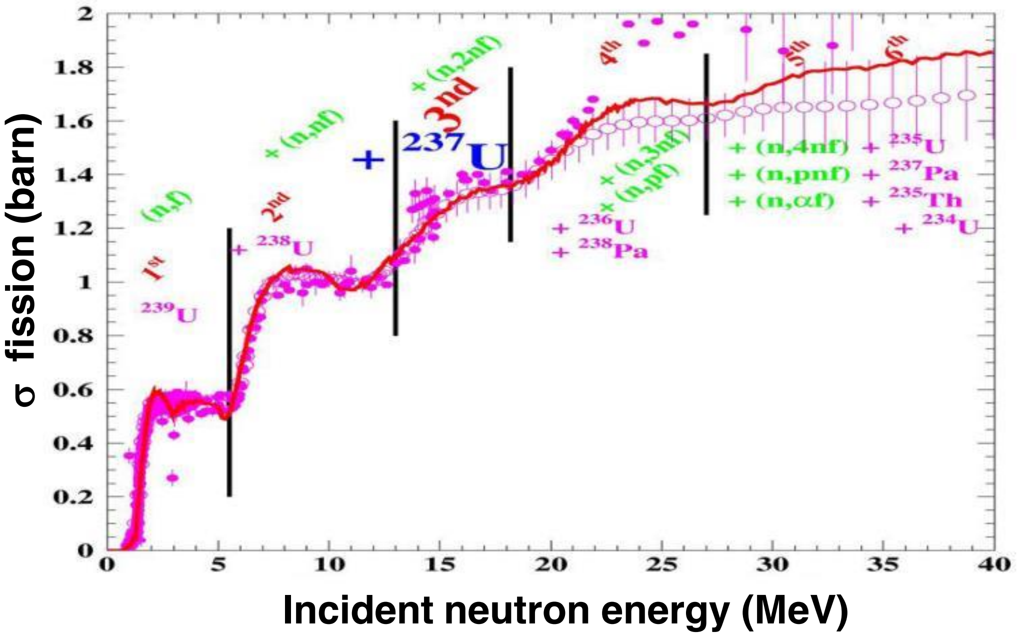
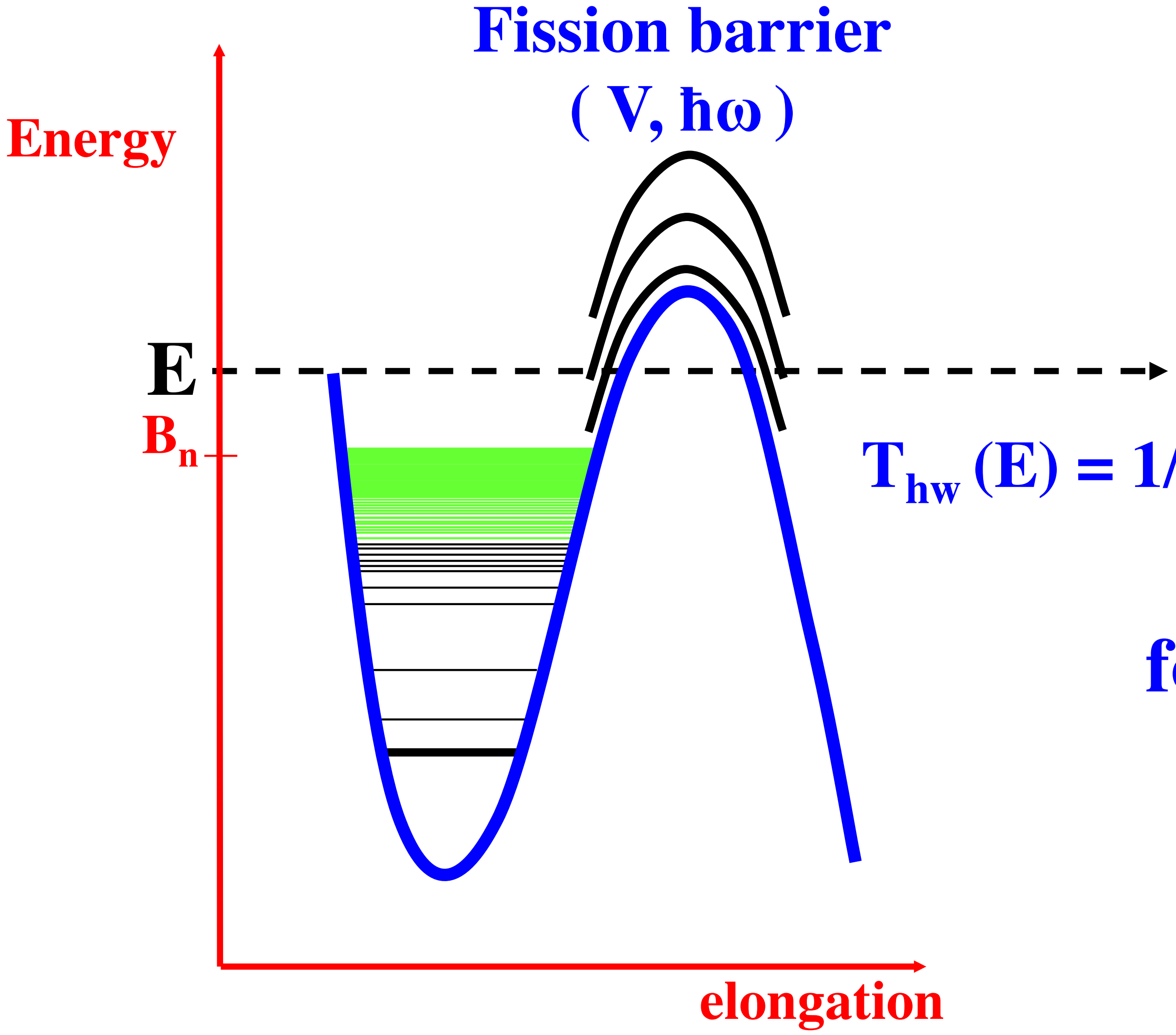








MISCELLANEOUS : THE FISSION PROCESS
(Fission penetrability: Hill-Wheeler)



$T_{hw}(E) = 1/[1 + \exp(2\pi(V\text{-}E)/\hbar\omega)]$

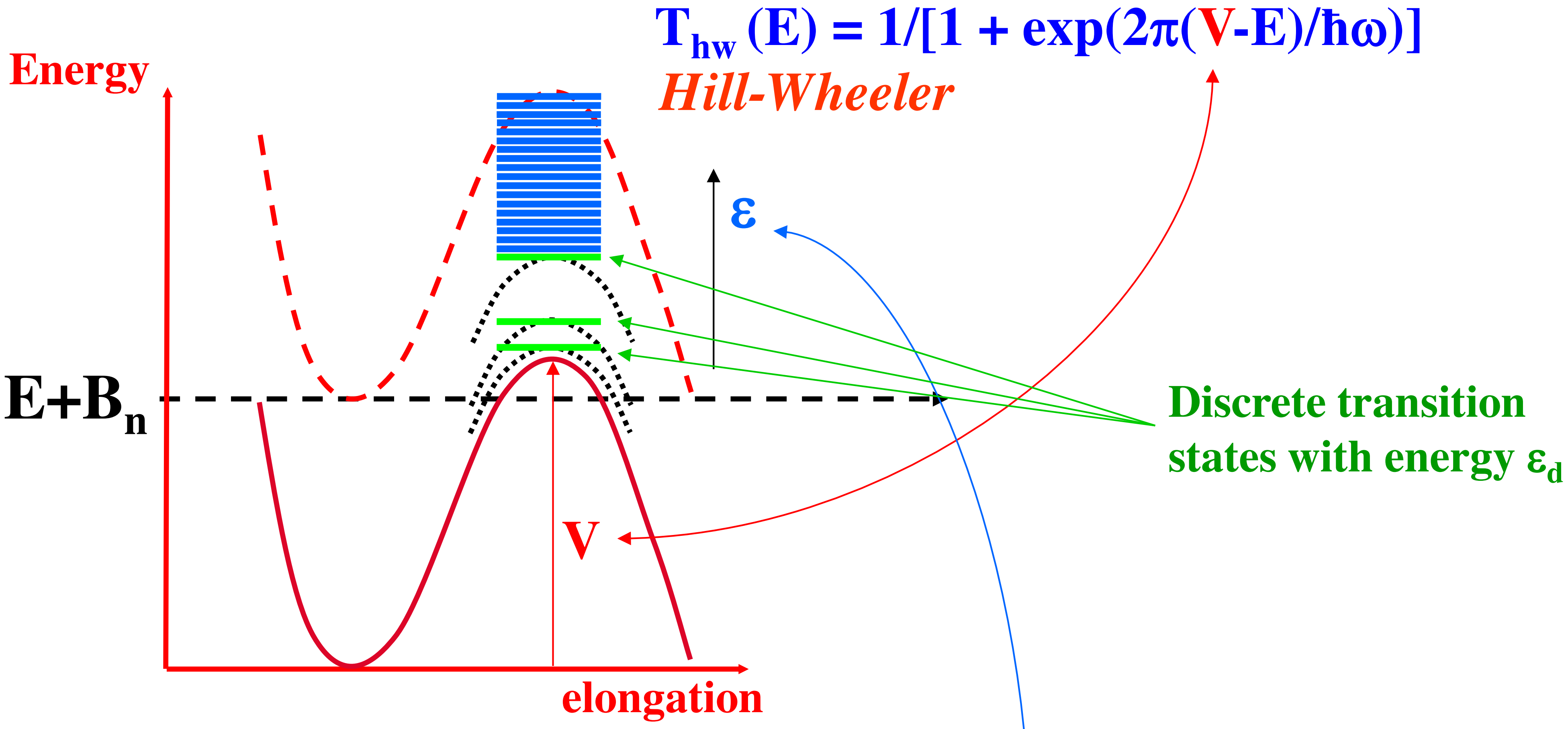
Hill-Wheeler

for one barrier !

+ transition state on top of the barrier !

Bohr hypothesys

MISCELLANEOUS : THE FISSION PROCESS
(Fission transmission coefficients)



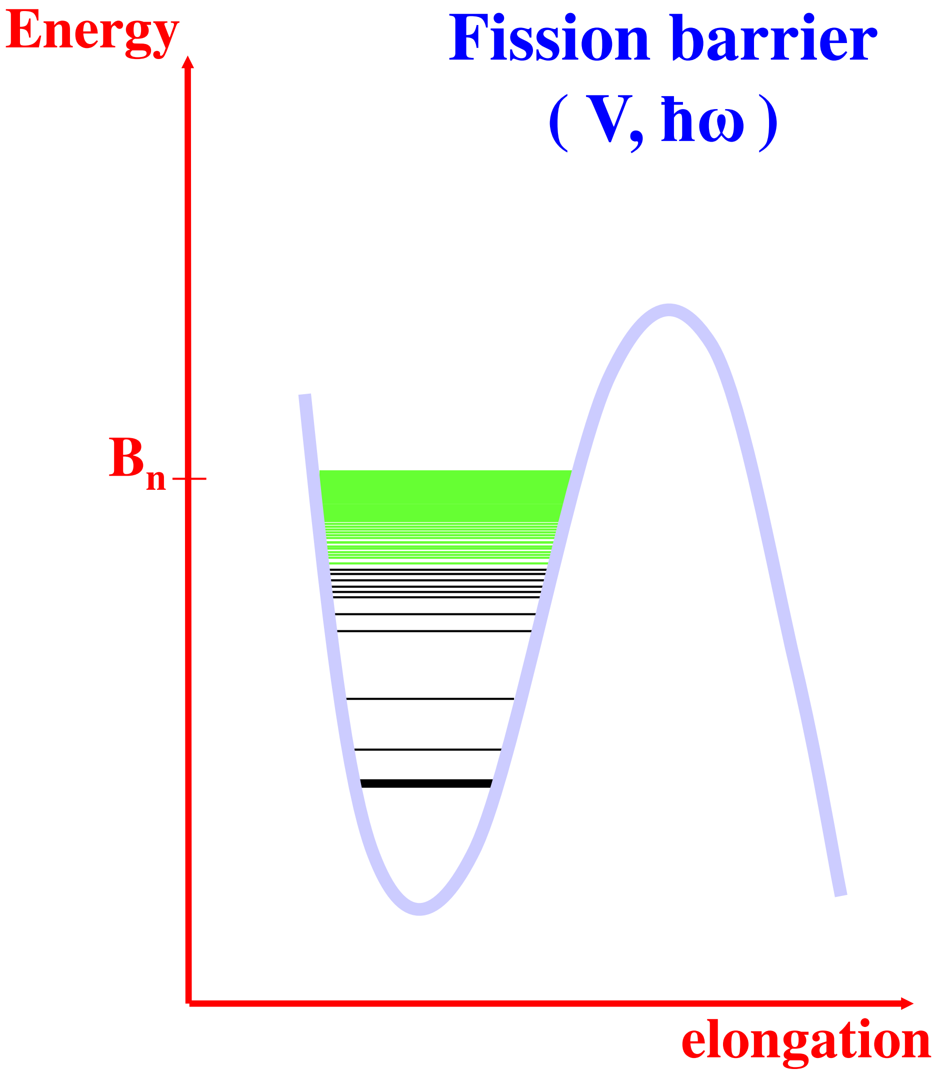
$T_{hw}(E) = 1/[1 + \exp(2\pi(V\text{-}E)/\hbar\omega)]$

Hill-Wheeler

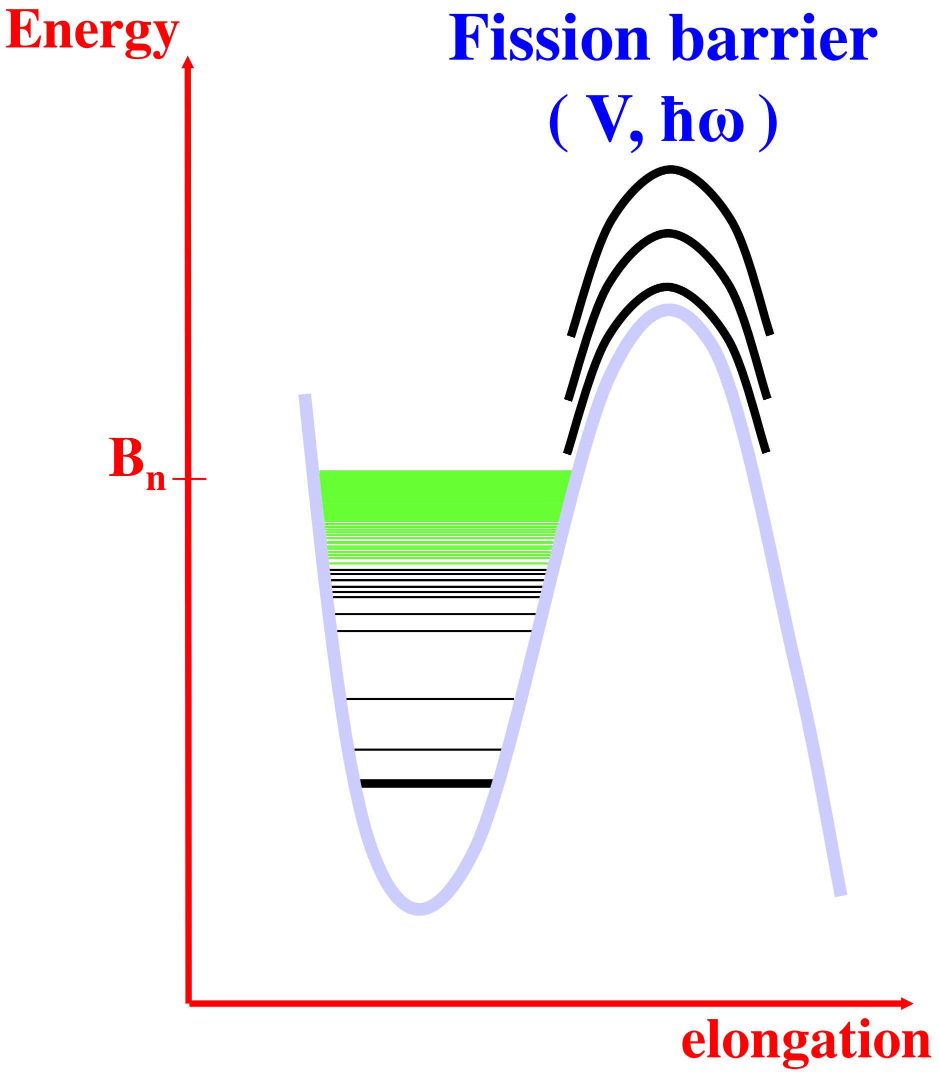
Discrete transition states with energy ε_d

$$T_f(E, J, \pi) = \sum_{\substack{\text{discrets} \\ J,\, \pi}} T_{hw}(E - \varepsilon_d) + \int_{E_s}^{E+B_n} \rho(\varepsilon,J,\pi)\, T_{hw}(E - \varepsilon)\, d\varepsilon$$

MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)

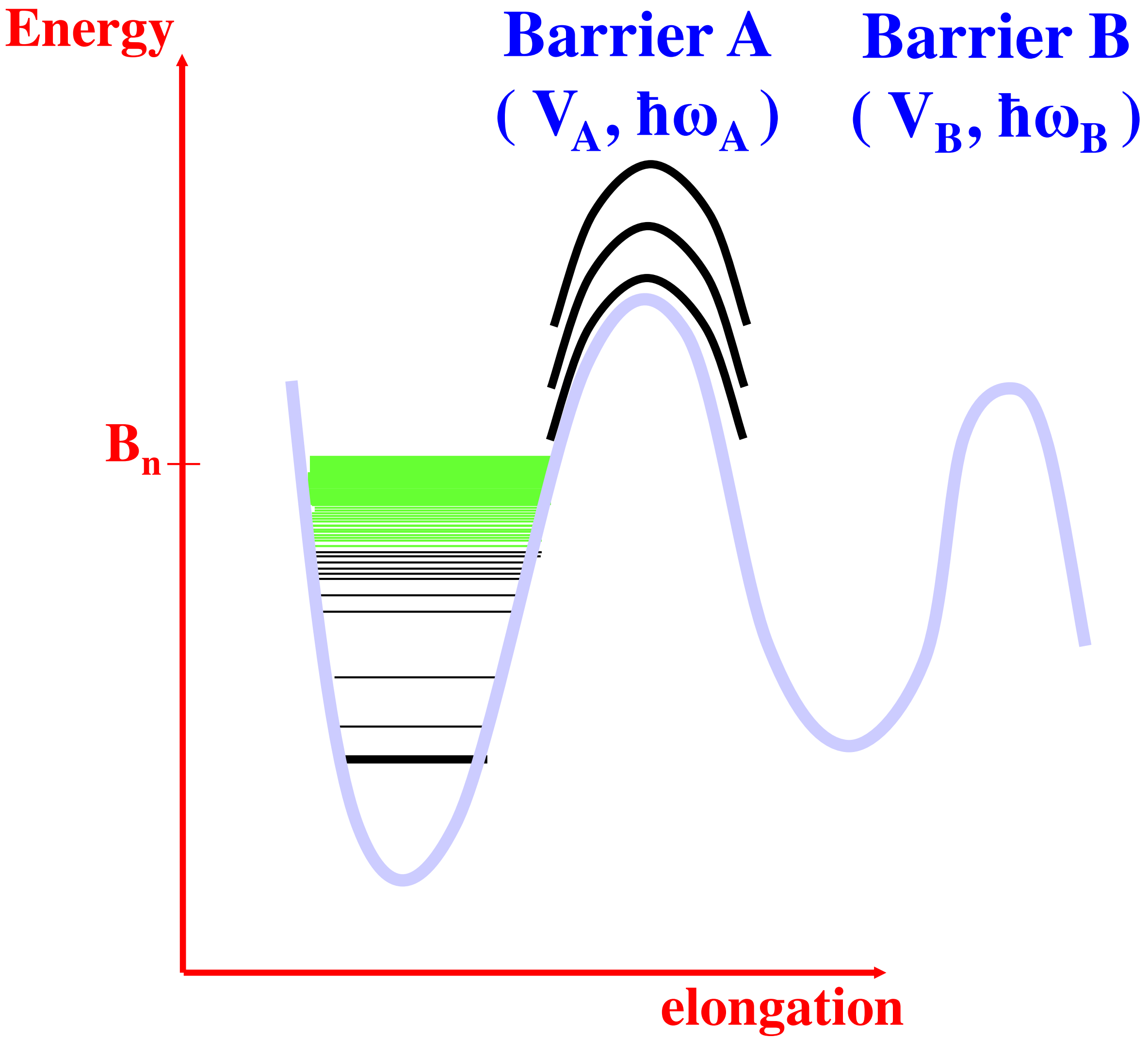


MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)



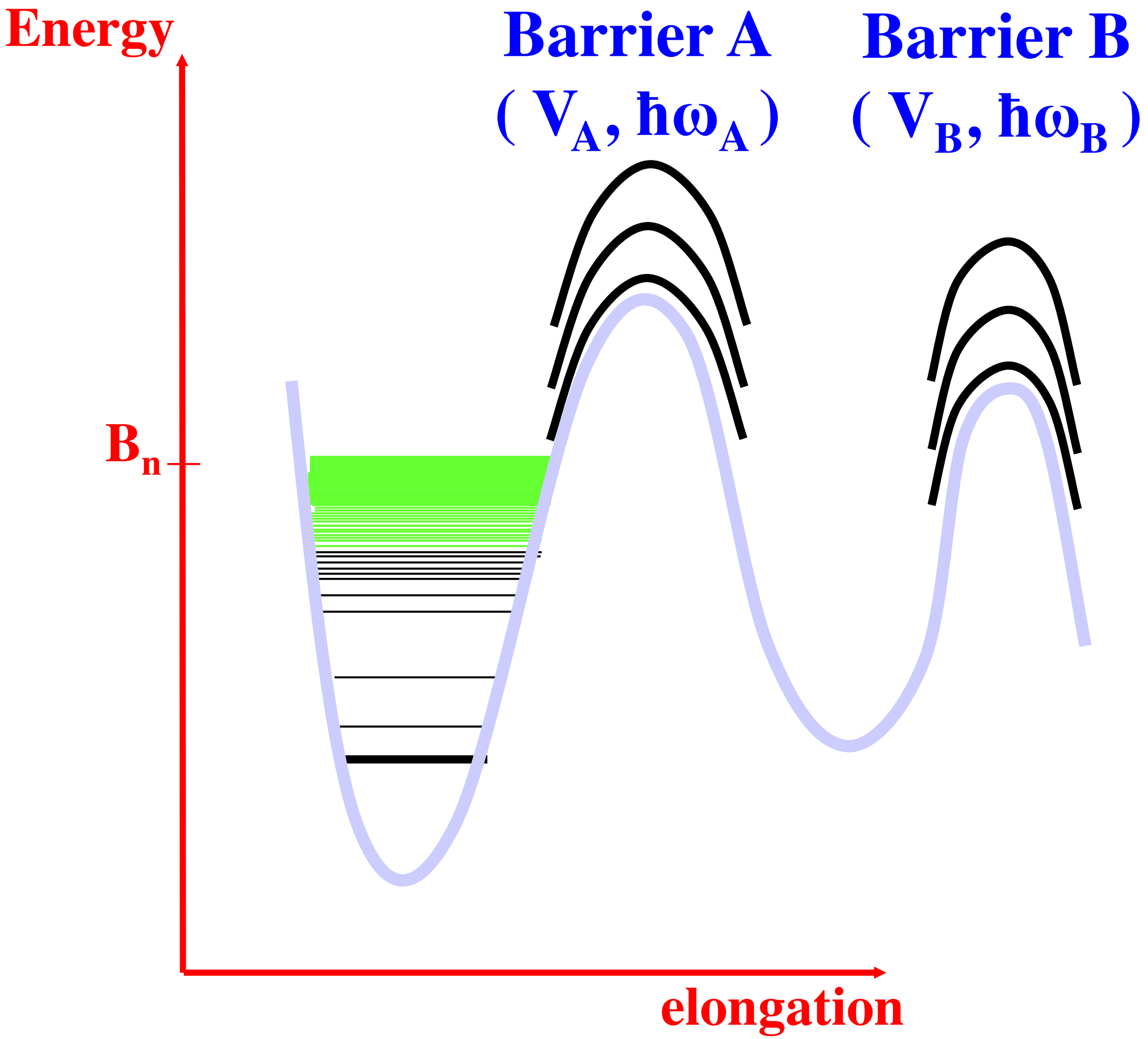
+ transition states on top of the barrier !

MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)



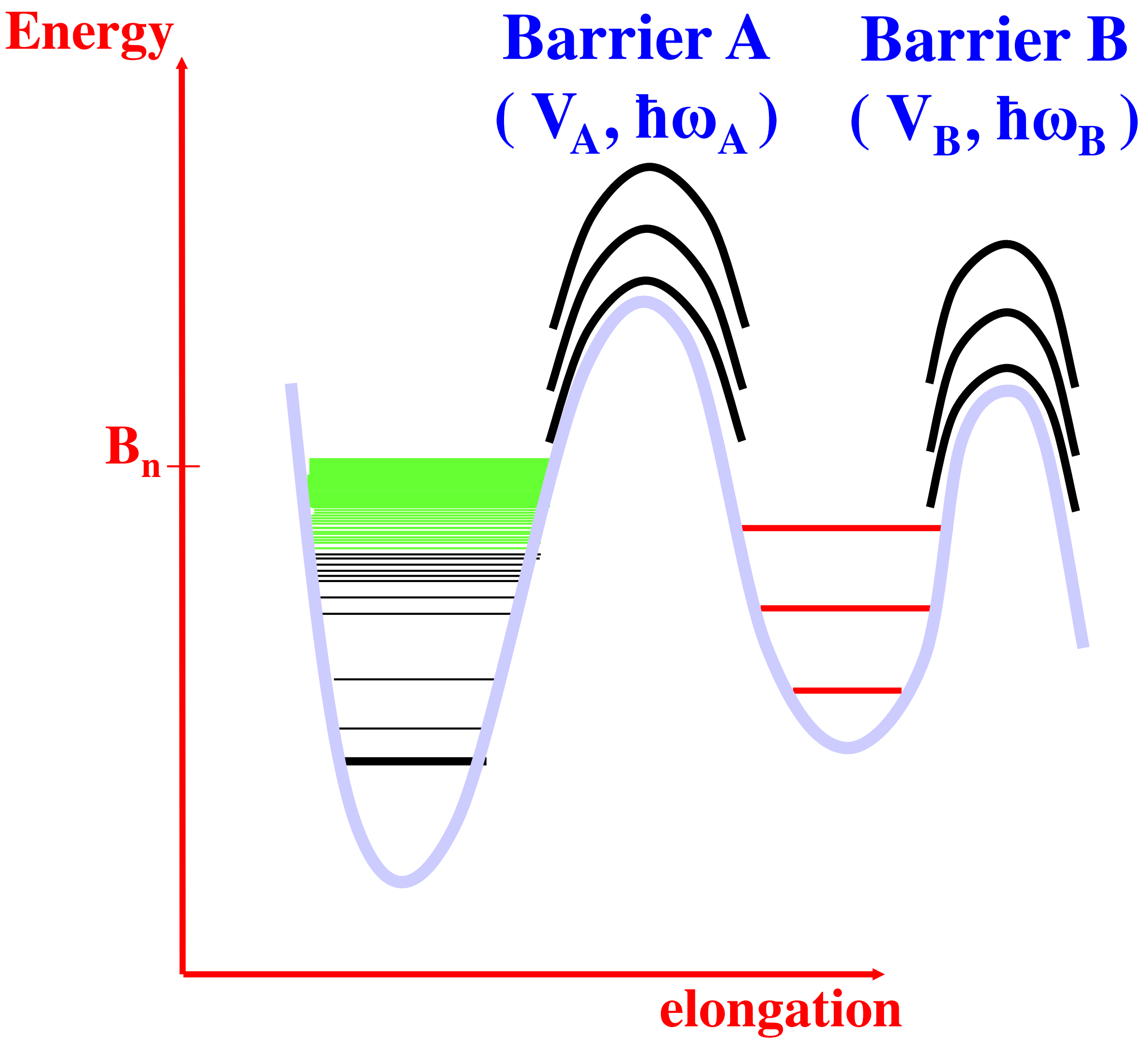
+ transition states on top of the barrier !

MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)



+ transition states on top of each barrier !

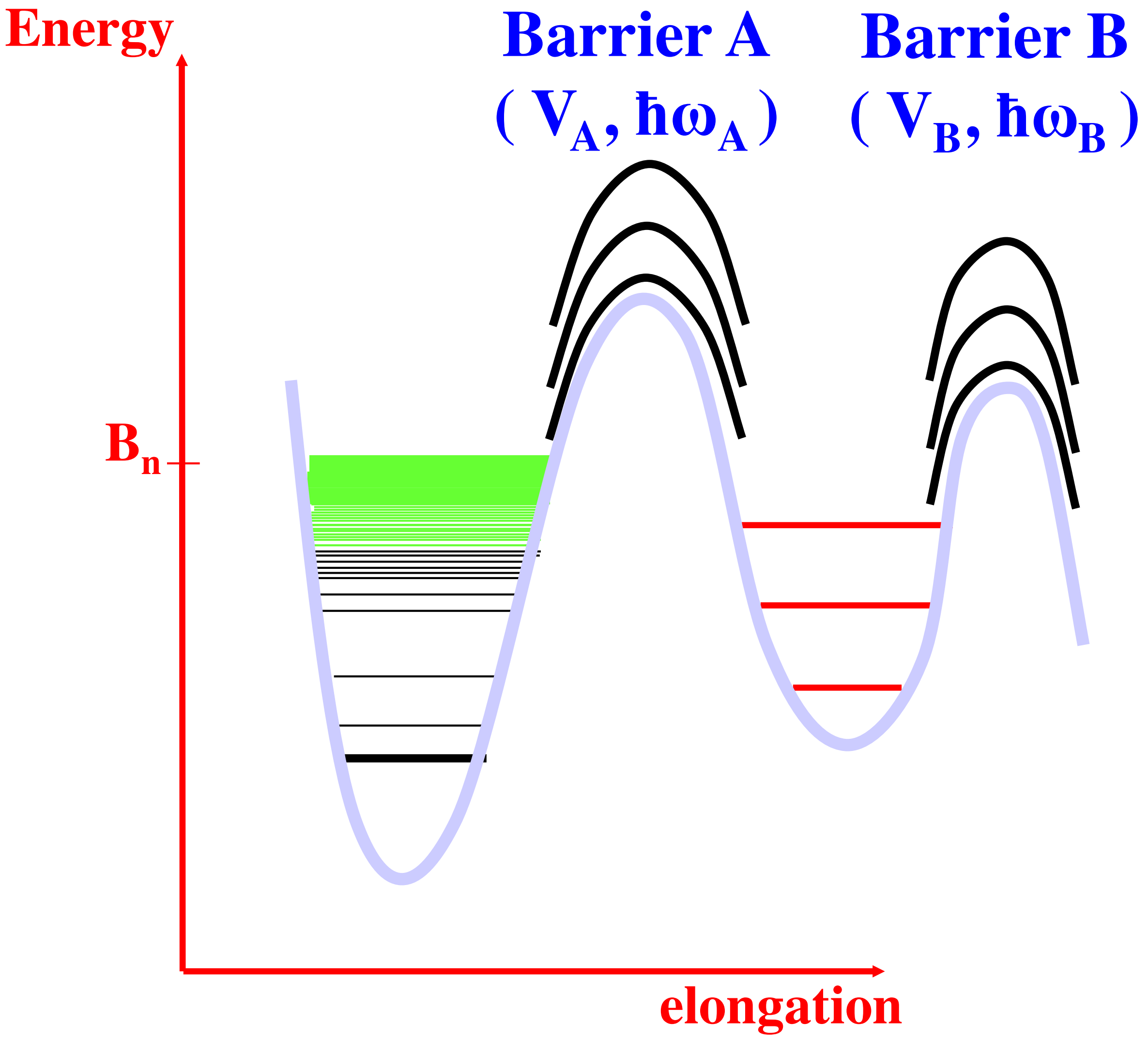
MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)

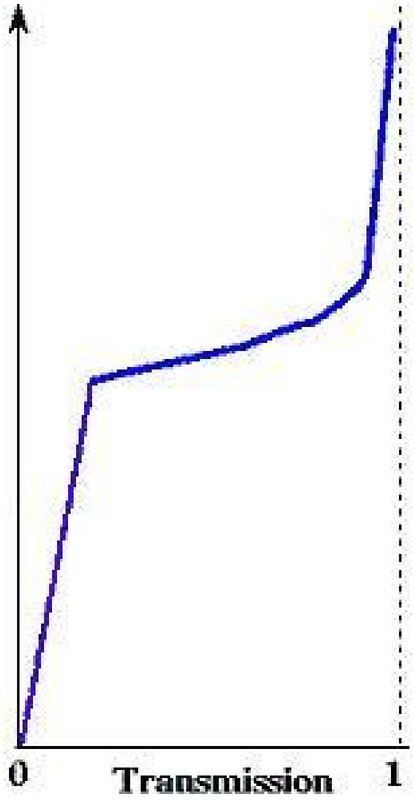


+ transition states on top of each barrier !

+ class II states in the intermediate well !

MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)

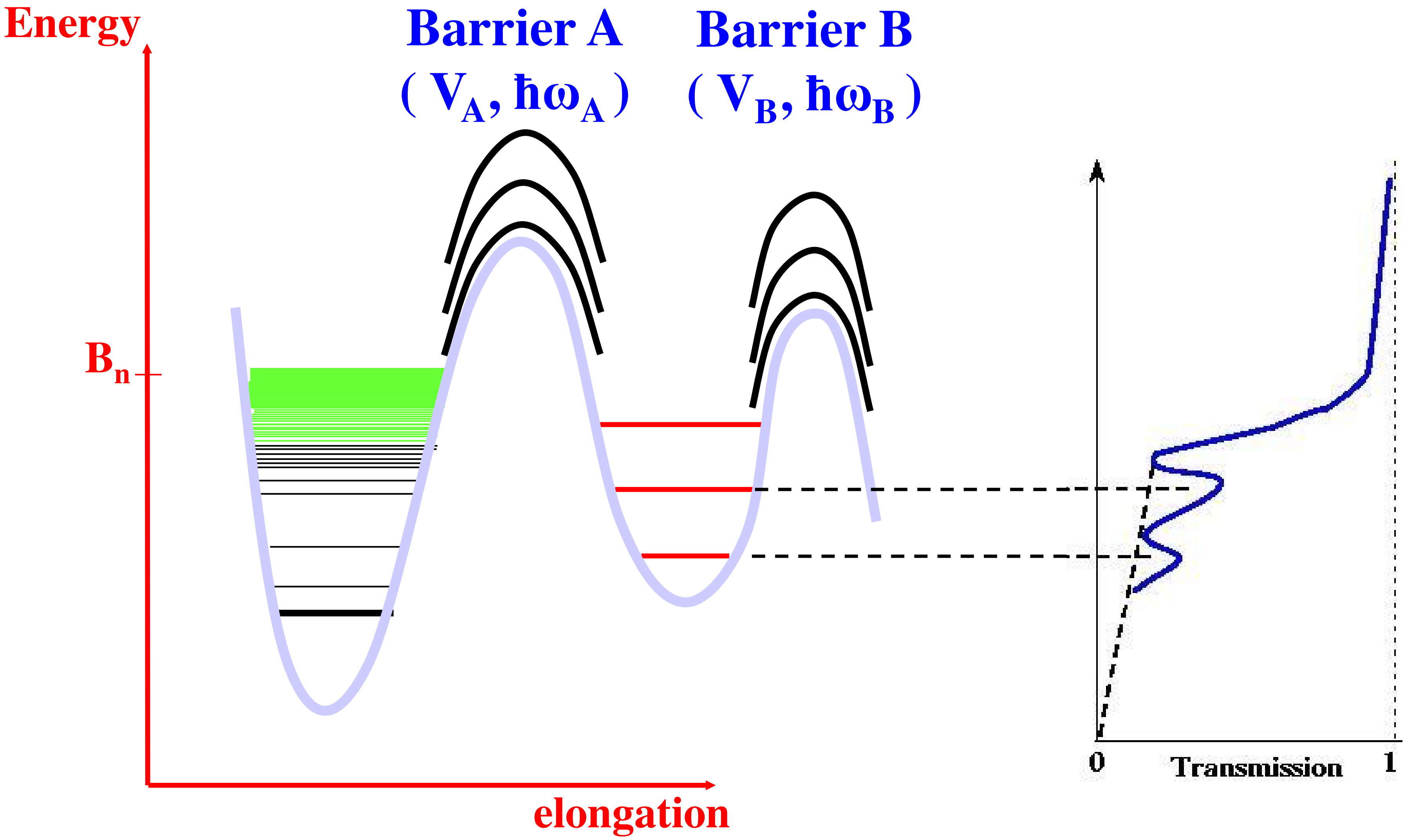




+ transition states on top of each barrier !

+ class II states in the intermediate well !

MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)



+ transition states on top of each barrier !

+ class II states in the intermediate well !

MISCELLANEOUS : THE FISSION PROCESS
(multiple humped barriers)

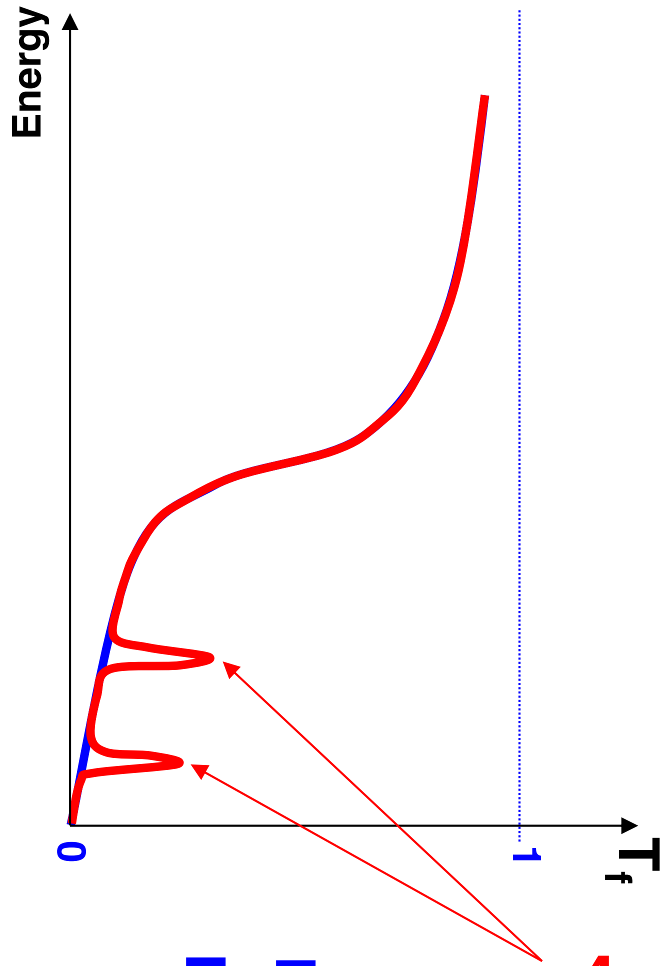
Two barriers A et B

$$T_f = \frac{T_A \, T_B}{T_A + T_B}$$

Three barriers A, B and C

$$T_f = \frac{\dfrac{T_A \, T_B}{T_A + T_B} \times T_C}{\dfrac{T_A \, T_B}{T_A + T_B} + T_C}$$

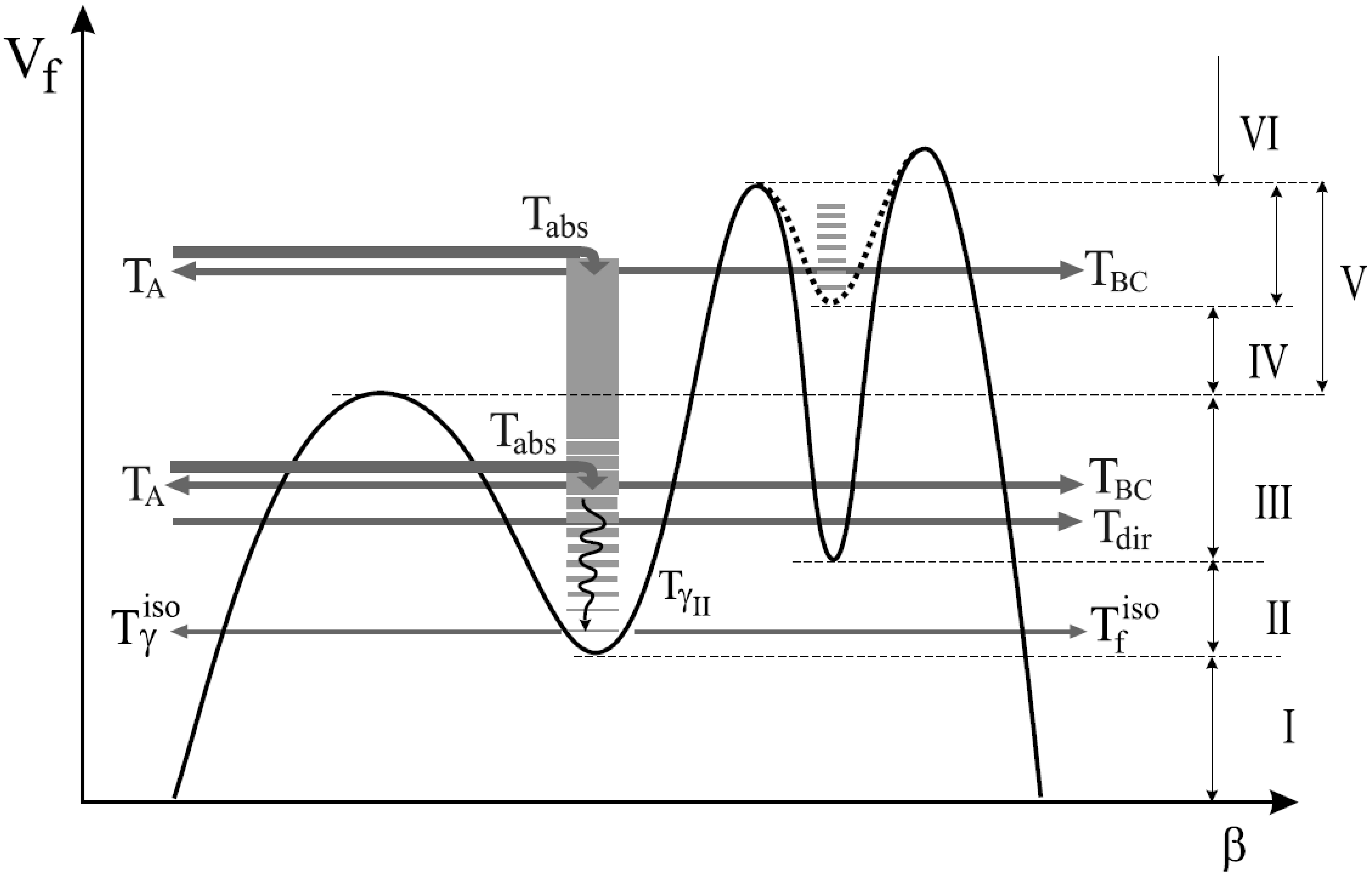
Resonant transmission



$$T_f = \frac{T_A \, T_B}{T_A + T_B} \quad \frac{4}{T_A + T_B}$$

More exact expressions in Sin et al., PRC 74 (2006) 014608

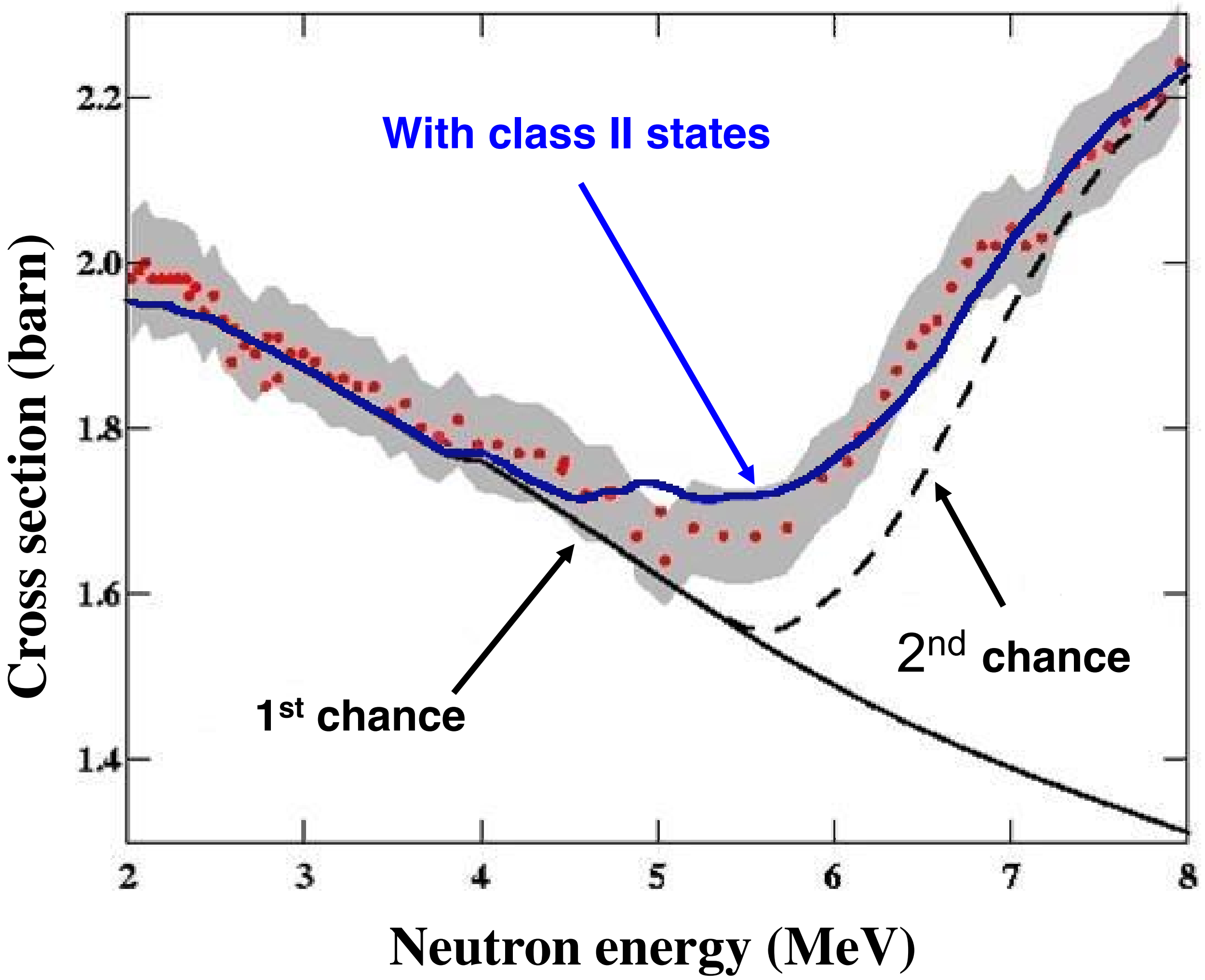
MISCELLANEOUS : THE FISSION PROCESS (multiple humped barriers with maximum complexity)



See in Sin et al., PRC 74 (2006) 014608
Bjornholm and Lynn, Rev. Mod. Phys. 52 (1980) 725.

MISCELLANEOUS : THE FISSION PROCESS
(Impact of class II states)

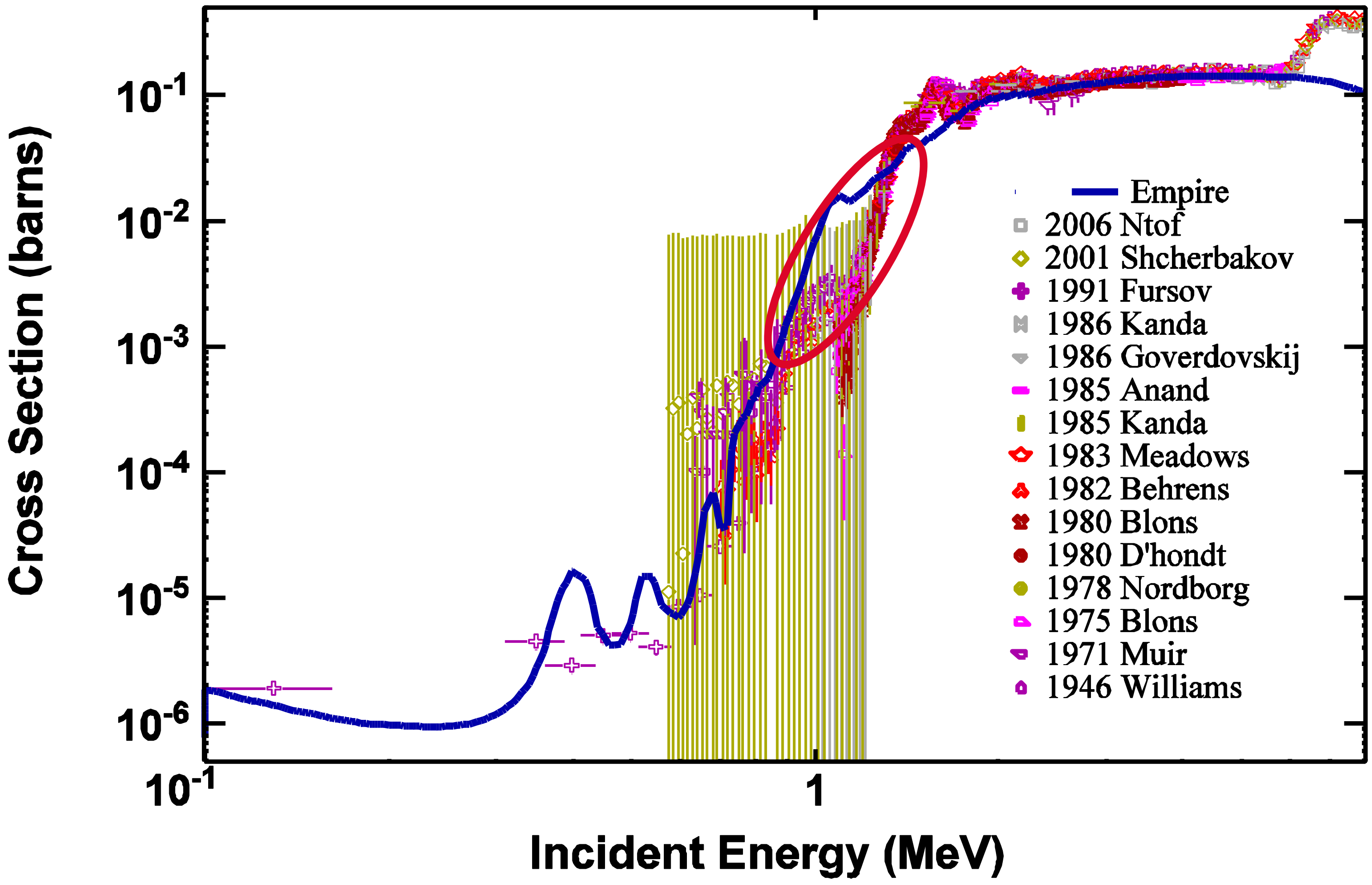
^{239}Pu (n,f)



MISCELLANEOUS : THE FISSION PROCESS (impact of class II and class III states)

Case of a fertile nucleus

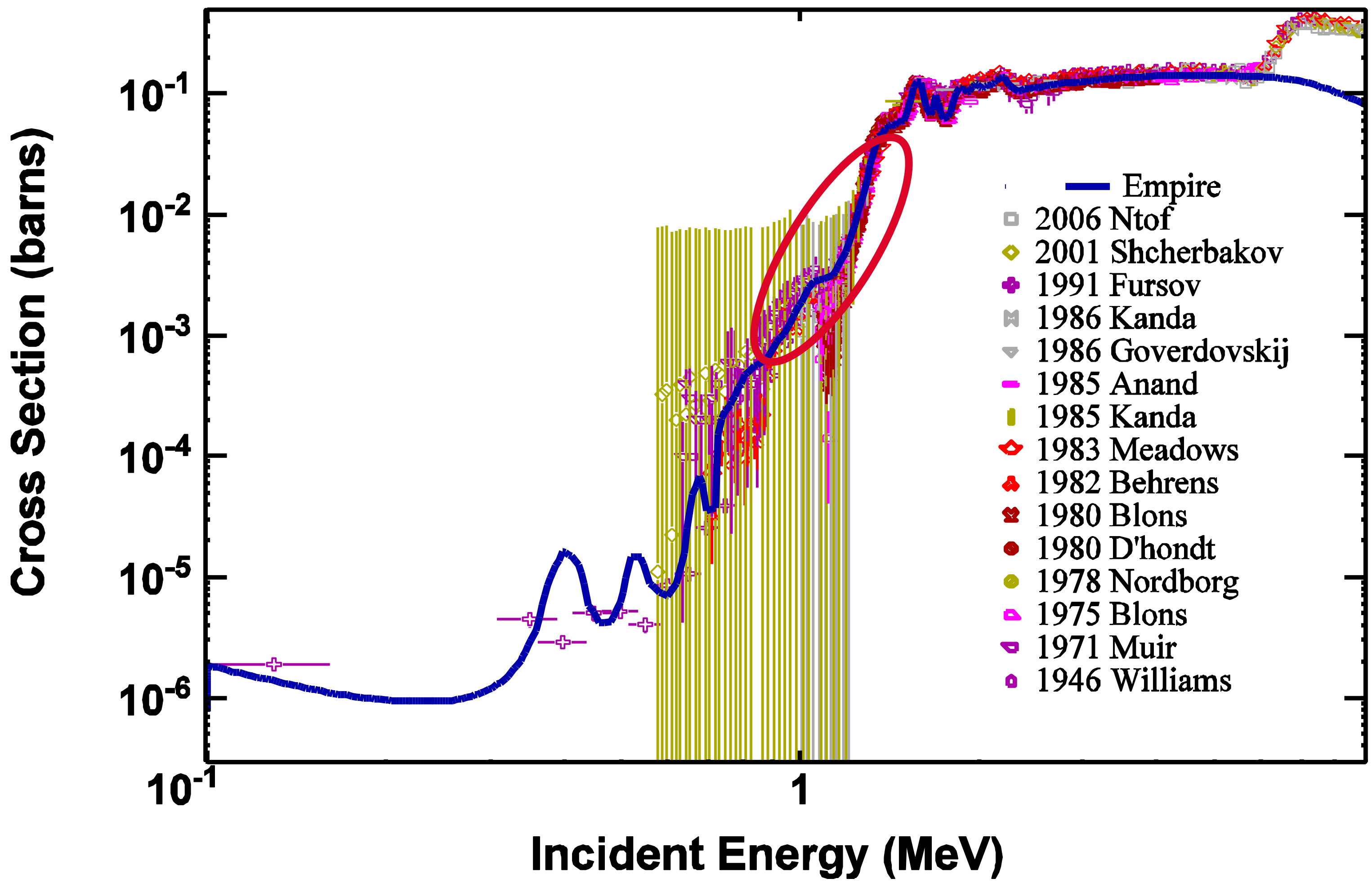
Partially damped class II states. No class III states



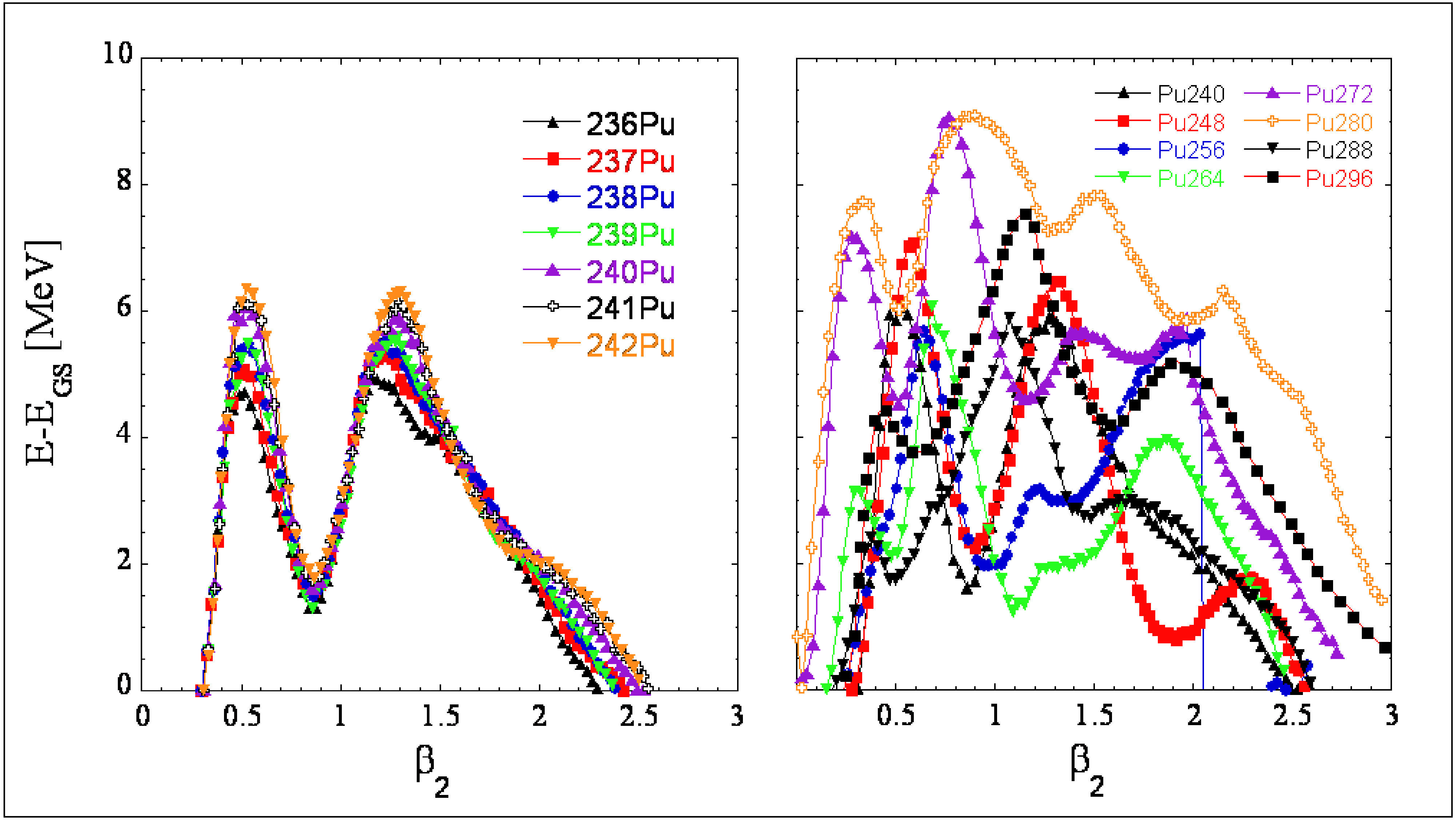
MISCELLANEOUS : THE FISSION PROCESS
(impact of class II and class III states)

Case of a fertile nucleus

Class II + III states. Partial damping.



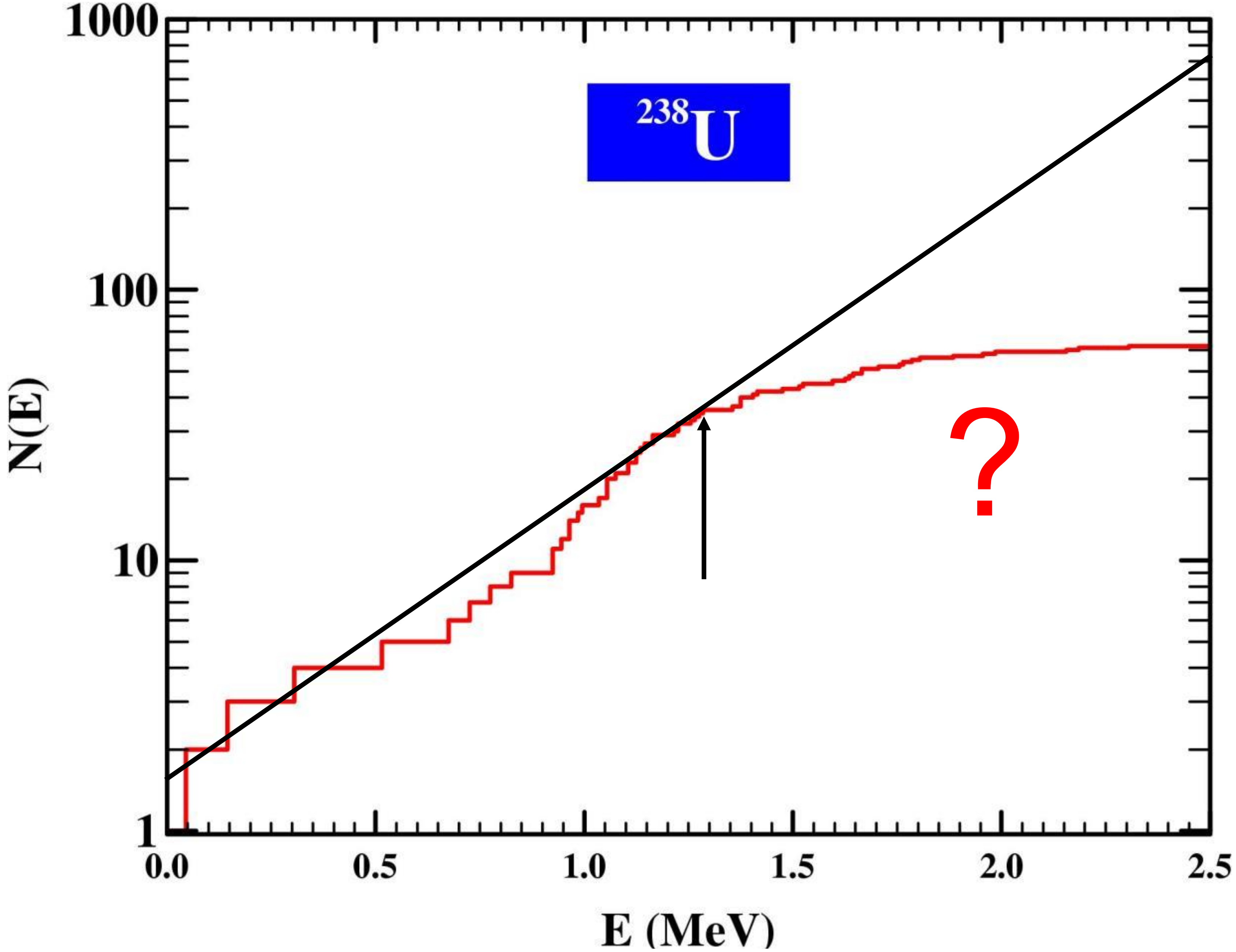
MISCELLANEOUS : THE FISSION PROCESS (Hill-Wheeler ?)



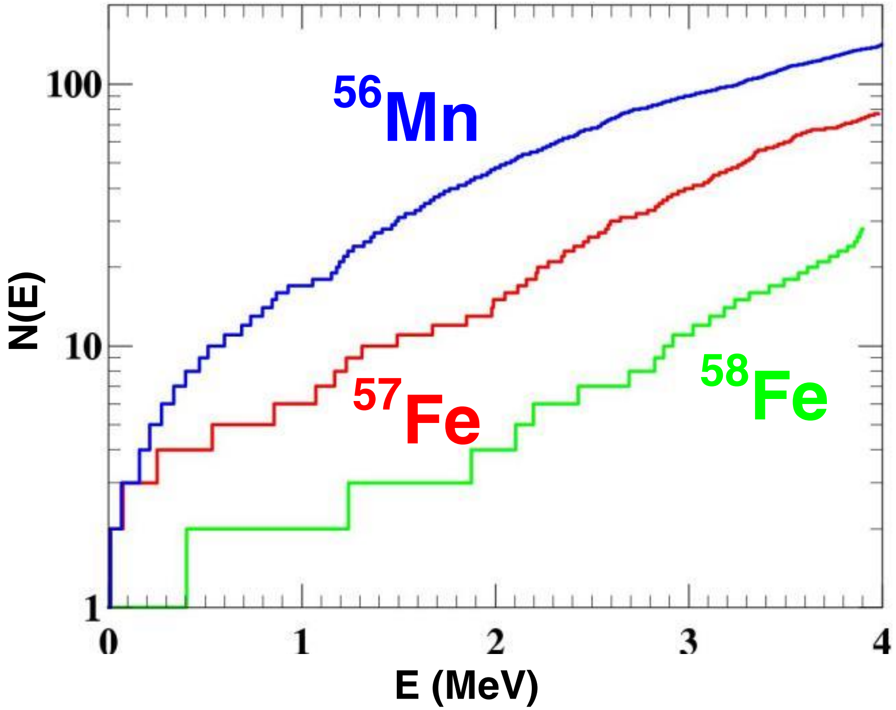
⇒ **For exotic nuclei : strong deviations from Hill-Wheeler.**

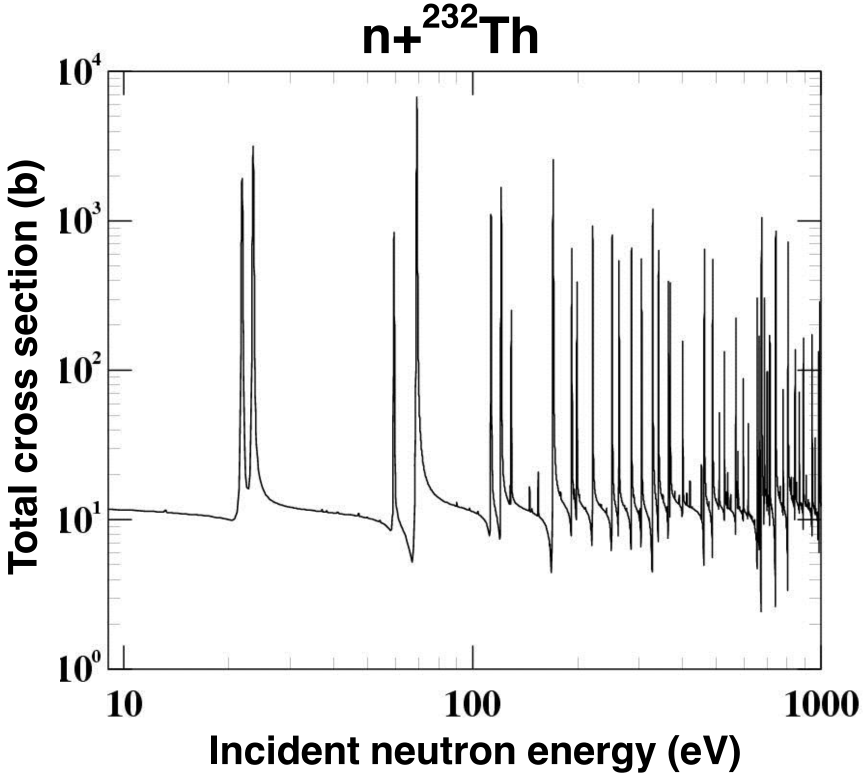
MISCELLANEOUS : THE FISSION PROCESS
(Microscopic fission cross sections)

MISCELLANEOUS : THE LEVEL DENSITIES
(Principle)



MISCELLANEOUS : THE LEVEL DENSITIES (Qualitative aspects 1/2)





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

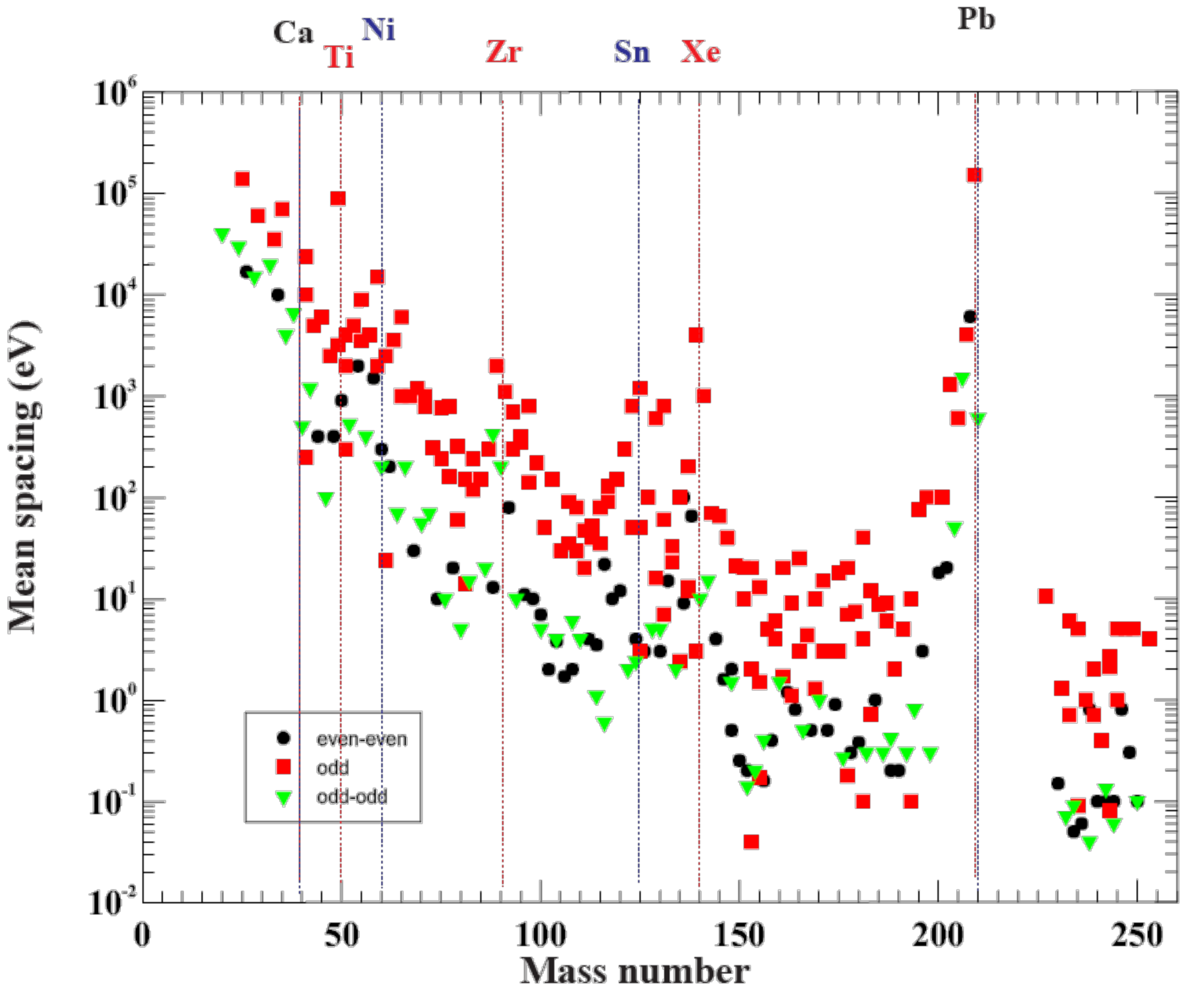
$\Rightarrow$ $\rho(E)= \dfrac{dN(E)}{dE}$ increases exponentially

$\Rightarrow$ 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

MISCELLANEOUS : THE LEVEL DENSITIES
(Qualitative aspects 2/2)



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

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

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

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

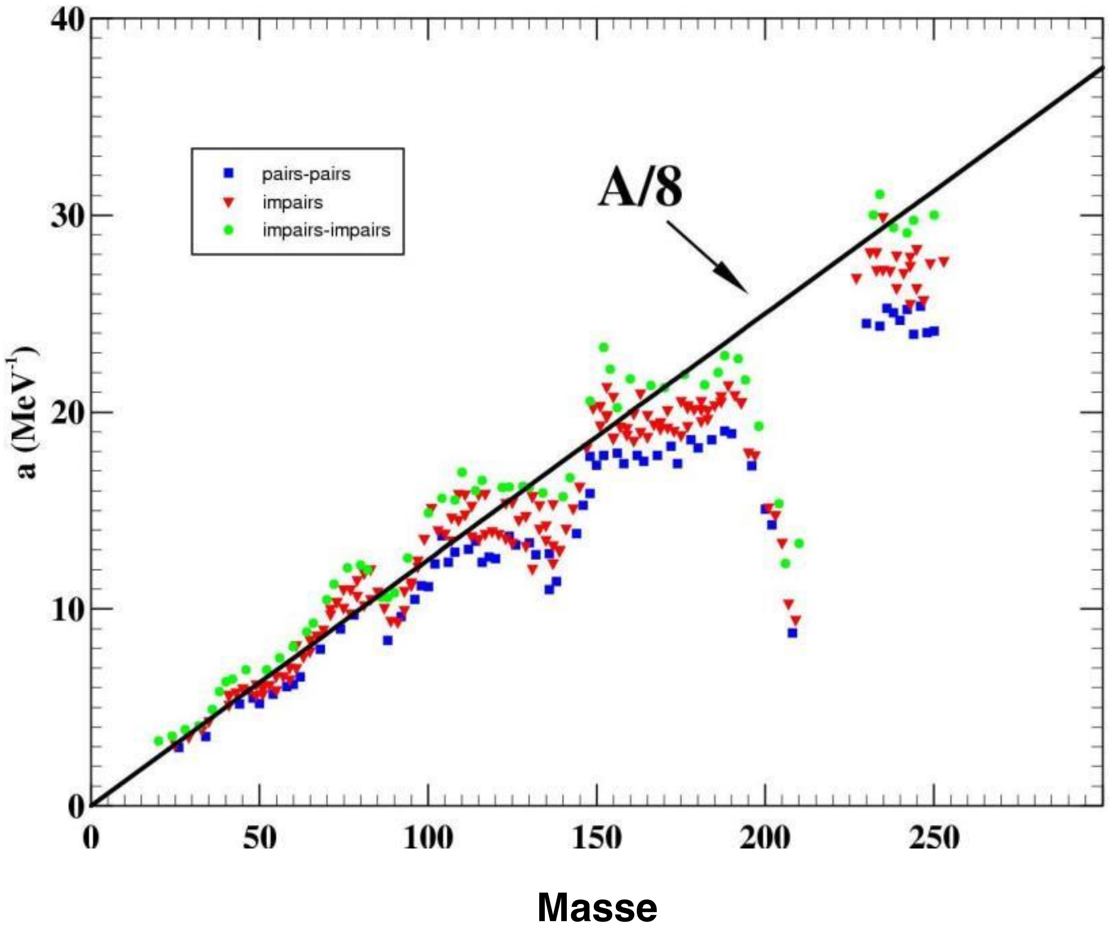
MISCELLANEOUS : THE LEVEL DENSITIES
(Quantitative analysis 1/2)

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

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

MISCELLANEOUS : THE LEVEL DENSITIES (Quantitative analysis 1/2)

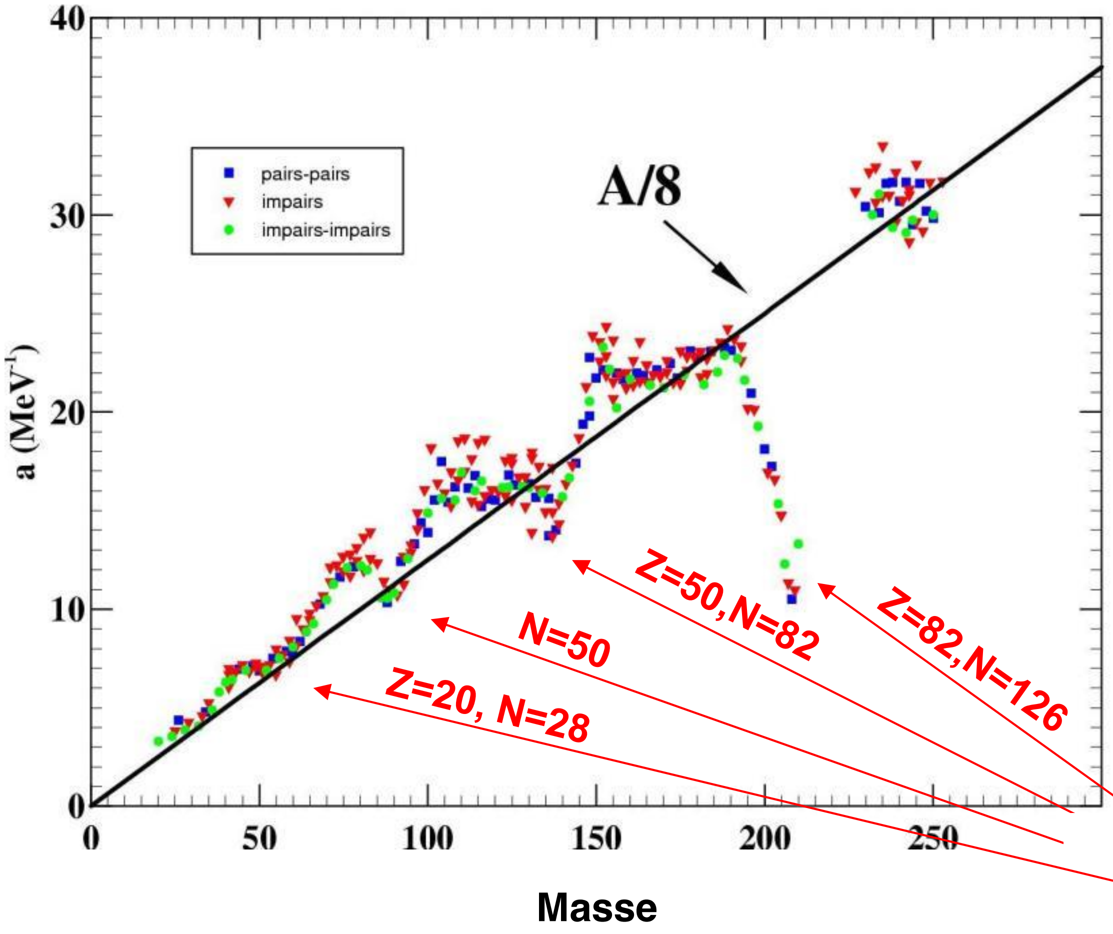
$$\rho\,(U, J, \pi) = \frac{1}{2}\ \frac{\sqrt{\pi}}{12}\ \frac{\exp\left(2\sqrt{aU}\right)}{a^{1/4}U^{5/4}}\ \frac{2J+1}{2\sqrt{2\pi}\,\sigma^3}\ \exp - \left[\frac{\left(J+\frac{1}{2}\right)^2}{2\sigma^2}\right]$$



⇒ odd-even effects

MISCELLANEOUS : THE LEVEL DENSITIES
(Quantitative analysis 1/2)

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



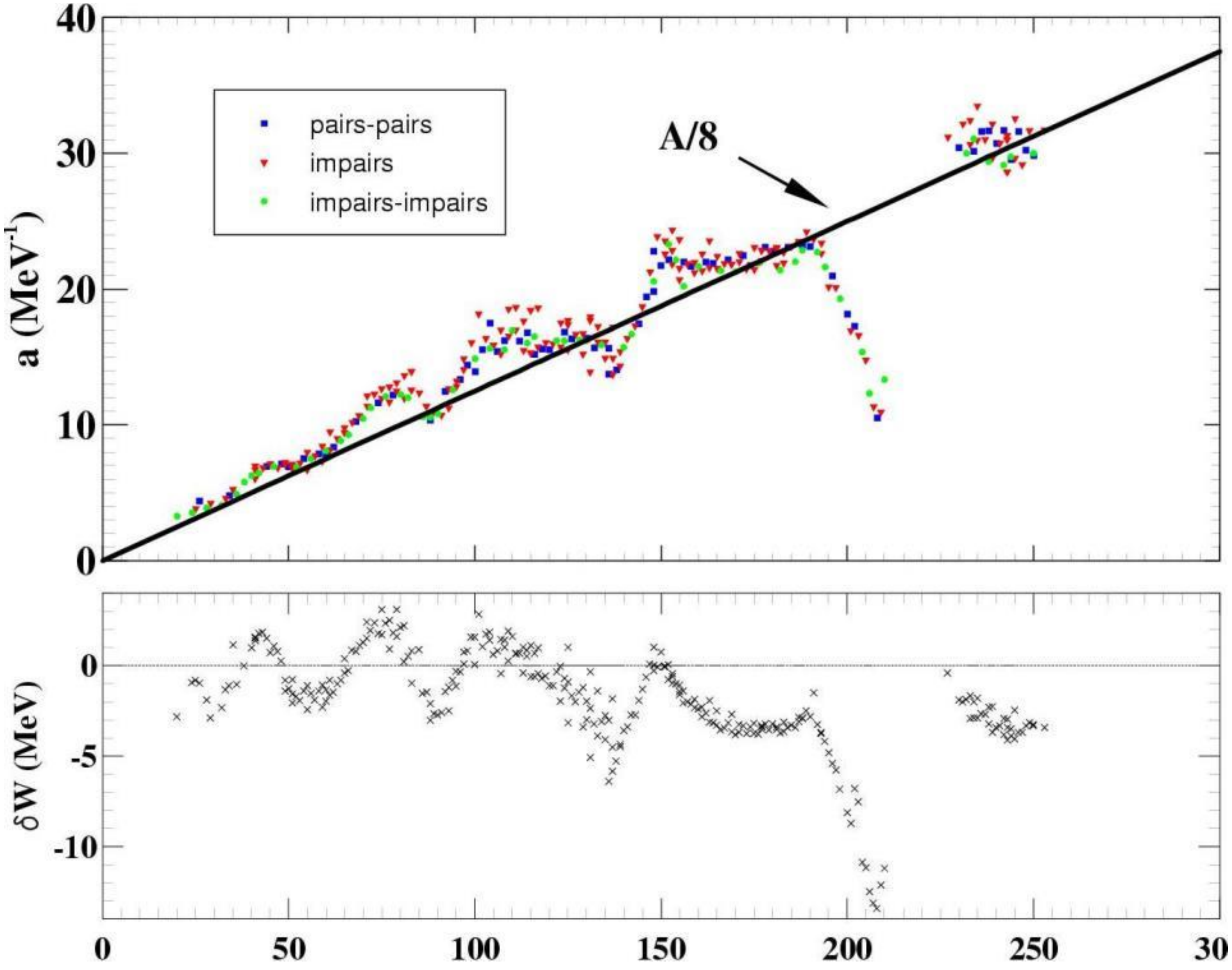
Odd-even effects accounted for

U → U*=U - Δ

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

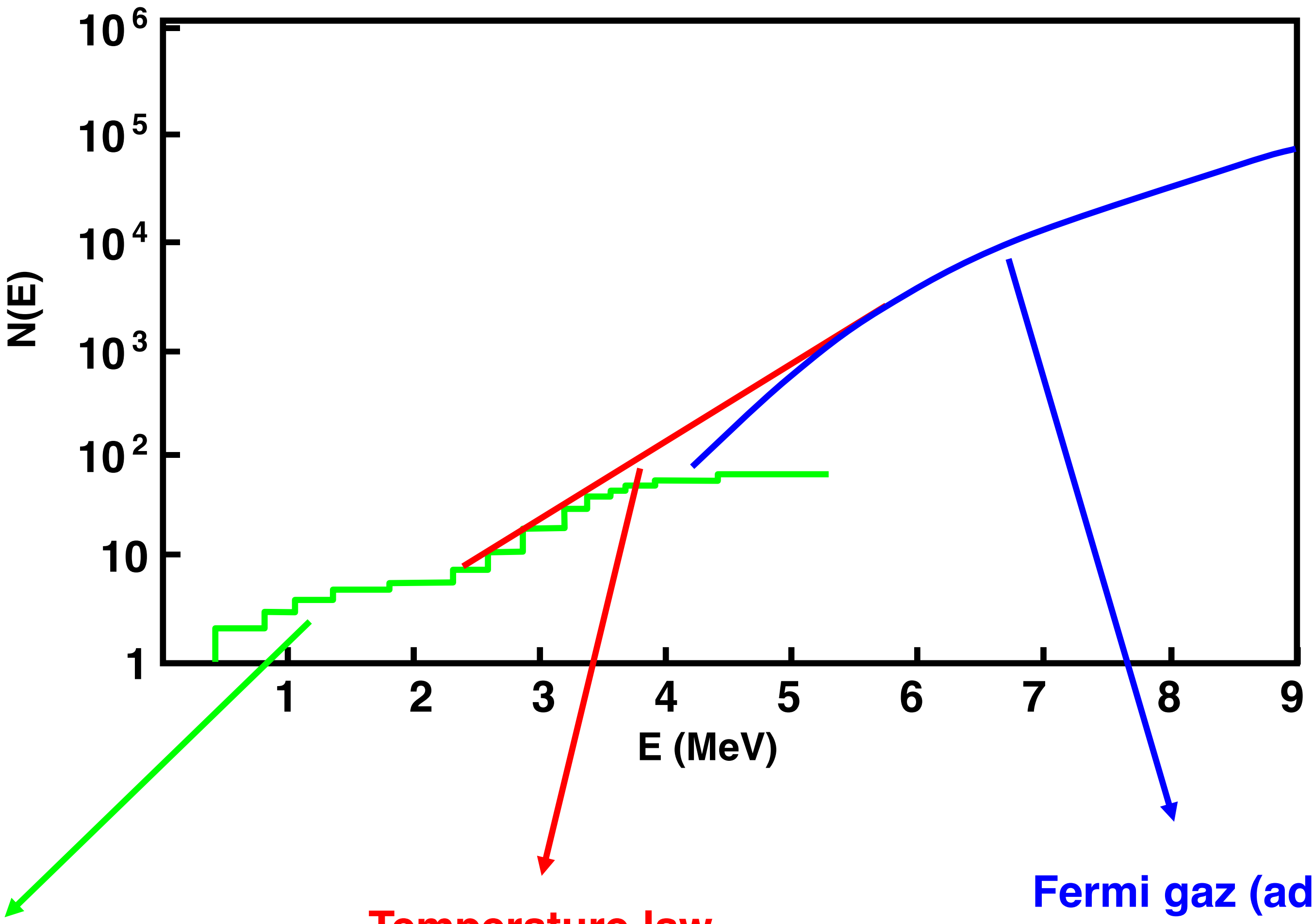
Shell effects

MISCELLANEOUS : THE LEVEL DENSITIES (Quantitative analysis 2/2)



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

MISCELLANEOUS : THE LEVEL DENSITIES
(Summary of most simple analytical description)



Discrete levels (spectroscopy)

Temperature law

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

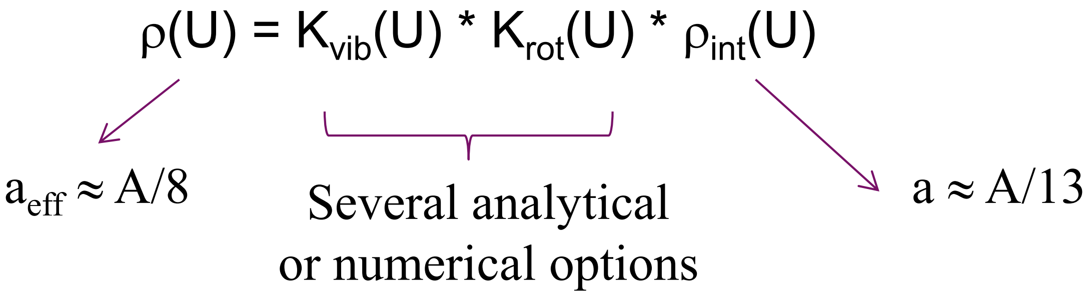
Fermi gaz (adjusted at B_n)

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

MISCELLANEOUS : THE LEVEL DENSITIES
(More sophisticated 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

MISCELLANEOUS : THE LEVEL DENSITIES
(More sophisticated approaches)

- **Superfluid model & Generalized superfluid model**

  Ignatyuk et al., PRC 47 (1993) 1504 & RIPL2 Tecdoc (IAEA)

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

Shell Model Monte Carlo approach
Agrawal et al., PRC 59 (1999) 3109

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

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
⇒ Global (tables)

THE LEVEL DENSITIES
(The combinatorial method 1/3)

See PRC 78 (2008) 064307 for details

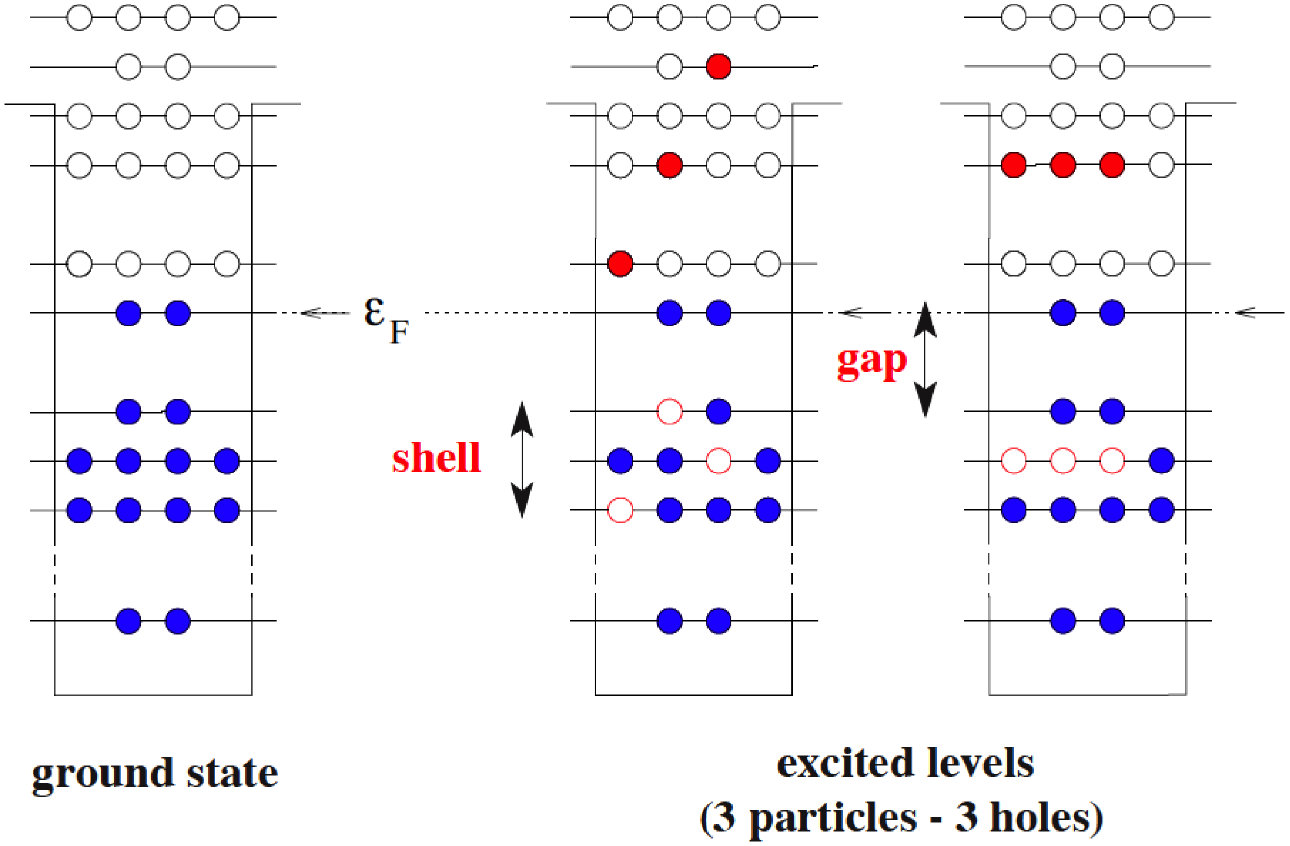
- **HFB + effective nucleon-nucleon interaction ⇒ single particle level schemes**

- **Combinatorial calculation ⇒ intrinsic p-h and total state densities ω (U, K, π)**

THE LEVEL DENSITIES
(The combinatorial method 1/3)

Level density estimate is a counting problem: $\rho(U)=dN(U)/dU$

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



THE LEVEL DENSITIES
(The combinatorial method 1/3)

See PRC 78 (2008) 064307 for details

- **HFB + effective nucleon-nucleon interaction ⇒ single particle level schemes**

- **Combinatorial calculation ⇒ intrinsic p-h and total state densities $\omega\,(U, K, \pi)$**

- **Collective effects ⇒ from state to level densities $\rho(U, J, \pi)$**

  1) folding of intrinsic and vibrational state densities

  2) construction of rotational bands for deformed nuclei

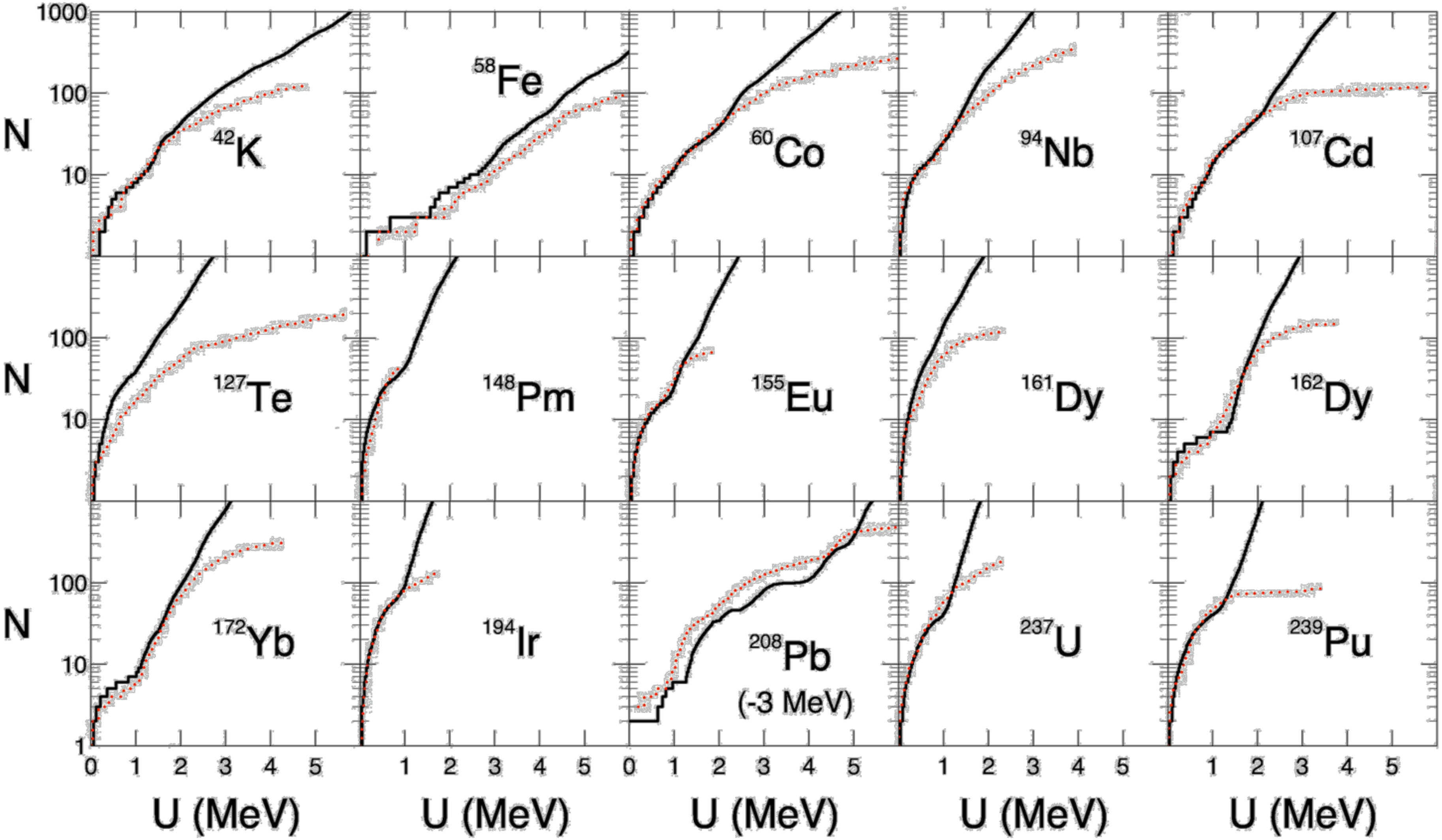
$$\rho(U, J, \pi) = \sum_{K} \omega\,(U-E_{rot}^{JK}, K, \pi)$$

  2) spherical nuclei

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

- **Phenomenological transition for deformed/spherical nucleus**

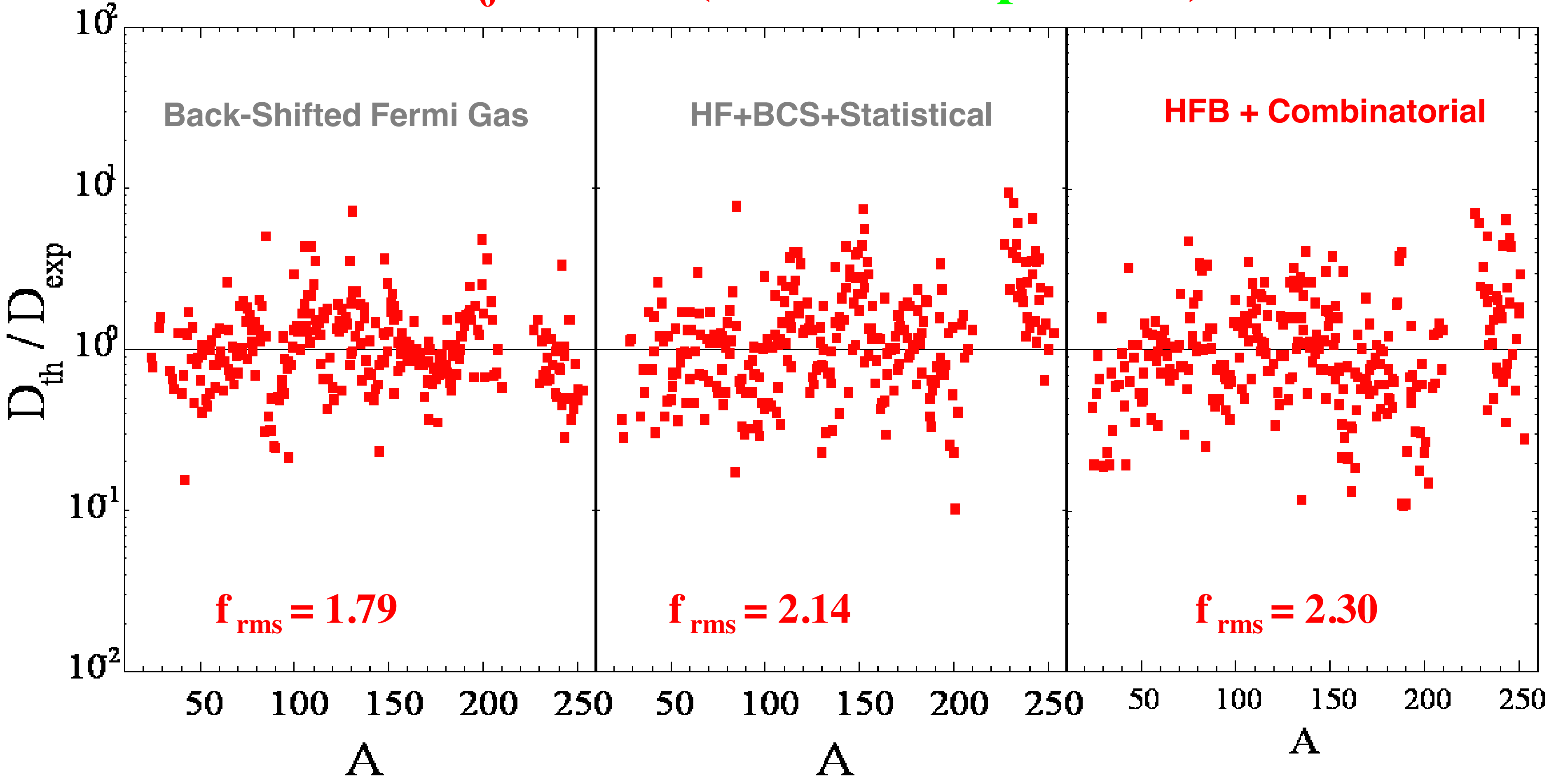
THE LEVEL DENSITIES
(The combinatorial method 2/3)



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

THE LEVEL DENSITIES
(The combinatorial method 3/3)

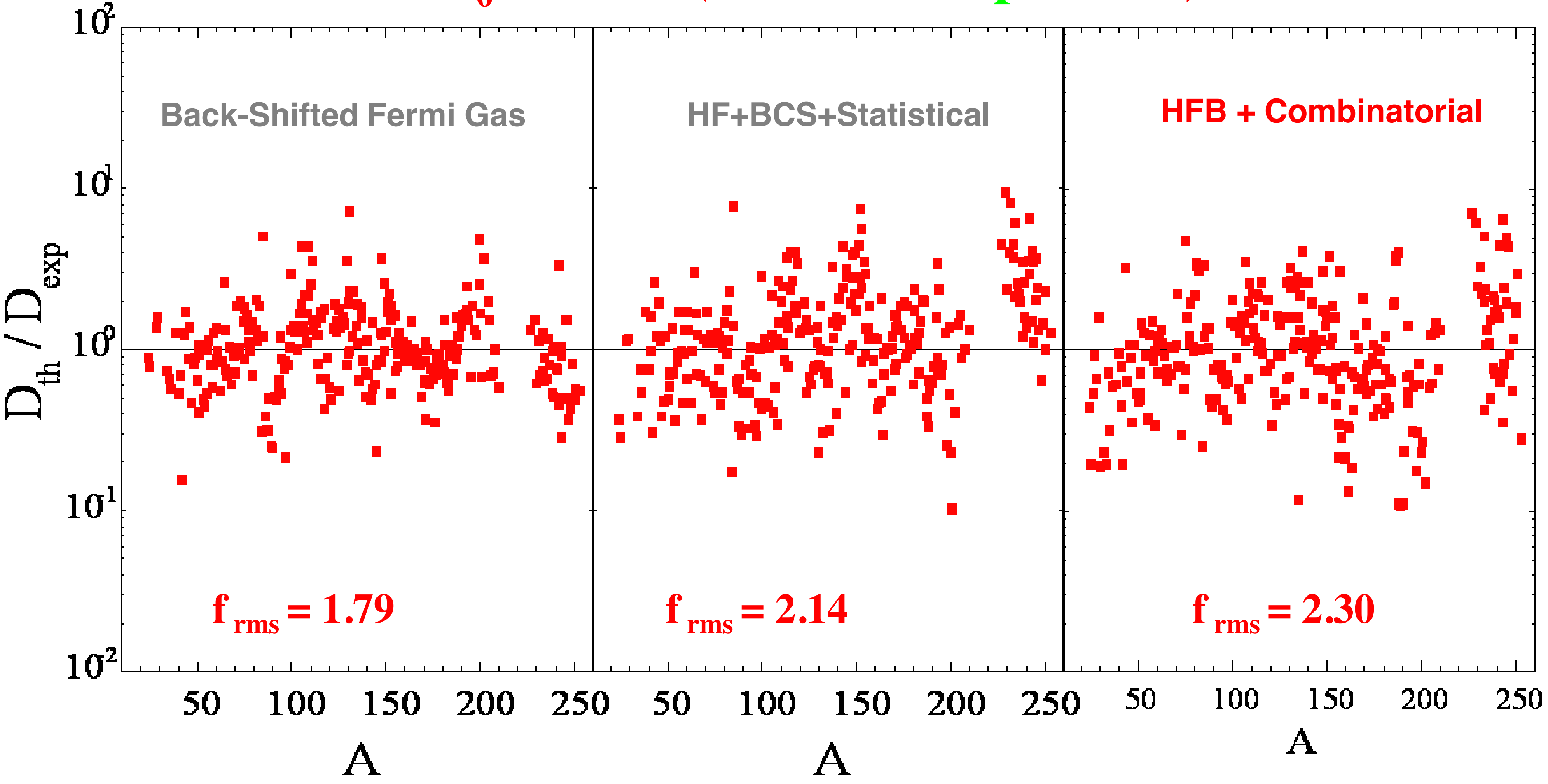
D_0 values (s-waves & p-waves)



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

THE LEVEL DENSITIES
(The combinatorial method 3/3)

D_0 values (s-waves & p-waves)



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

CONCLUSIONS & PROPECTS

- Nuclear reaction modeling complex and no yet fully satisfactory

  ⇒ pre-equilibrium phenomenon must be improved

  ⇒ fission related phenomena (fission, FF yields & decay) must be improved

- Formal and technical link between structure and reactions has to be pushed further

  ⇒ pre-equilibrium and OMP efforts already engaged

  ⇒ computing time is still an issue

- Fundamental ν-ν interaction knowledge (and treatment) has to be improved

  ⇒ Ab-initio not universal (low mass or restricted mass regions)

  ⇒ Relativistic aspects not included systematically

  ⇒ Human & computing time is still an issue