Optical model and compound nucleus model

S. Hilaire

CEA, DAM, DIF

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

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**
  - 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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1. INTRODUCTION

The references today

ELSEVIER

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*

(Received July 20, 2009)

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

Eur. Phys. J. A (2023) 59:131
https://doi.org/10.1140/epja/s10050-023-01034-3

THE EUROPEAN PHYSICAL JOURNAL A

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Review

TALYS: modeling of nuclear reactions

Arjan Koning[1,a], **Stephane Hilaire**[2,3,b], **Stephane Goriely**[4,c]

[1] Nuclear Data Section, IAEA, Wagrammerstrasse 5, Vienna 1400, Austria
[2] CEA, DAM, DIF, Arpajon 91297, France
[3] Université Paris-Saclay, CEA, LMCE, 91680 Bruyères-le-Châtel, France
[4] Institut d'Astronomie et d'Astrophysique, Université Libre de Bruxelles, Campus de la Plaine, CP-226, Brussels 1050, Belgium

Received: 16 February 2023 / Accepted: 6 May 2023 / Published online: 14 June 2023

Communicated by Nicolas Alamanos

Abstract TALYS is a software package for the simulation of nuclear reactions below 200 MeV. It is used worldwide for the analysis and prediction of nuclear reactions and is based on state-of-art nuclear structure and nuclear reaction models. A general overview of the implemented physics and capabilities of TALYS is given. The general nuclear reaction mechanisms described are the optical model, direct reactions, compound nucleus model, pre-equilibrium reactions and fission. The most important nuclear structure models are those for masses, discrete levels, level densities, photon strength functions and fission barriers. A wide variety of nuclear reactions simulated with TALYS will be demonstrated, ranging from low-energy neutron cross sections, astrophysics, high-energy charged particle reactions and other reactions. TALYS is a nuclear reaction software which aims to give a complete description of nuclear reaction observables, and to be an important link between fundamental nuclear physics and applications.

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Why do we need nuclear data and which accuracy ?

Nuclear data needed for

Understanding basic reaction mechanism between particles and nuclei

Good accuracy if possible $\Rightarrow$ good understanding or room for improvements

Why do we need nuclear data and which accuracy ?

Nuclear data needed for

Understanding basic reaction mechanism between particles and nuclei

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

Good accuracy if possible ⇒ good understanding or room for improvements

Predictive power important ⇒ sound physics (first principles)

Why do we need nuclear data and which accuracy ?

Nuclear data needed for

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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Nuclear data needed for

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Good accuracy required ⇒ reproduction of data

Predictive power less important ⇒ Reproductive power

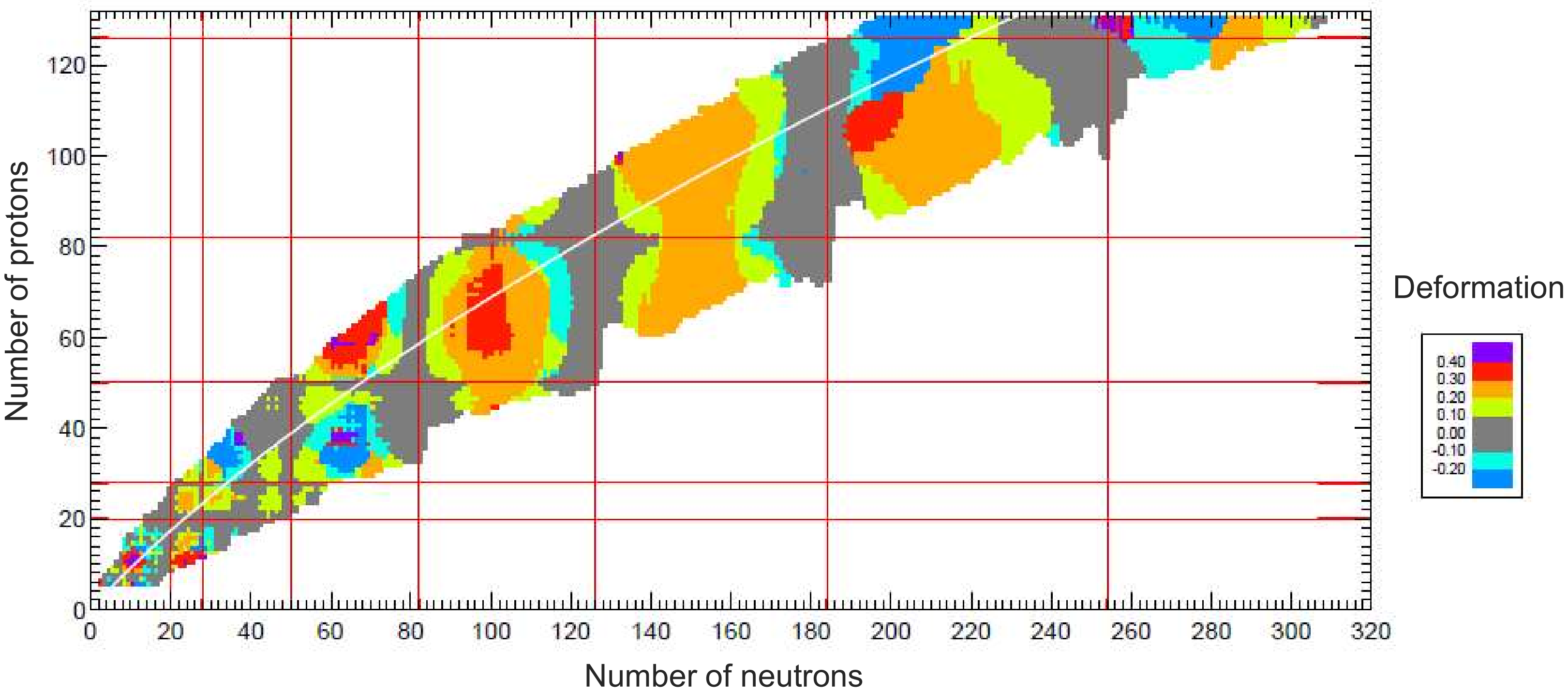
But

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

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

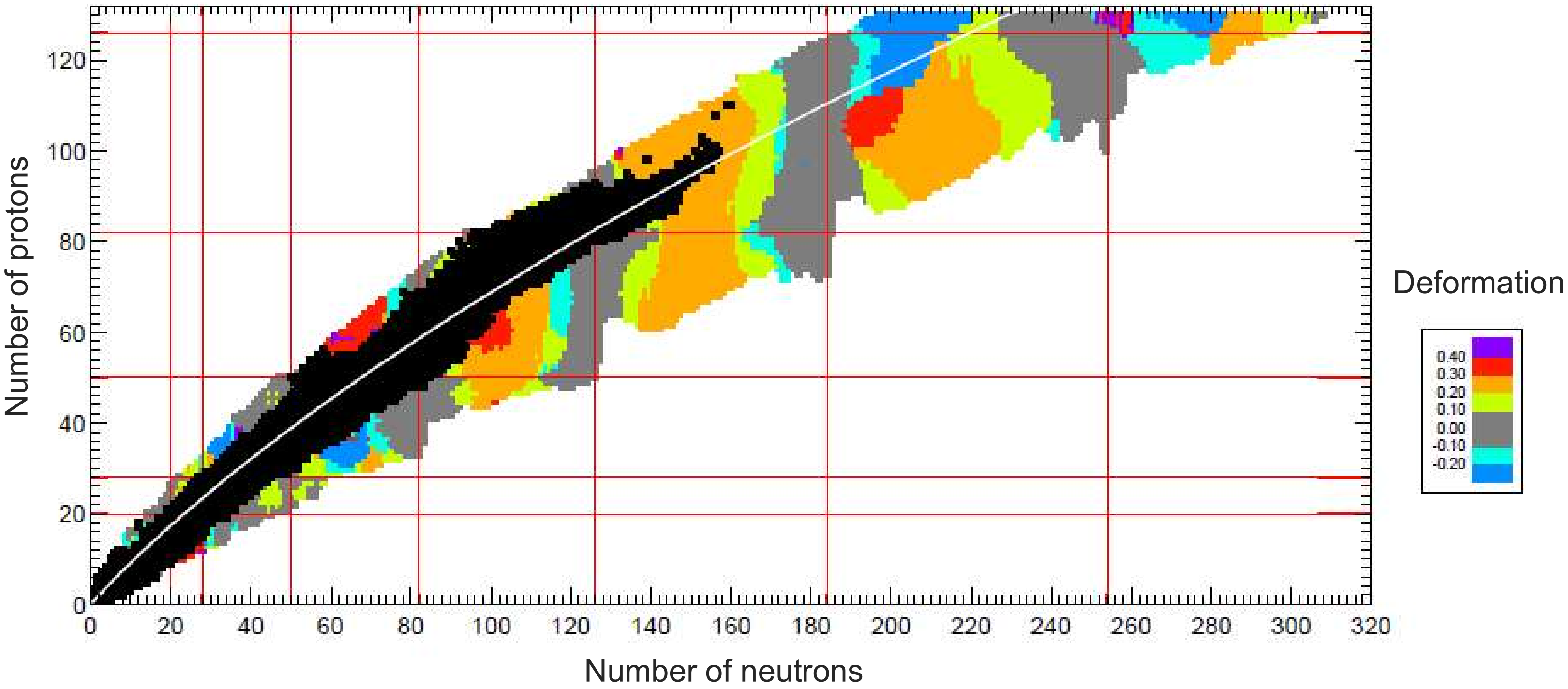
➡ **Predictive & Robust Nuclear models (codes) are essential**

Predicted nuclei



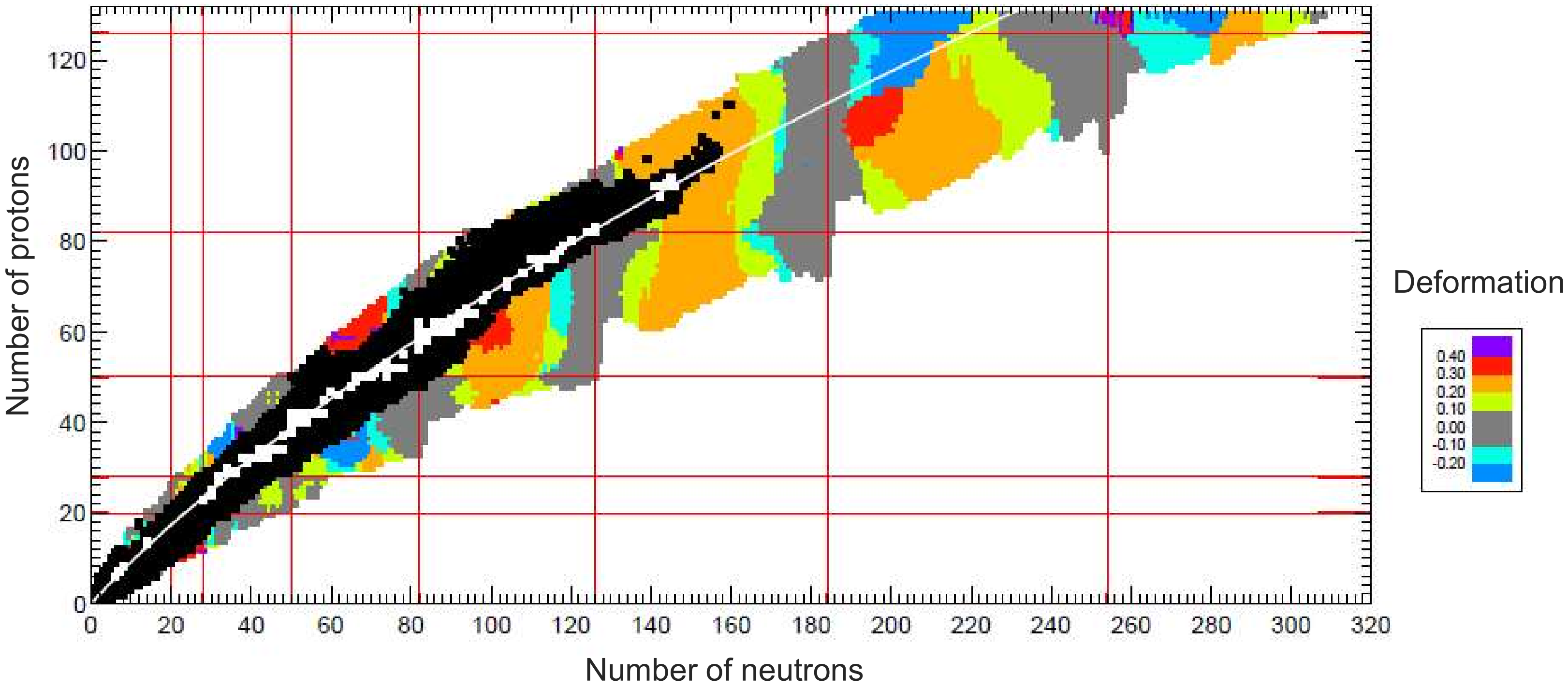
⇒ nearly 9200 nuclei predicted up to Z=130
⇒ 256 stable nuclei + few tens of quasi-stable (half life many years)

Predicted nuclei, known masses



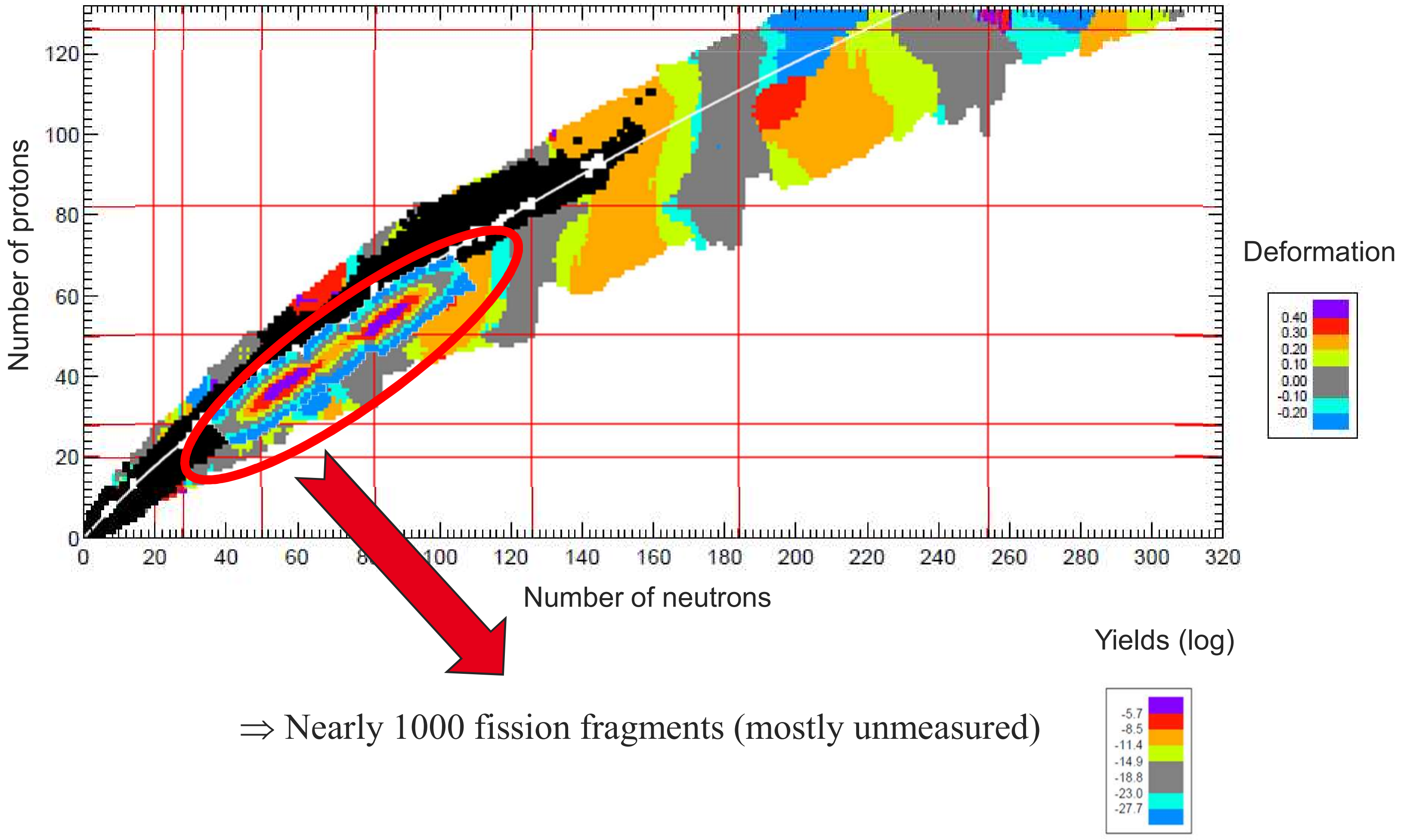
⇒ nearly 9200 nuclei predicted up to Z=130
⇒ 256 stable nuclei + few tens of quasi-stable (half life many years)
⇒ less than 2600 known masses up to Z=110

Predicted nuclei, known masses, known capture



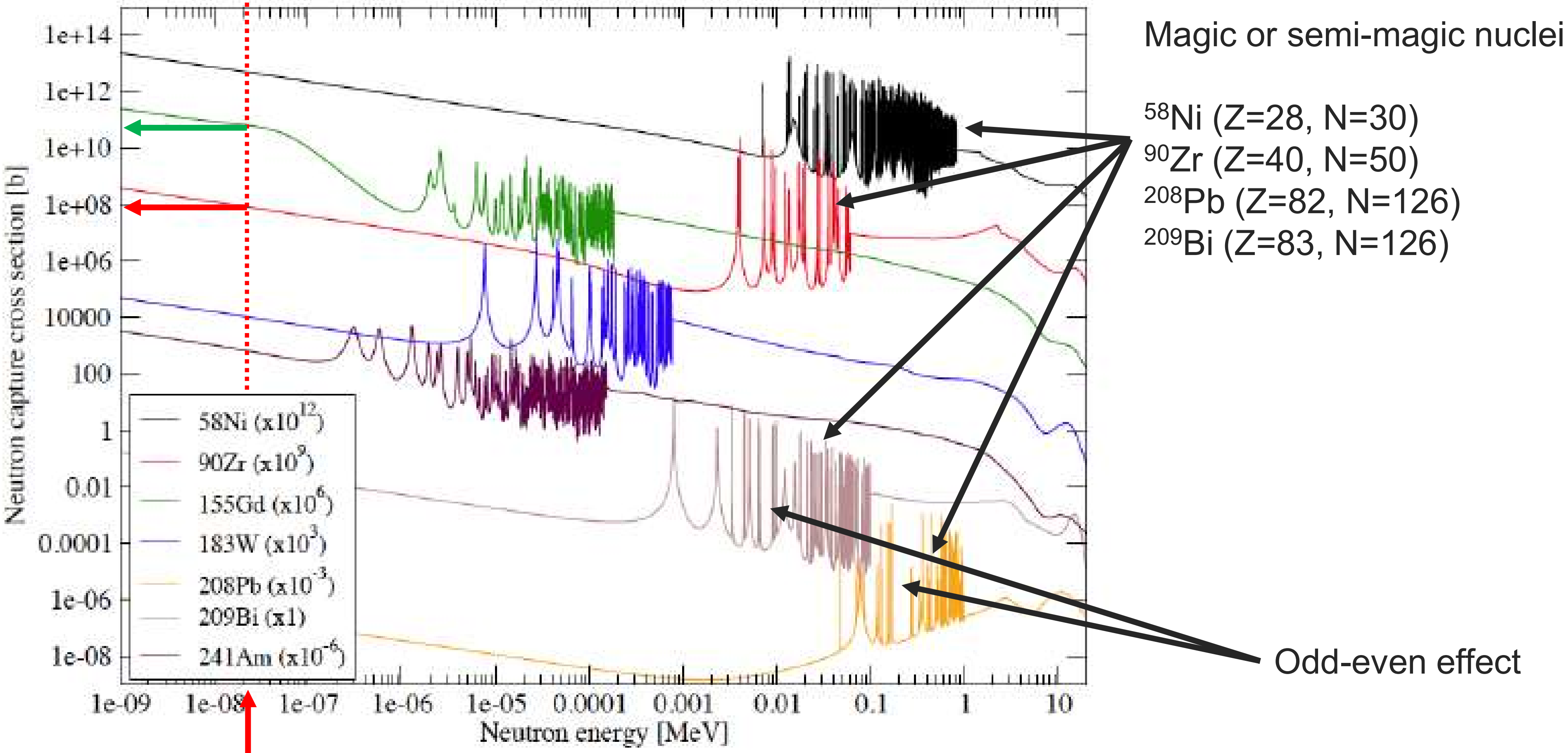
⇒ nearly 9200 nuclei predicted up to Z=130
⇒ 256 stable nuclei + few tens of quasi-stable (half life many years)
⇒ 2550 known masses up to Z=110
⇒ less than 150 known capture cross sections

Do application (except astrophysics) care about exotic nuclei ?



⇒ Nearly 1000 fission fragments (mostly unmeasured)

Cross section stongly vary !



Thermal capture very different (Gadolinium 10^5 b, Zirconium 0.1 b)

2. GENERAL FEATURES ABOUT NUCLEAR REACTIONS

Content

- Introduction

- General features about nuclear reactions

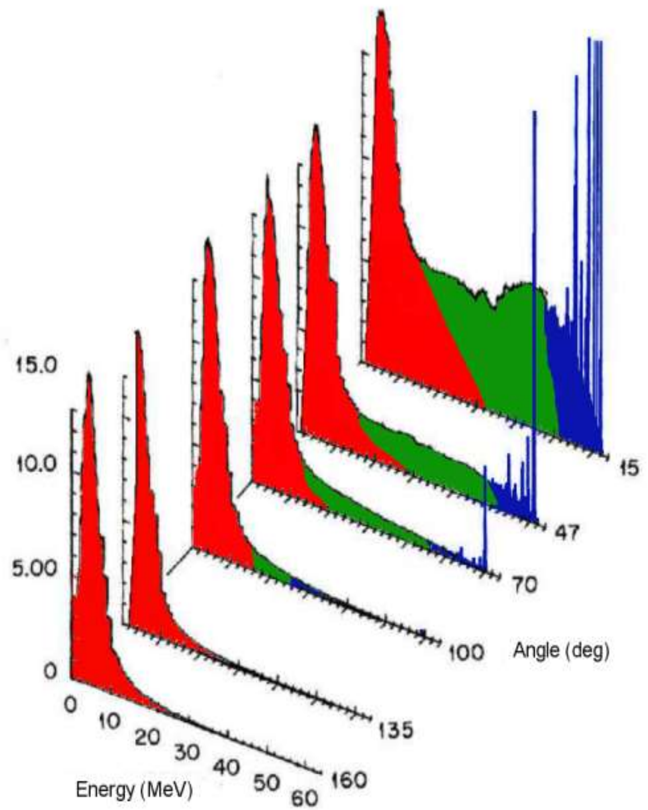
  - **Time scales and associated models**
  - Types of data needed
  - Data format = f (users)

- Nuclear Models

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

Typical spectrum shape

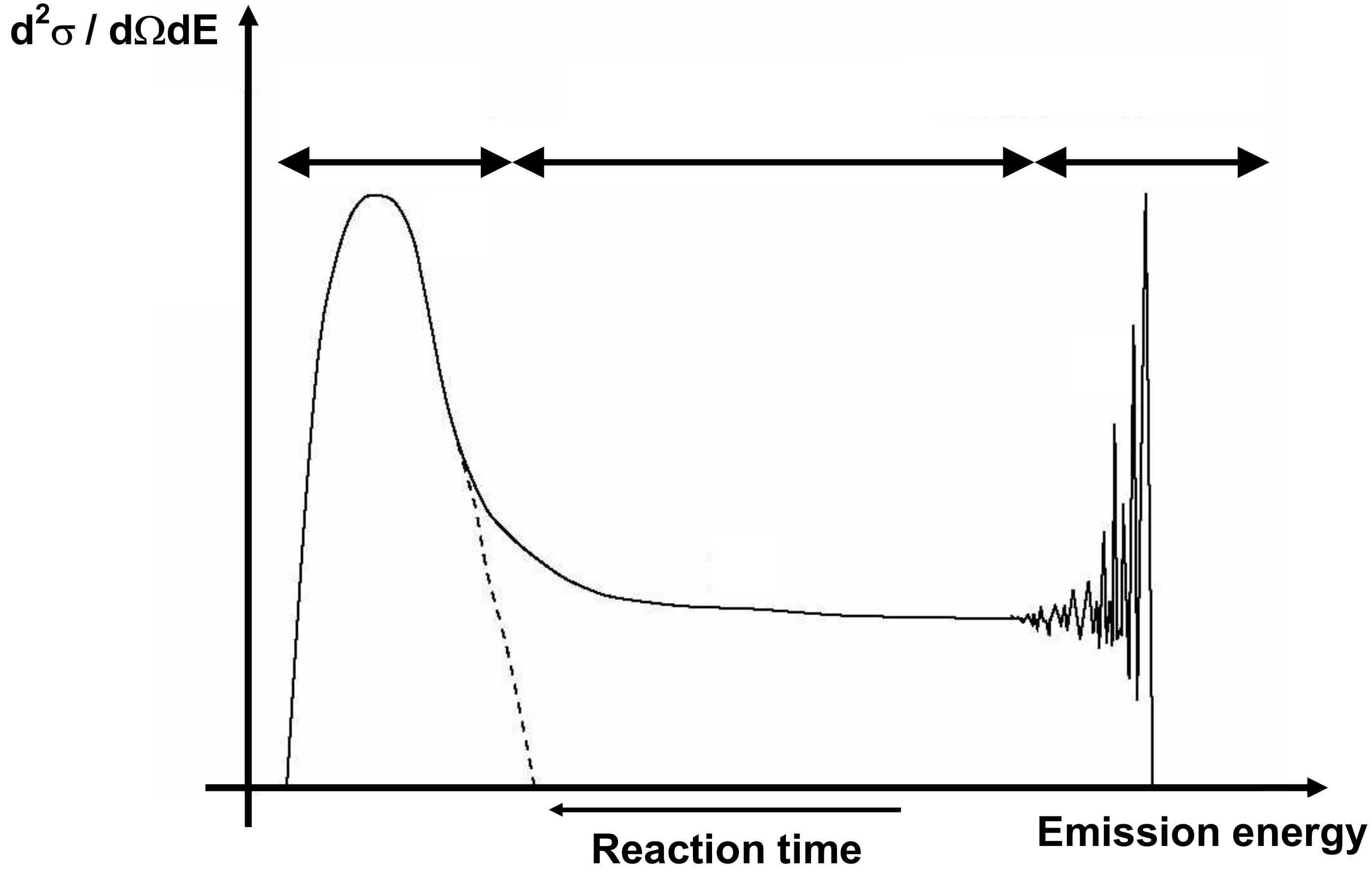
$^{56}Fe(p,xp)$ @ 62 MeV
Double differential cross sections



3 regions :

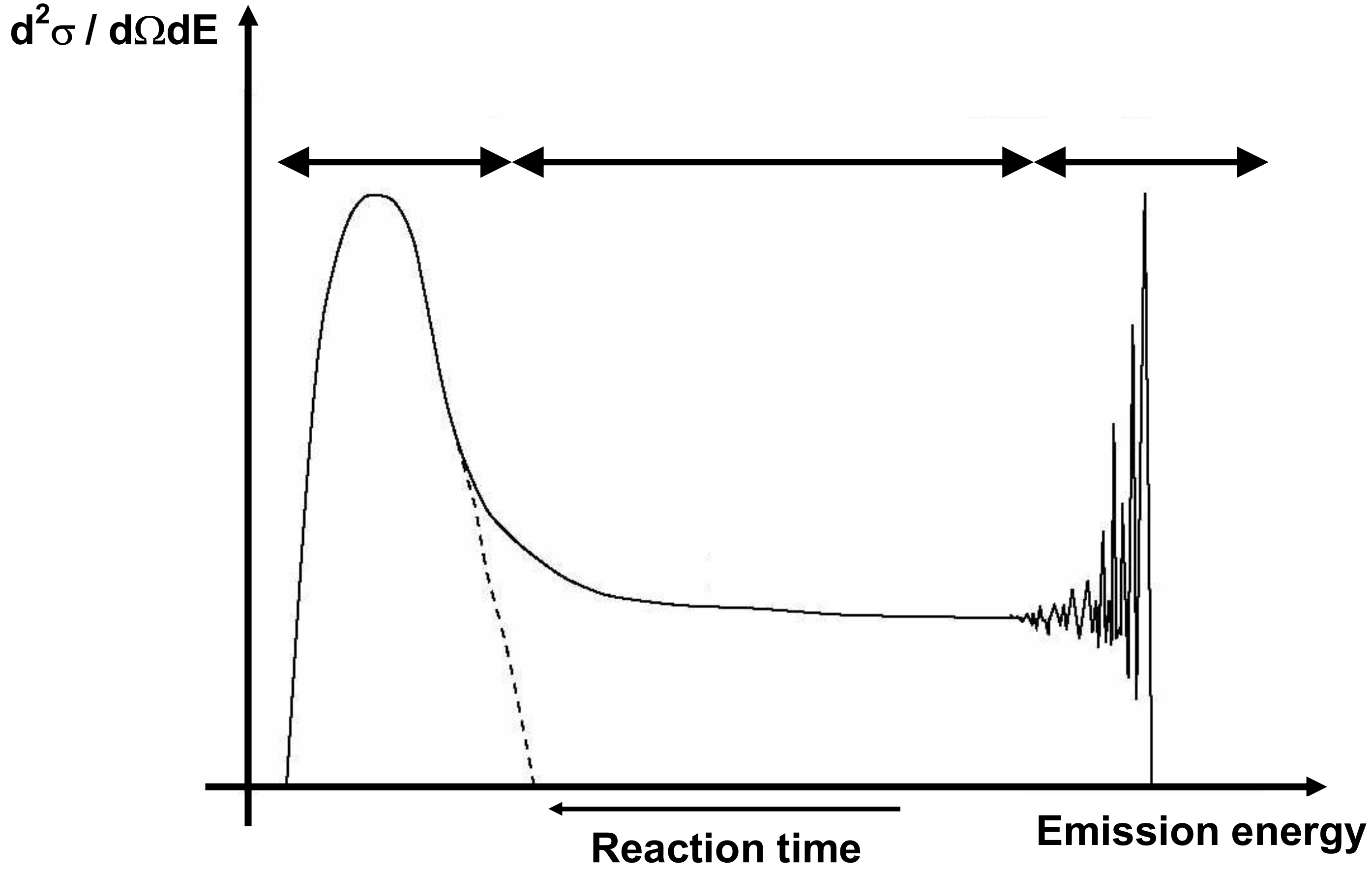
- Red : « evaporation » peak
  always present and low outgoing energy
- Green : « flat » intermediate region
  width increases with incident energy
- Blue : « discrete » peaks
  outgoing energy close to incident energy

Time scales and associated models



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

Time scales and associated models



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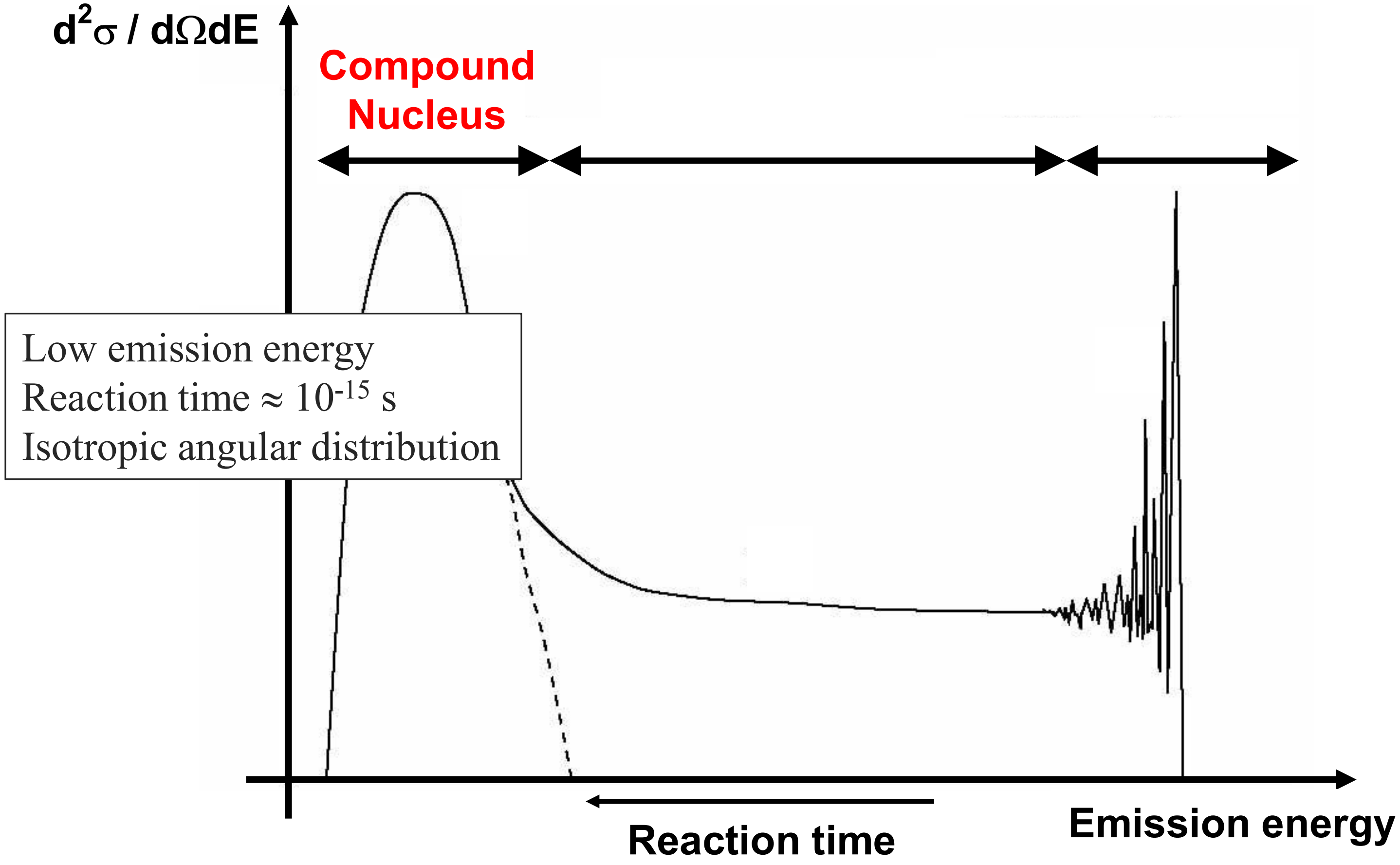
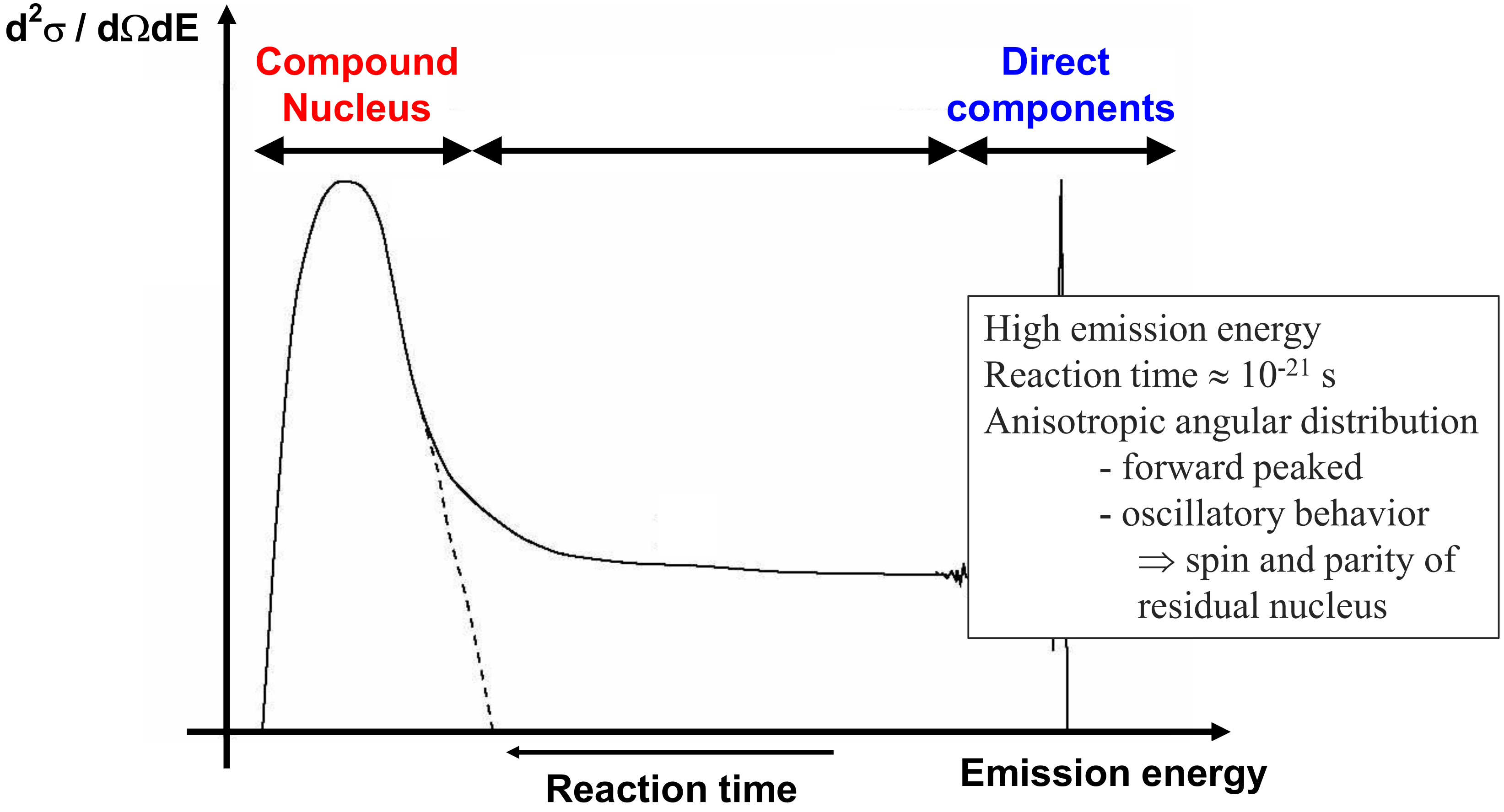


Real scale : 10^{-15} s 10^{-22} s

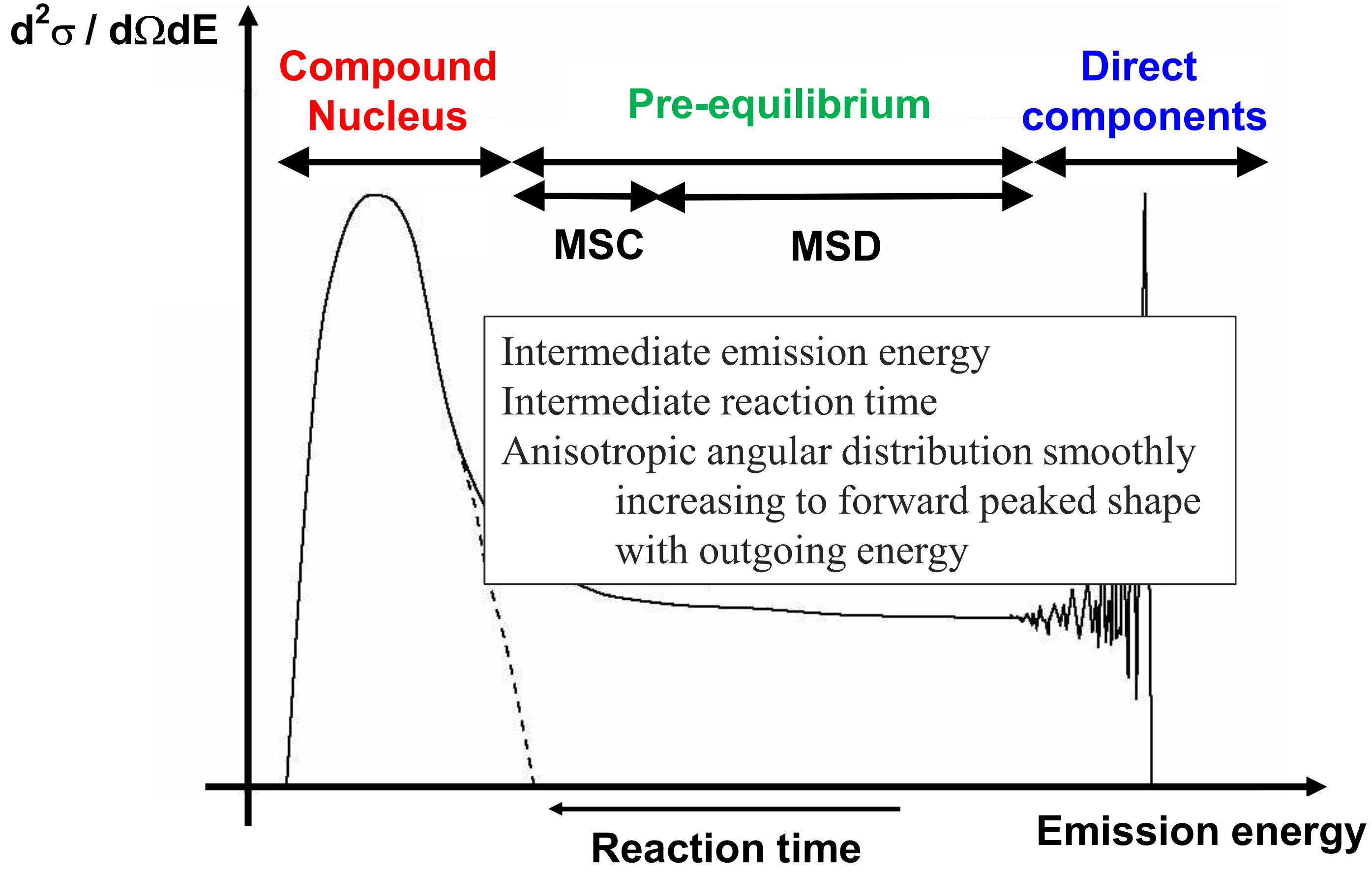
Human scale : year s

Time scales and associated models



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

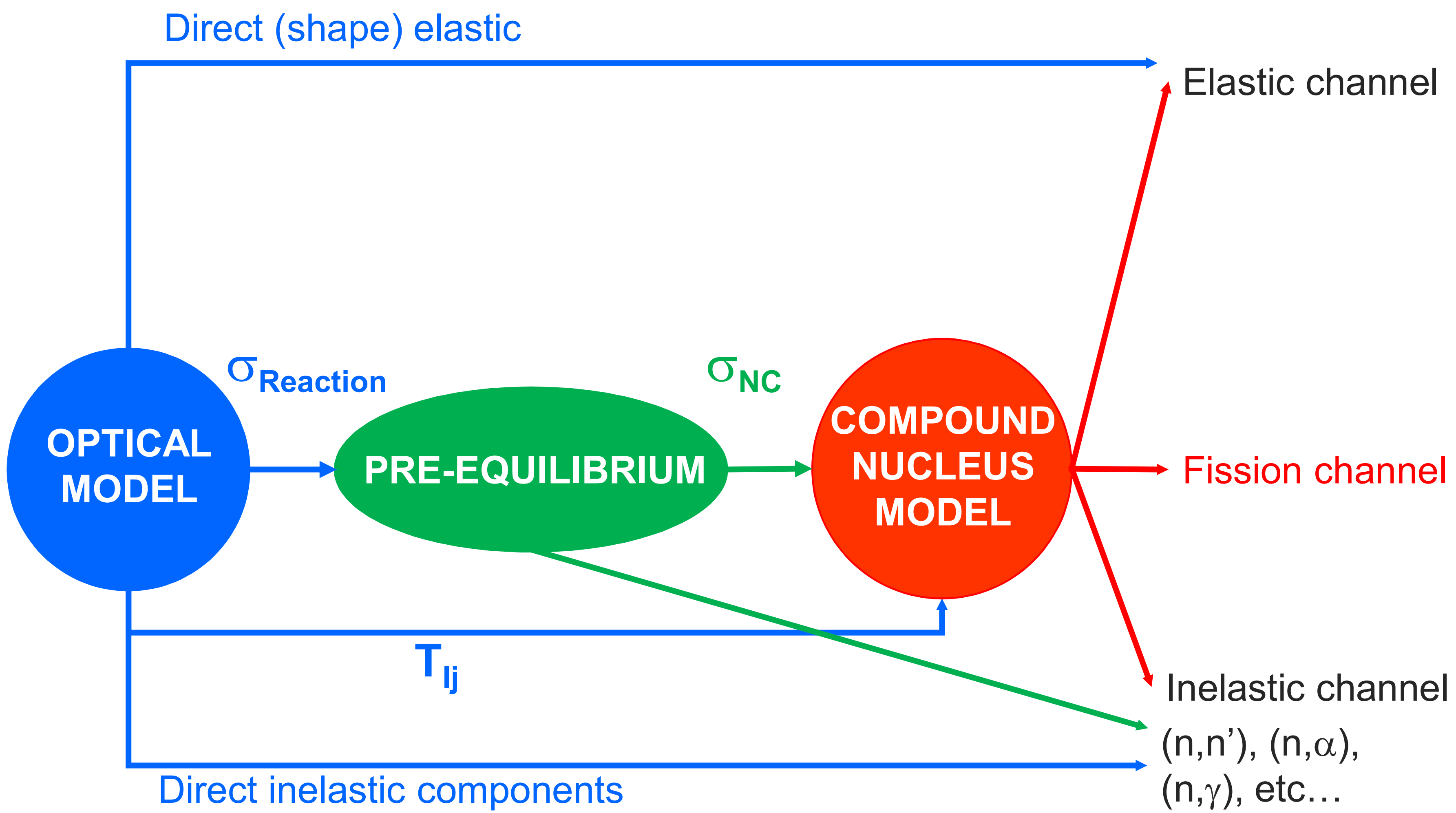
Time scales and associated models



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

Human scale : year s

Models sequence and required ingredients



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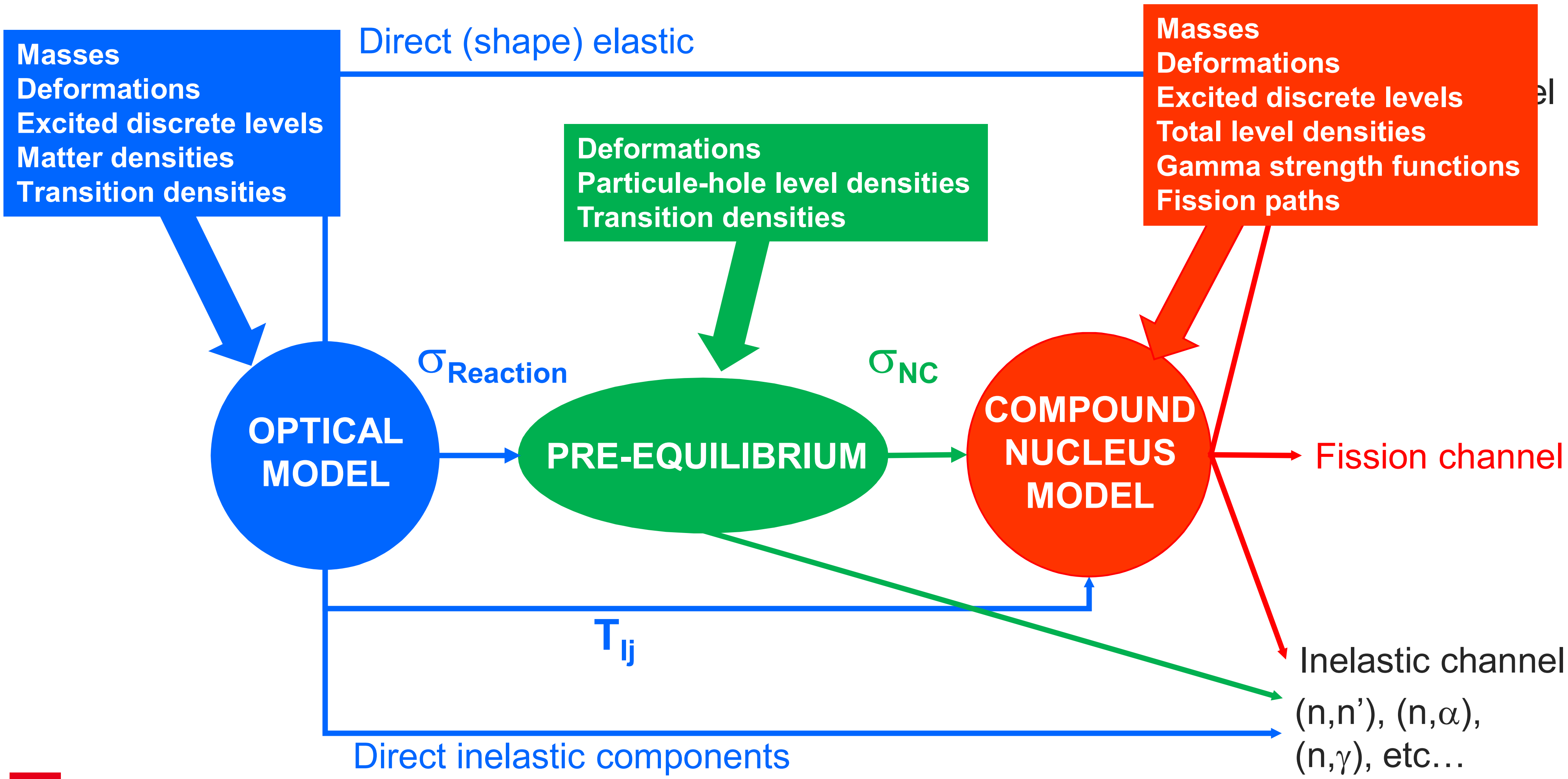


Time scales and associated models

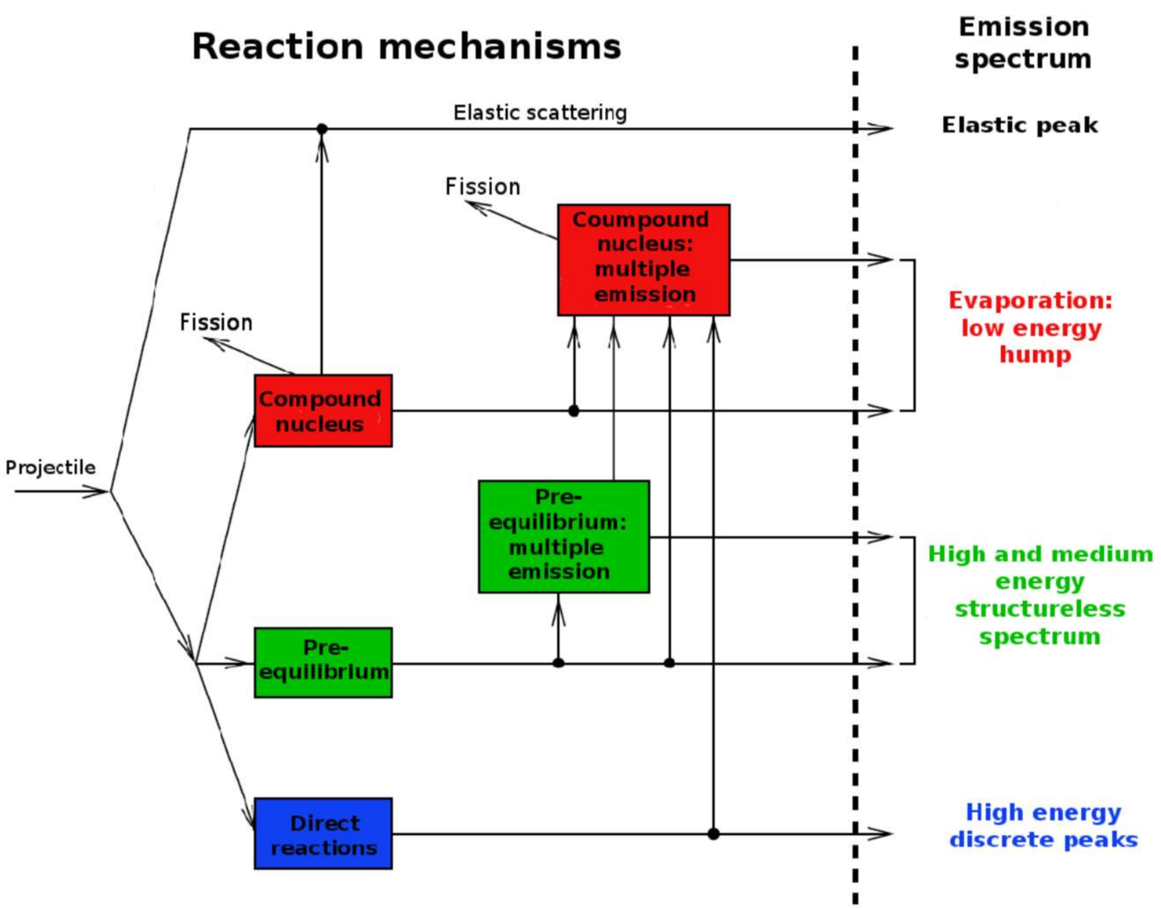
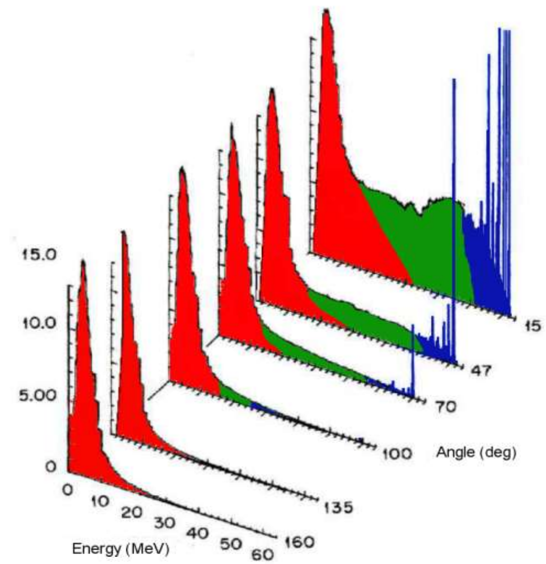


Fig.2 in TALYS paper

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



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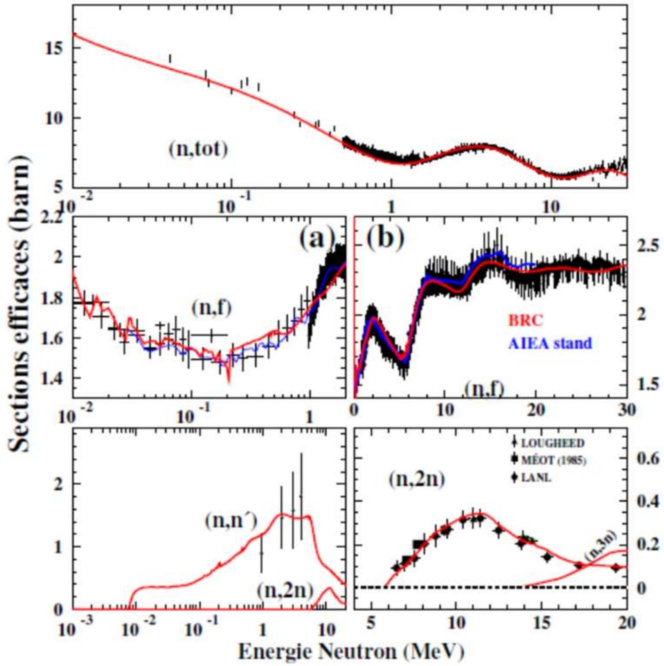
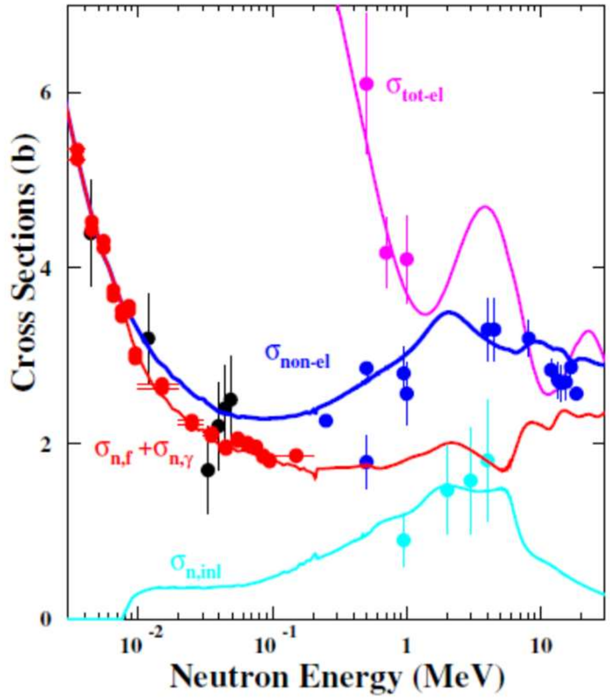
Types of data needed

Cross sections :

total, reaction, elastic (shape & compound), non-elastic, inelastic (discrete levels & total)
total particle (residual) production
all exclusive reactions (n,2n), (n,p), …., (n,nd2a)
all exclusive isomer production
all exclusive discrete and continuum γ-ray production





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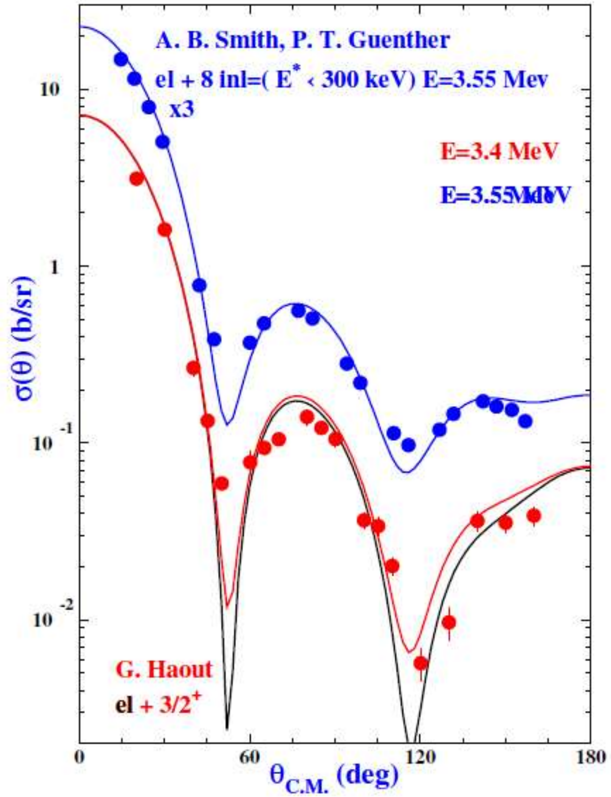
all exclusive reactions (n,2n), (n,p), …., (n,nd2a)
all exclusive isomer production
all exclusive discrete and continuum γ-ray production

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.



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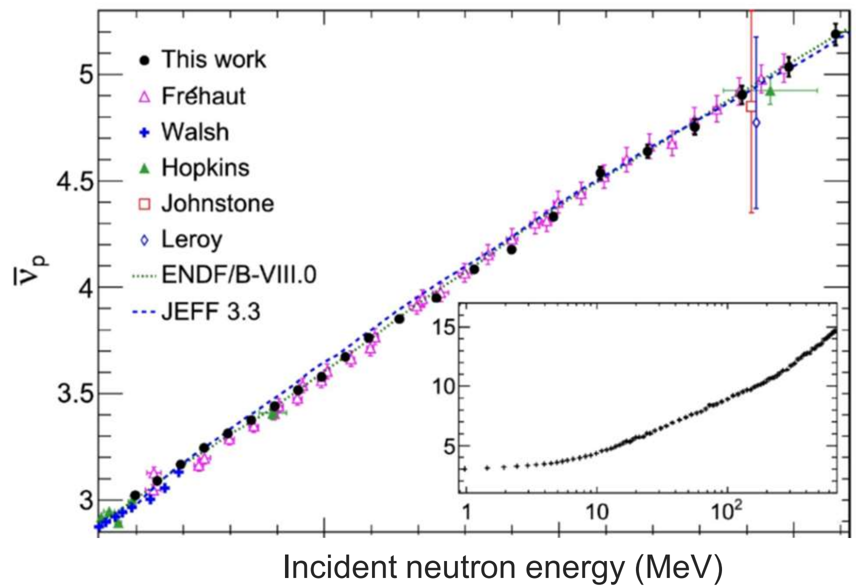
Spectra :

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)

^{239}Pu neutron multiplicity



Types of data needed

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total, reaction, elastic (shape & compound), non-elastic, inelastic (discrete levels & total)
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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

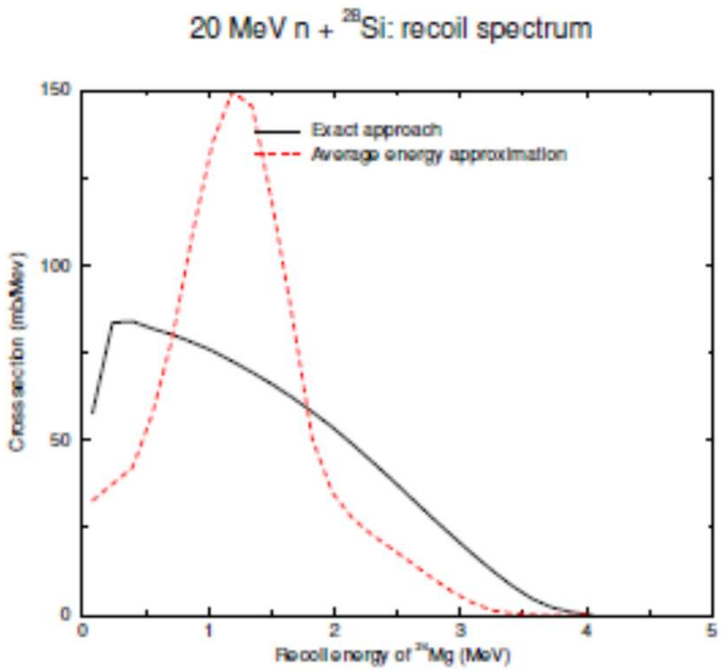

Fig. 8 Example of the difference between exact and approximative recoil treatment in TALYS.

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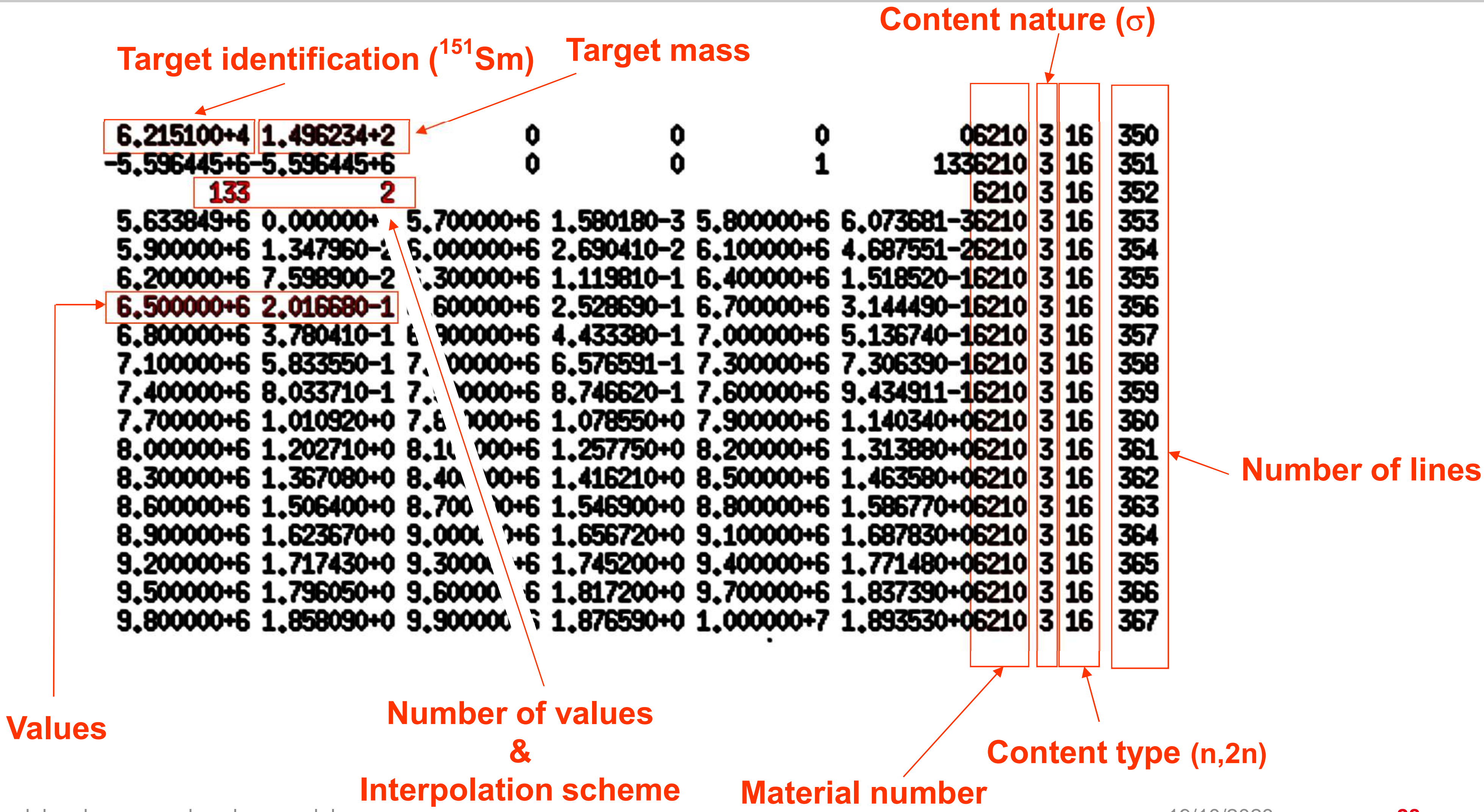
Data format

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

Data format : ENDF file



6.215100+4	1.496234+2	0	0	0	0	6210	3	16	350
-5.596445+6	-5.596445+6	0	0	1	133	6210	3	16	351
133	2					6210	3	16	352
5.633849+6	0.000000+	5.700000+6	1.580180-3	5.800000+6	6.073681-3	6210	3	16	353
5.900000+6	1.347960-2	6.000000+6	2.690410-2	6.100000+6	4.687551-2	6210	3	16	354
6.200000+6	7.598900-2	.300000+6	1.119810-1	6.400000+6	1.518520-1	6210	3	16	355
6.500000+6	2.016680-1	.600000+6	2.528690-1	6.700000+6	3.144490-1	6210	3	16	356
6.800000+6	3.780410-1	6.900000+6	4.433380-1	7.000000+6	5.136740-1	6210	3	16	357
7.100000+6	5.833550-1	7.00000+6	6.576591-1	7.300000+6	7.306390-1	6210	3	16	358
7.400000+6	8.033710-1	7.0000+6	8.746620-1	7.600000+6	9.434911-1	6210	3	16	359
7.700000+6	1.010920+0	7.8000+6	1.078550+0	7.900000+6	1.140340+0	6210	3	16	360
8.000000+6	1.202710+0	8.1000+6	1.257750+0	8.200000+6	1.313880+0	6210	3	16	361
8.300000+6	1.367080+0	8.400+6	1.416210+0	8.500000+6	1.463580+0	6210	3	16	362
8.600000+6	1.506400+0	8.700+6	1.546900+0	8.800000+6	1.586770+0	6210	3	16	363
8.900000+6	1.623670+0	9.000+6	1.656720+0	9.100000+6	1.687830+0	6210	3	16	364
9.200000+6	1.717430+0	9.3000+6	1.745200+0	9.400000+6	1.771480+0	6210	3	16	365
9.500000+6	1.796050+0	9.60000 6	1.817200+0	9.700000+6	1.837390+0	6210	3	16	366
9.800000+6	1.858090+0	9.900000	1.876590+0	1.000000+7	1.893530+0	6210	3	16	367

3. NUCLEAR MODELS

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Basic structure properties : 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 are missing
Recommended databases (RIPL !)

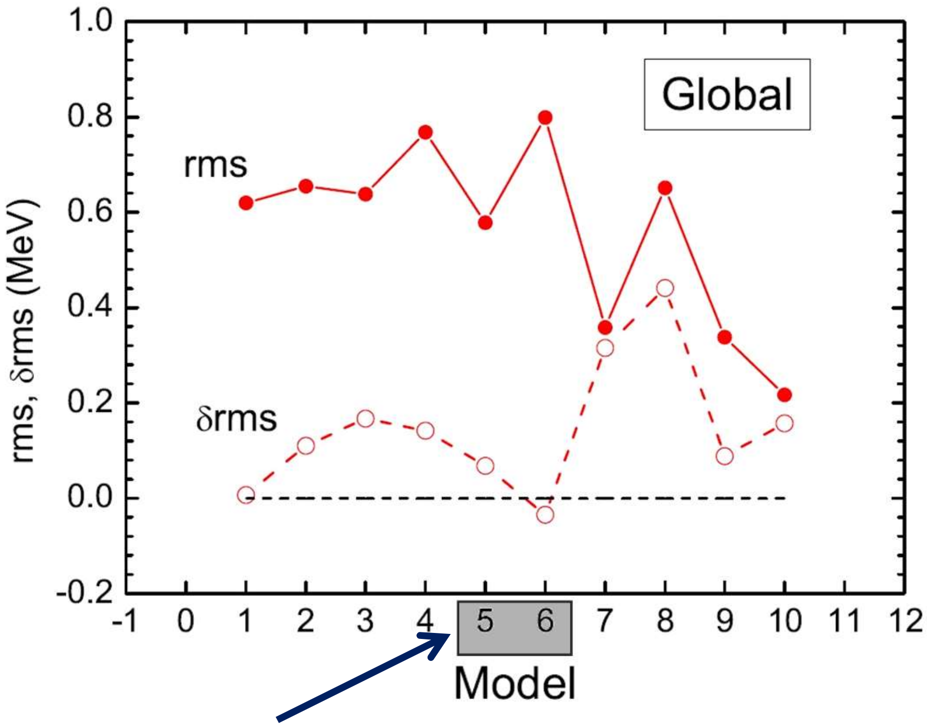
Basic structure properties : mass models

	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) = 500-700 keV on Z ≥ 8 experimental masses**

Basic structure properties : mass models' predictive power

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



Microscopic models

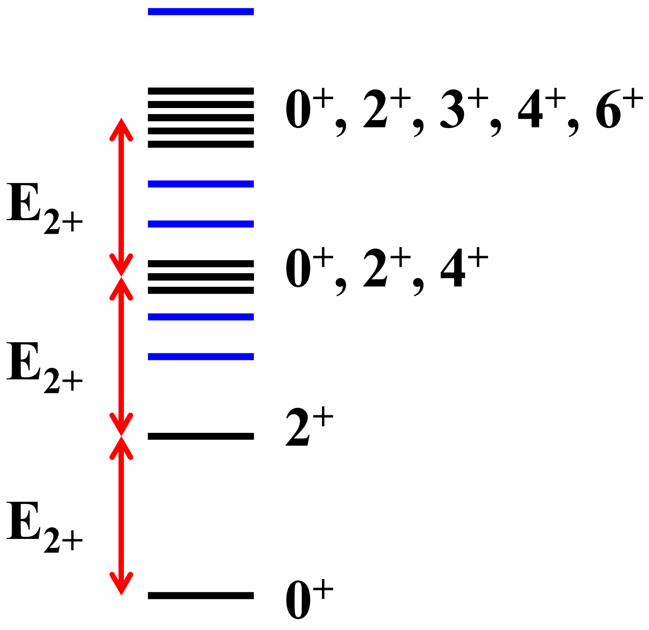
Current status
- **rms < 1 MeV (masses ≈ GeV)**
- **micro ~ macro**
- **micro more predictive**

PHYSICAL REVIEW C **90**, 017302 (2014)

Predictive power of nuclear-mass models

Adam Sobiczewski[1,2,3,*] and Yuri A. Litvinov[2]
[1]*National Centre for Nuclear Research, Hoża 69, 00-681 Warsaw, Poland*

⇒ General level sequence for a spherical even-even nucleus

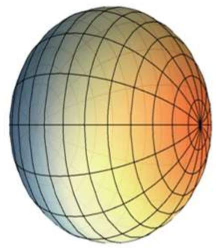


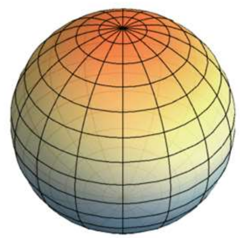
3 coupled phonons

2 coupled phonons

1 phonon

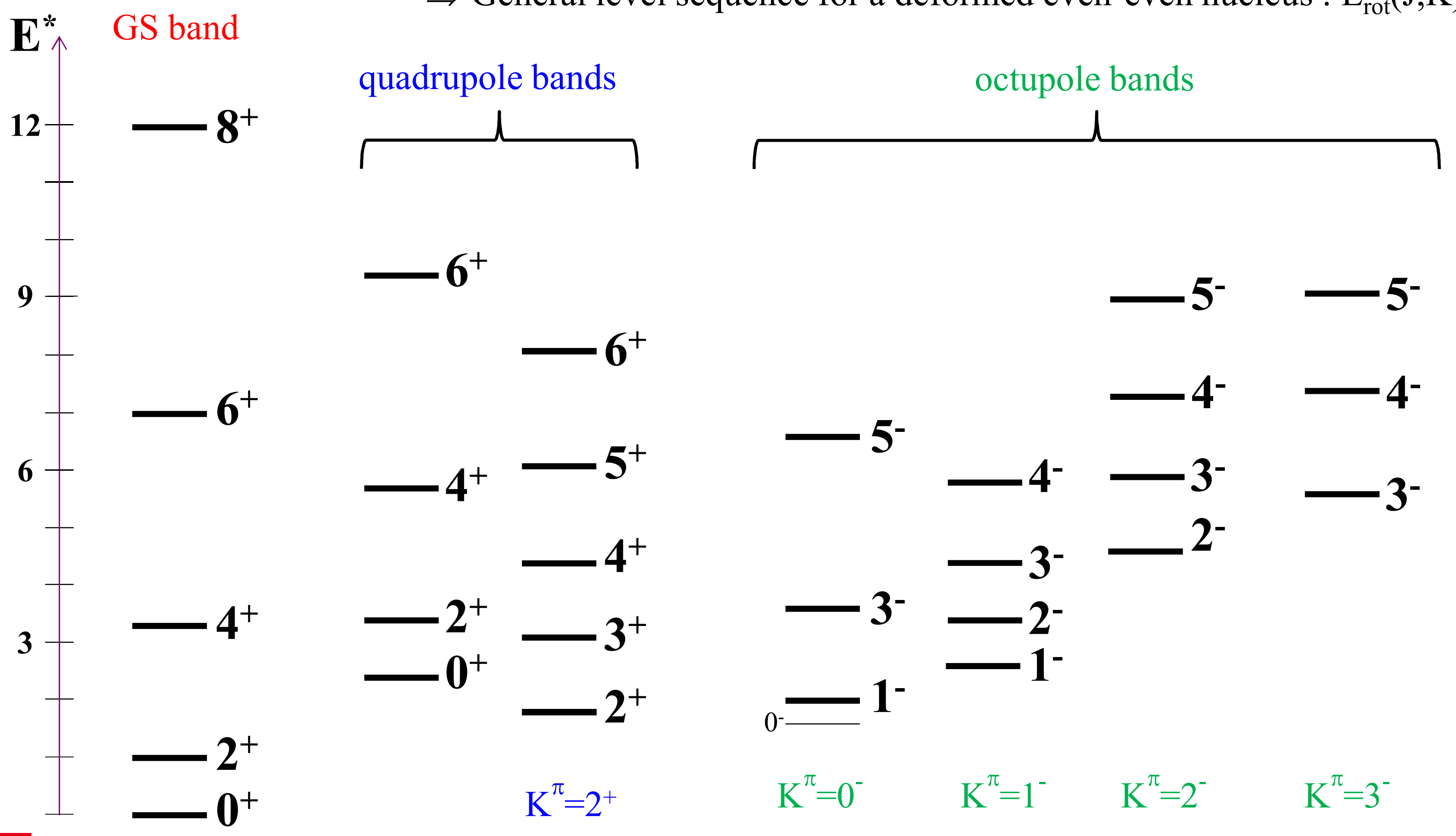
other levels





Basic structure properties : Nuclear structure & level scheme

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



Basic structure properties : Nuclear structure & level scheme

$^{106}_{46}Pd_{60}$-1 $^{106}_{46}Pd_{60}$-1

Adopted Levels, Gammas

Type	Author	Citation	Cutoff Date
	History		
Full Evaluation	D. De Frenne and A. Negret	NDS 109, 943 (2008)	1-May-2007

$Q(\beta^-)$=−2965 *3*; S(n)=9561.0 *3*; S(p)=9345.8 *24*; $Q(\alpha)$=−3229.4 *16* 2012Wa38
Note: Current evaluation has used the following Q record.
$Q(\beta^-)$=−2965 *3*; S(n)=9561.0 *3*; S(p)=9345.8 *25*; $Q(\alpha)$=−3229 *4* 2003Au03

^{106}Pd Levels

Cross Reference (XREF) Flags

A	^{106}Rh β^- decay (30.07 s)	I	^{105}Pd(n,γ) E=res: av	Q	^{106}Pd(p,p′γ)
B	^{106}Rh β^- decay (131 min)	J	^{105}Pd(n,γ) E=2 keV res	R	^{106}Pd(α,α′)
C	^{106}Ag ε decay (23.96 min)	K	^{105}Pd(n,γ) E=24 keV res	S	Coulomb excitation
D	^{106}Ag ε decay (8.28 d)	L	^{105}Pd(d,p)	T	^{108}Pd(p,t)
E	^{96}Zr(^{13}C,3nγ)	M	^{106}Pd(γ,γ′)	U	^{109}Ag(p,α)
F	^{104}Ru(α,2nγ)	N	^{106}Pd(e,e′)	V	^{106}Cd 2β+ decay
G	^{105}Pd(n,γ),(n,α) E=thermal	O	^{106}Pd(n,n′γ)		
H	^{105}Pd(n,γ) E=resonance	P	^{106}Pd(p,p′),(d,d′)		

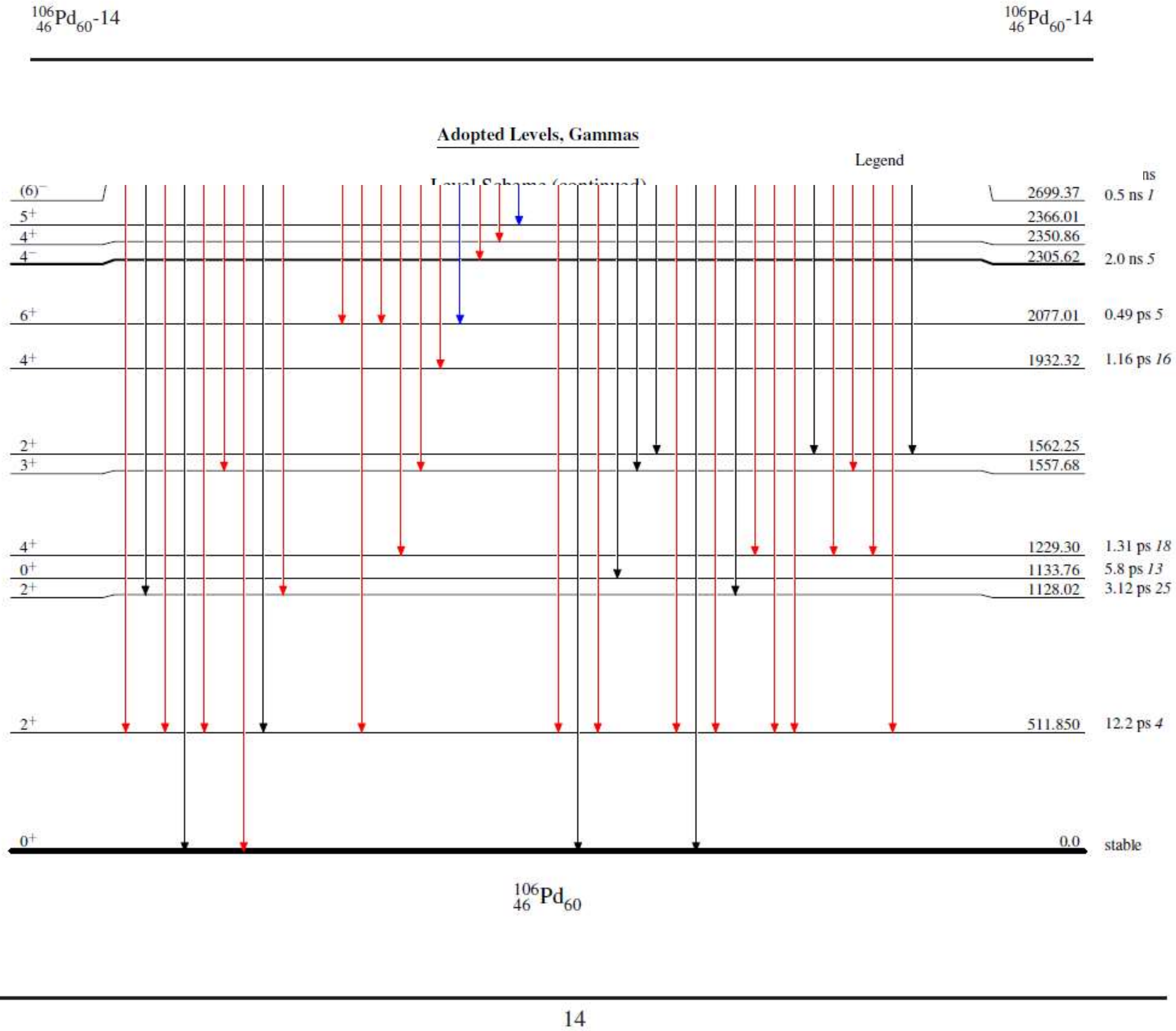
E(level)	J^π	$T_{1/2}$	XREF	Comments
0.0[a]	0+	stable	ABCDEFGHIJKLMNOP RSTUV	rms charge radius: 4.5322 fm 28 (2004An14).
511.850[a] *23*	2+	12.2 ps *4*	ABCDEFGHIJKLMNOP RSTUV	μ= 0.74 *3* Q=−0.51 7 $T_{1/2}$: from B(E2)=0.670 *19* in Coul. ex. Others: 13.6 ps *44* via (γ,γ′) (1977Ga06) 14.3 ps 4 from (e,e′) (1991We15). μ: Other: +0.80 4 (1989Ra17). J^π: L(p,t)=2. Q: Deduced from (e,e′) E=183,250 MeV (1973Ho05). Others: -0.56 8 or −0.41 and −0.51 7 (1989Ra17).
1128.02 *3*	2+	3.12 ps *25*	ABCDEFGHIJKL NOP RSTUV	μ=+0.58 *9* $T_{1/2}$: from B(E2)=0.0175 *13* in Coul. ex. with branching (1128γ)=35.2% *6*. J^π: from E2 to g.s. μ: Other: +0.60 12 (1989Ra17).
1133.76 *4*	0+	5.8 ps *13*	A C GH JK O RST V	J^π: from E0 to g.s. B(E2)[2+(511 keV) to 0+(1133 keV)]=0.021 *4*: weighted average of 0.0184 (1969Ro05) and 0.026 *5*(1995Sv01) in Coul. ex. $T_{1/2}$: from B(E2)[2+(511 keV) to 0+(1133 keV)]=0.021 *4*.

⇒ energy, spin, parity, decay modes, … :

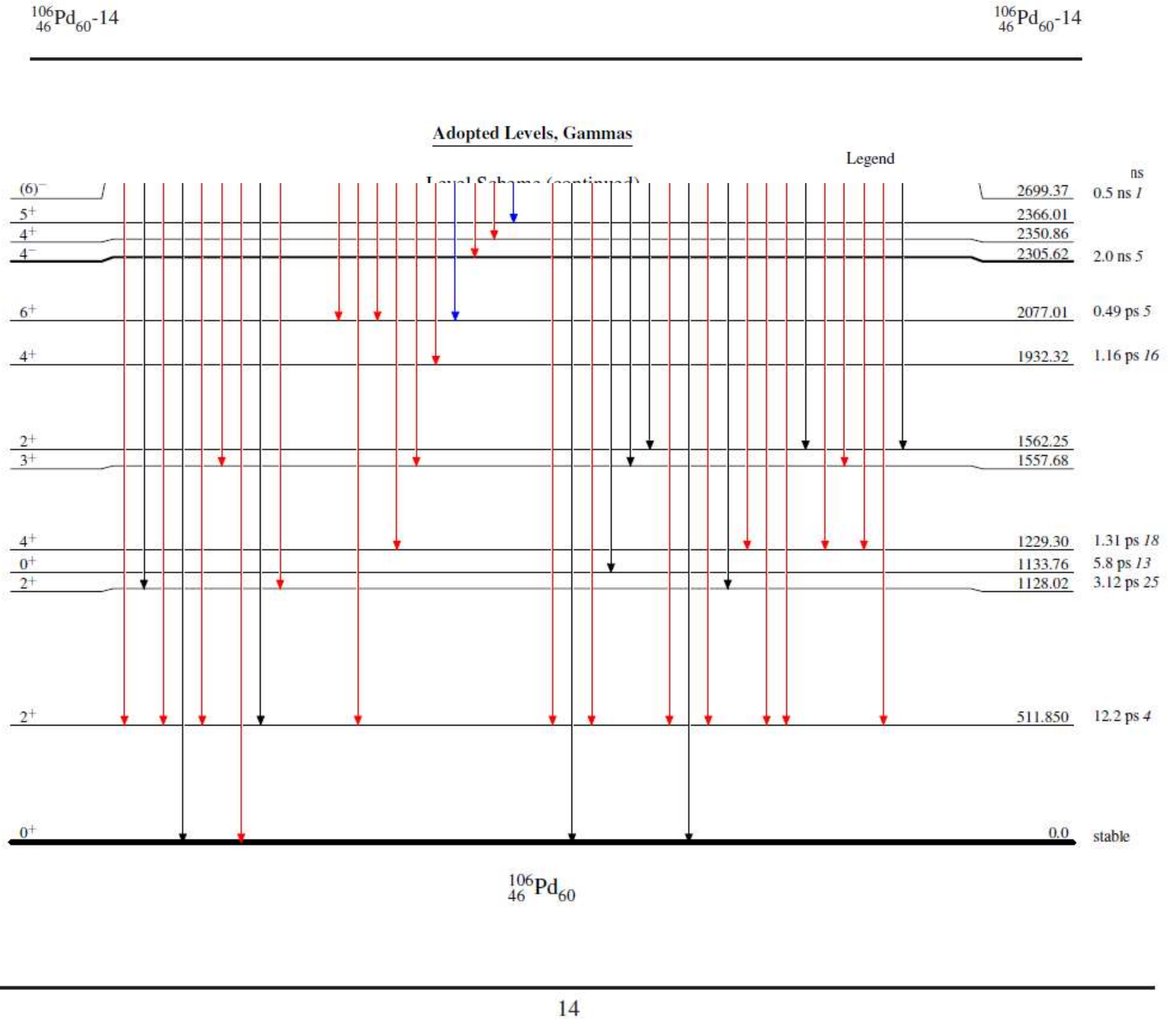
informations compiled in ENSDF database

⇒ Level scheme = deformation evidence

Nuclear structure & level scheme : spherical nucleus

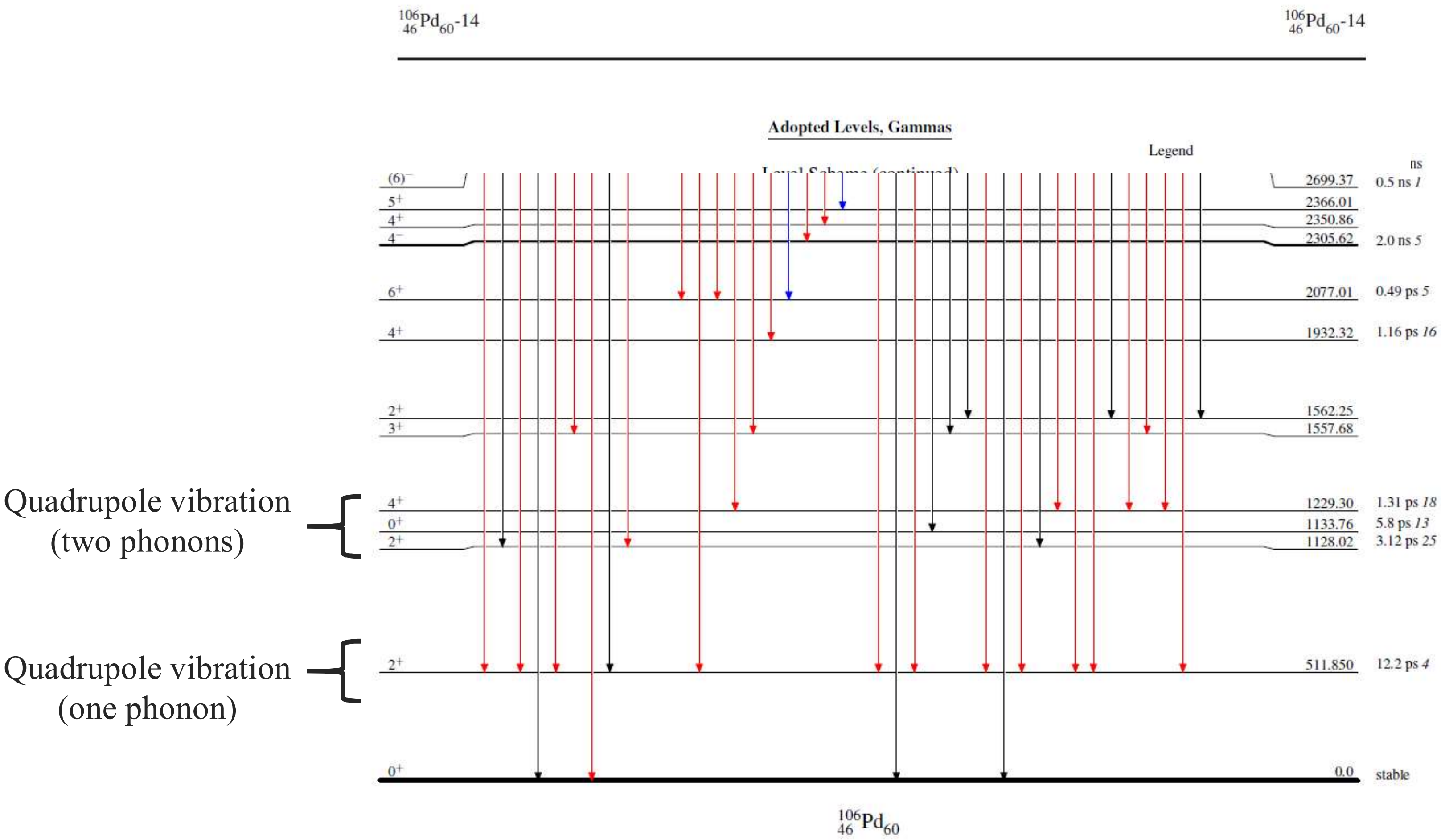


Nuclear structure & level scheme : spherical nucleus



Quadrupole vibration
(one phonon)

Nuclear structure & level scheme : spherical nucleus

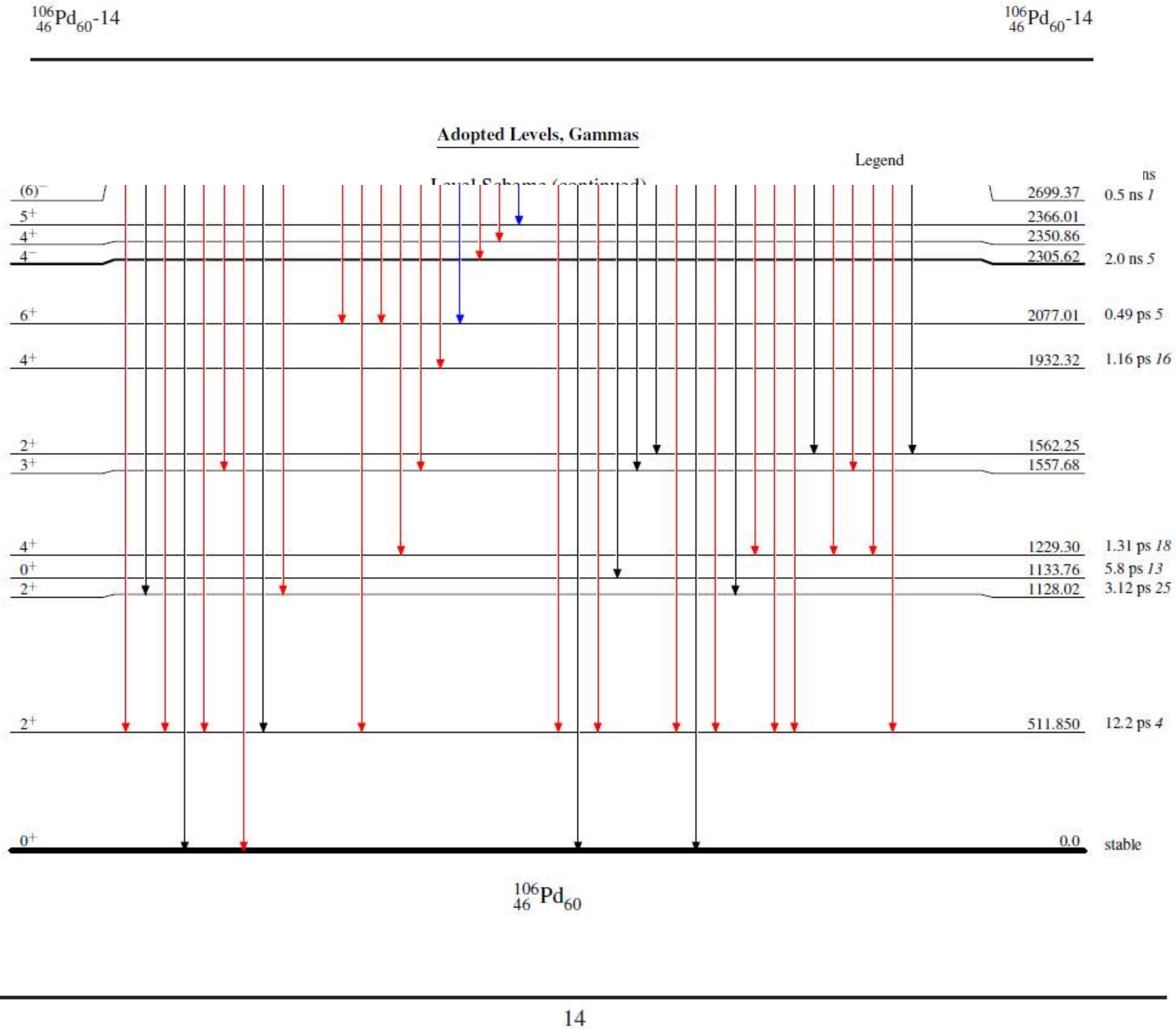


Nuclear structure & level scheme : spherical nucleus

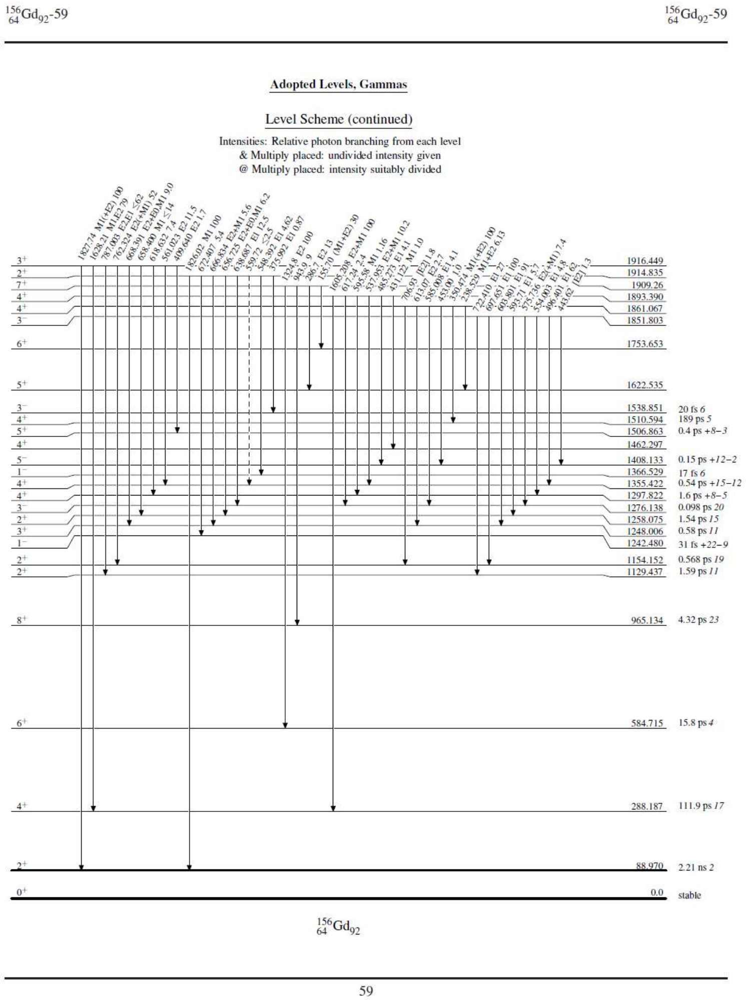
Quadrupole vibration
(three phonons)

Quadrupole vibration
(two phonons)

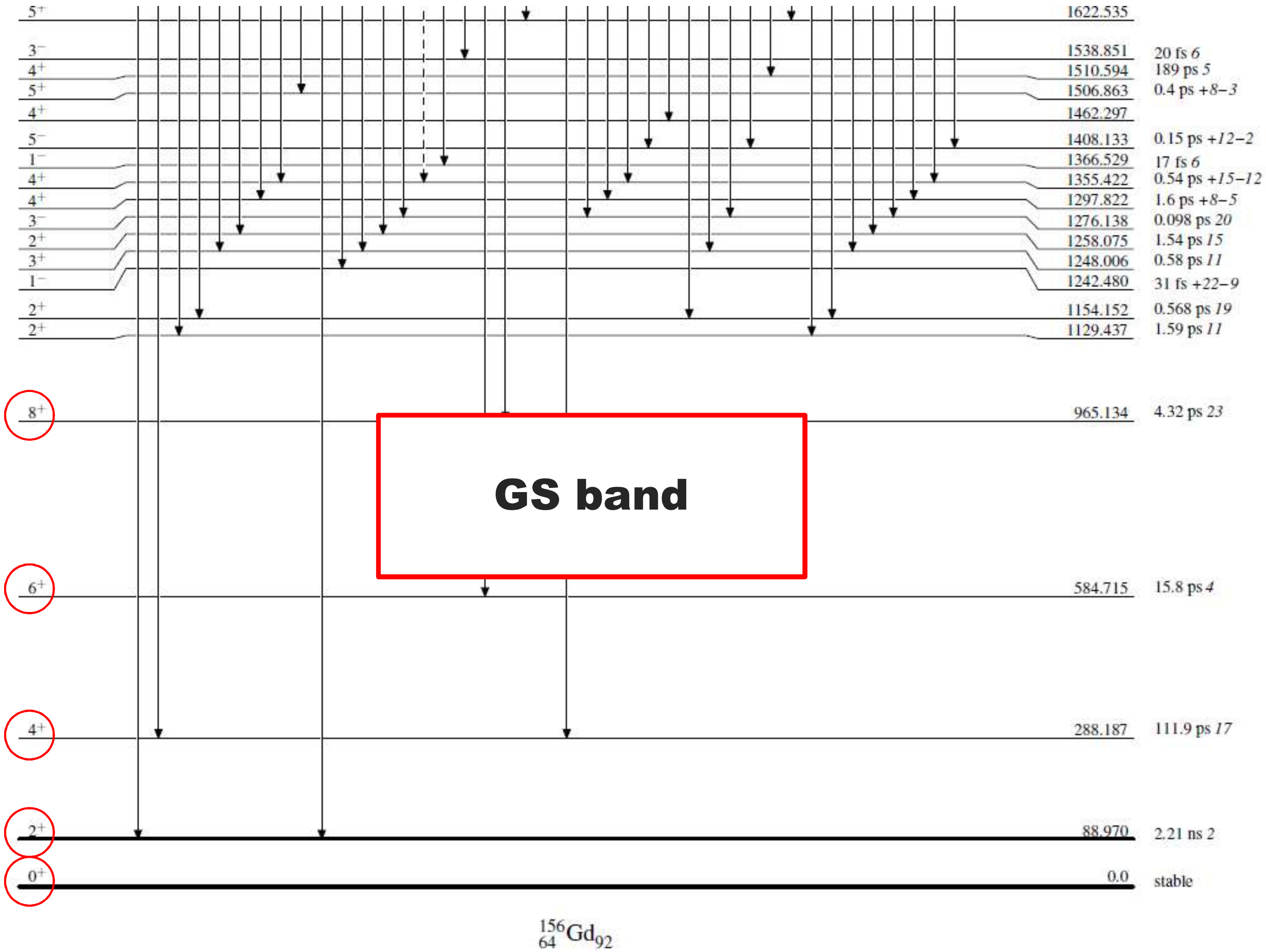
Quadrupole vibration
(one phonon)



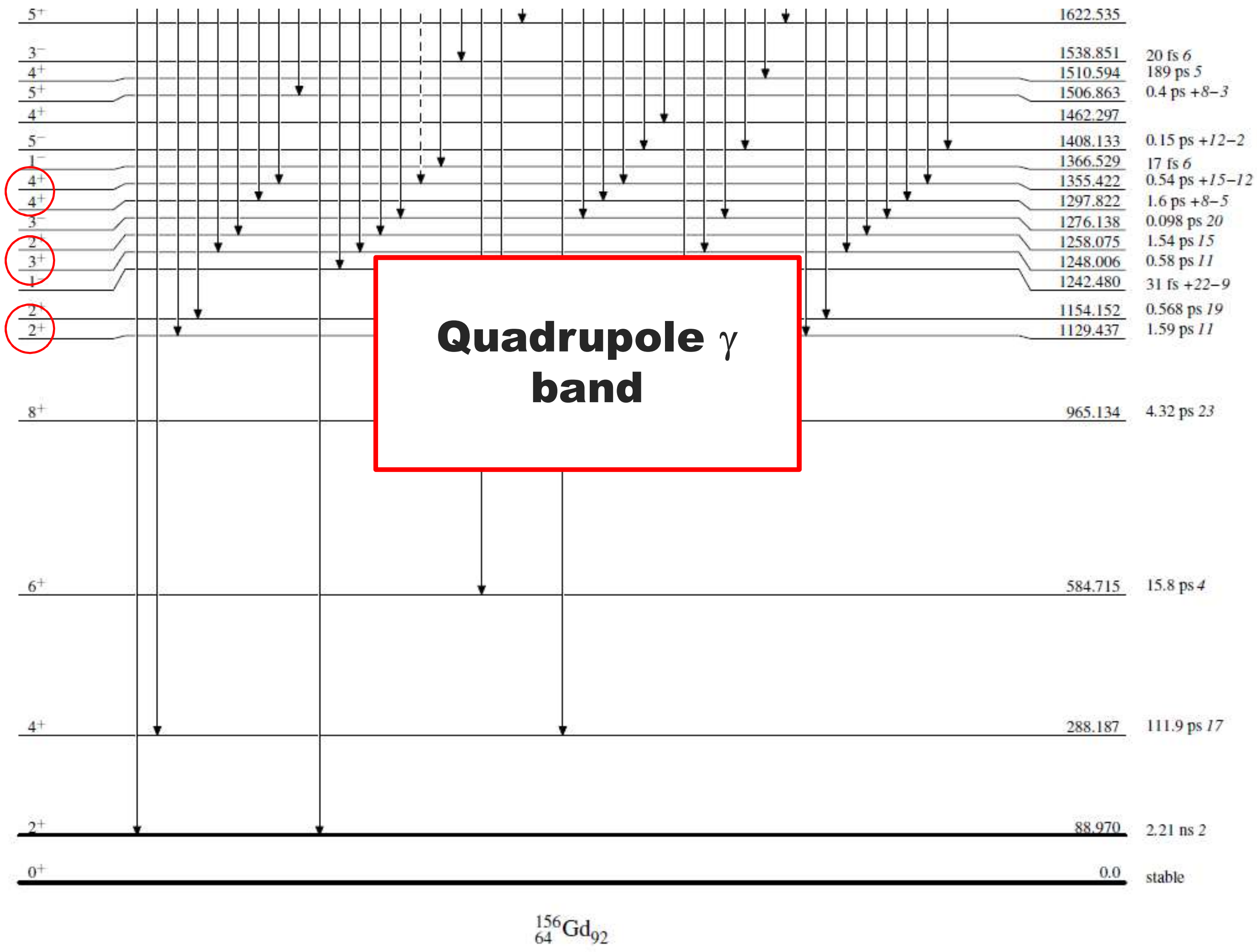
Nuclear structure & level scheme : deformed nucleus



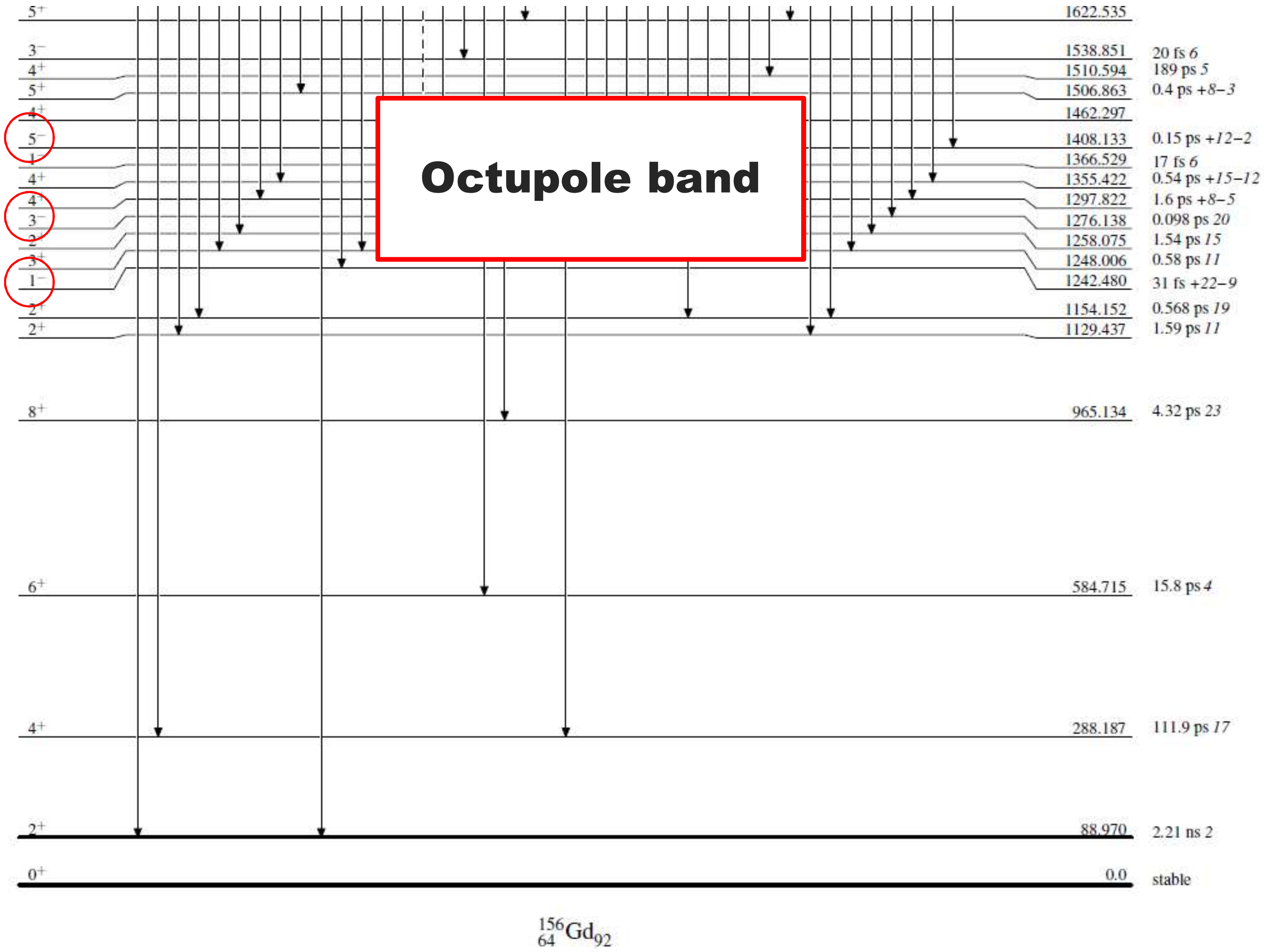
Nuclear structure & level scheme : deformed nucleus



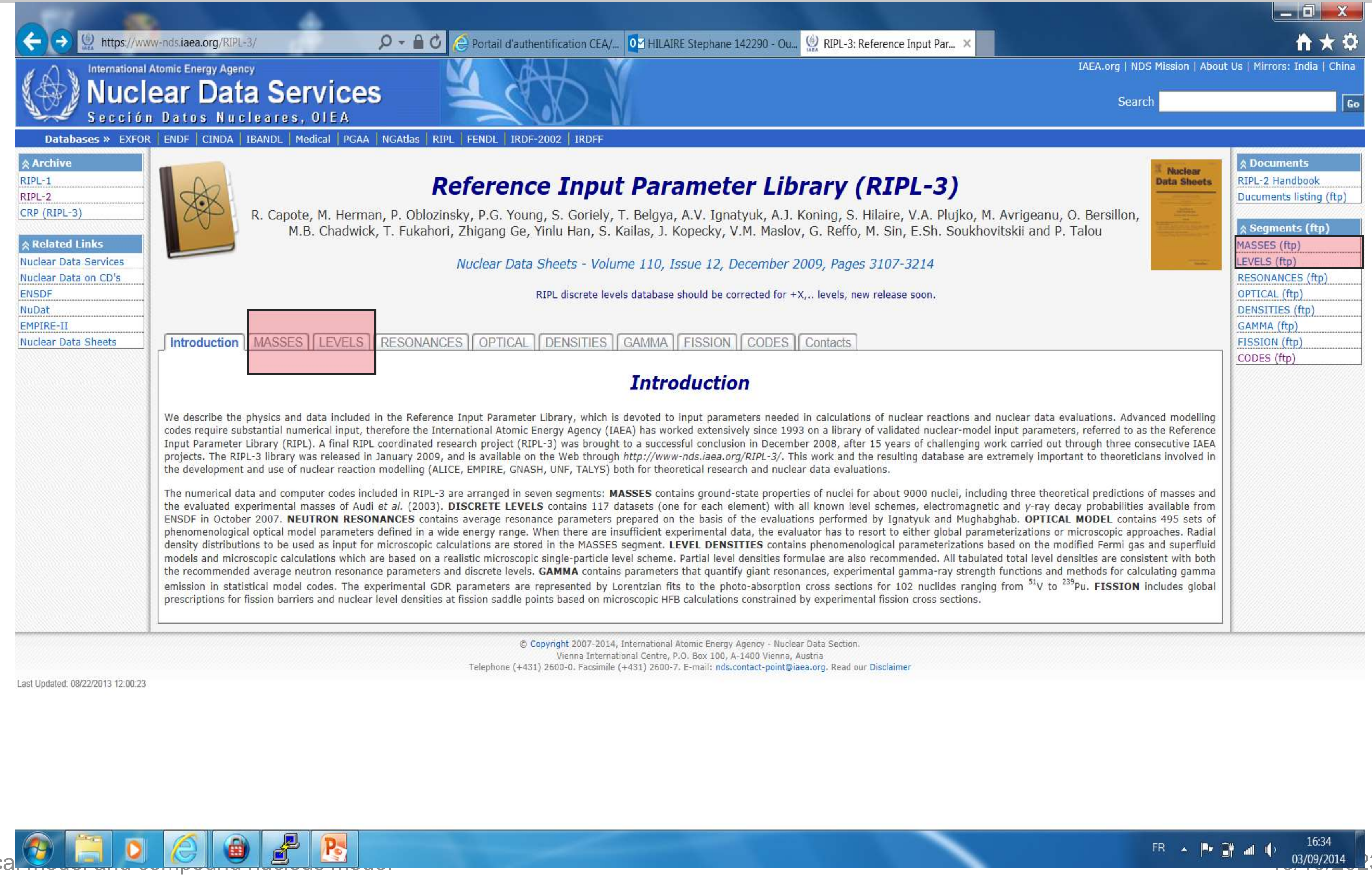
Nuclear structure & level scheme : deformed nucleus



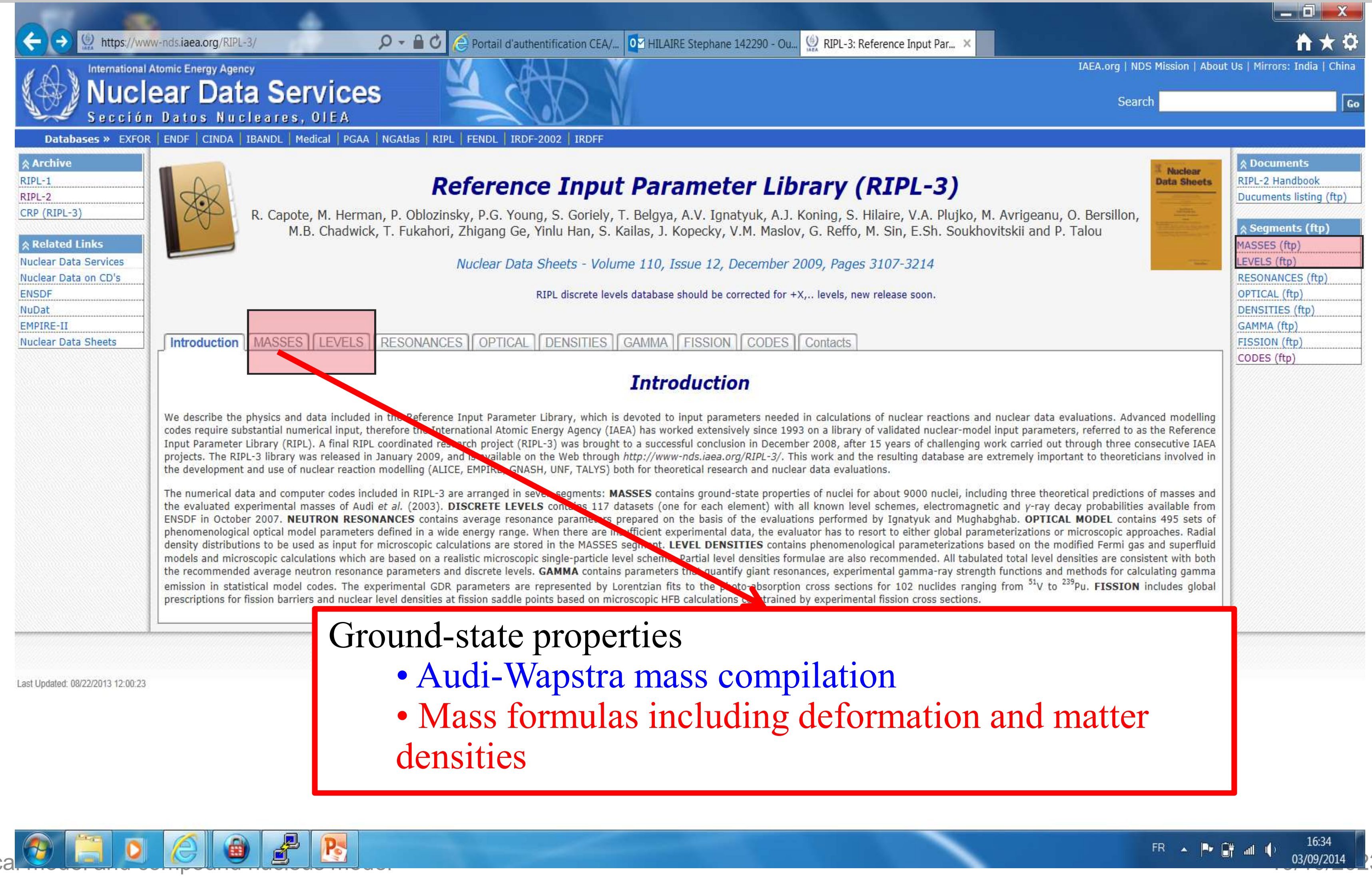
Nuclear structure & level scheme : deformed nucleus



Basic structure properties : RIPL inputs



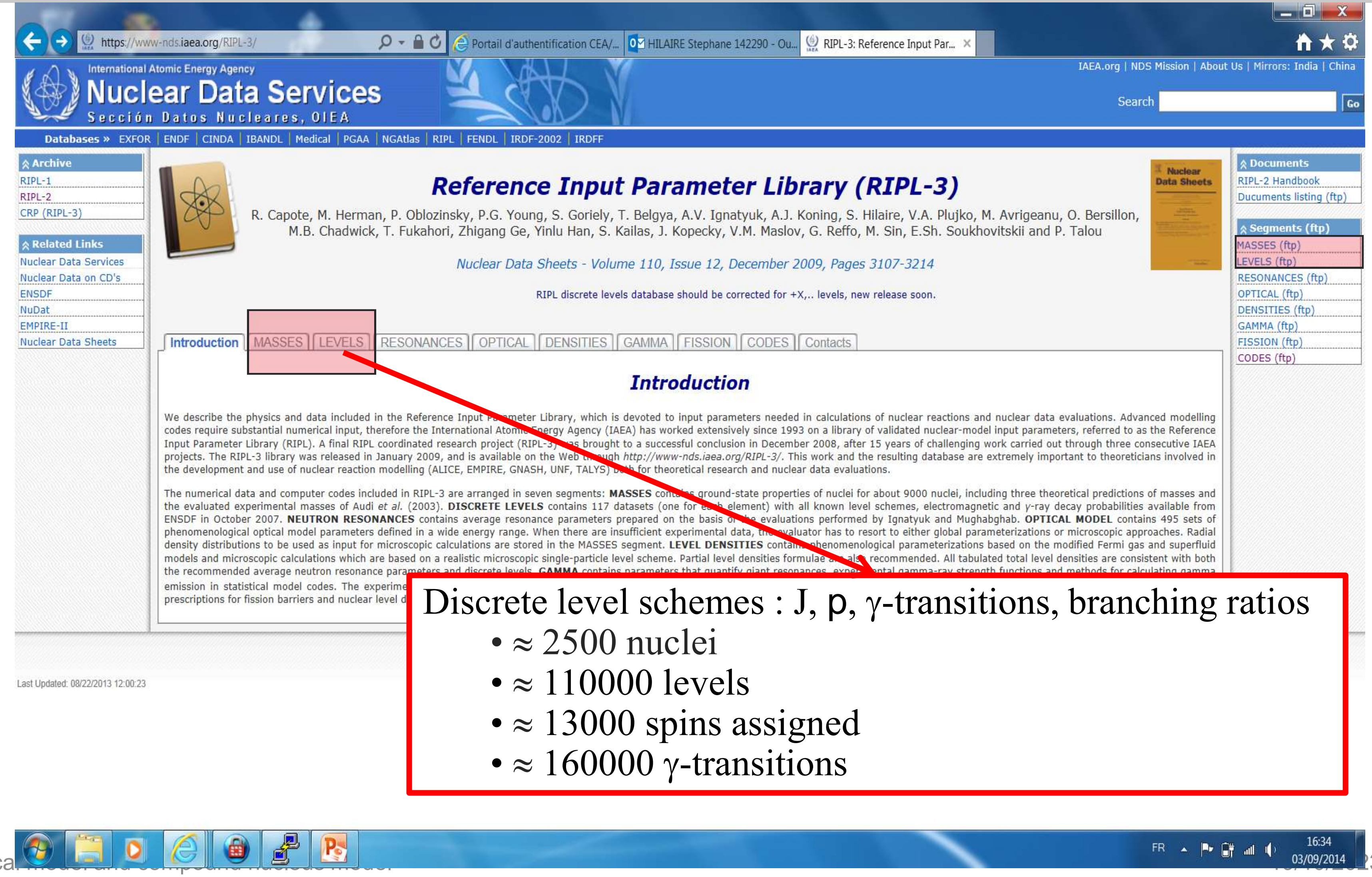
Basic structure properties : RIPL inputs



Ground-state properties

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

Basic structure properties : RIPL inputs



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

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

Content

- Introduction

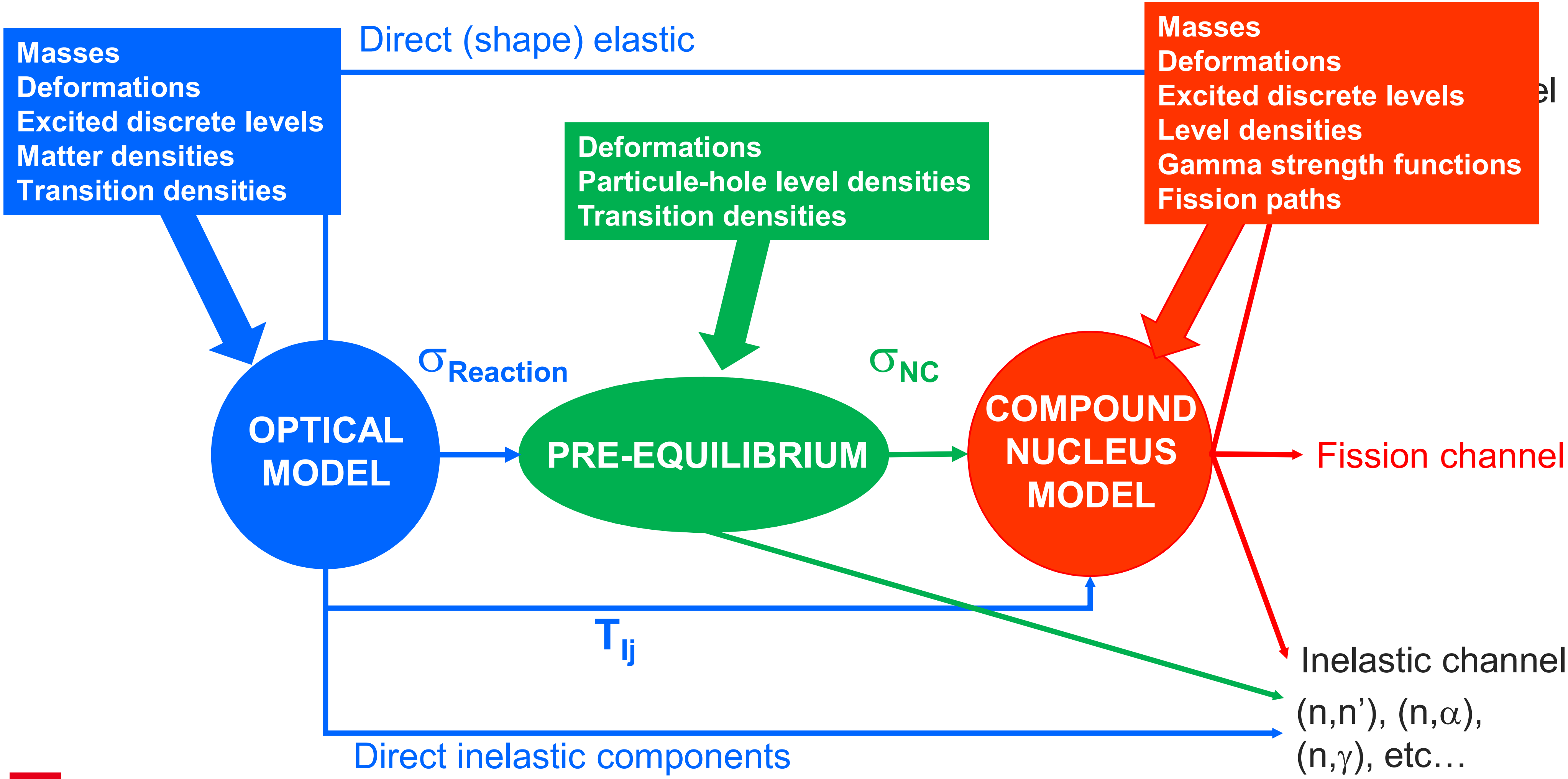
- General features about nuclear reactions

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

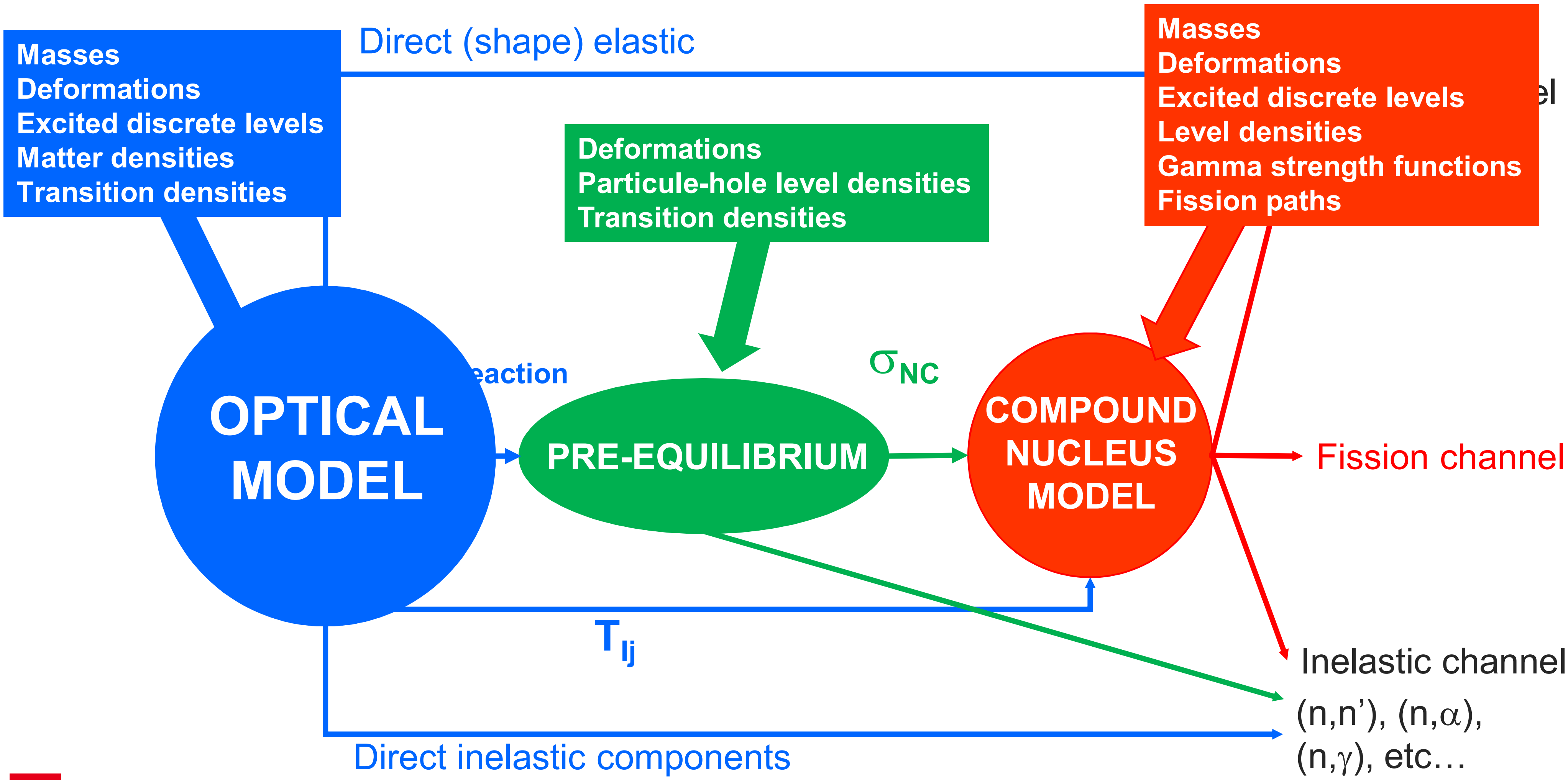
- Nuclear Models

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

Models sequence and required ingredients

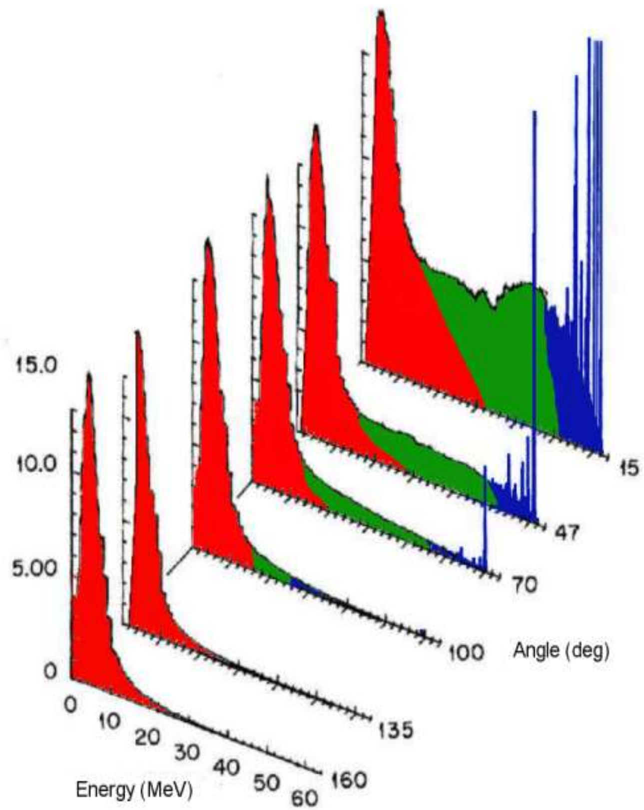


Models sequence and required ingredients



Typical spectrum shape

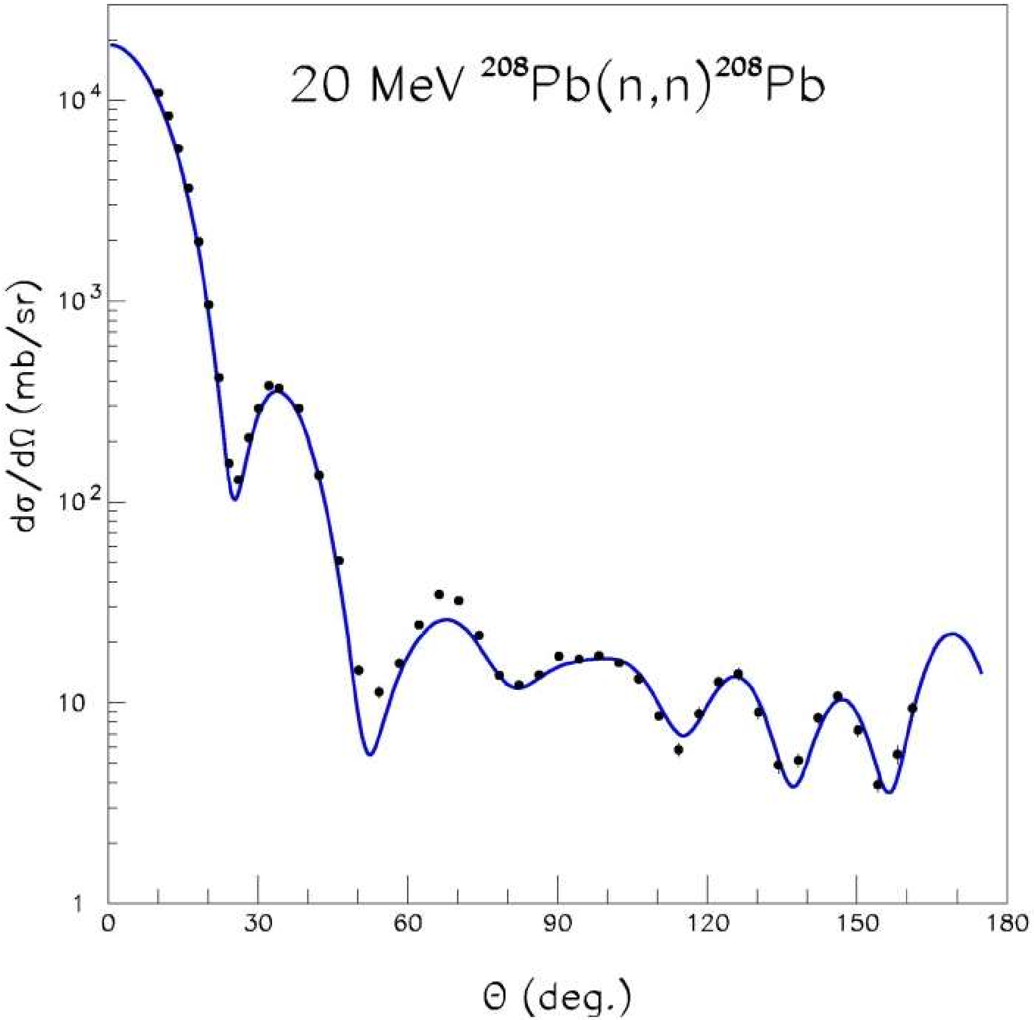
^{56}Fe(p,xp) @ 62 MeV
Double differential cross sections



3 regions :

- Red : « evaporation » peak
  always present and low outgoing energy
- Green : « flat » intermediate region
  width increases with incident energy
- **Blue : « discrete » peaks**
  outgoing energy close to incident energy

The optical model : why such a name ?



⇒ diffraction patterns observed experimentally

⇒ optical model

The optical model : basics

Direct interaction of a projectile with a target nucleus considered as a whole

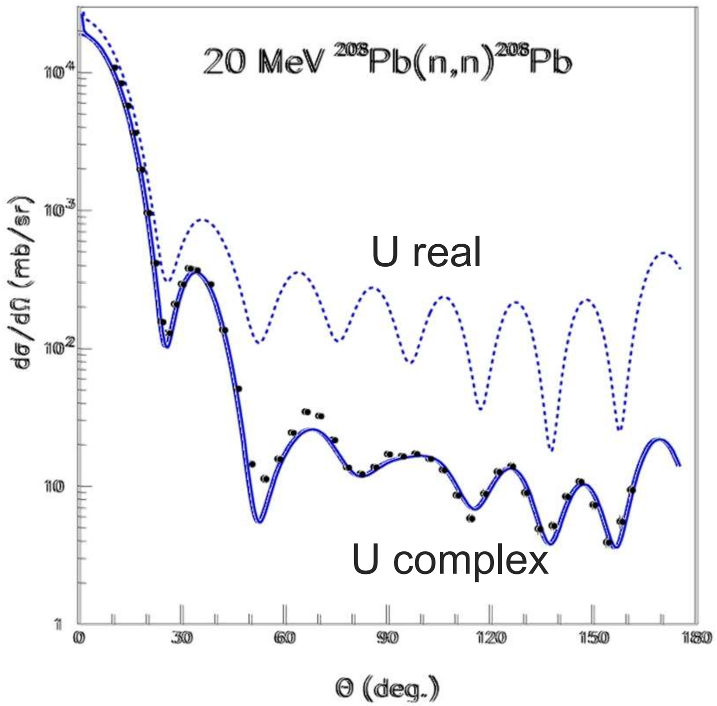
Quantum model $\rightarrow$ Schrödinger equation

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

Complex potential:

$$U = V + iW$$

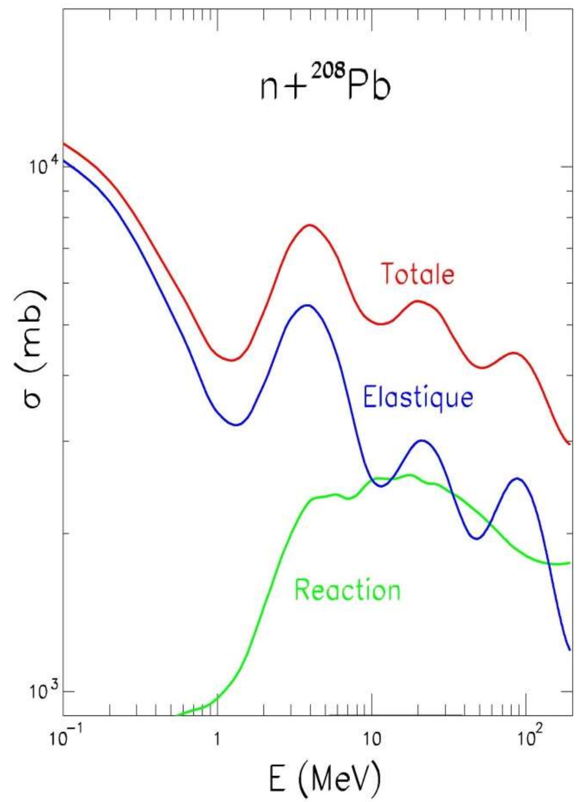
Refraction (V) — Absorption (iW)



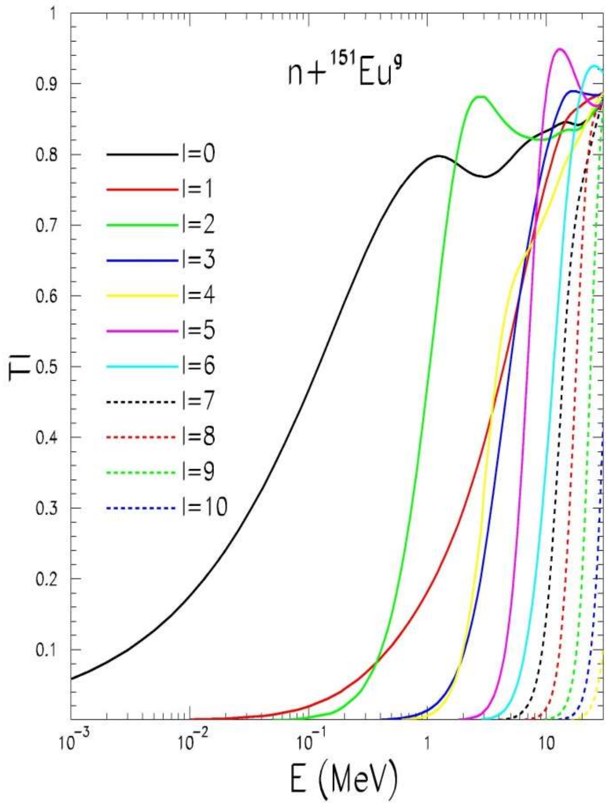
The optical model : output ?

The optical model yields :

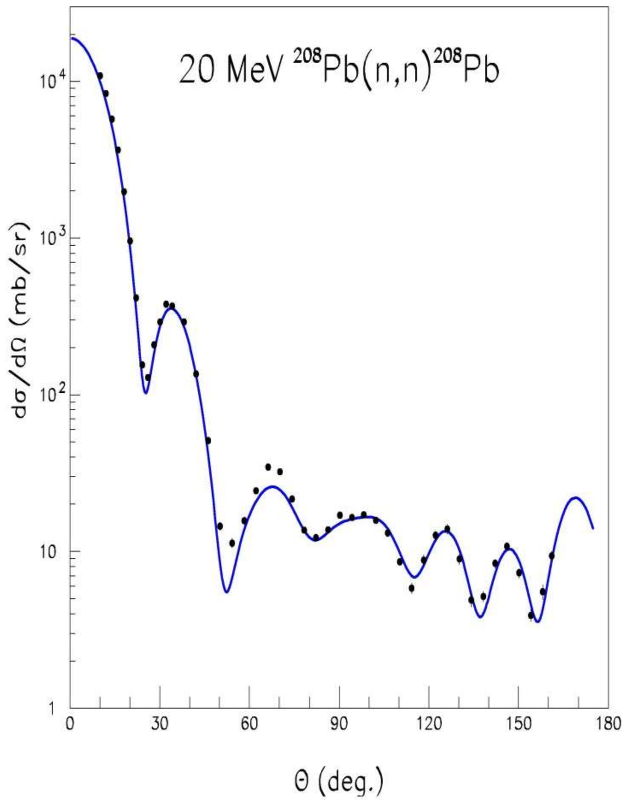
Integrated cross sections



Transmission coefficients



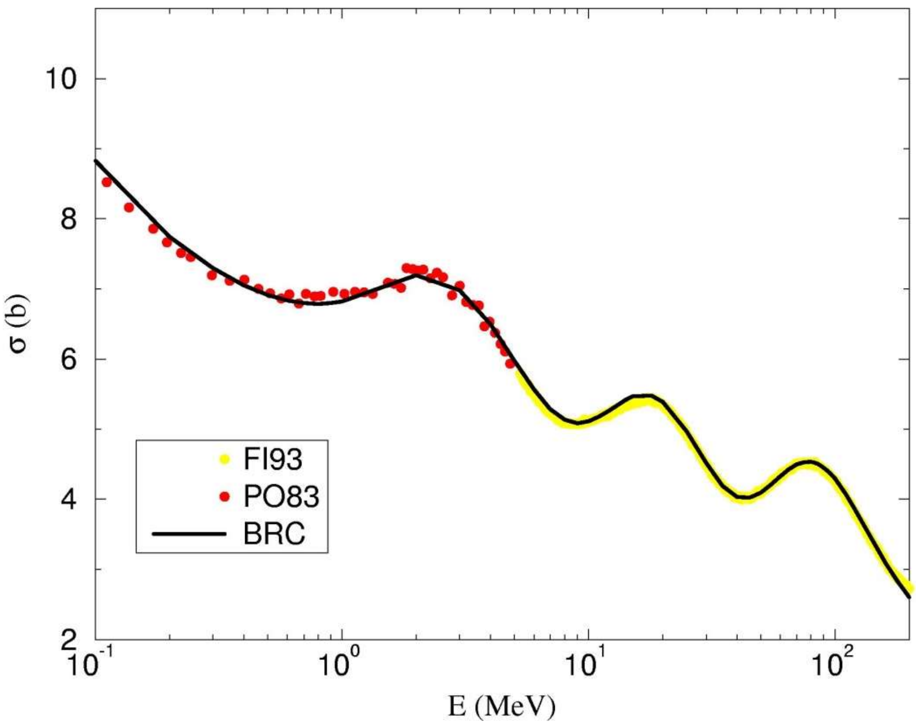
Angular distributions



The optical model : various approaches

Phenomenological

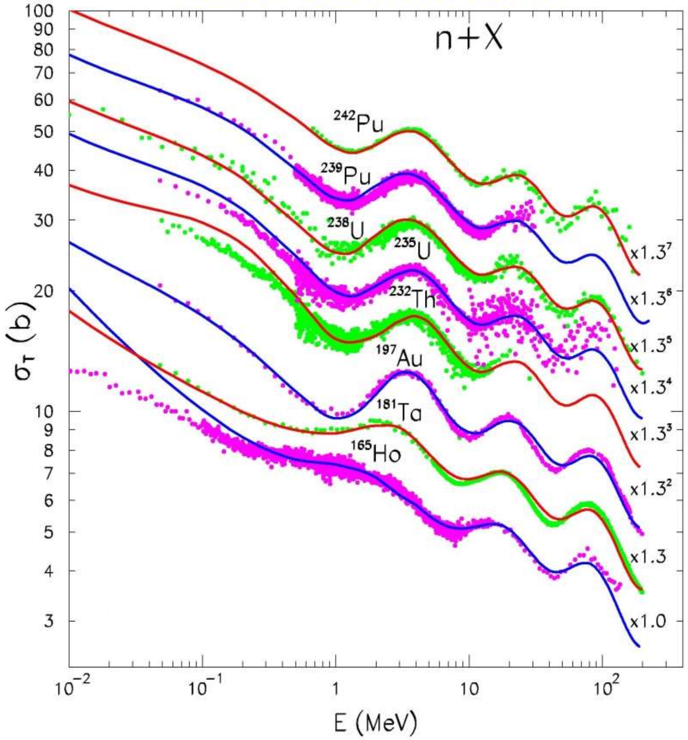
20 adjusted parameters
Weak predictive power
Very precise (≈ 1%)
Important work



(Semi-)microscopic

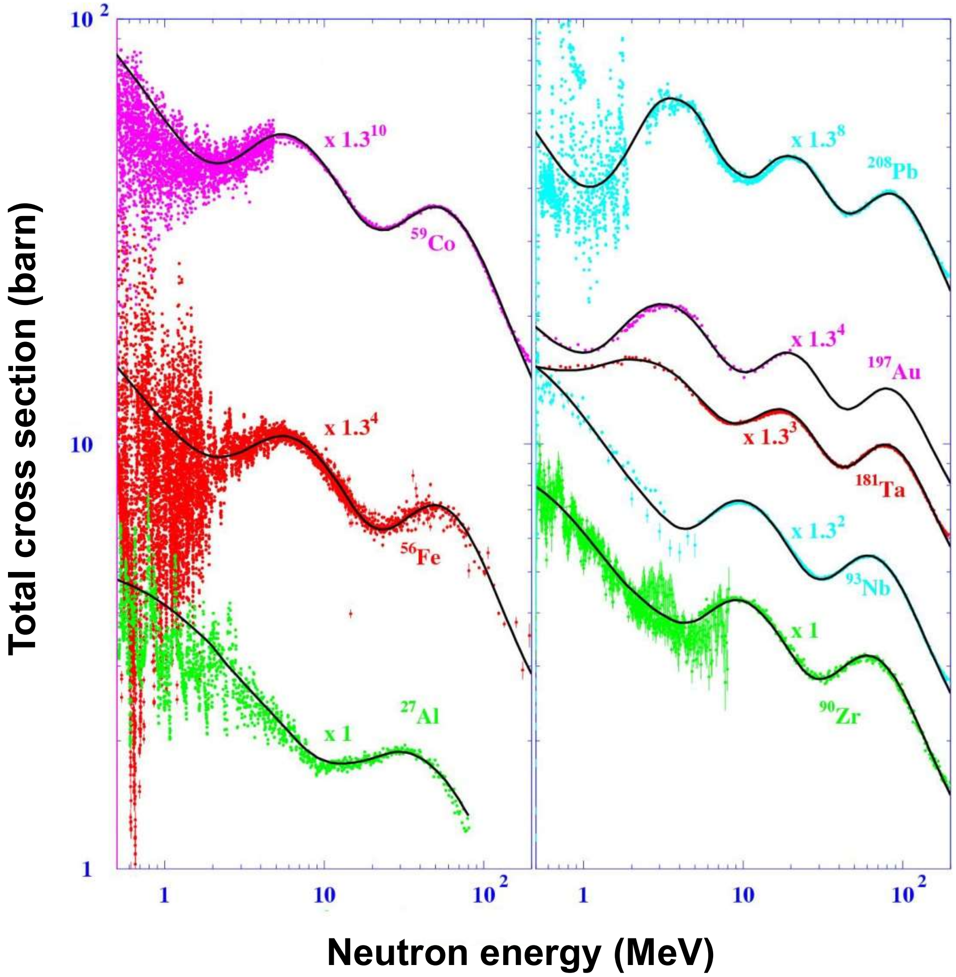
No adjustable parameters
Usable without exp. data
Less precise (≈ 5-10 %)
Quasi-automated

Total cross sections



The optical model : phenomenological model

- ≈ 20 adjusted parameters
- Very precise (1%)
- Weak predictive power
- Requires data
- Local models
  => Global models



The optical model : phenomenological model

$$U(r,E) = V(E,r) + i\,W(E,r) + \{V_{so}(E,r) + i\,W_{so}(E,r)\}\,\vec{l}.\vec{s}$$

Central term **Spin orbit term**

The optical model : phenomenological model

$$U(r,E) = V(E,r) + i\,W(E,r) + \{V_{so}(E,r) + i\,W_{so}(E,r)\}\,\vec{l}.\vec{s}$$

Central term **Spin orbit term**

Let's neglect SO

The optical model : phenomenological model

$$U(r,E) = V(E,r) + i\,W(E,r)$$

Central term

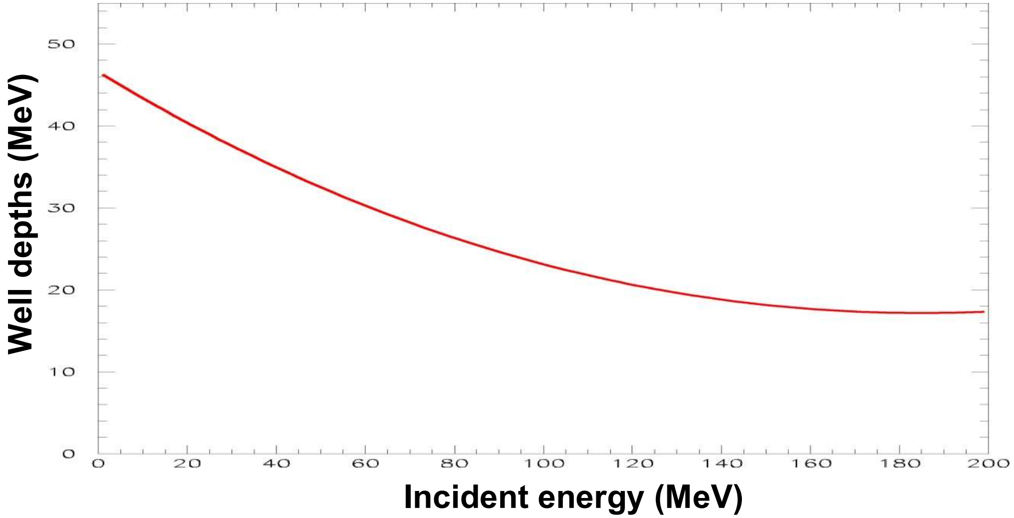
The optical model : phenomenological model

$$U(r,E) = \left[V_V(E)\, f(r, \mathbf{R}_V, a_V) + V_S(E)\, g(r, R_S, a_S) \right]$$

$$+\, i \left[W_V(E)\, f(r, R_V, a_V) + W_S(E)\, g(r, R_S, a_S) \right]$$

The optical model : phenomenological model

$$U(r,E) = \left[V_V(E)\, f(r, R_V, a_V) + V_S(E)\, g(r, R_S, a_S) \right] + i \left[W_V(E)\, f(r, R_V, a_V) + W_S(E)\, g(r, R_S, a_S) \right]$$



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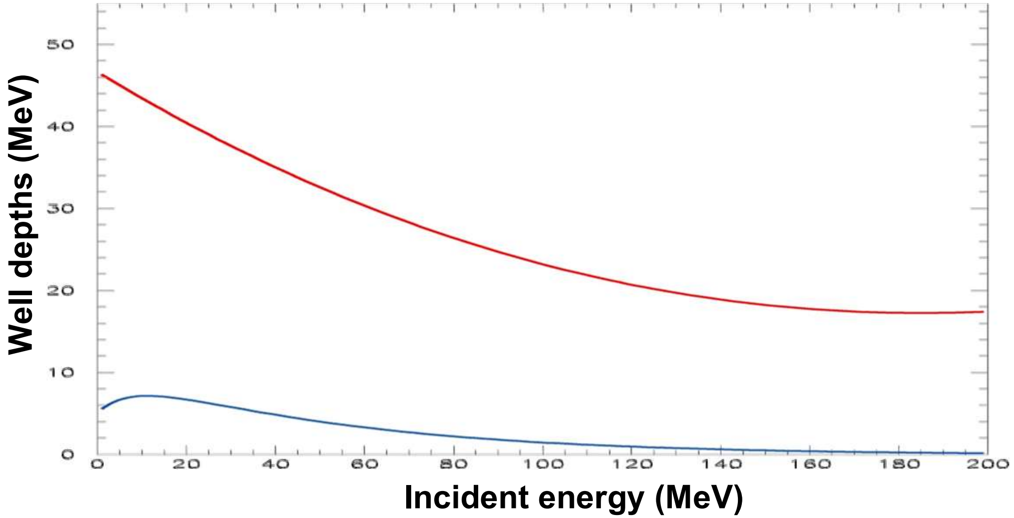

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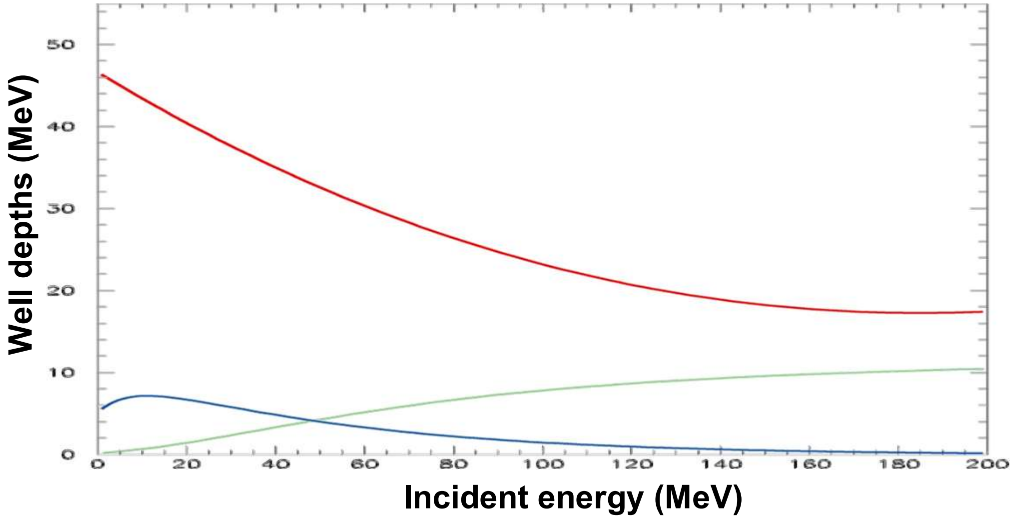

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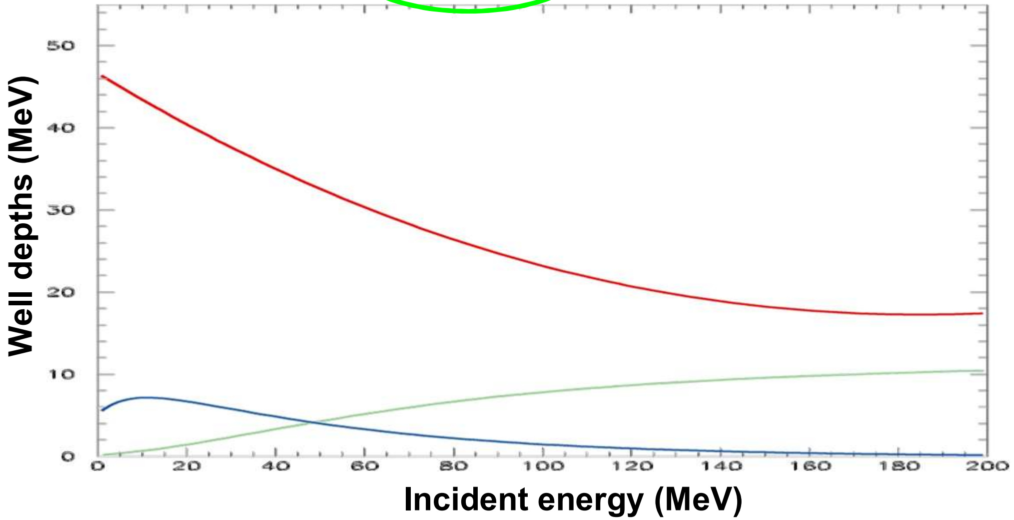
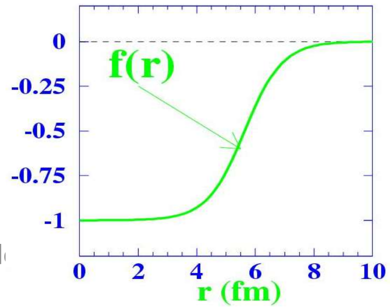


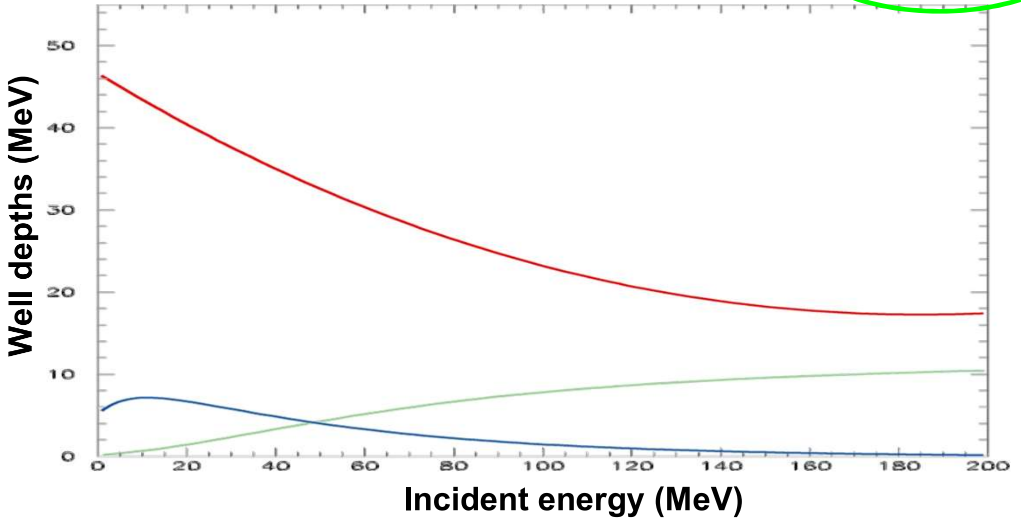
$$f(r,R,a) = \frac{-1}{1+\exp((r-R)/a)}$$



The optical model : phenomenological model

$$U(r,E) = \left[V_V(E)\, f(r, \mathbf{R}_V, a_V) + V_S(E)\, g(r, R_S, a_S) \right]$$

$$+\, i \left[W_V(E)\, f(r, R_V, a_V) + W_S(E)\, g(r, R_S, a_S) \right]$$



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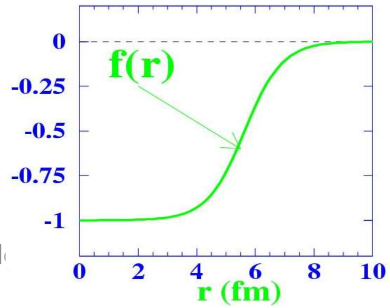
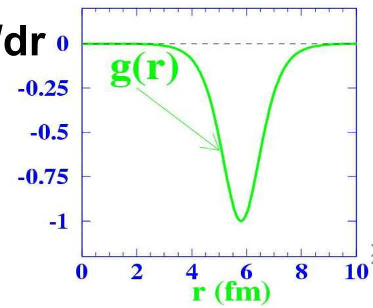
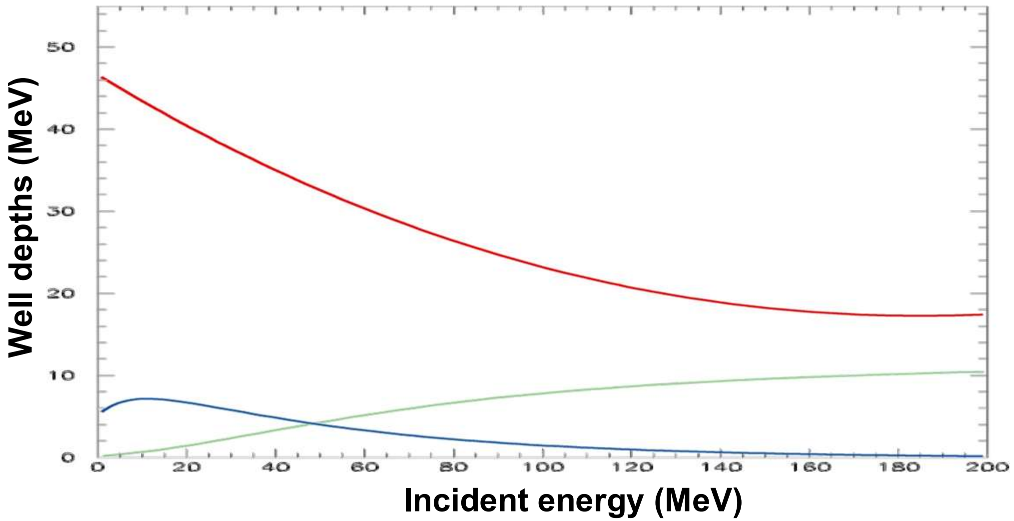


$$g(r,R,a) = -\,df/dr$$



The optical model : phenomenological model

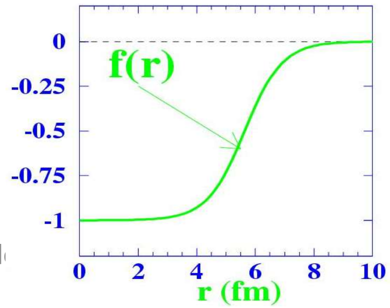
$$U(r,E) = \left[V_V(E)\, f(r, R_V, a_V) + V_S(E)\, g(r, R_S, a_S) \right] + i \left[W_V(E)\, f(r, R_V, a_V) + W_S(E)\, g(r, R_S, a_S) \right]$$



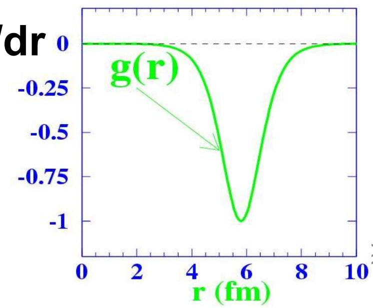
Surface absorption vanishes with increasing energy

Volume absorption increases with increasing energy

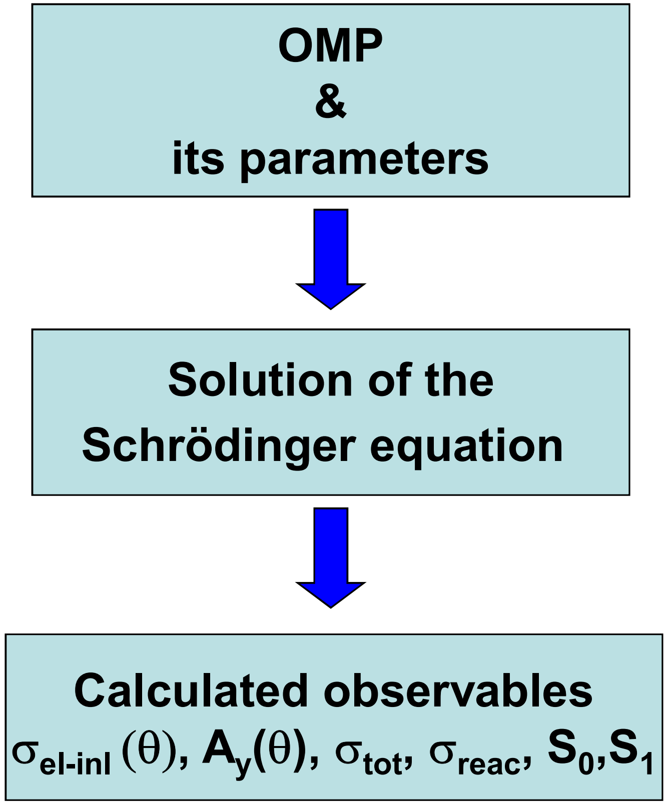
$$f(r,R,a) = \frac{-1}{1+\exp((r-R)/a)}$$



$$g(r,R,a) = -\,df/dr$$



The optical model : phenomenological model



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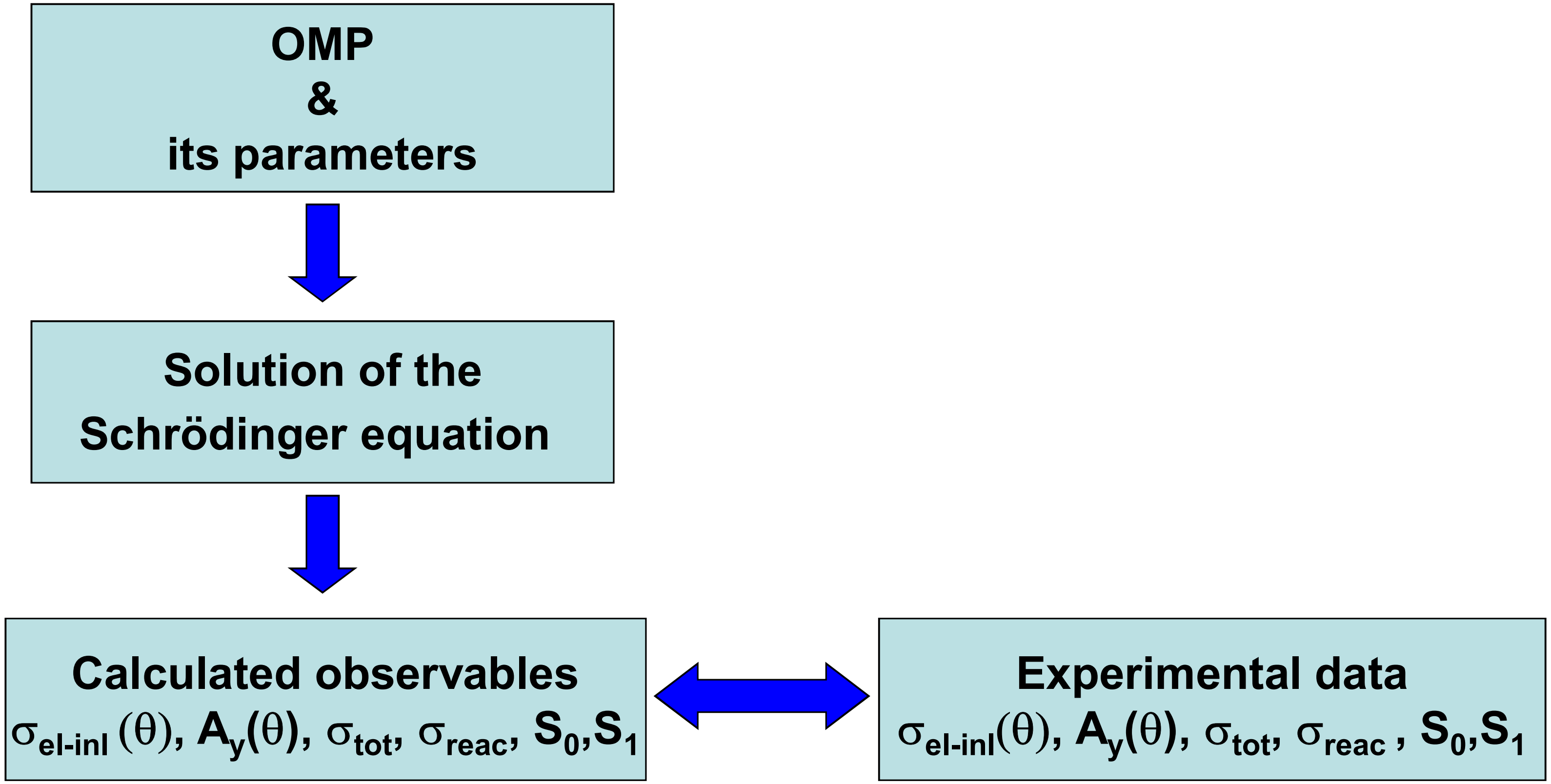
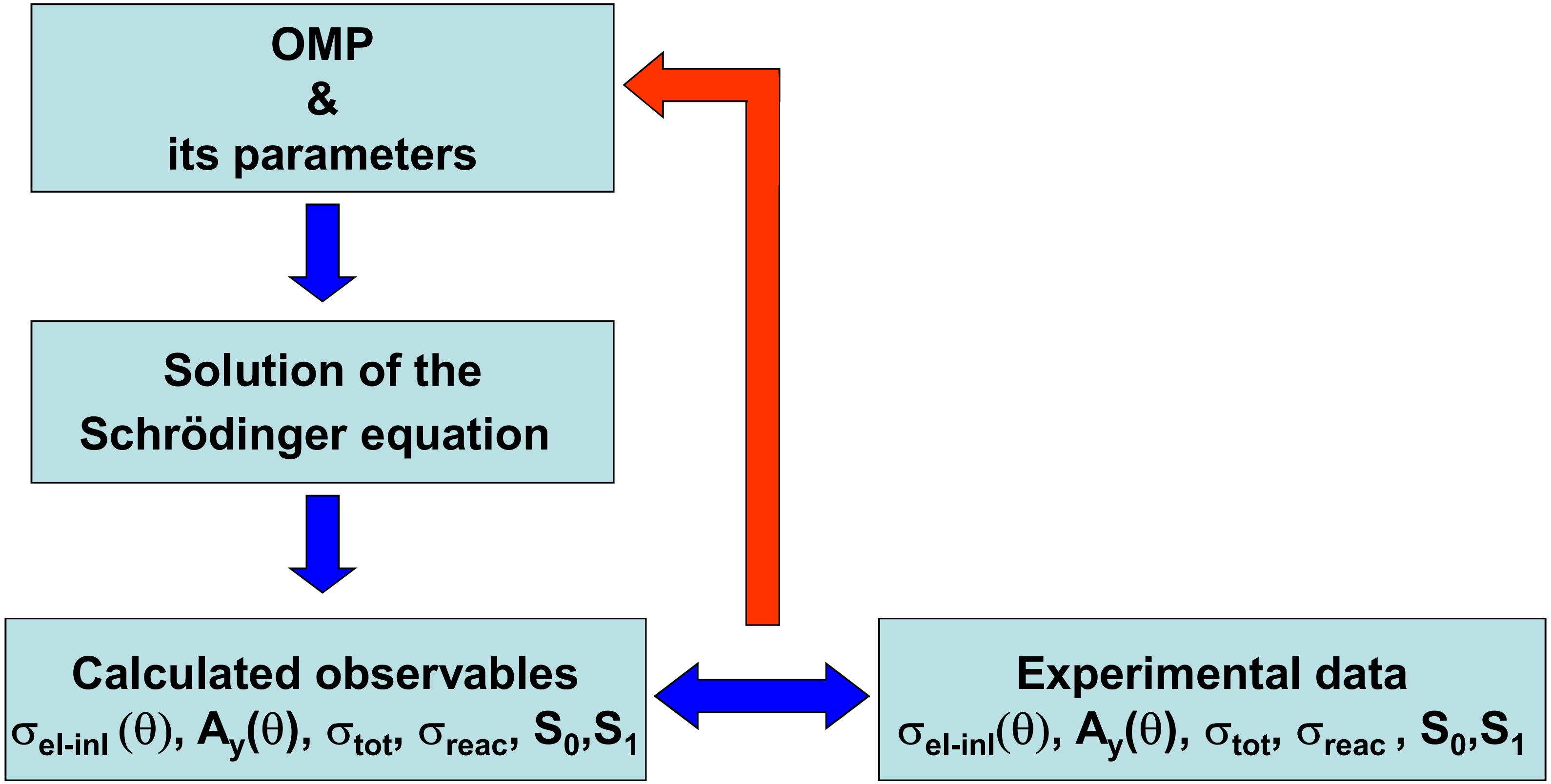
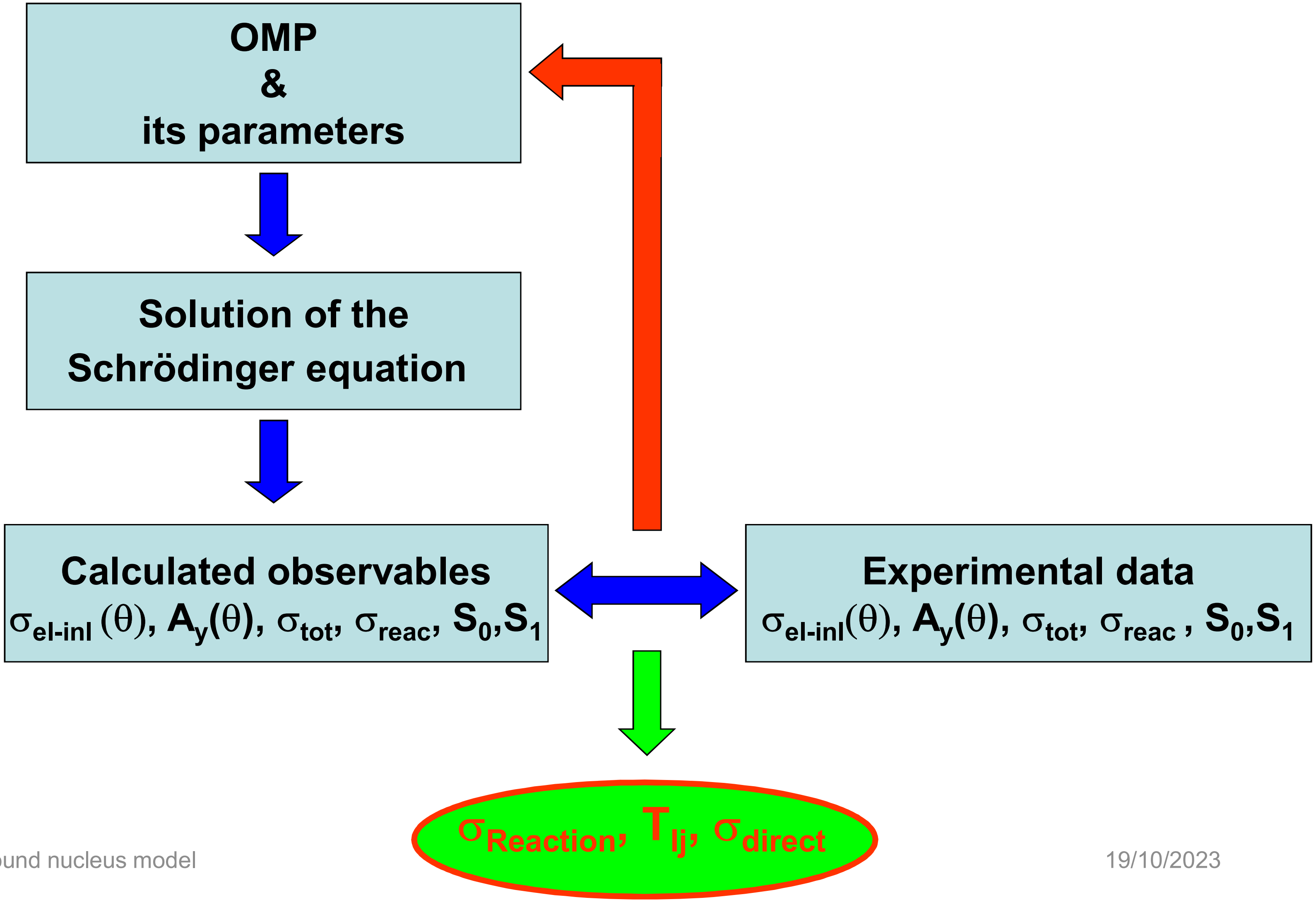


The optical model : phenomenological model



The optical model : phenomenological model

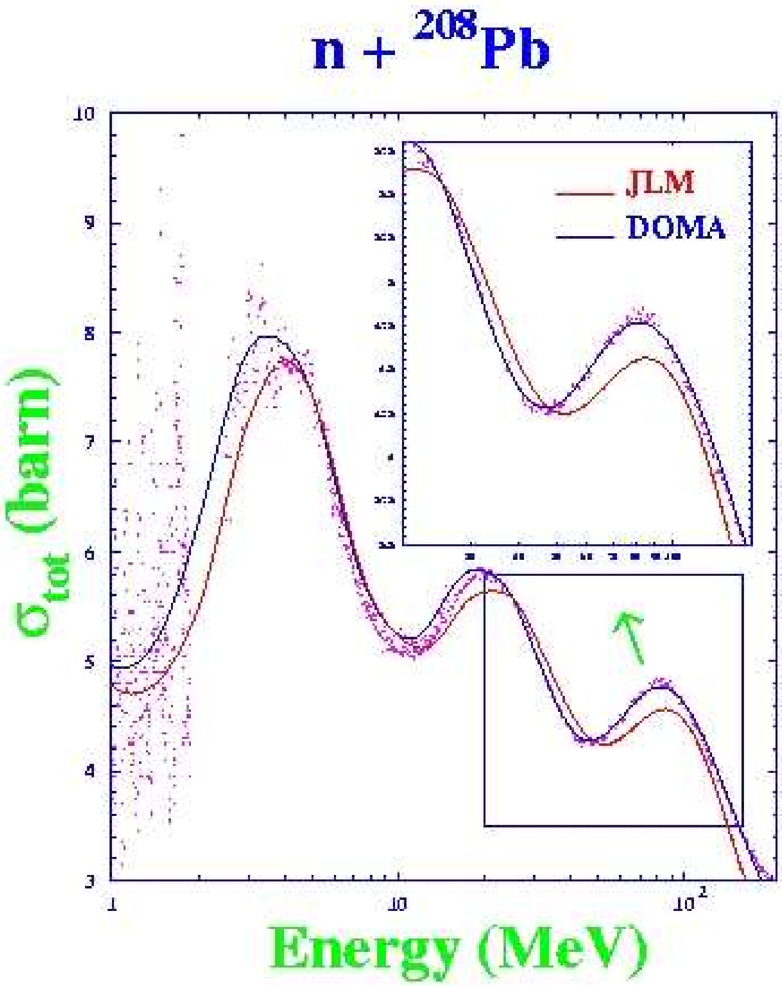


The optical model : semi-microscopic model

- No adjustable parameters
- Based on nuclear structure properties

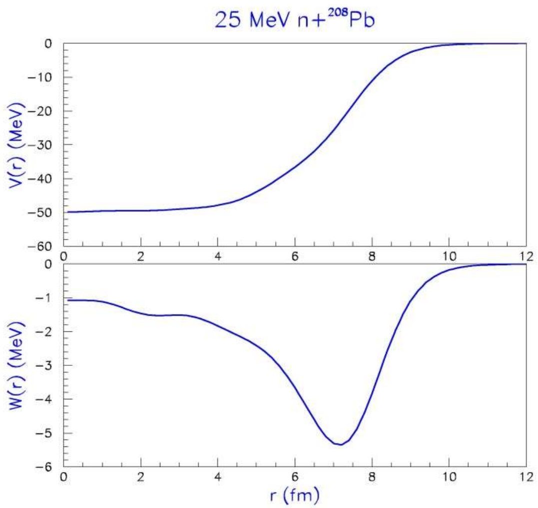
$\Rightarrow$ usable for any nucleus

- Less precise than the phenomenological approach



The optical model : semi-microscopic model

Optical potential = **Effective Interaction** ⊗ **Radial densities**



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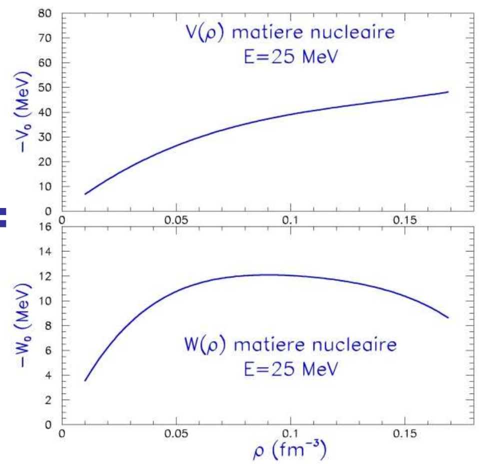
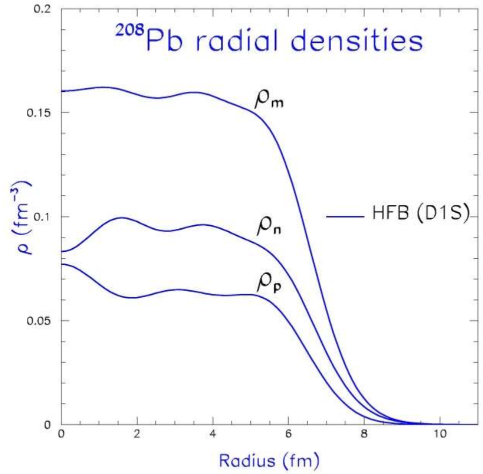


⊗



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

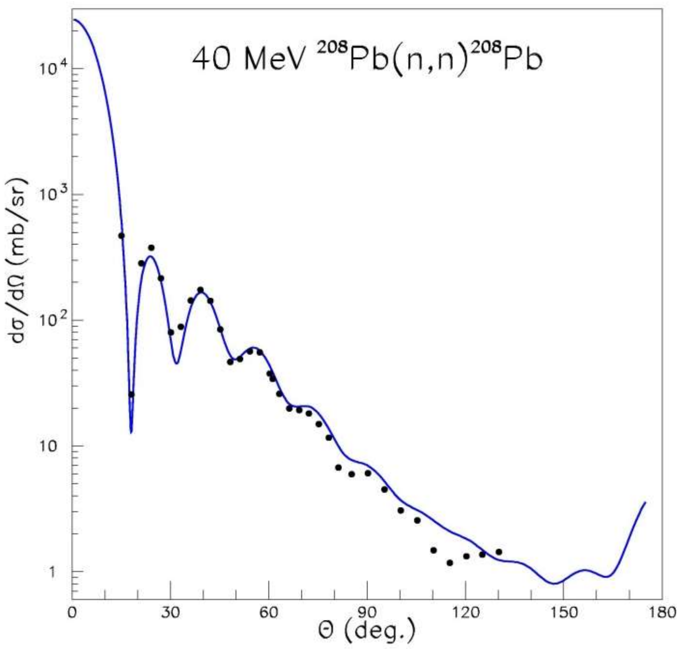
Depends on the nucleus | Independent of the nucleus | Depends on the nucleus

The optical model : semi-microscopic model

Unique description of elastic scattering

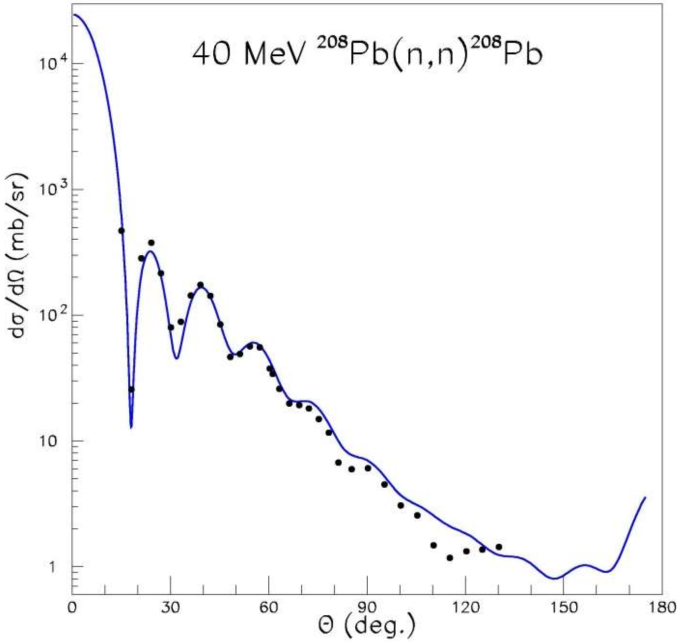
The optical model : semi-microscopic model

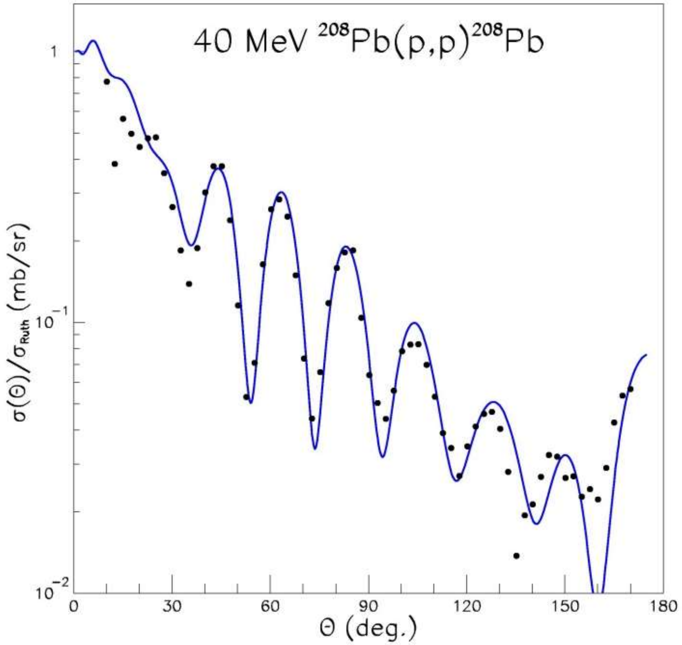
Unique description of elastic scattering (n,n)



The optical model : semi-microscopic model

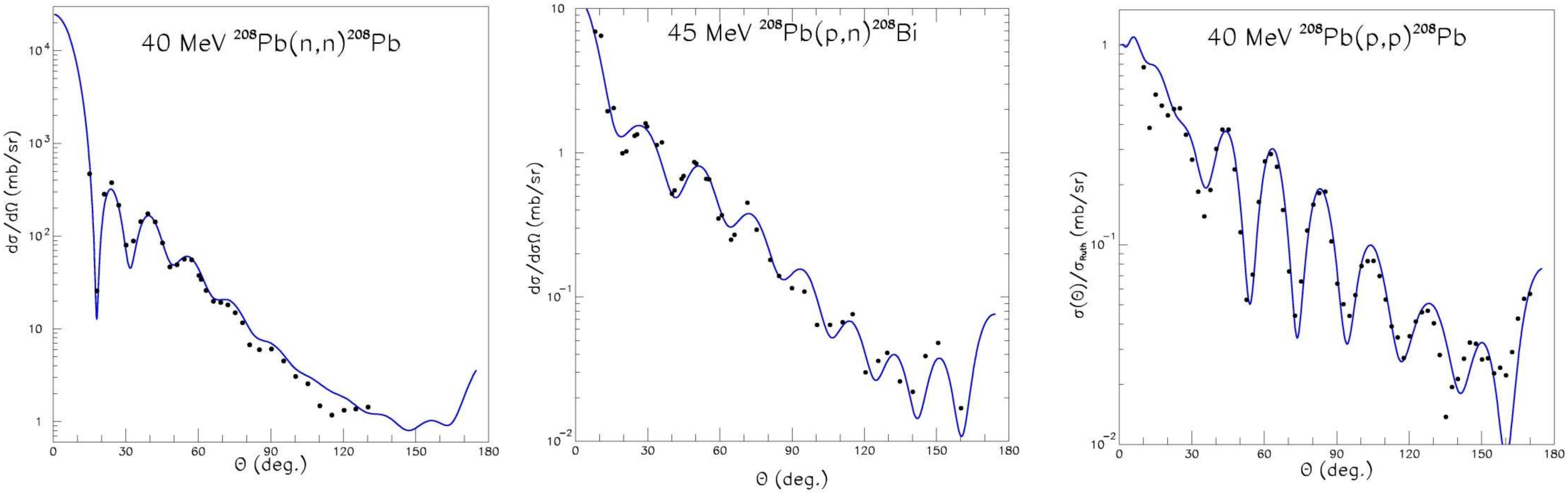
Unique description of elastic scattering (n,n), (p,p)





The optical model : semi-microscopic model

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



The optical model : semi-microscopic model

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

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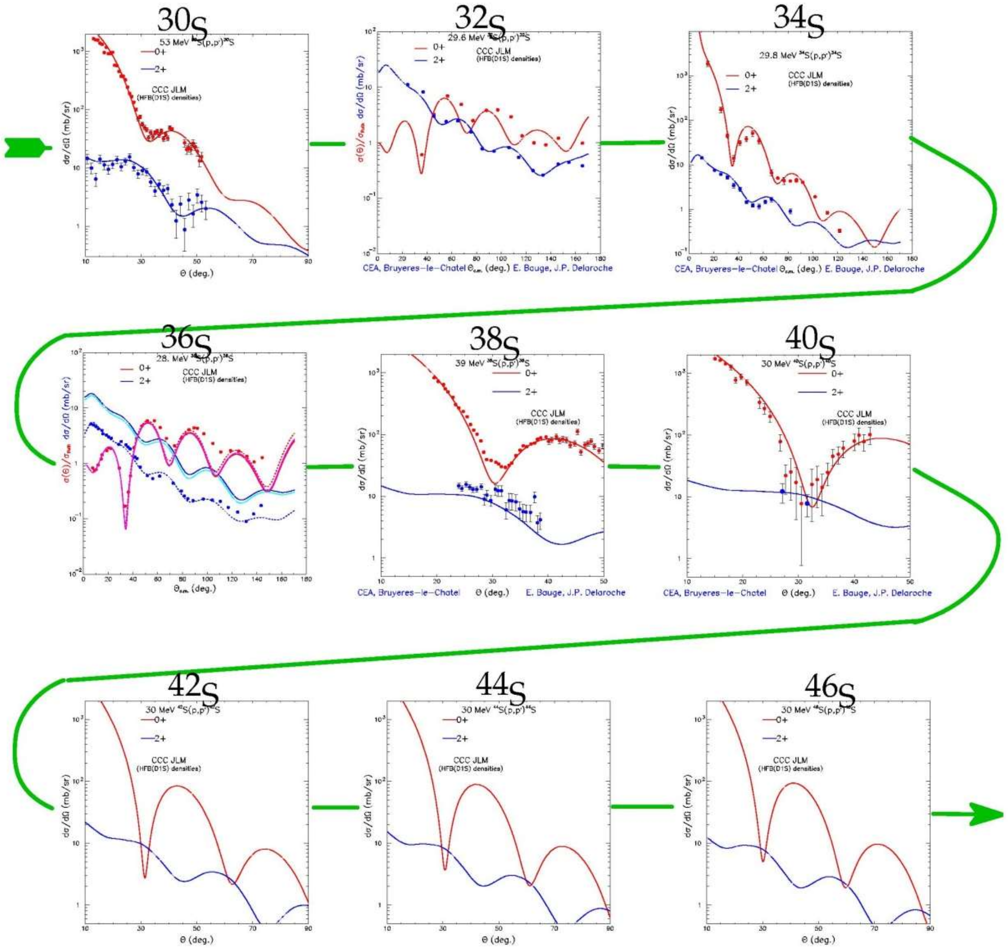
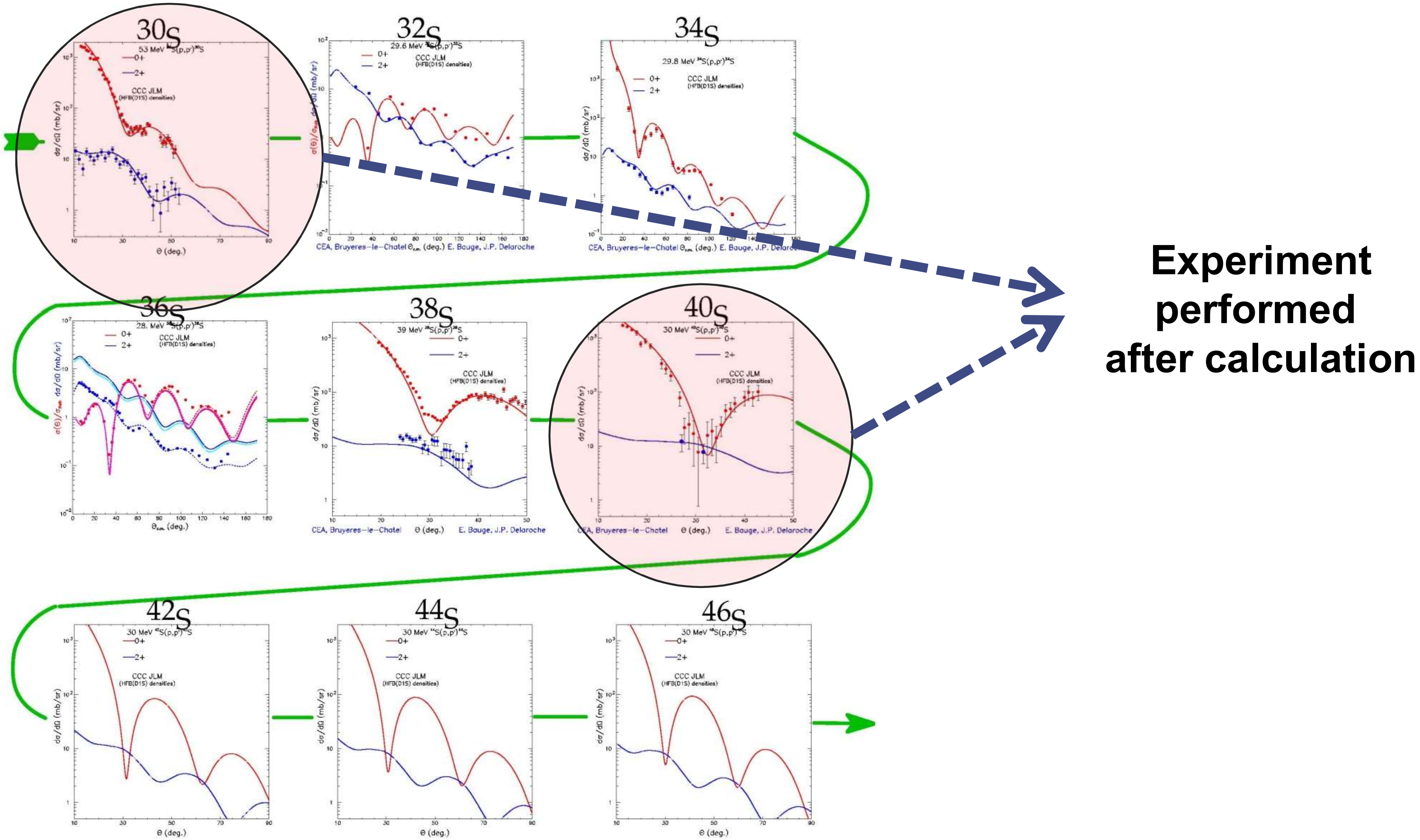


The optical model : semi-microscopic model

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



The optical model : direct reaction description

- Spherical OMP

⇒ Shape elastic only
⇒ Absorbed flux distributed with CN model
⇒ Generally bad for inelastic scattering off collective levels

- Coupled chanel approach

⇒ Both elastic and few « **well chosen** » inelastic levels
⇒ Absorbed flux distributed with CN model
⇒ Good description of collective levels if the coupling model is appropriate

- DWBA approximation for spherical or weakly deformed nuclei
- CC approach for well deformed nuclei (various options)

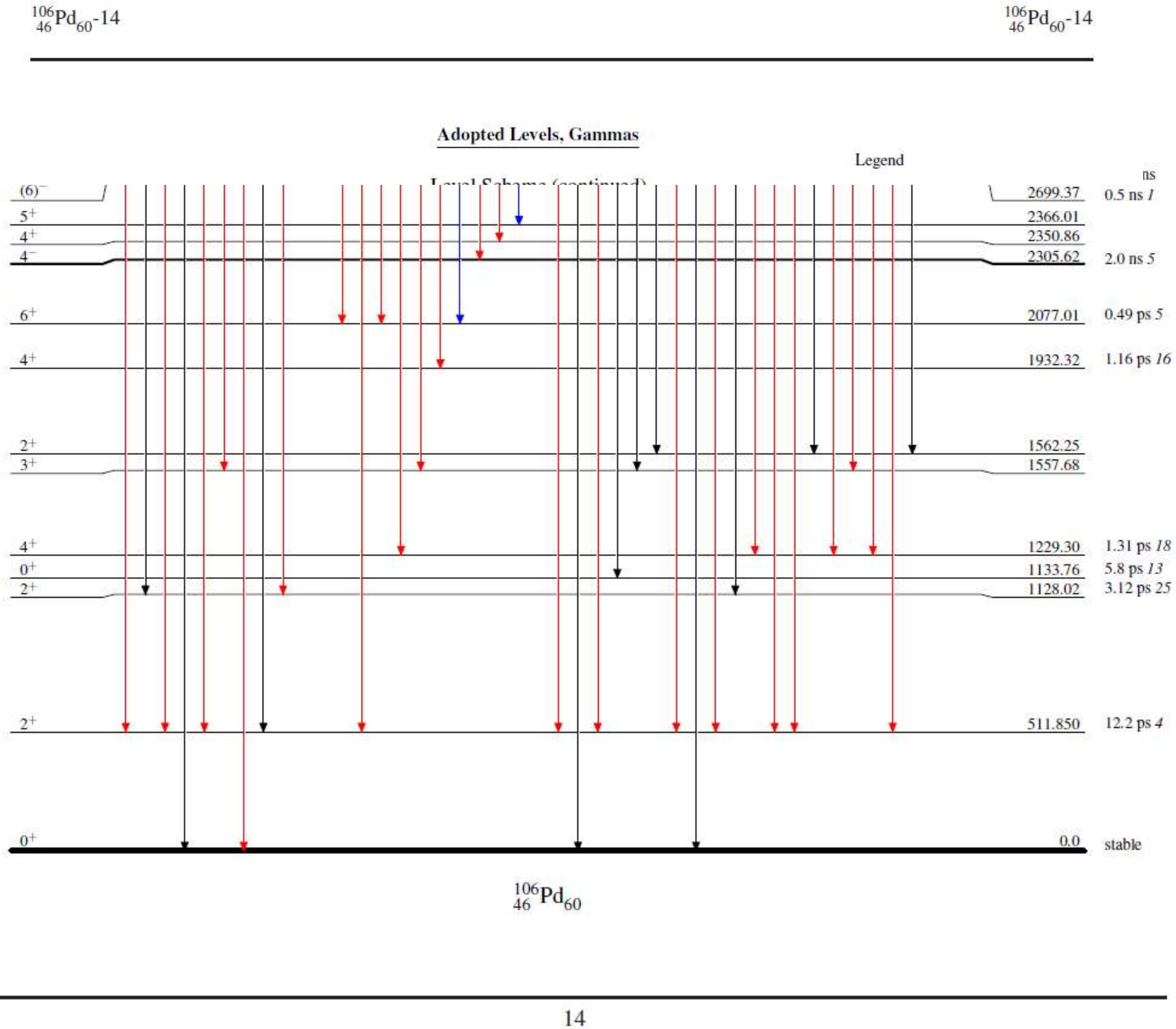
⇒The choice of the « **well chosen** » inelastic levels relies on the experimental level scheme or on theoretical predictions of the nuclear deformation and excited levels

Nuclear structure & level scheme : spherical nucleus

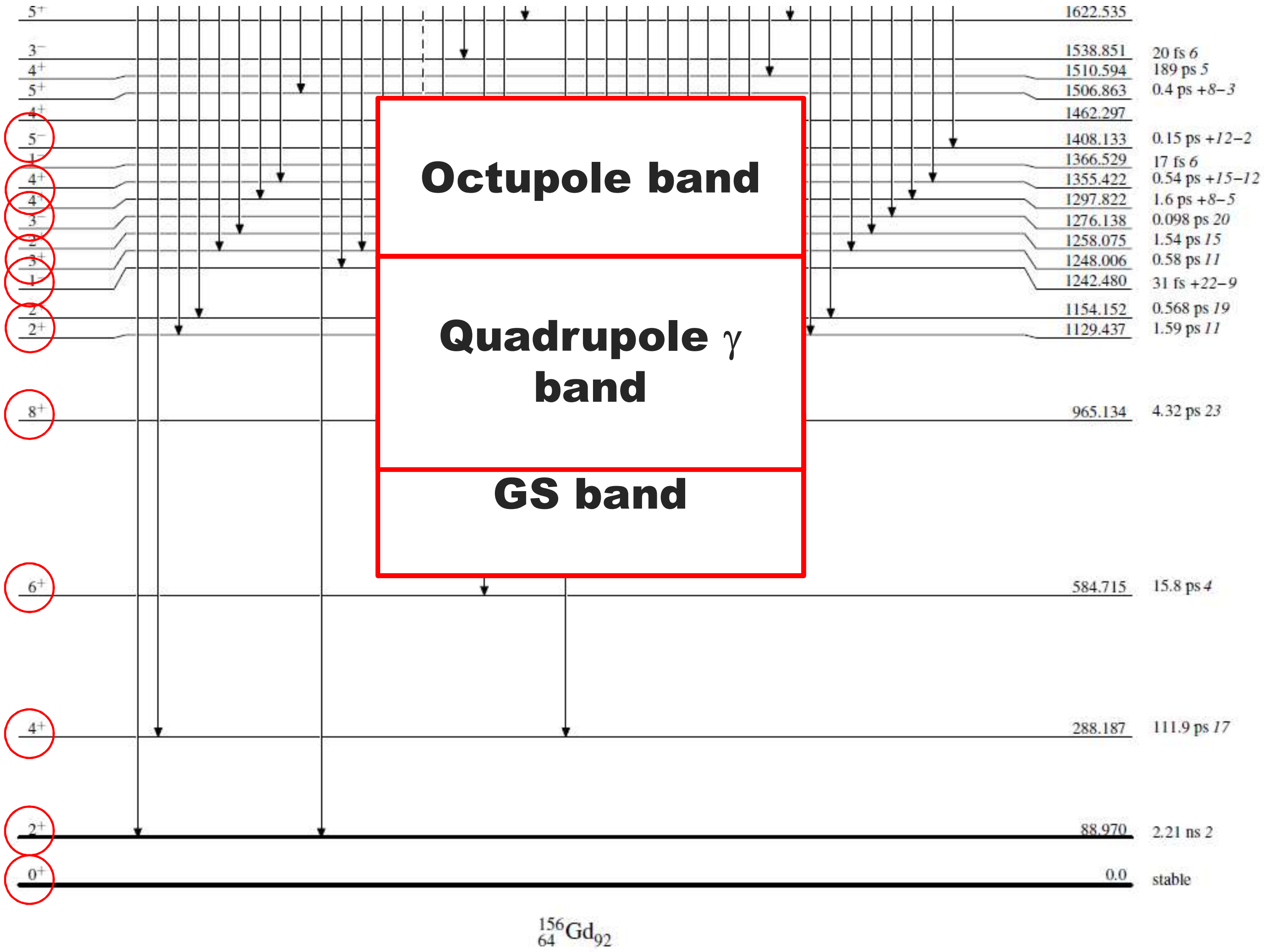
Quadrupole vibration
(three phonons)

Quadrupole vibration
(two phonons)

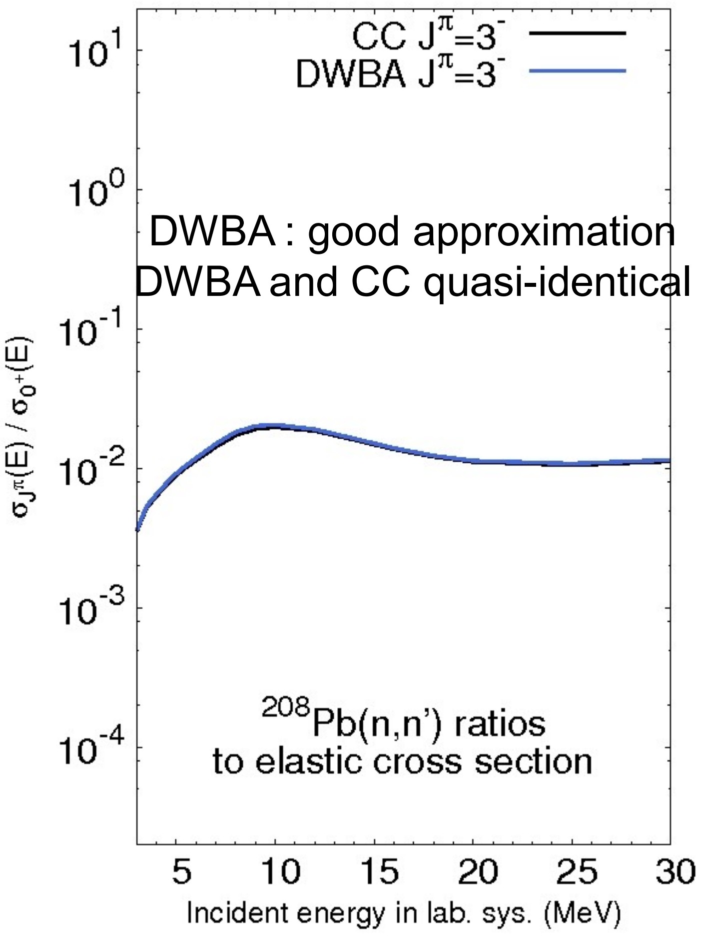
Quadrupole vibration
(one phonon)

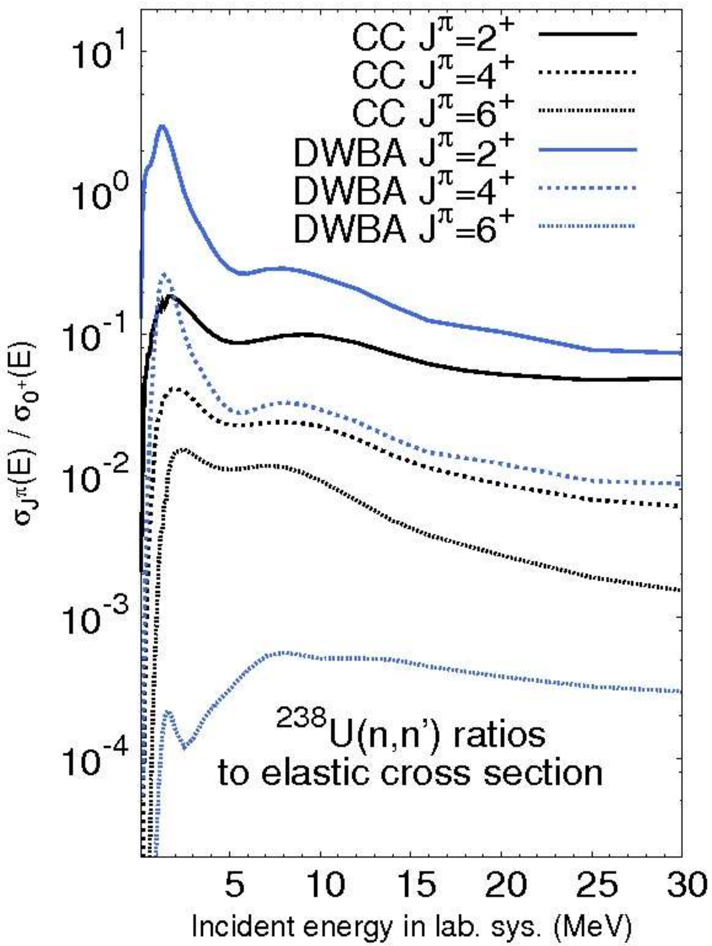


Nuclear structure & level scheme : deformed nucleus



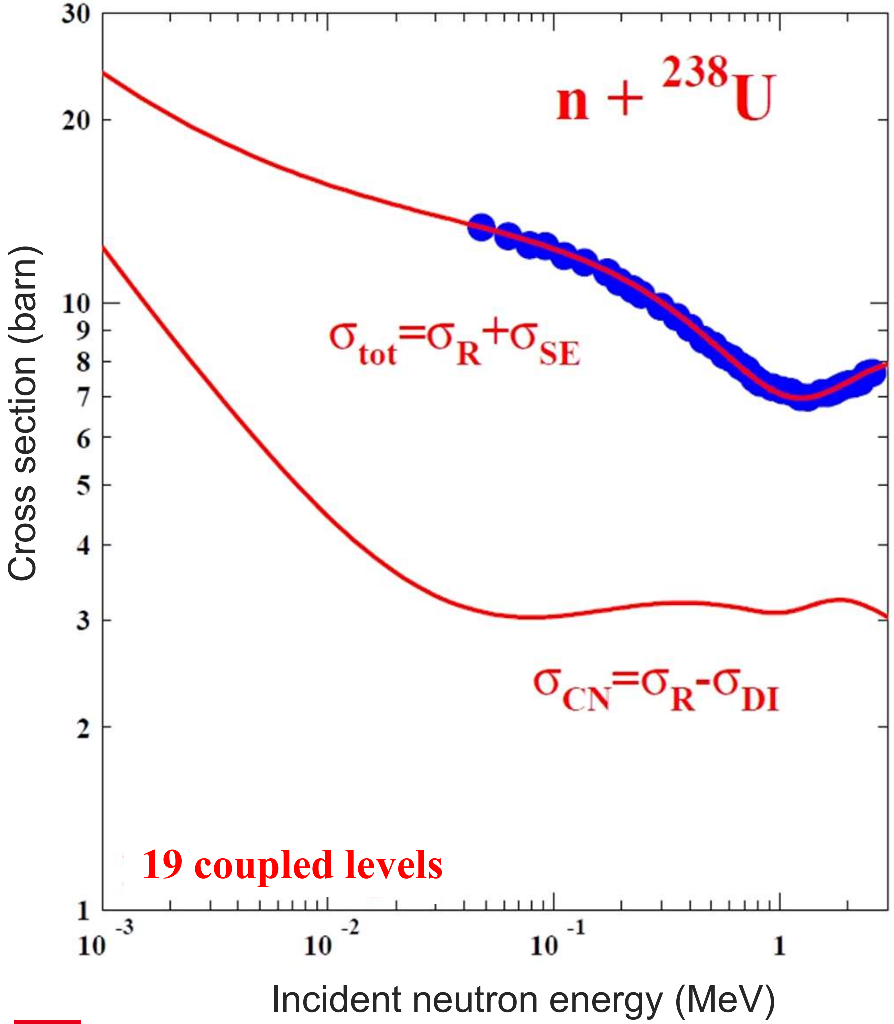
The optical model : DWBA vs CC





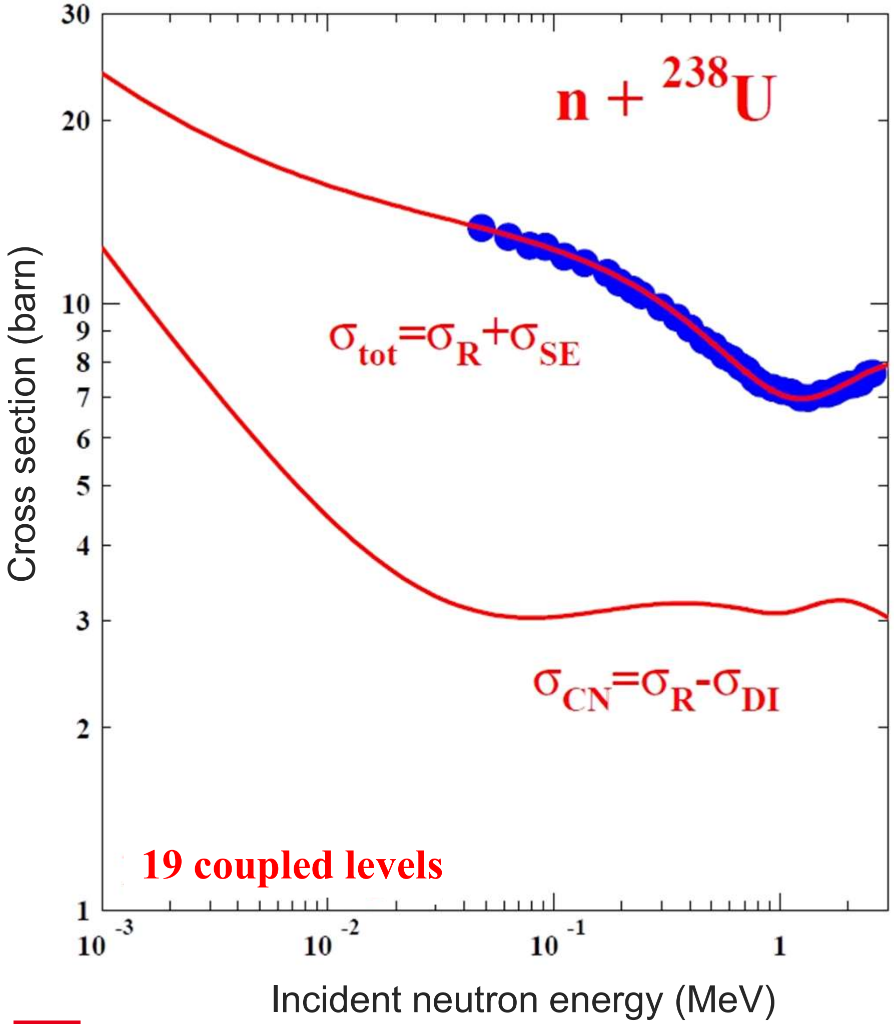
DWBA : bad approximation
factor 100
between DWBA and CC !!!

The optical model : coupling scheme saturation



Great but
not trivial

The optical model : coupling scheme saturation



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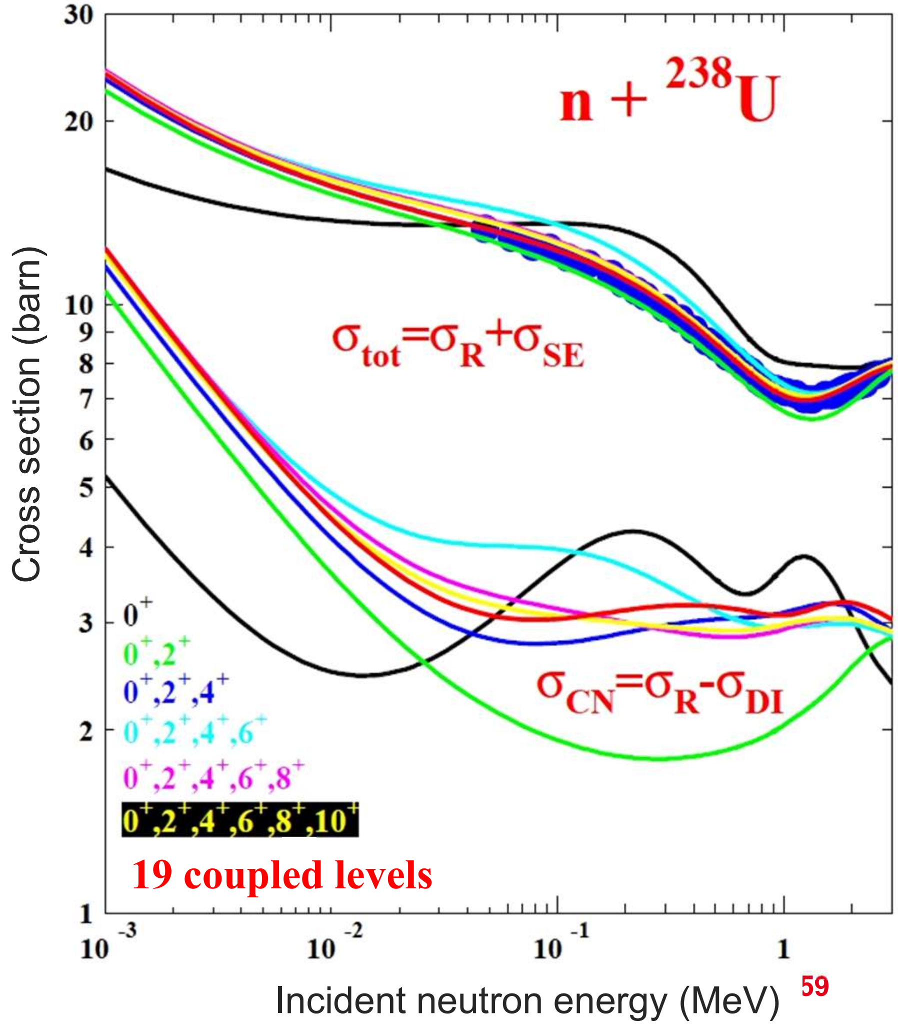
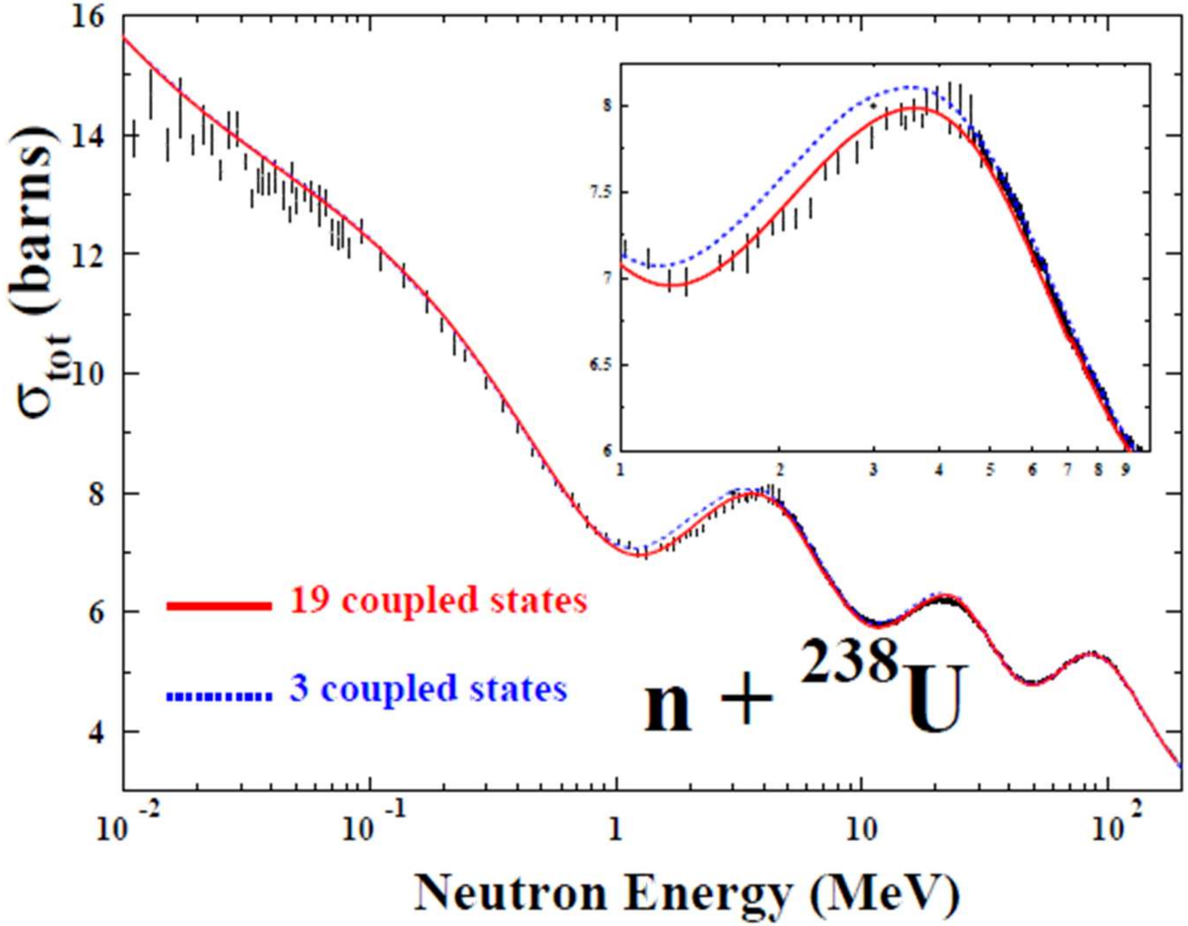


The optical model : optimisation

All data must be simultaneously described at best



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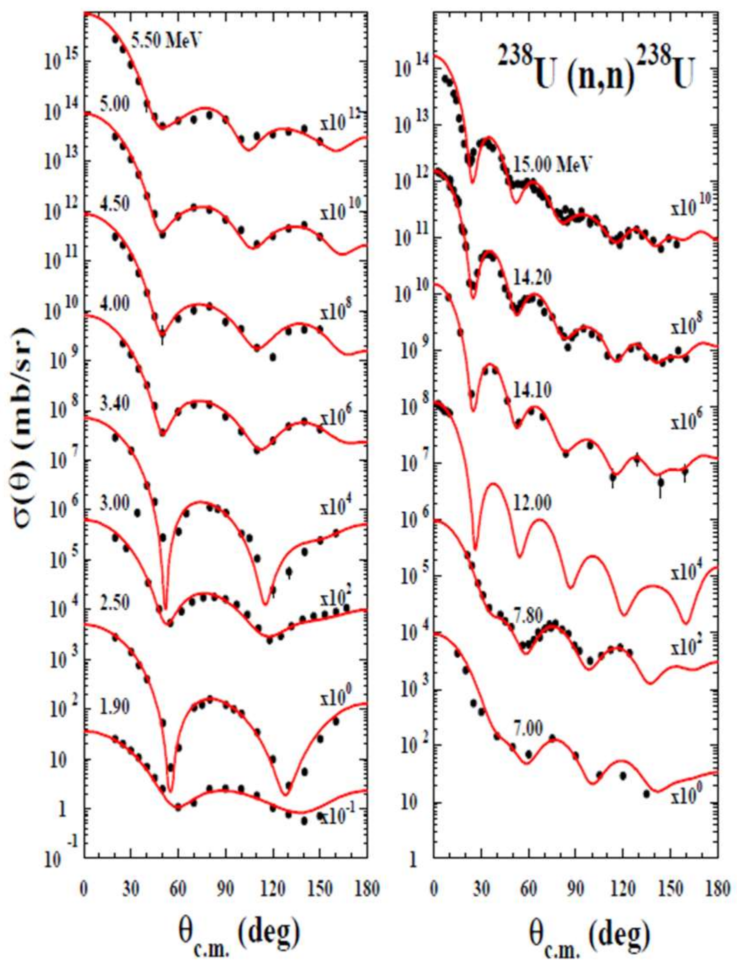

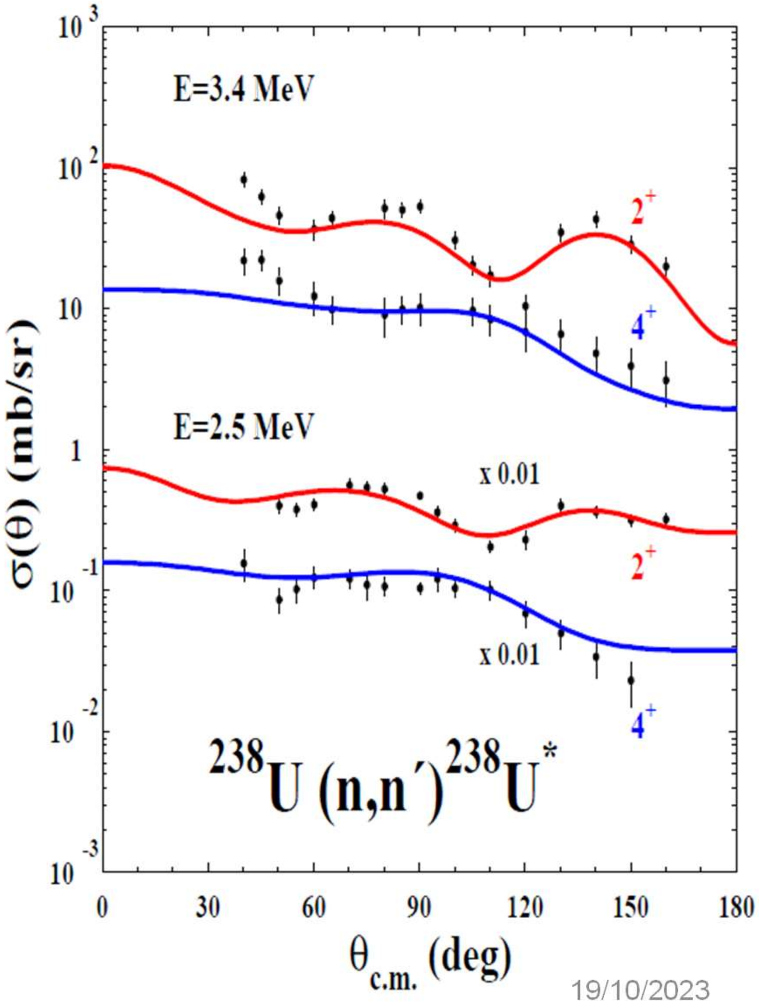

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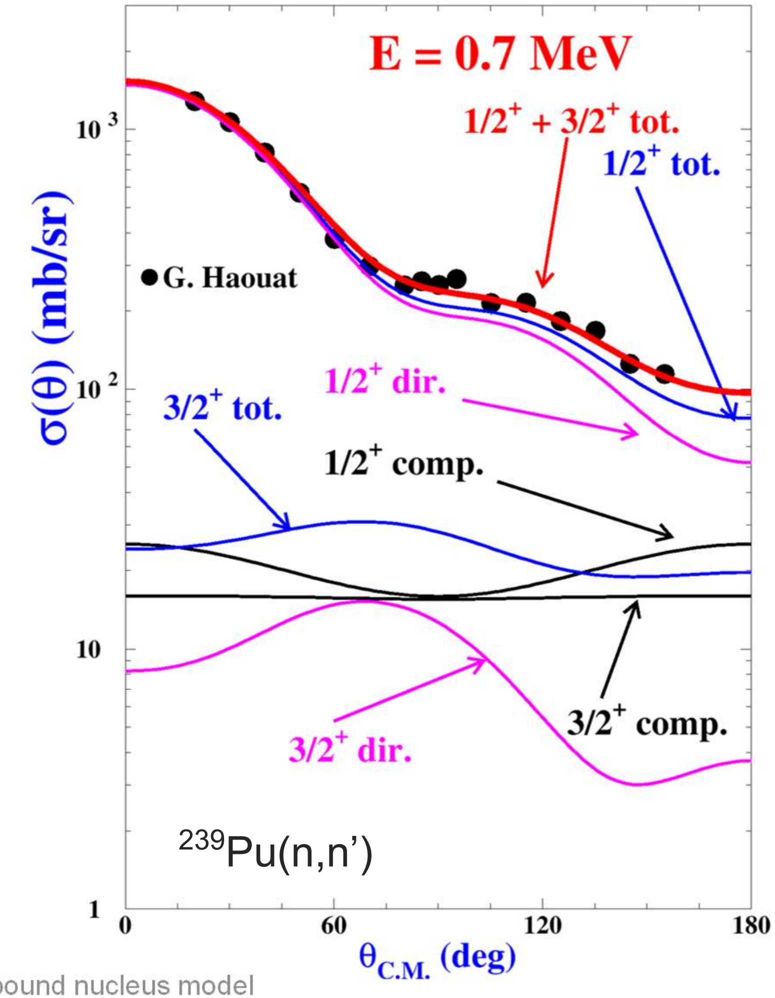
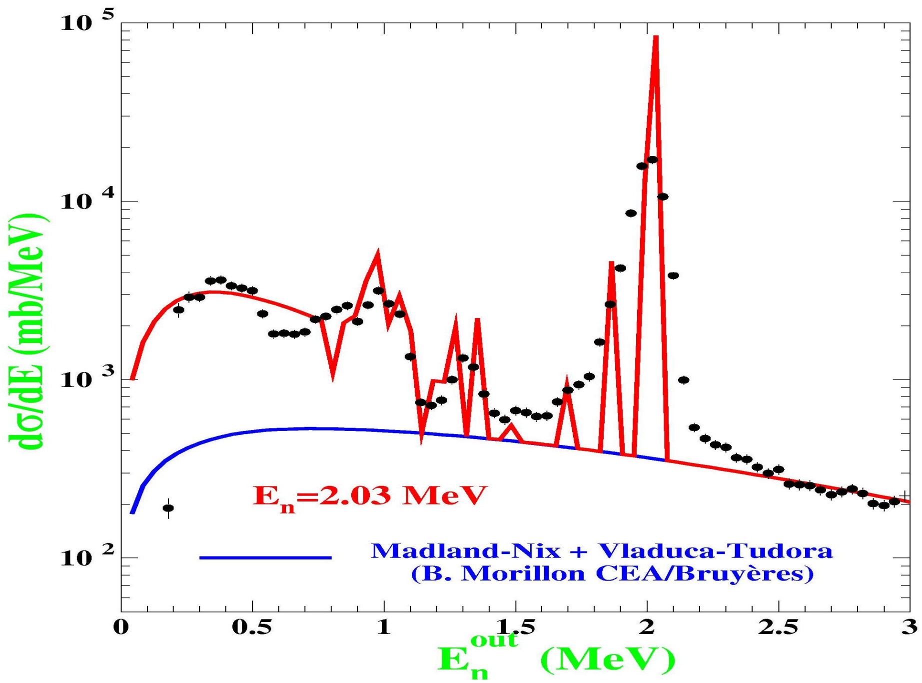


and the whole reaction process matters

The optical model : optimisation

All data must be simultaneously described at best

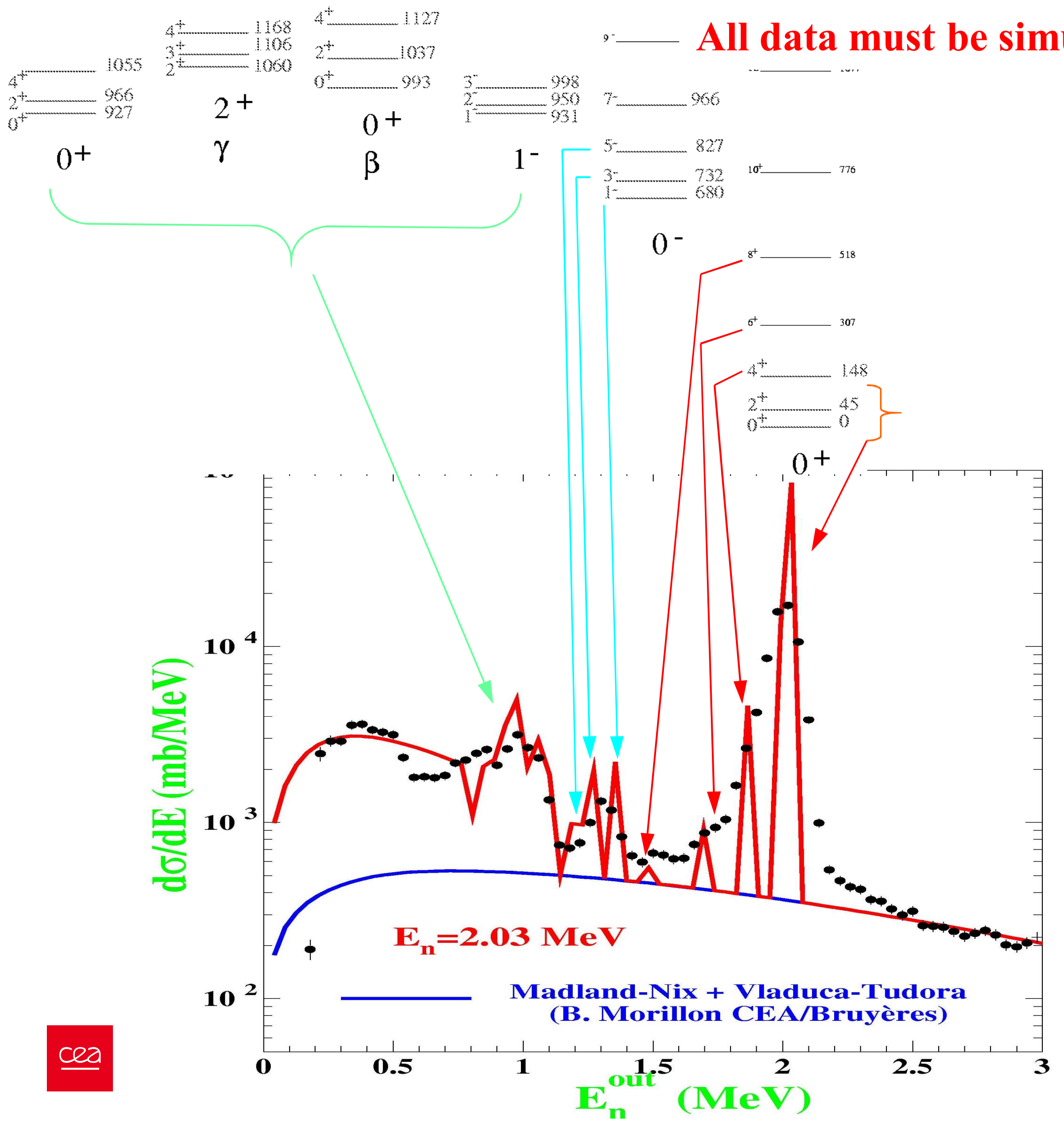
^{238}U outgoing neutron spectrum



and the whole reaction process matters

The optical model : optimisation

All data must be simultaneously described at best



and the whole reaction process matters

The optical model : impact of deformation

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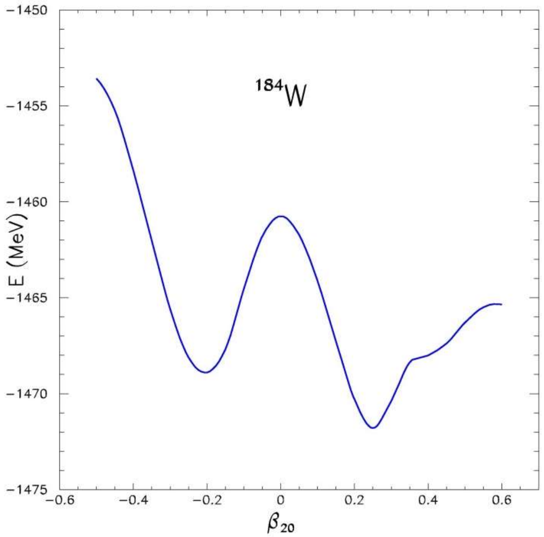

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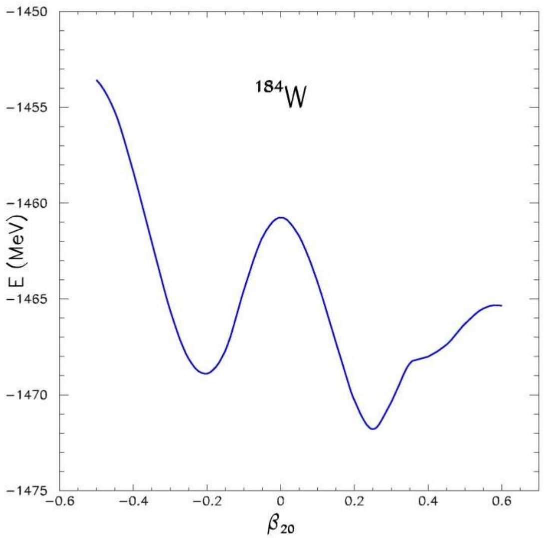

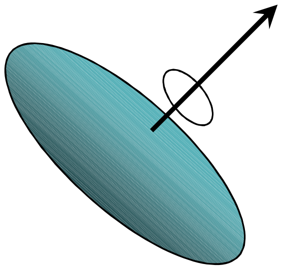

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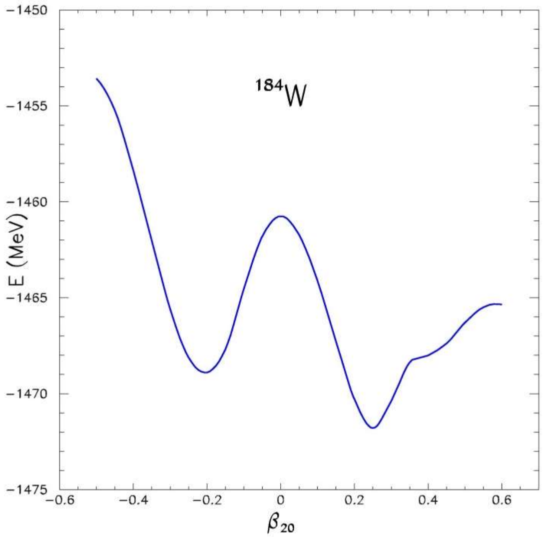

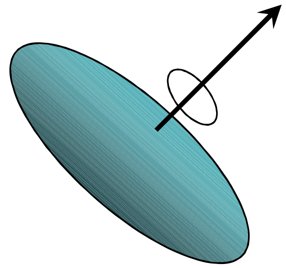

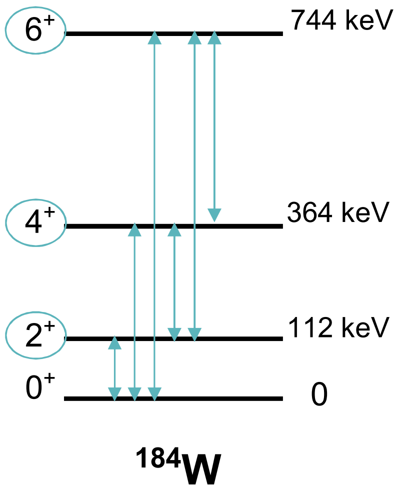

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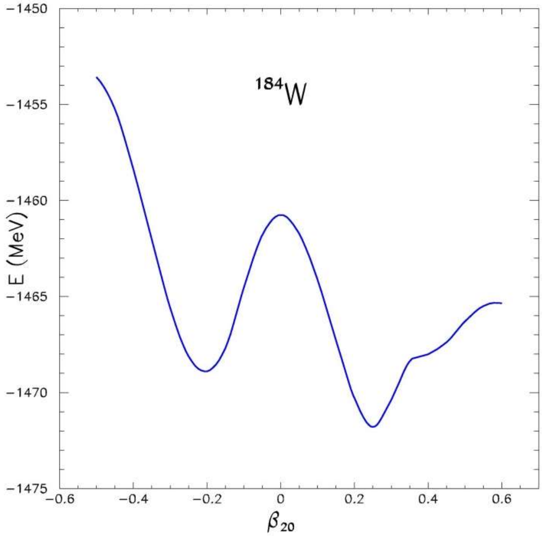
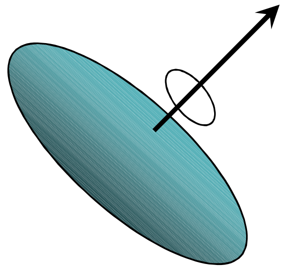
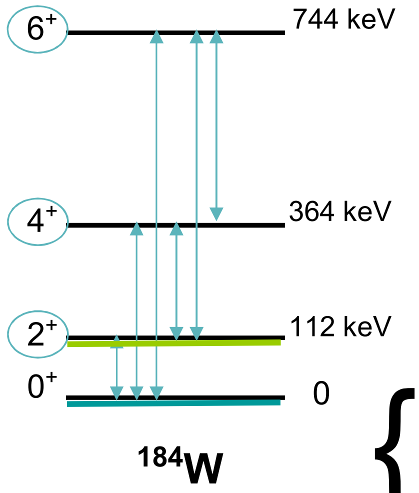
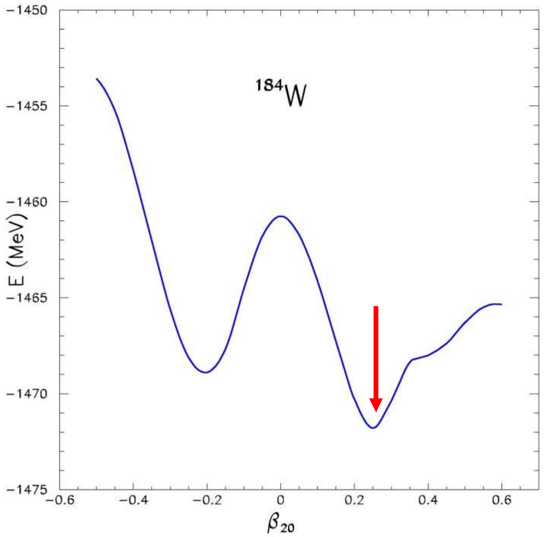


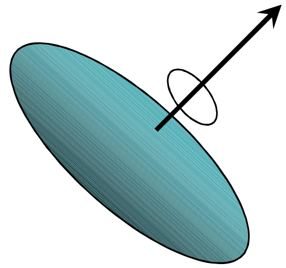


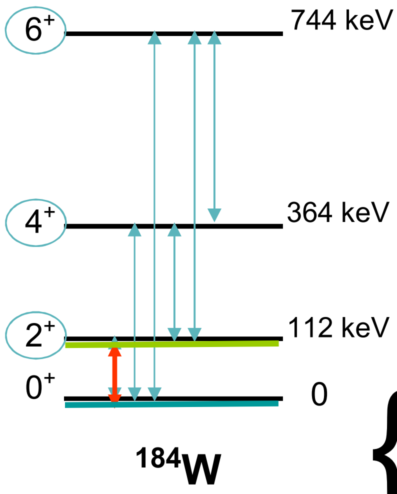


$$\begin{cases} (T+V_{00}-E)\,\Psi_0 = V_{02}\,\Psi_2 \\ (T+V_{22}-E)\,\Psi_2 = V_{20}\,\Psi_0 \end{cases}$$

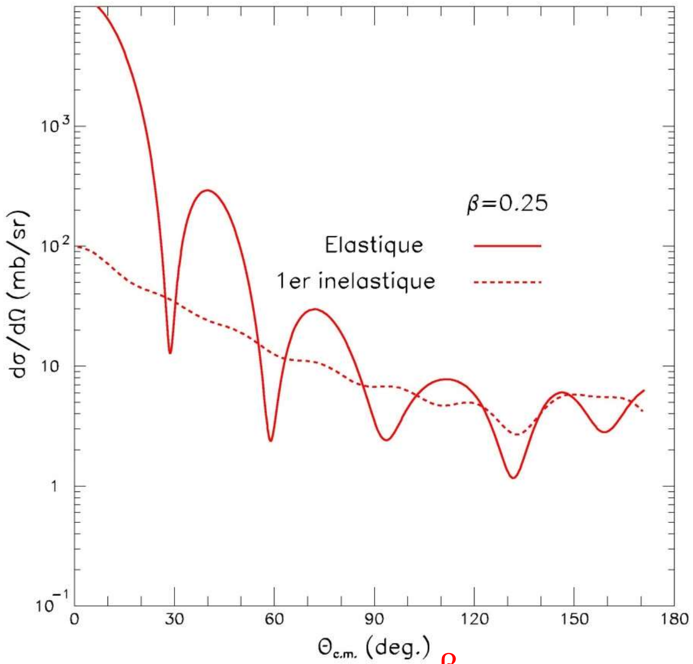
The optical model : impact of deformation







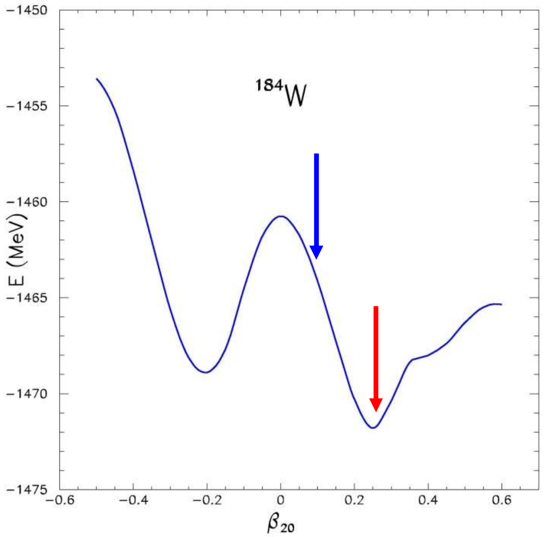
14 MeV ^{184}W(n,n')

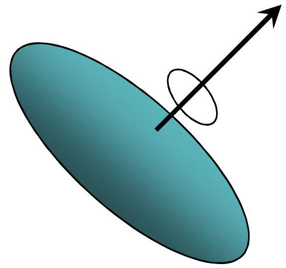


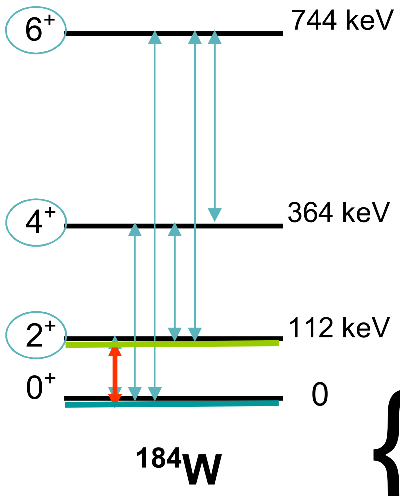
β ↓

$$\begin{cases} (T+V_{00}-E)\,\Psi_0 = V_{02}\,\Psi_2 \\ (T+V_{22}-E)\,\Psi_2 = V_{20}\,\Psi_0 \end{cases}$$

The optical model : impact of deformation







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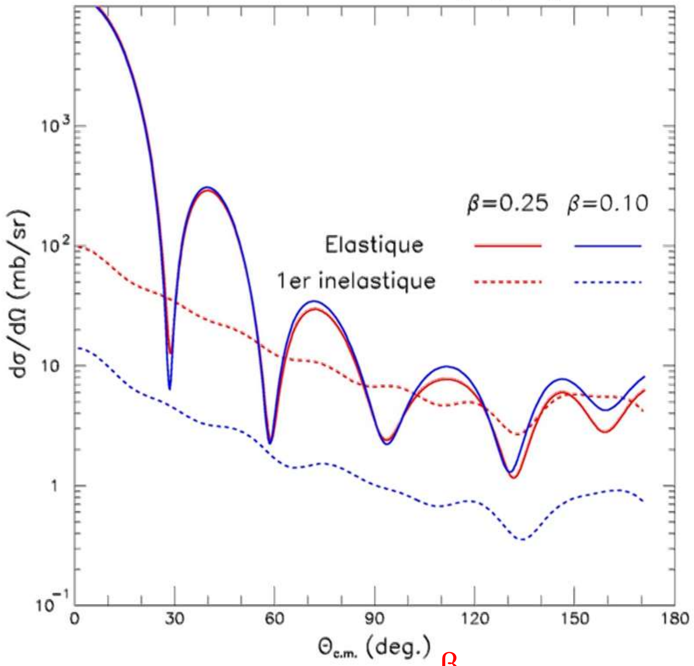
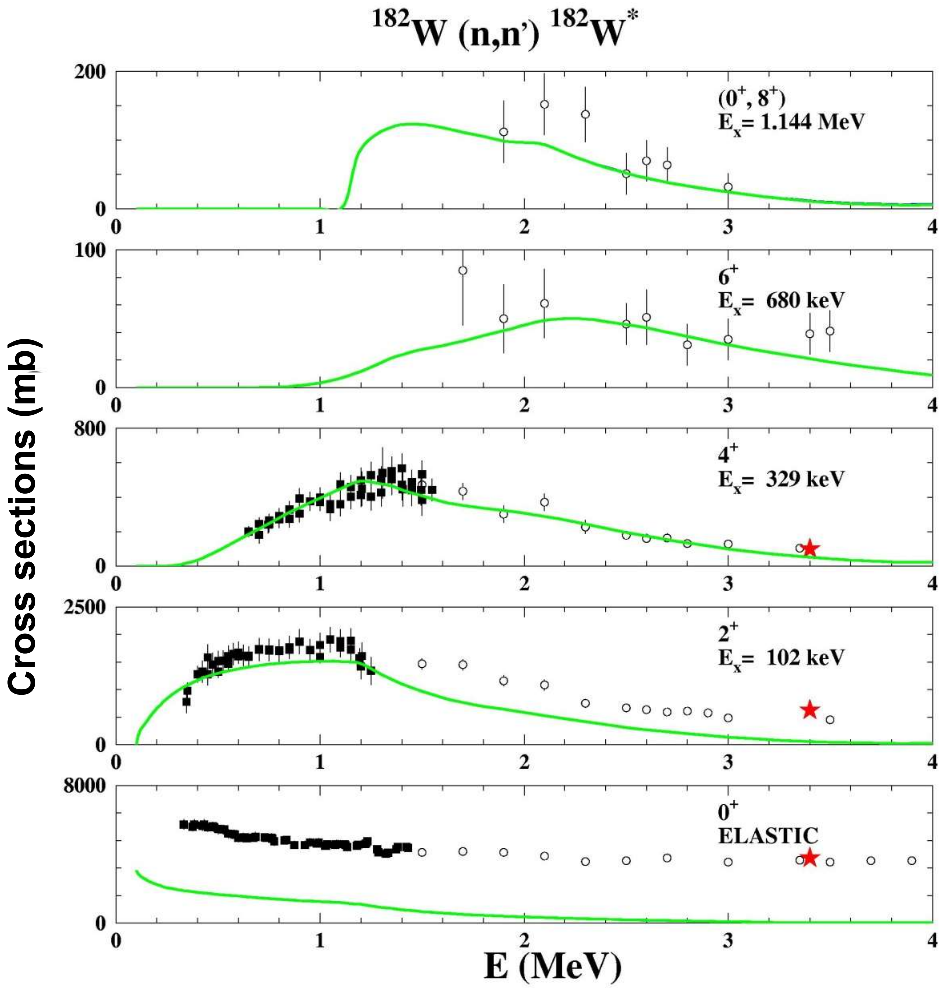


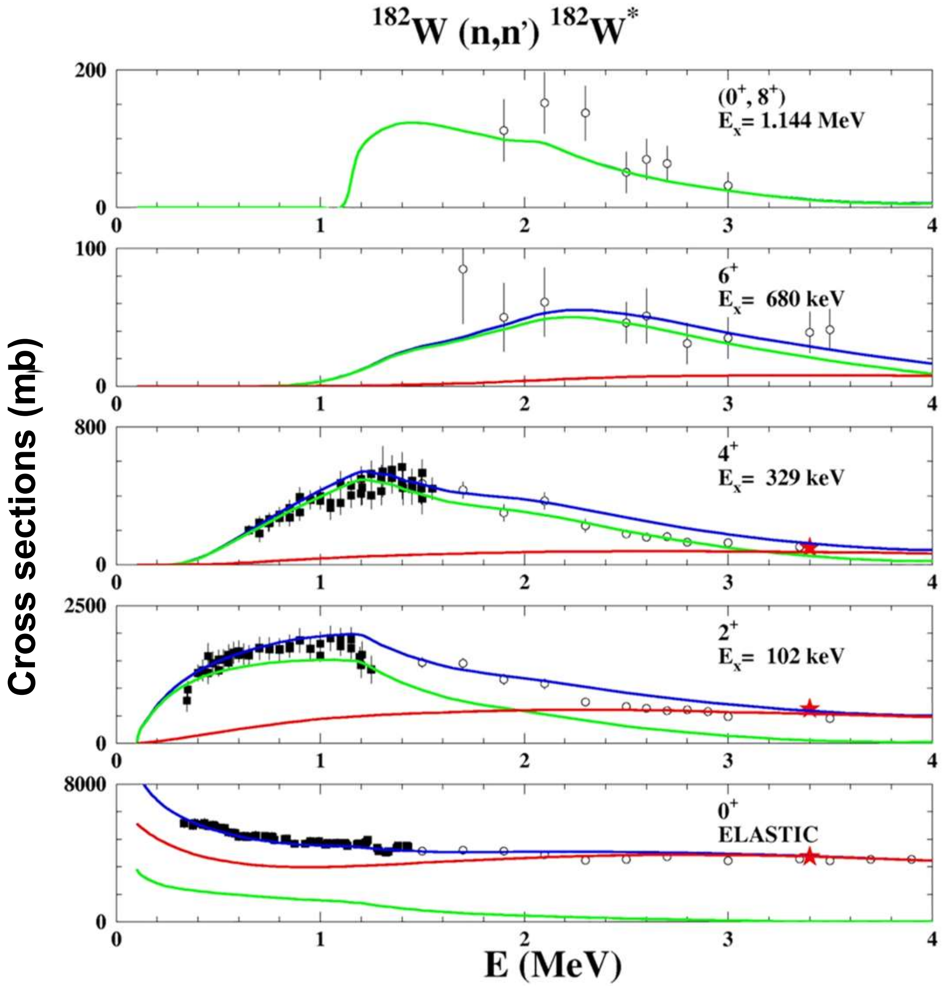
$$\begin{cases} (T+V_{00}-E)\,\Psi_0 = \overset{\beta}{V_{02}}\,\Psi_2 \\ (T+V_{22}-E)\,\Psi_2 = V_{20}\,\Psi_0 \end{cases}$$

The optical model : impact of deformation on cross sections



Compound nucleus component

The optical model : impact of deformation on cross sections

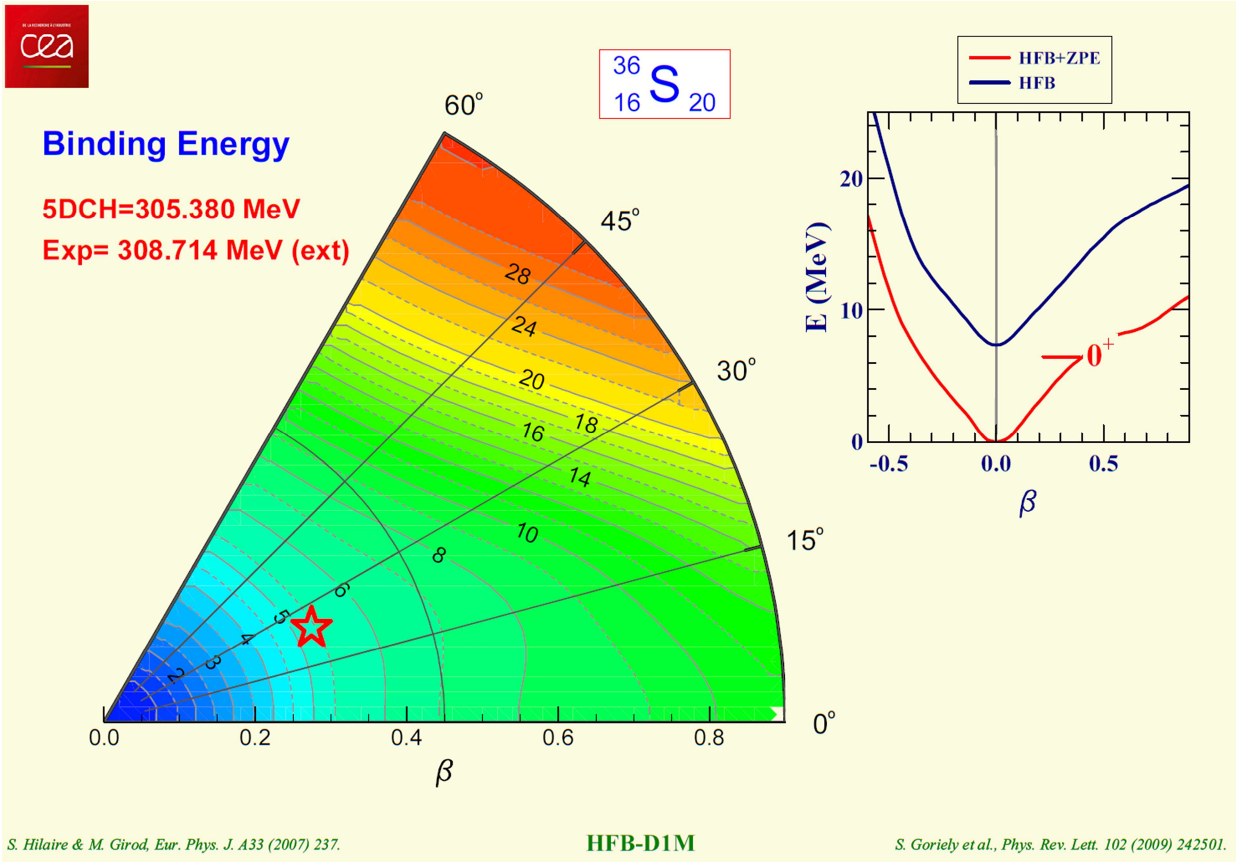


Compound nucleus component

Direct component

Sum

The optical model : impact of structure description

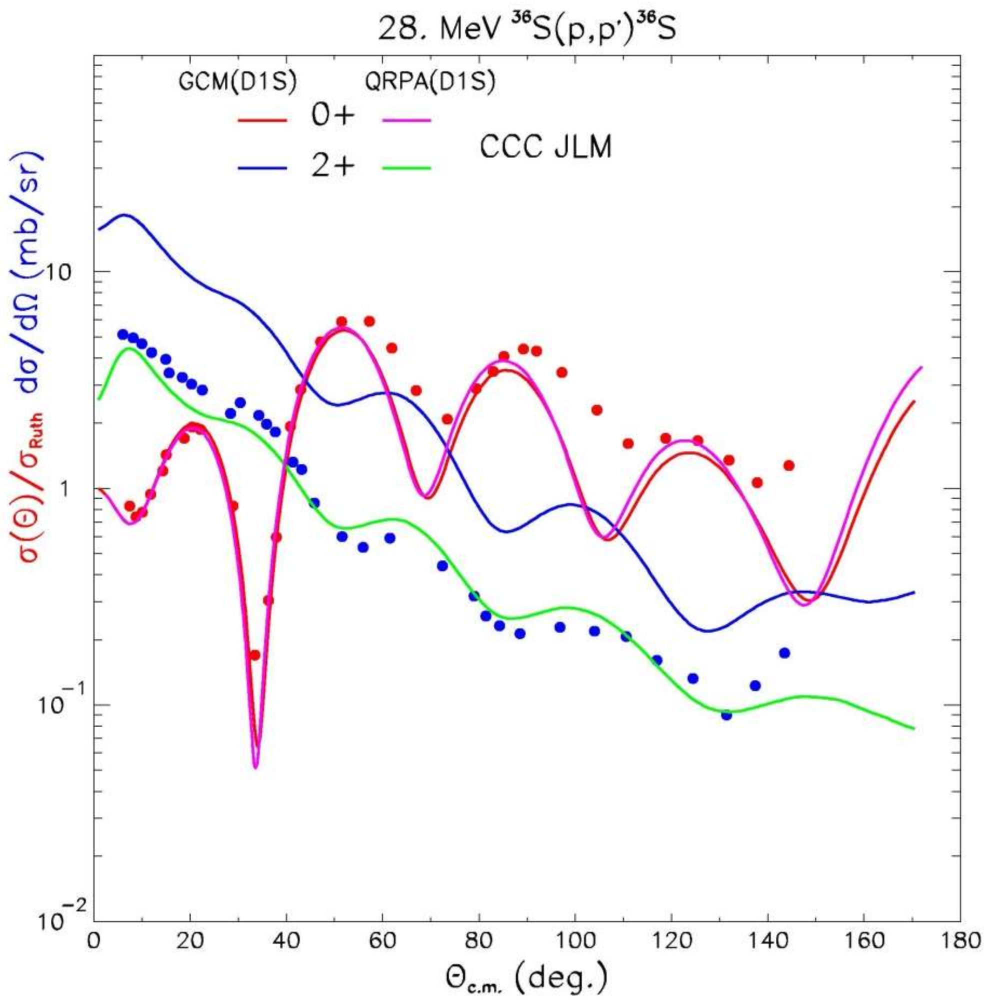


⇒ Nearly spherical nucleus

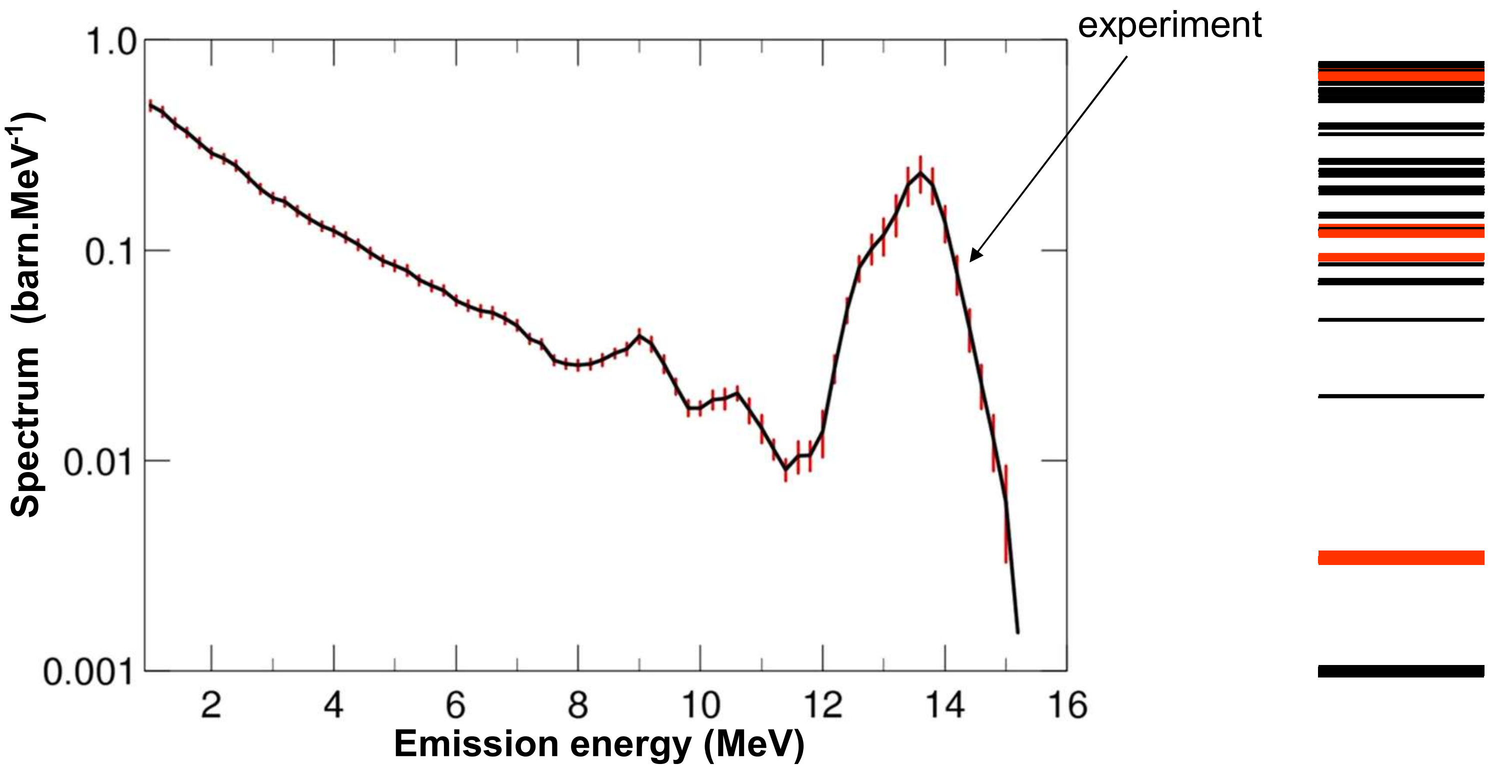
⇒ Structure with 5DCH (GCM) probably not perfect

⇒ QRPA option could be more appropriate

The optical model : impact of structure description



The optical model : deformation and outgoing spectrum



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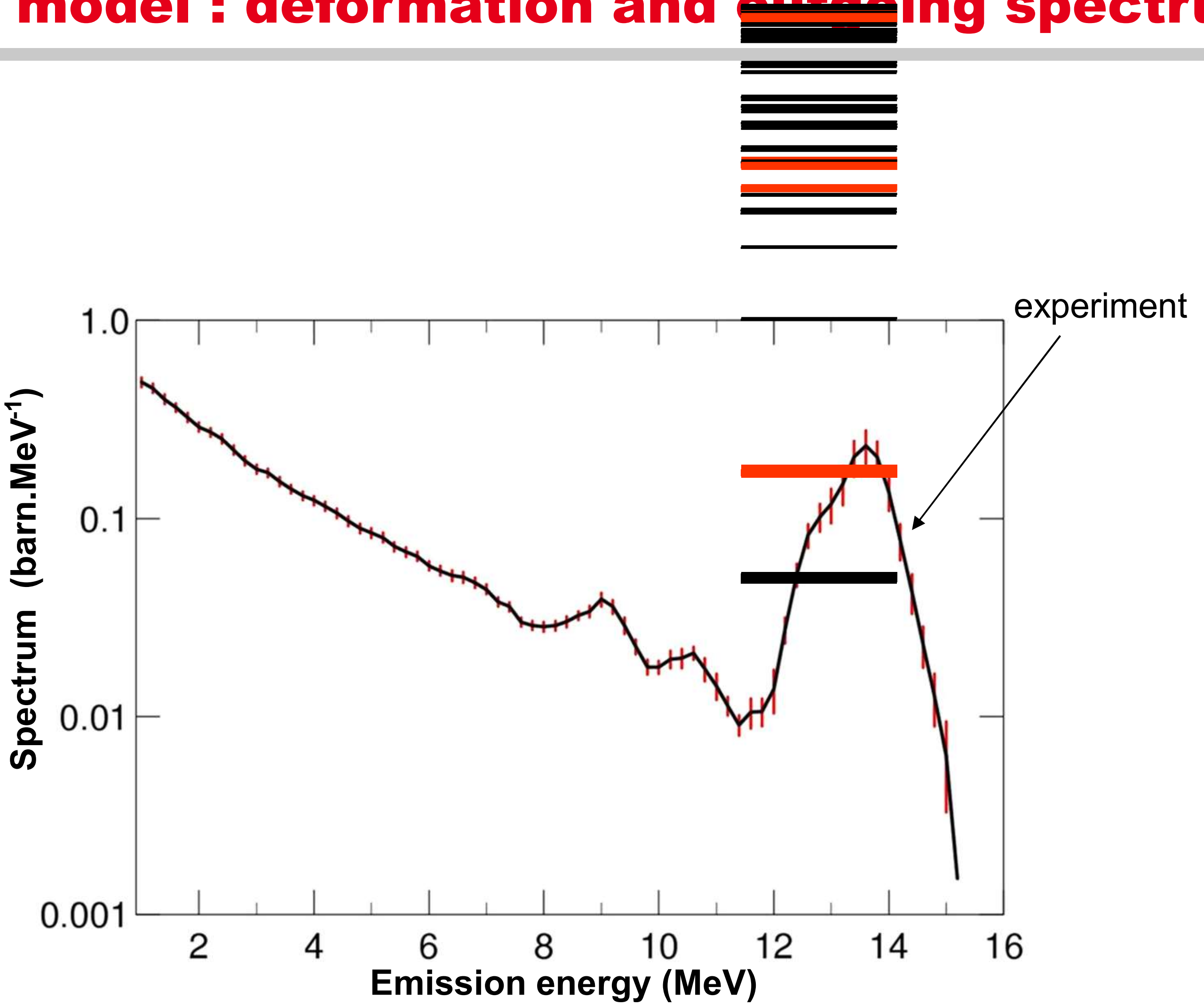

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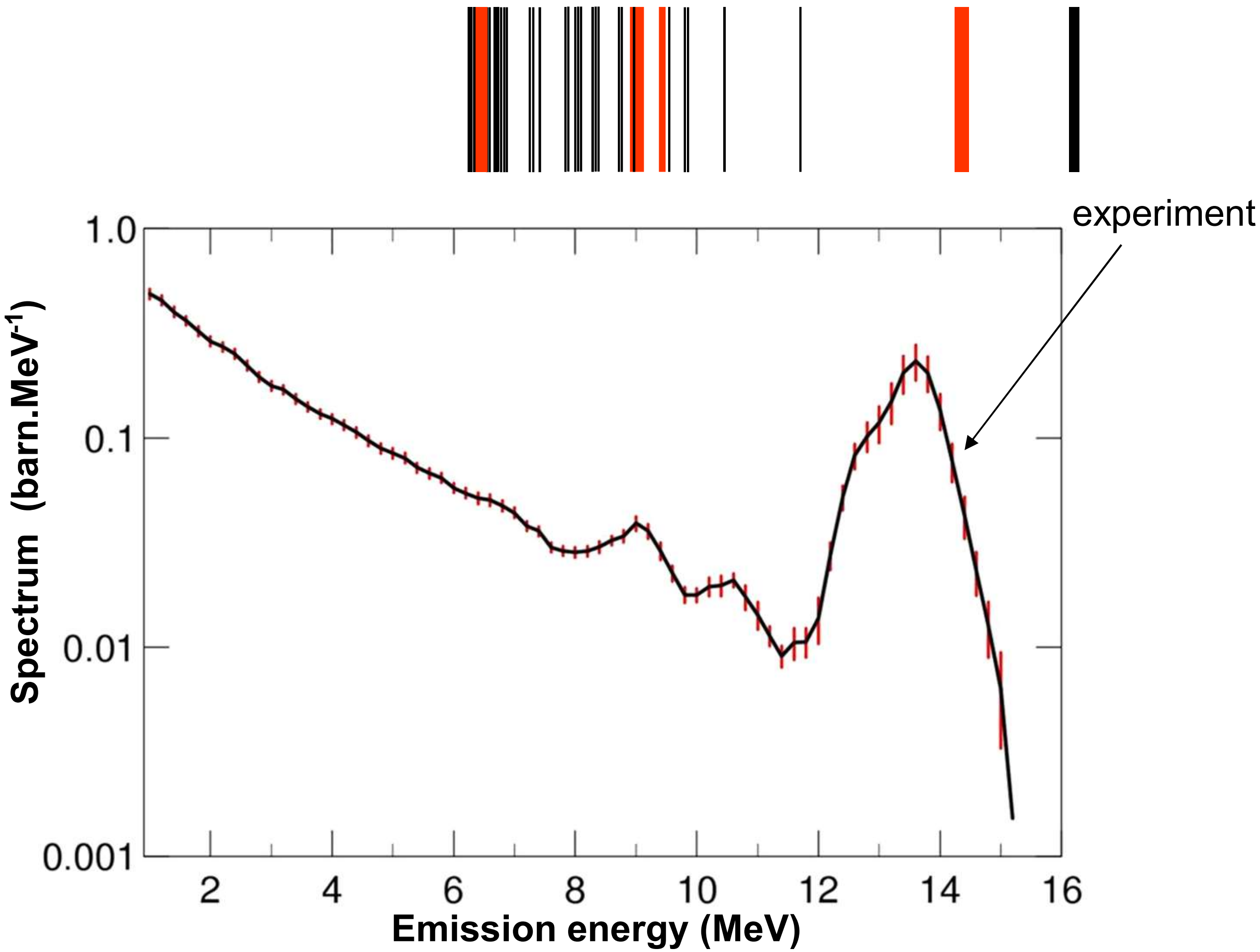

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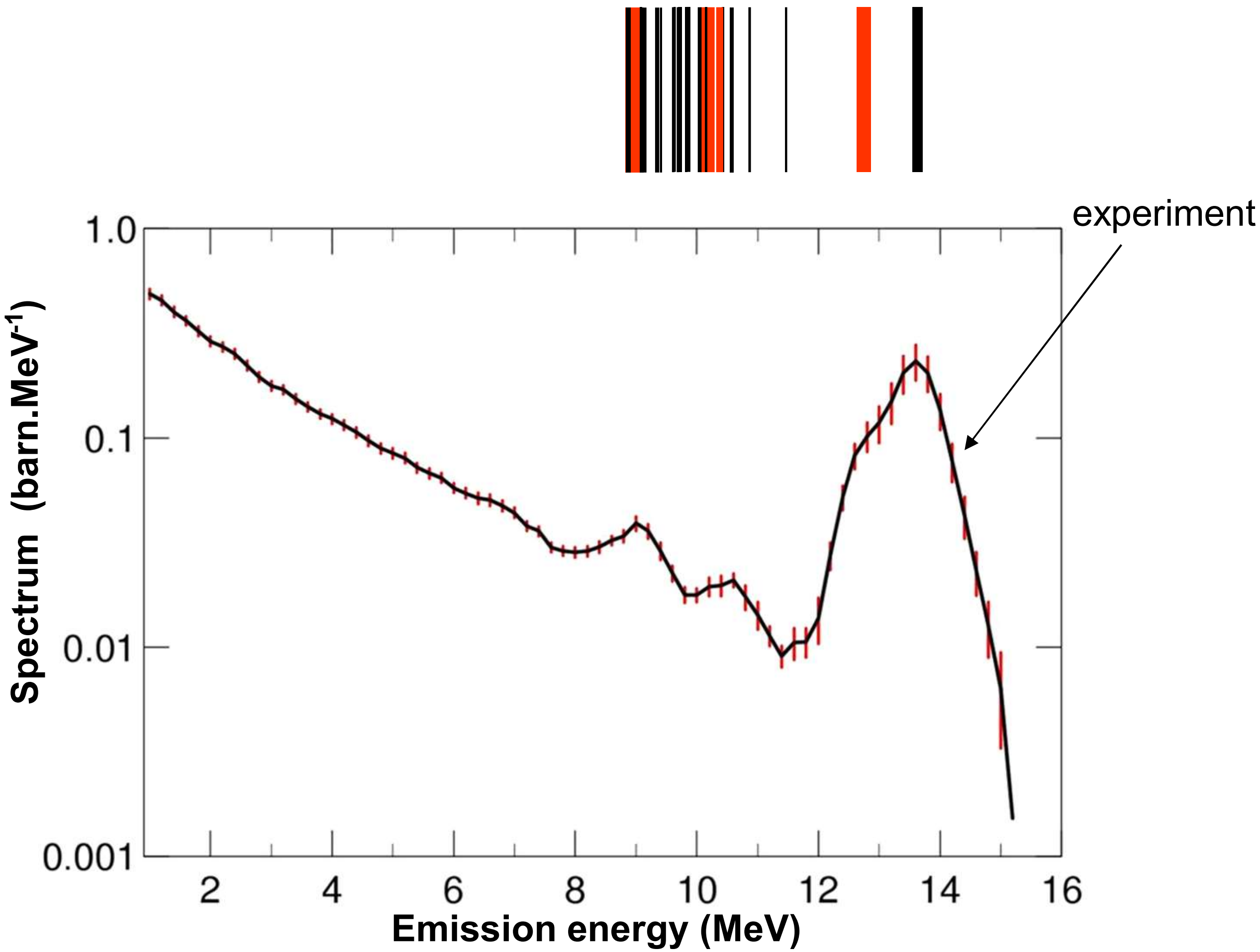

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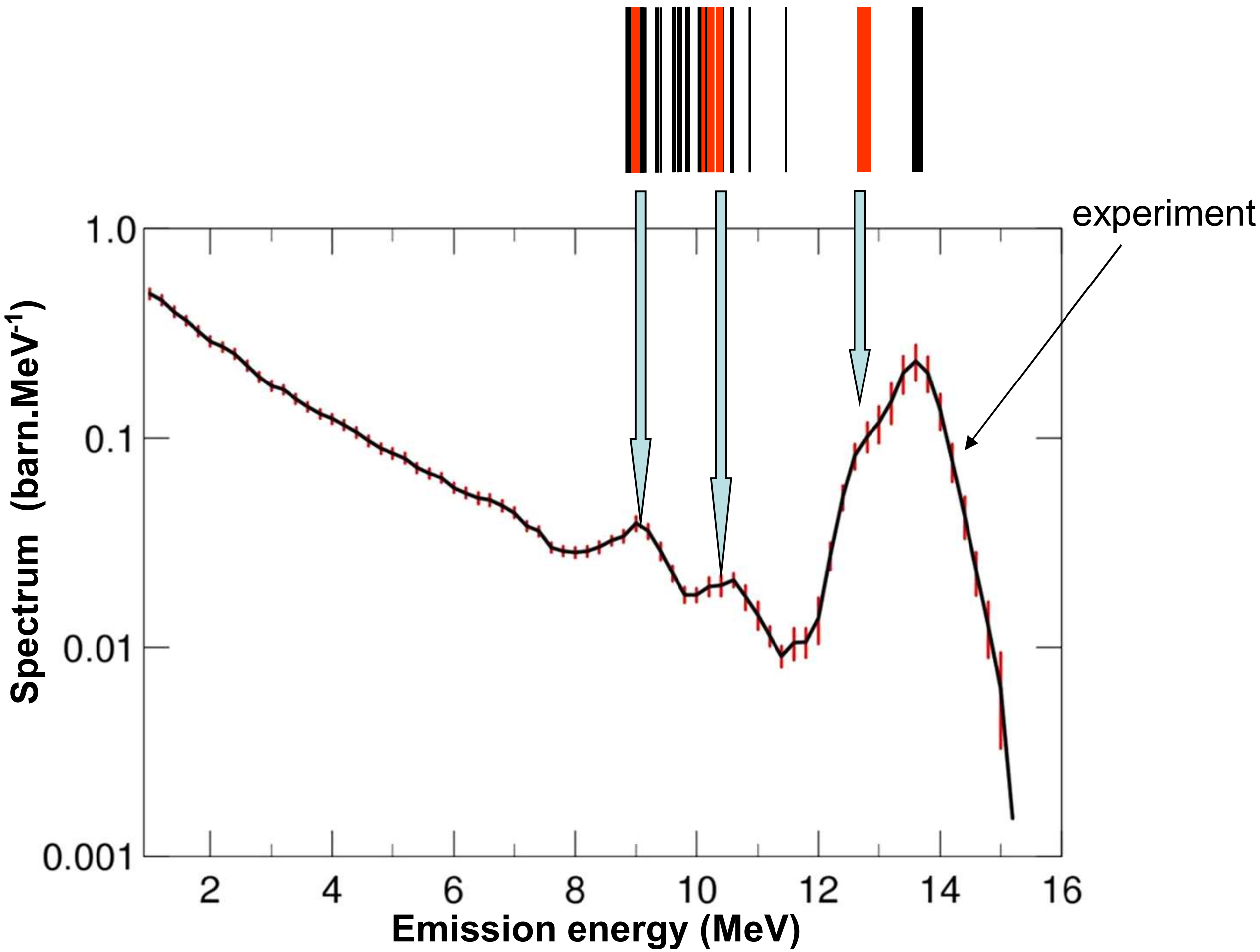

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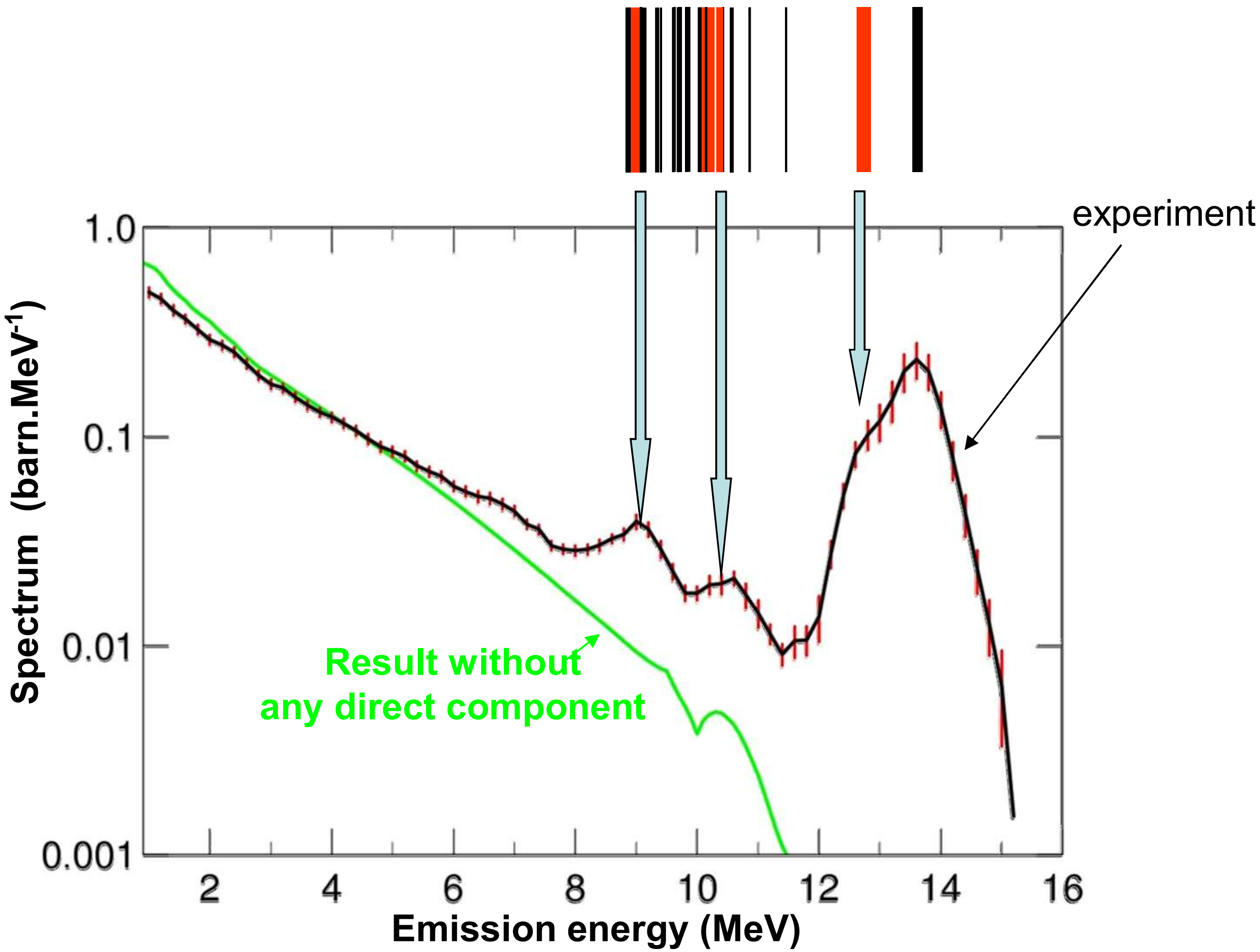
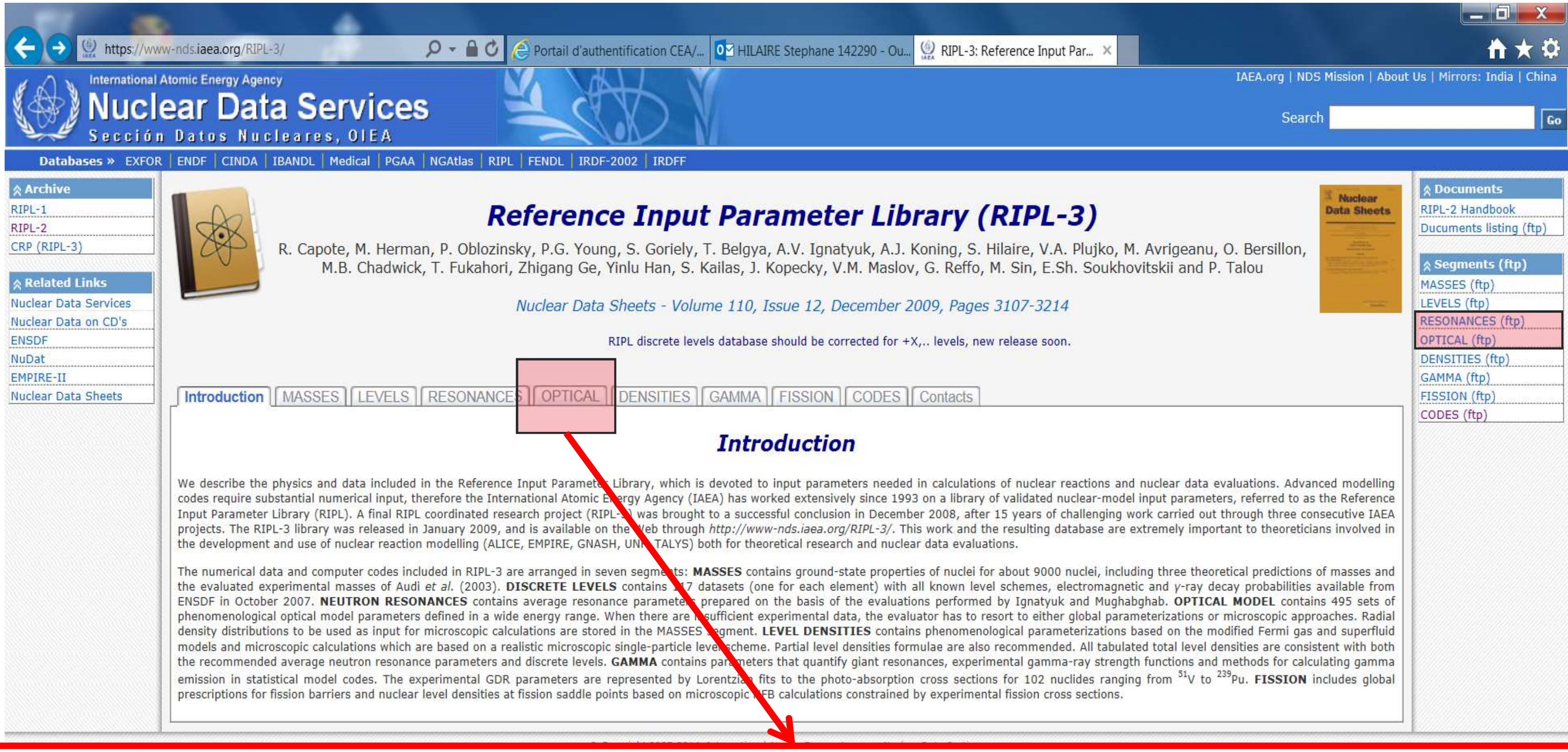


The optical model : RIPL inputs



OMP for more than 500 nuclei with projectiles ranging 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)

Content

- Introduction

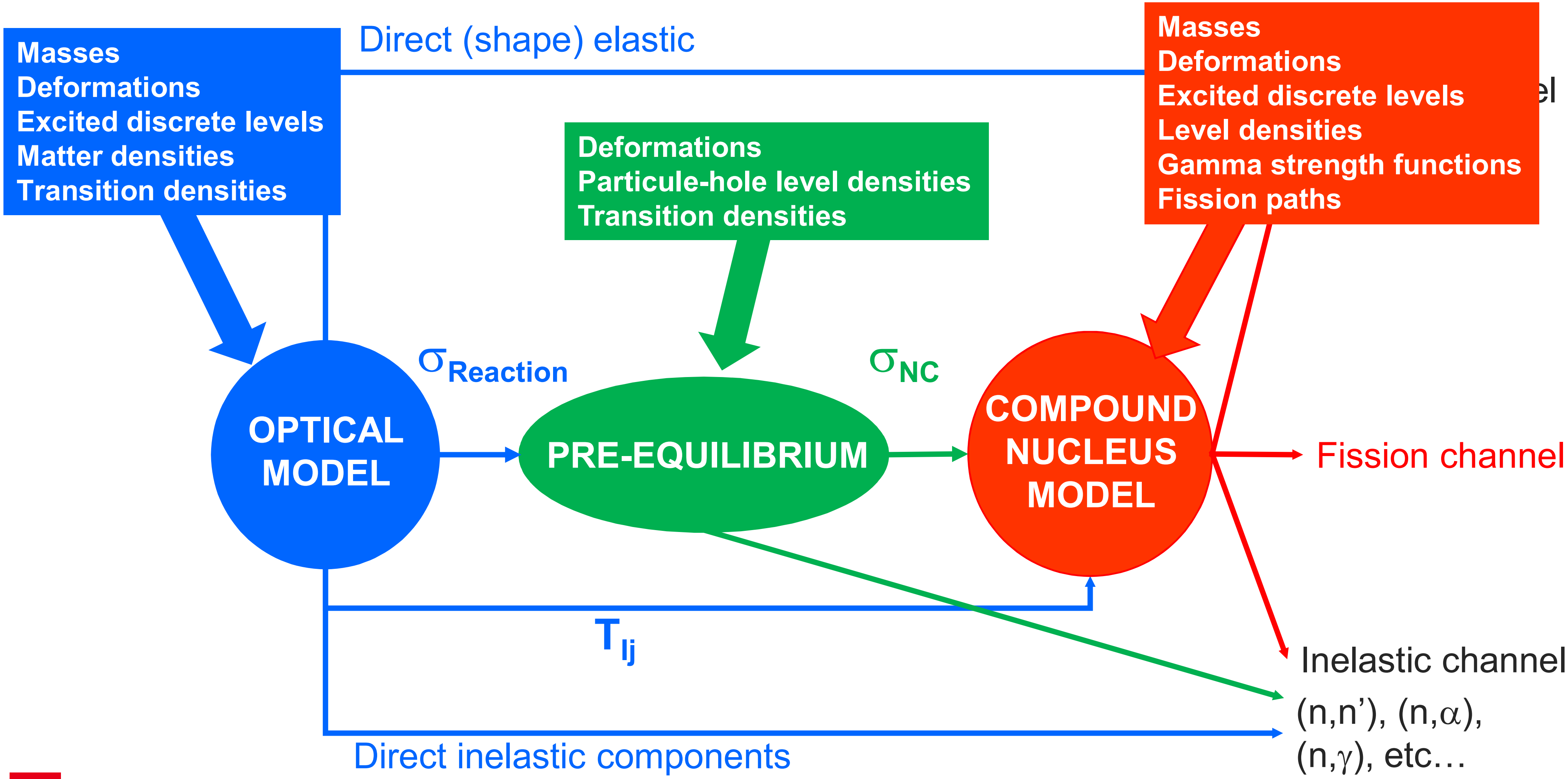
- General features about nuclear reactions

  - 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

Models sequence and required ingredients



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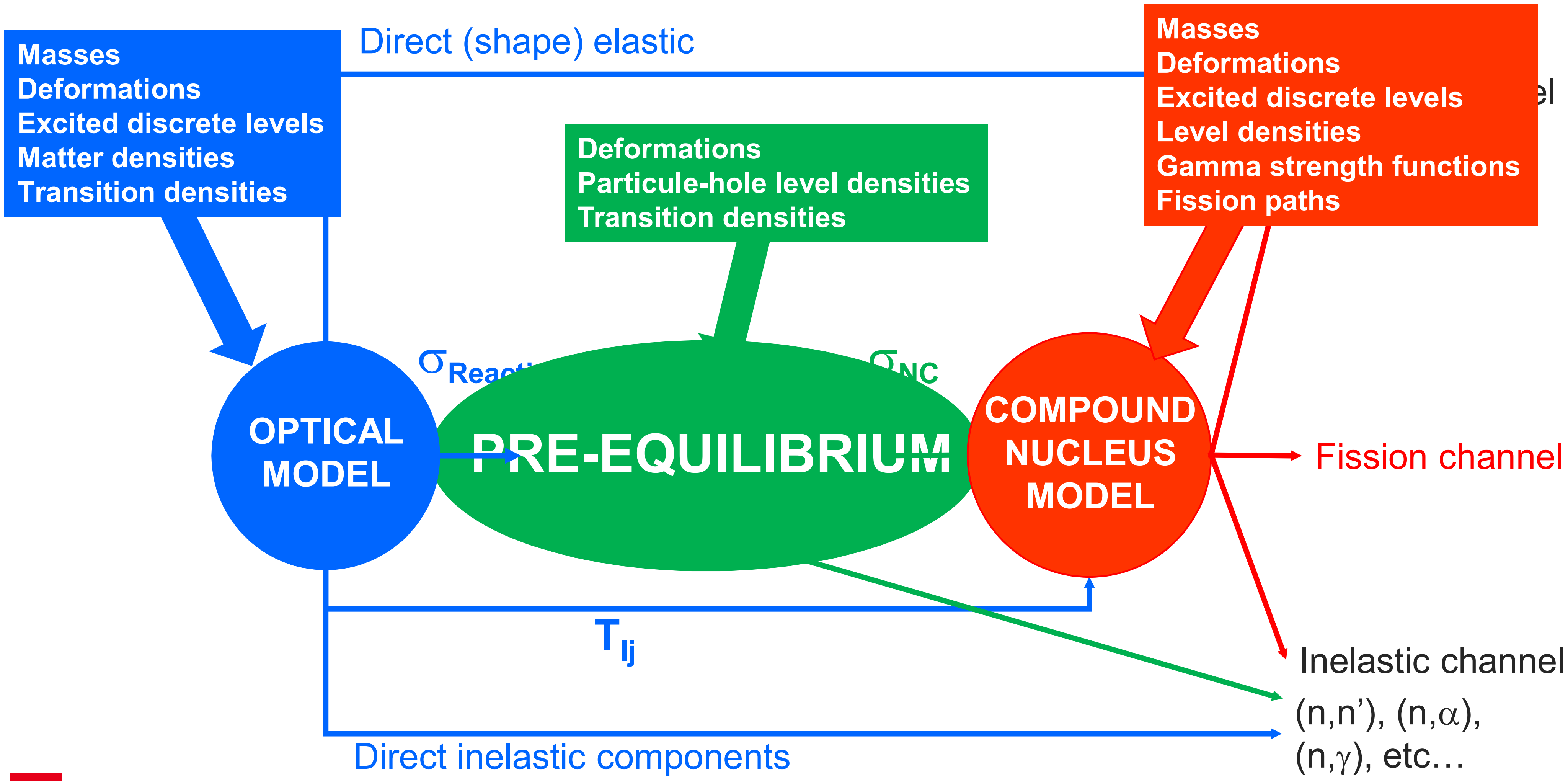
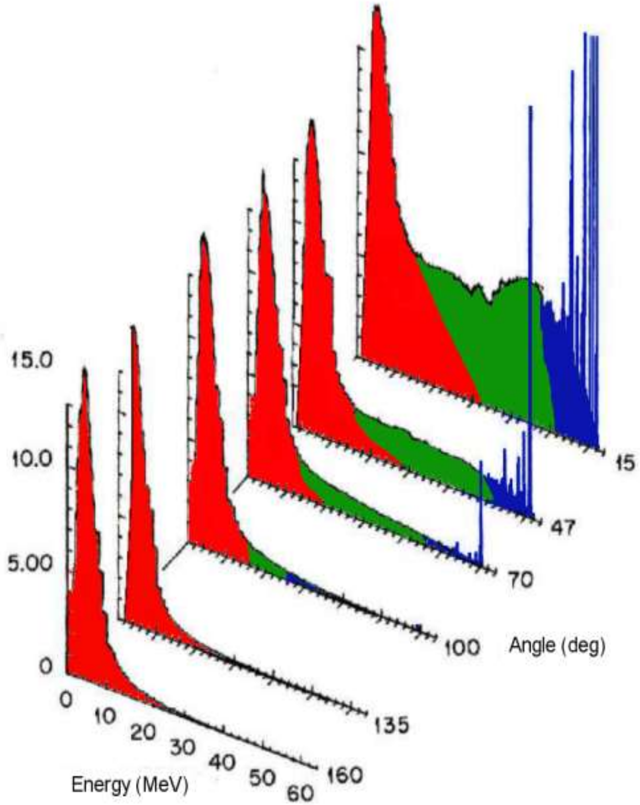


Typical spectrum shape

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



3 regions :

- Red : « evaporation » peak
  always present and low outgoing energy
- **Green : « flat » intermediate region**
  width increases with incident energy
- Blue : « discrete » peaks
  outgoing energy close to incident energy

The pre-equilibrium model : history

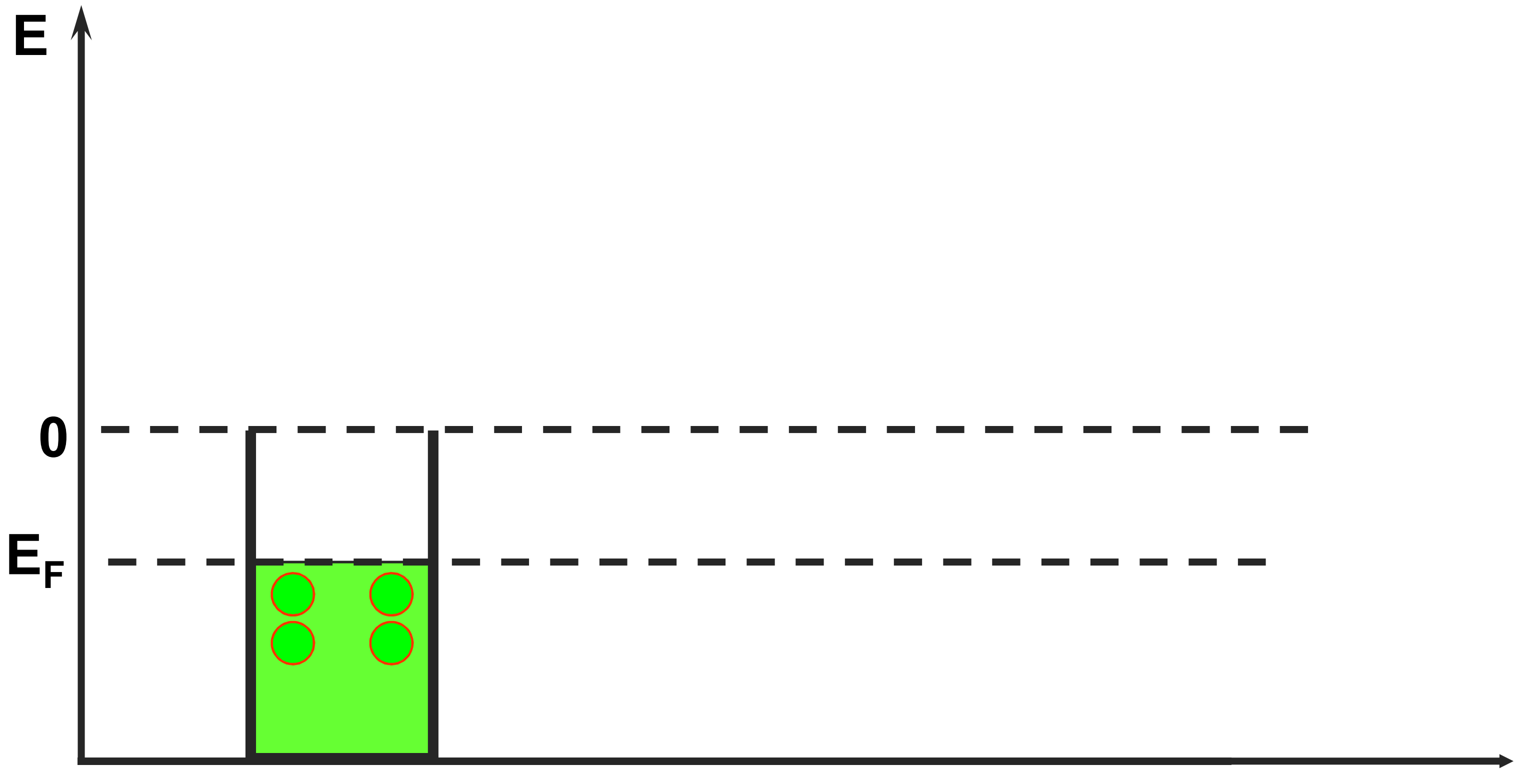
Semi-classical approaches

- 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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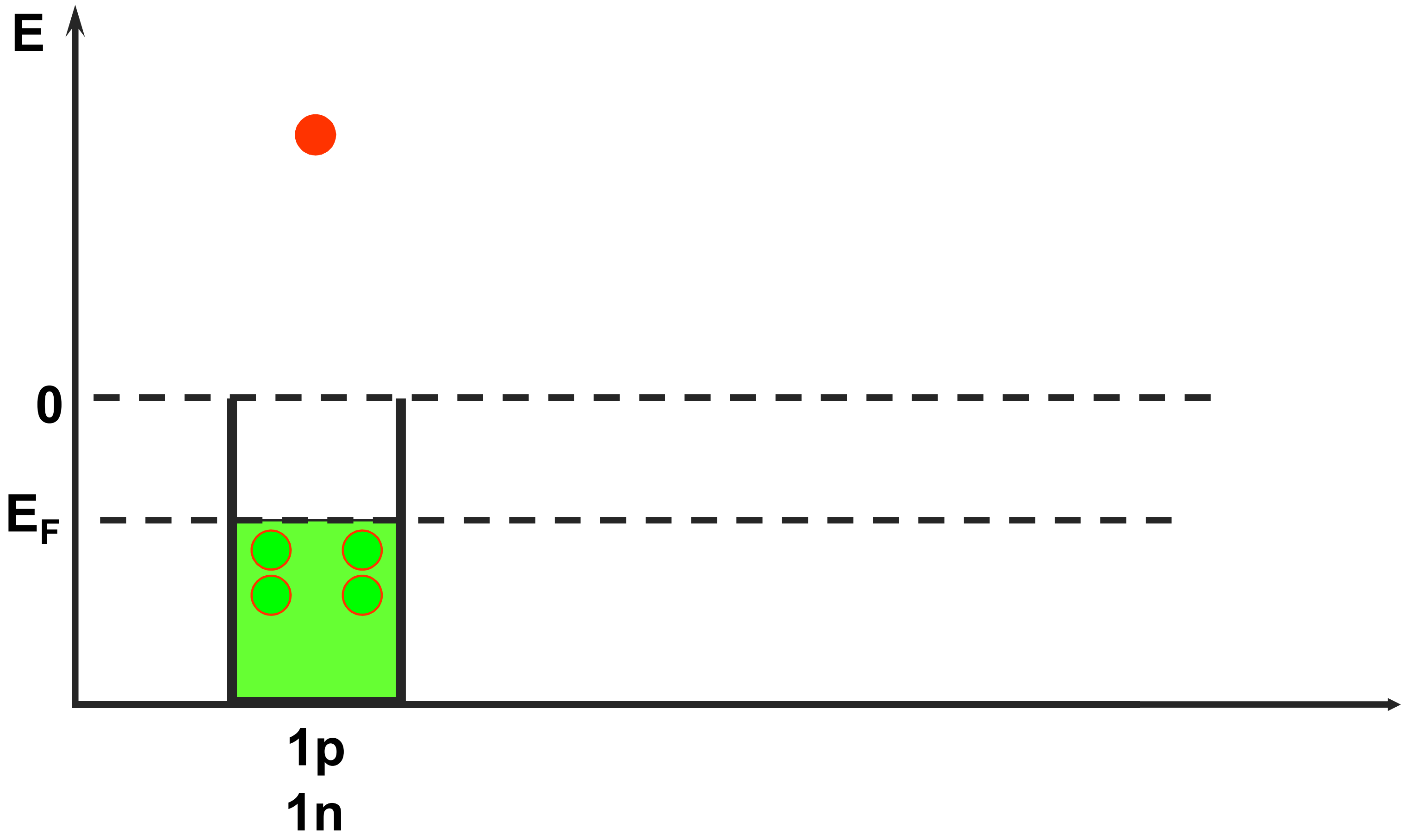

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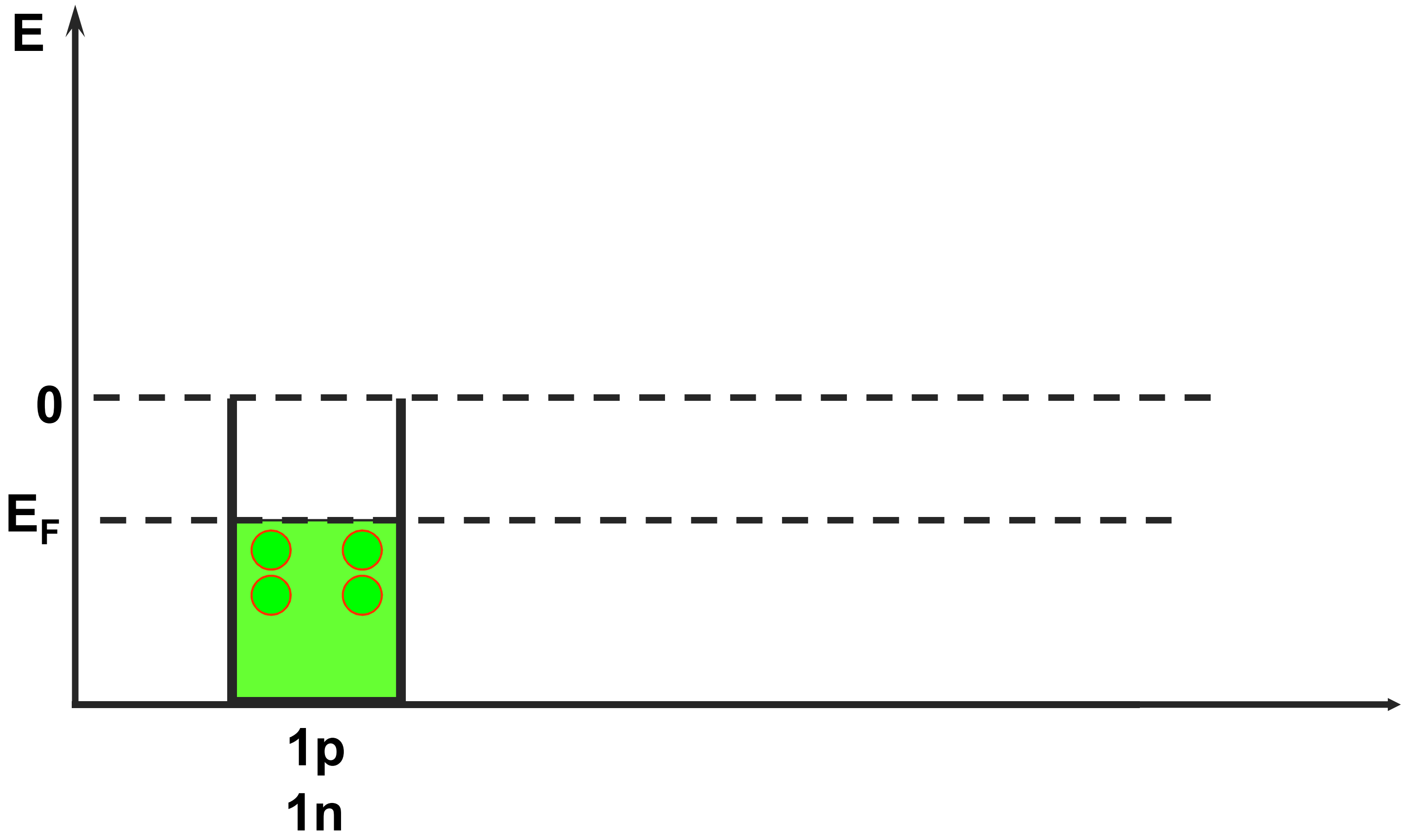

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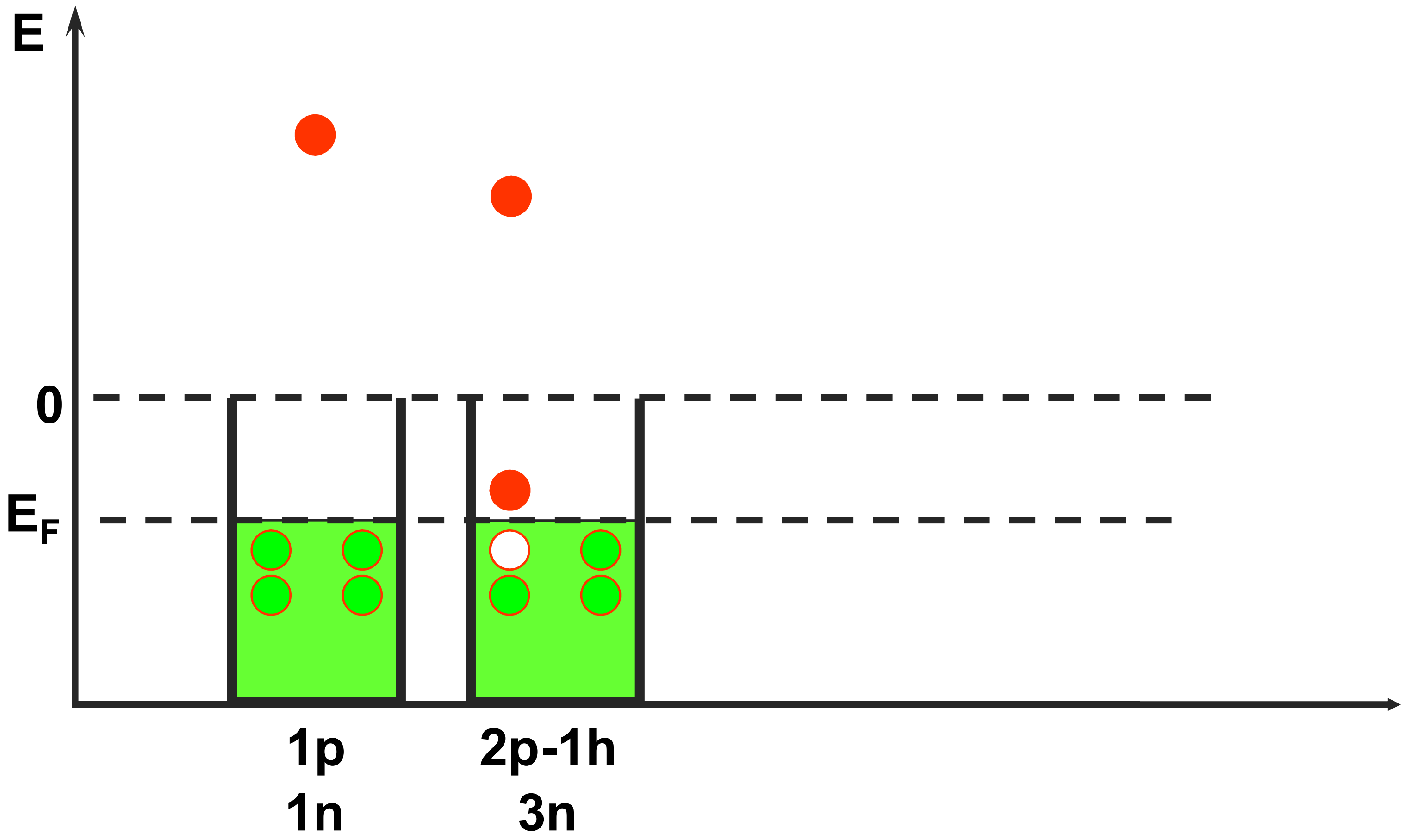

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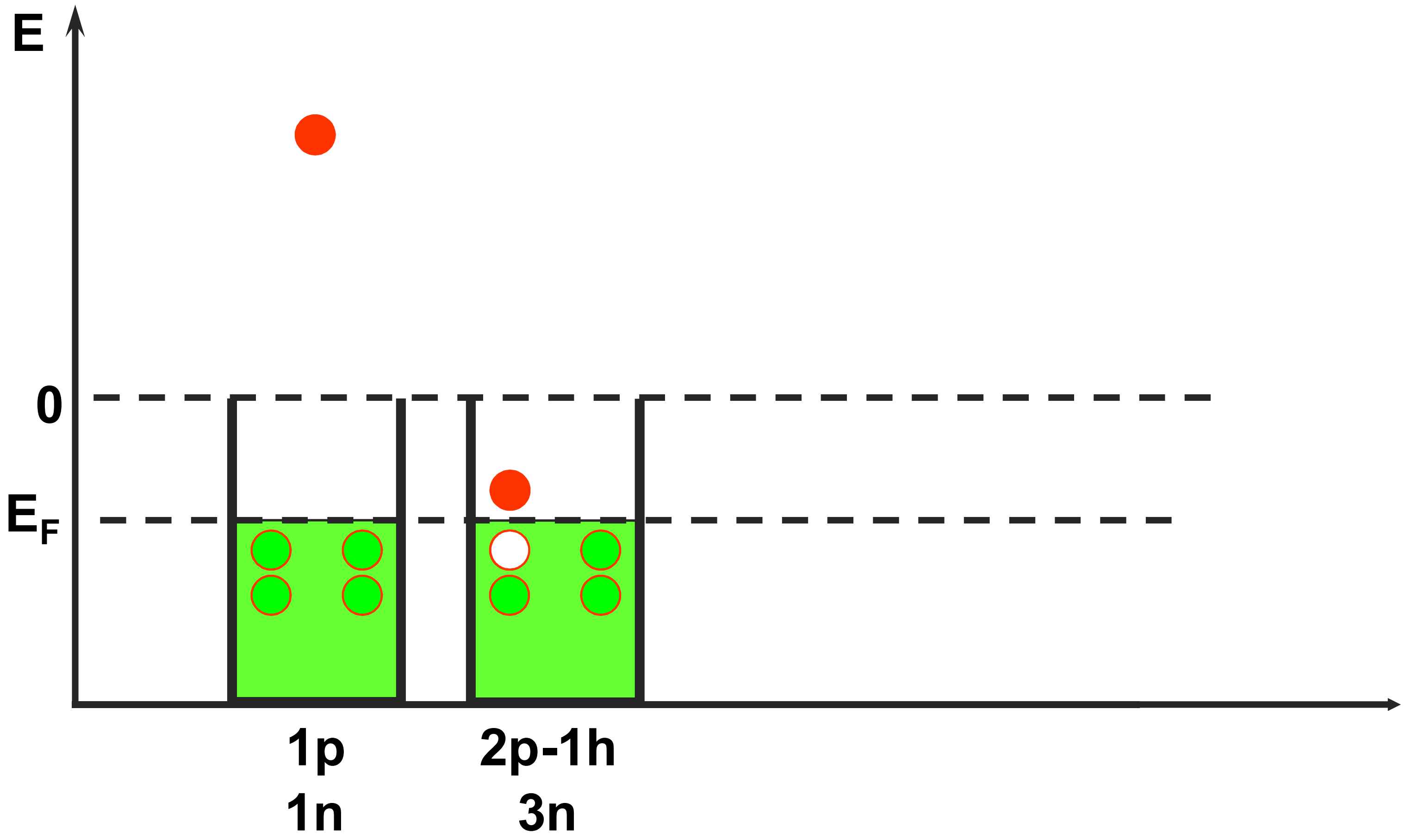

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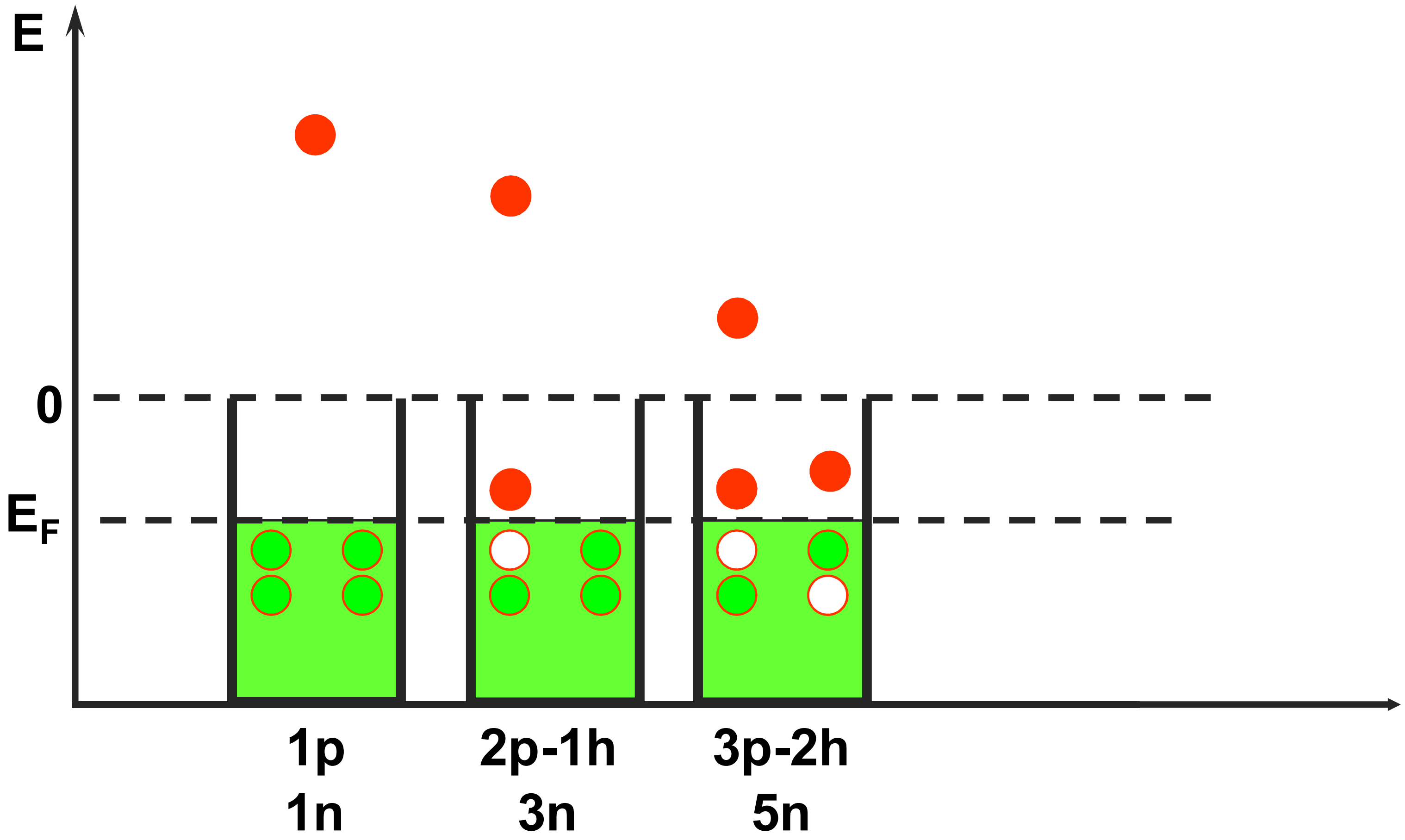

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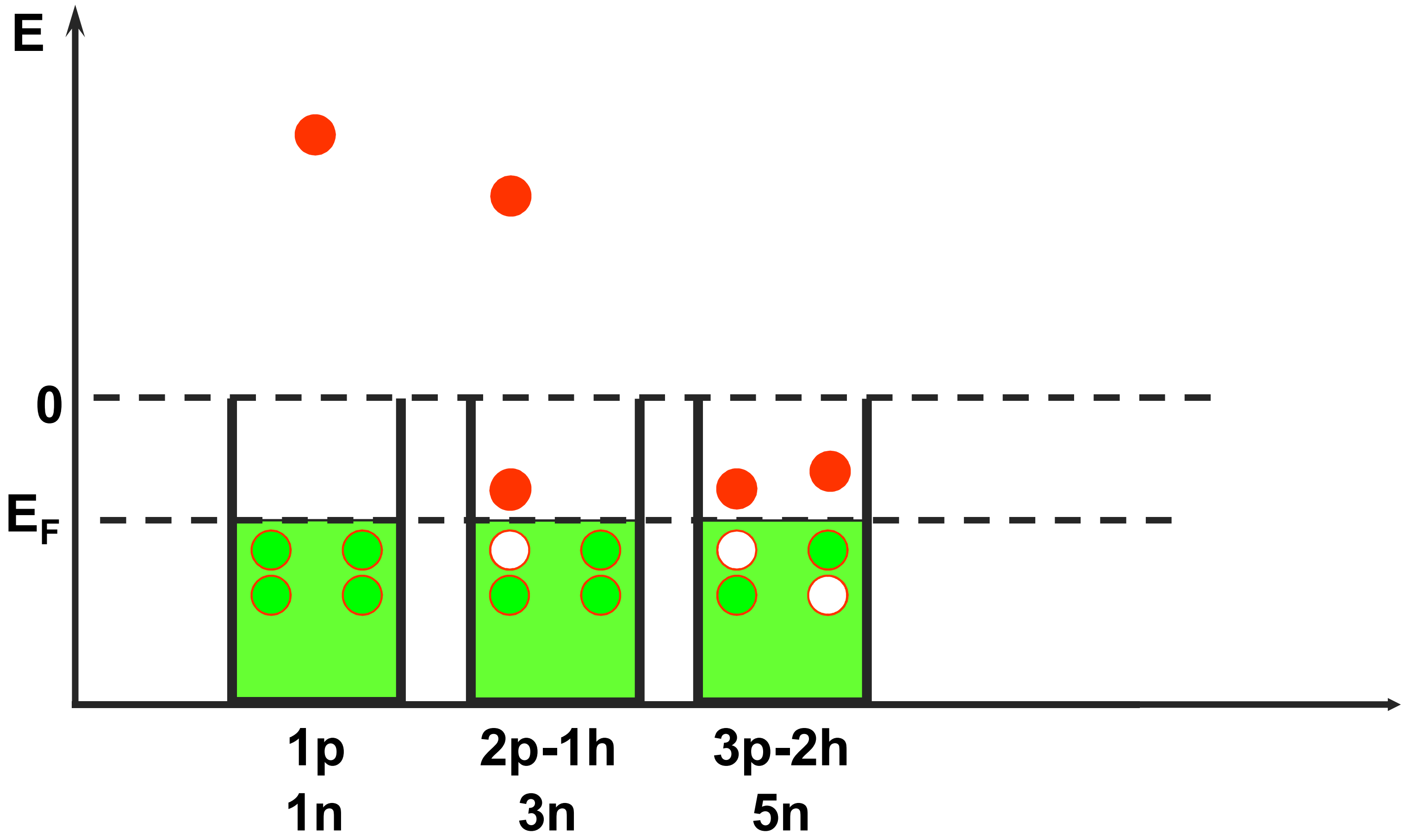

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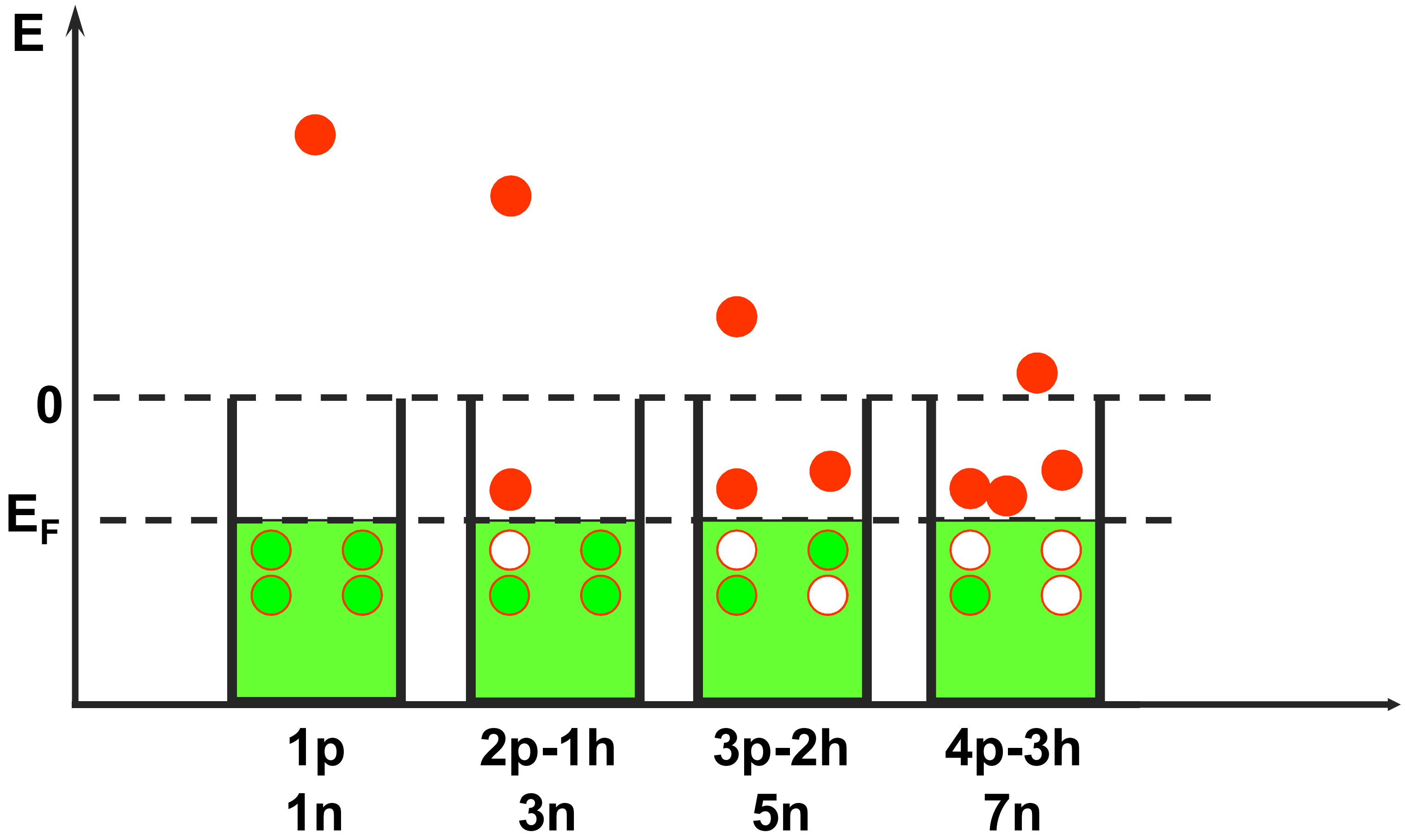

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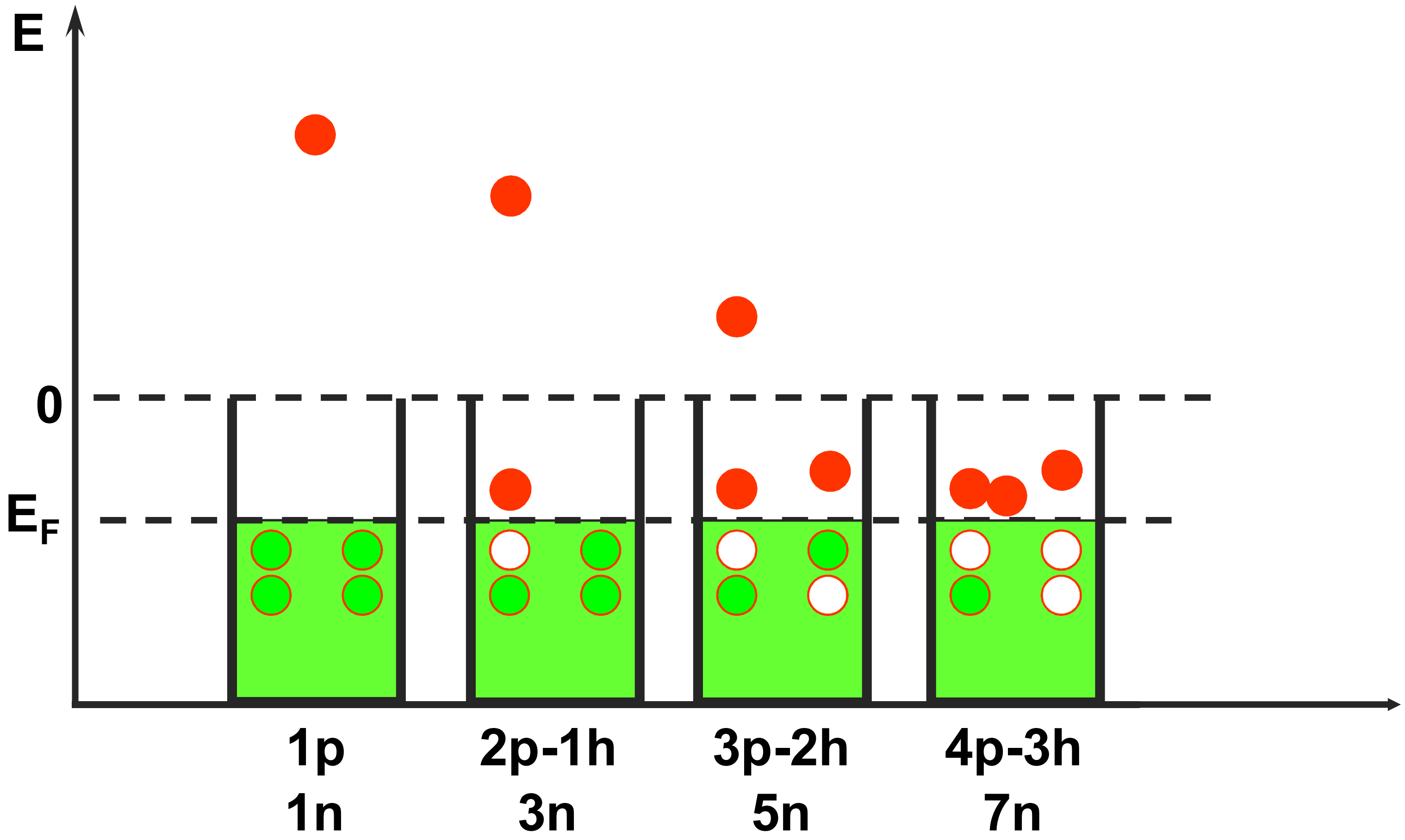

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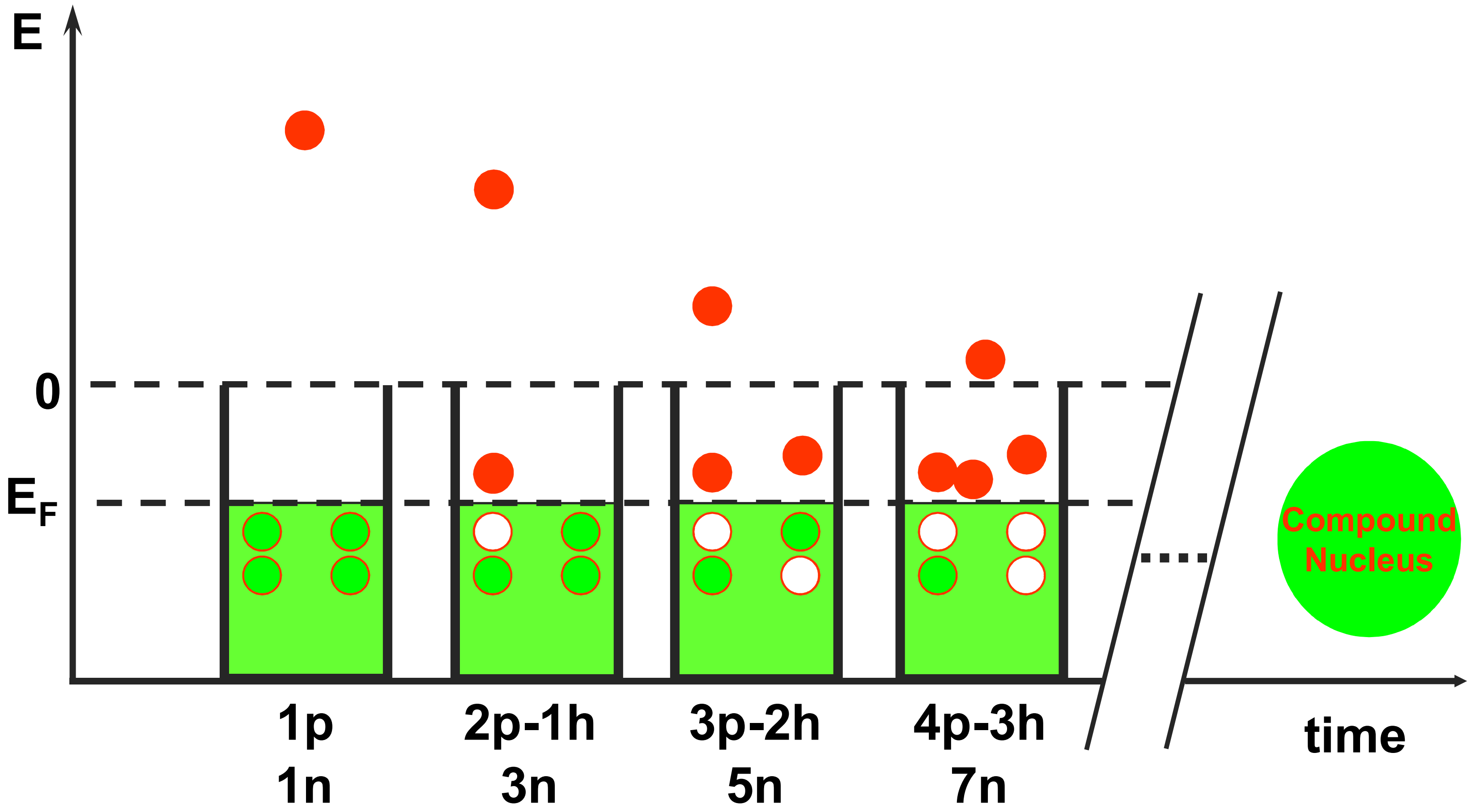

The pre-equilibrium model : master equation

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

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

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Evolution equation

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

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Evolution equation

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

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

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Evolution equation

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

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

The pre-equilibrium model : master equation

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

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

Evolution equation

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

Emission cross section in channel c

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

The pre-equilibrium model : initialisation & transition rates

Initialisation

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

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

Transition rates

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

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

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

Original formulation

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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Corrections for proton-neutron distinguishability & complex particle emission

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

Corrections for proton-neutron distinguishability & complex particle emission

State densities

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

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**

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

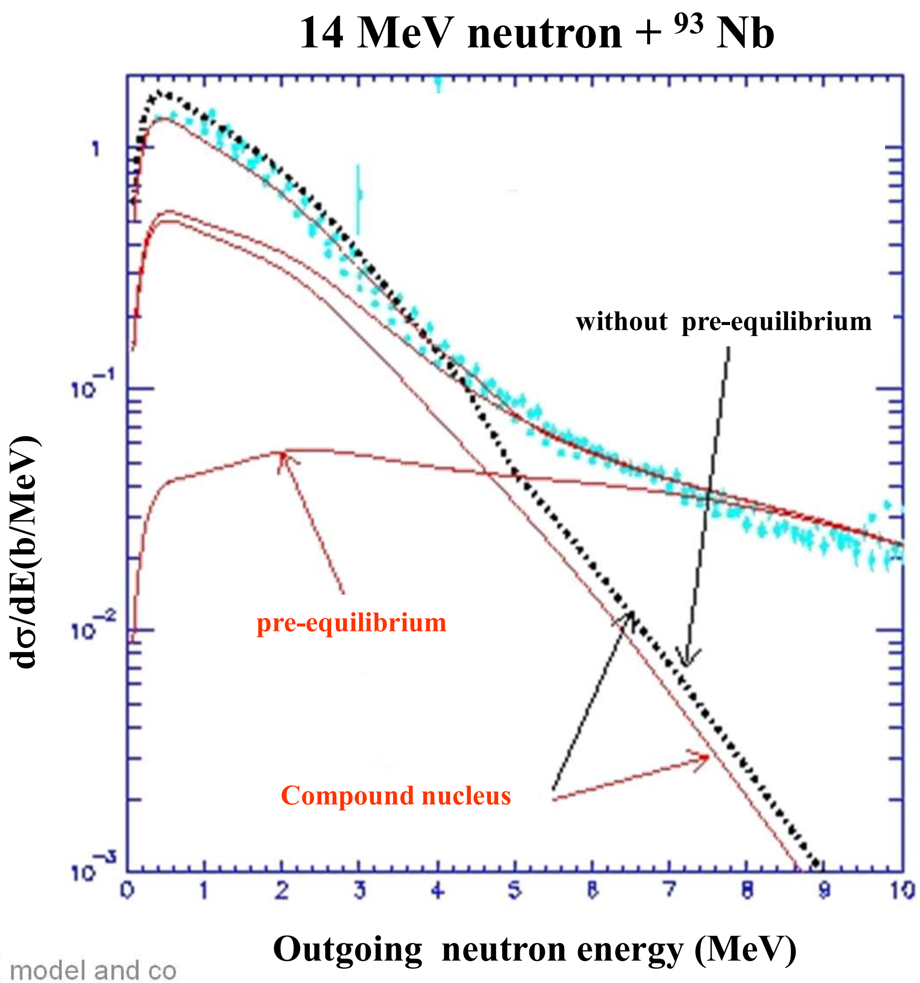
where M is the total number of particles and holes of both kinds and

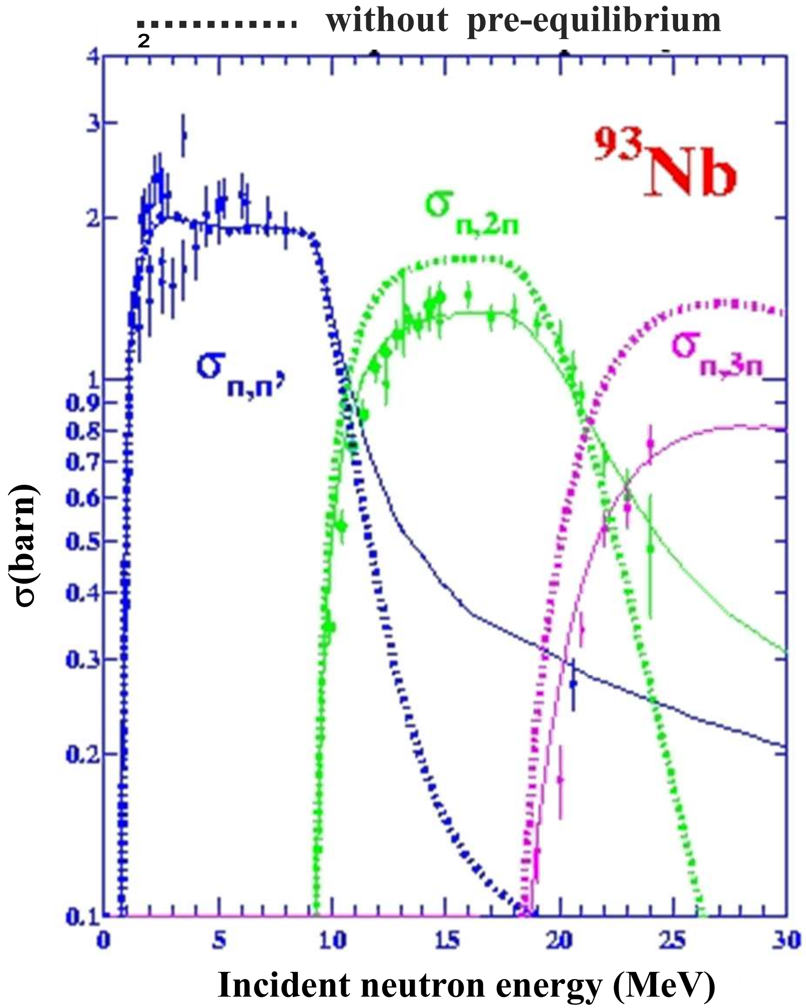
$$B = \frac{1}{4}\left(\frac{p_\pi^2 + h_\pi^2 + p_\pi - h_\pi}{g_\pi} + \frac{p_\nu^2 + h_\nu^2 + p_\nu - h_\nu}{g_\nu}\right) - \frac{1}{2}\left(\frac{h_\pi}{g_\pi} + \frac{h_\nu}{g_\nu}\right)$$

State densities in ESM

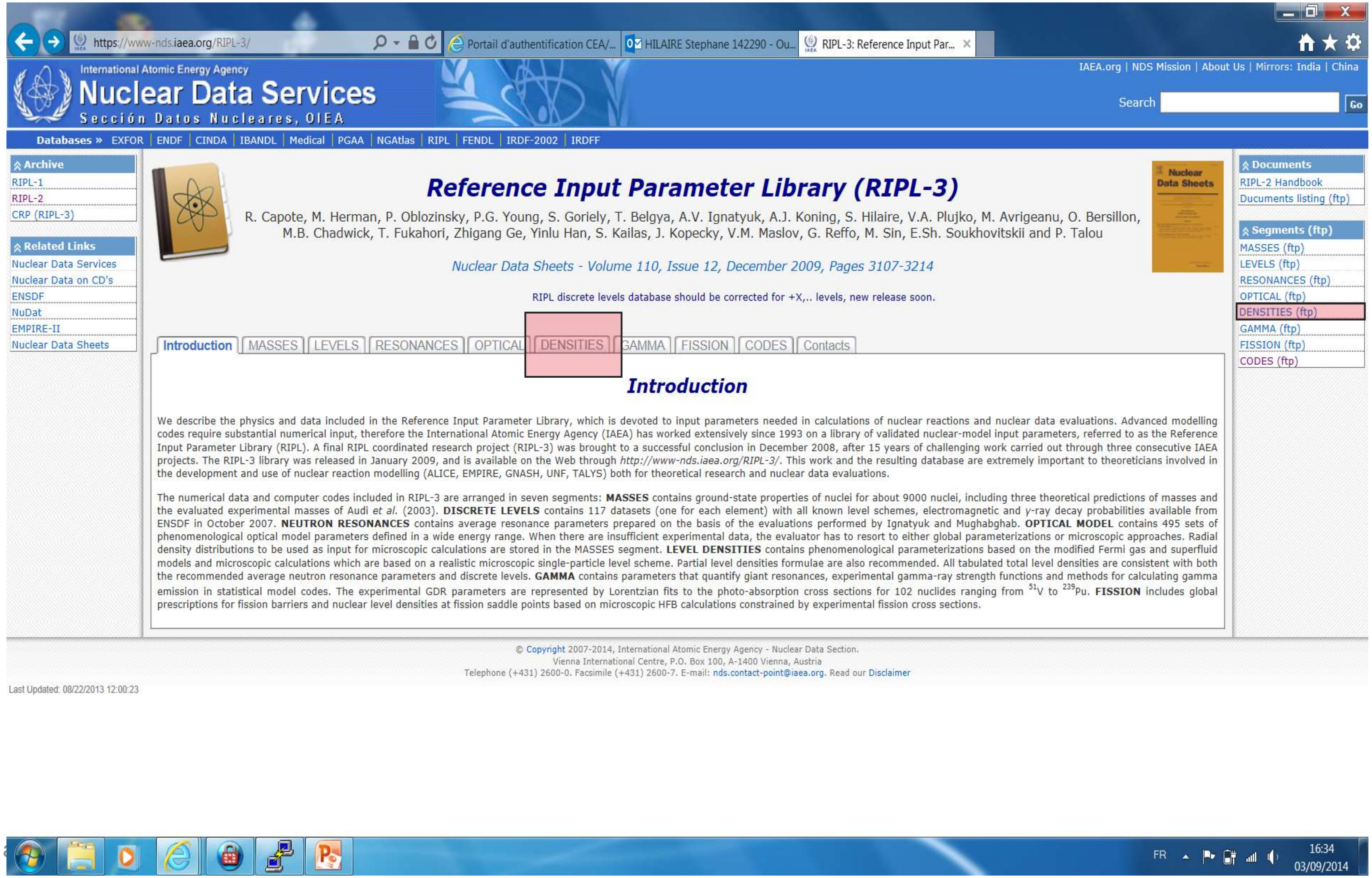
- **Ericson 1960 : no Pauli principle**
- **Griffin 1966 : no distinction between particles and holes**
- **Williams 1971 : distinction between particles and holes as well as between neutrons and protons but infinite number of accessible states for both particle and holes**
- **Běták and Doběs 1976 :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

The pre-equilibrium model : master equation





The pre-equilibrium model : RIPL inputs



https://www-nds.iaea.org/RIPL-3/

International Atomic Energy Agency
Nuclear Data Services
Sección Datos Nucleares, OIEA

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Databases » EXFOR | ENDF | CINDA | IBANDL | Medical | PGAA | NGAtlas | RIPL | FENDL | IRDF-2002 | IRDFF

Archive: RIPL-1, RIPL-2, CRP (RIPL-3)

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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.

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Introduction

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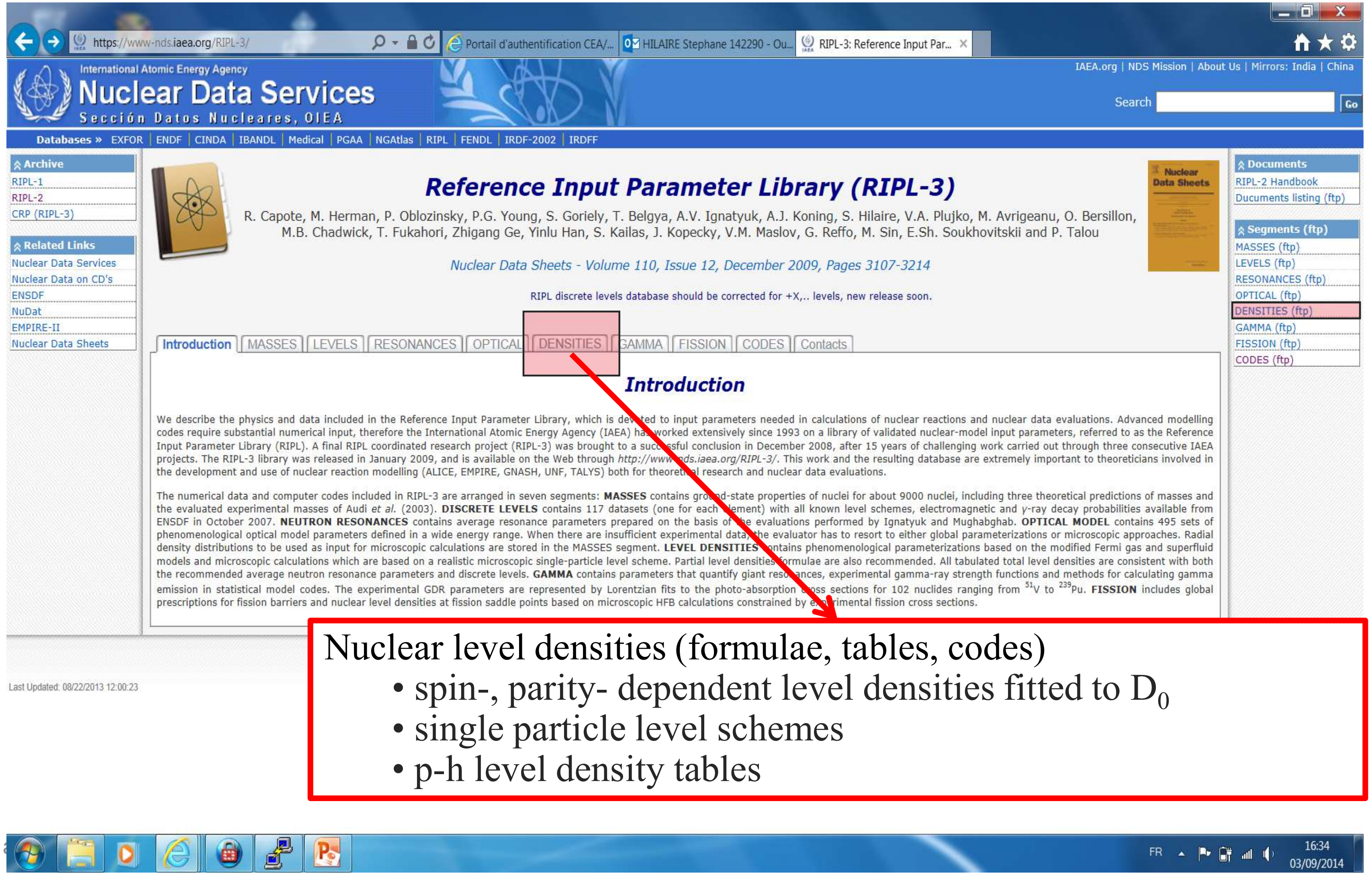
The numerical data and computer codes included in RIPL-3 are arranged in seven segments: **MASSES** contains ground-state properties of nuclei for about 9000 nuclei, including three theoretical predictions of masses and the evaluated experimental masses of Audi *et al.* (2003). **DISCRETE LEVELS** contains 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.

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

The pre-equilibrium model : RIPL inputs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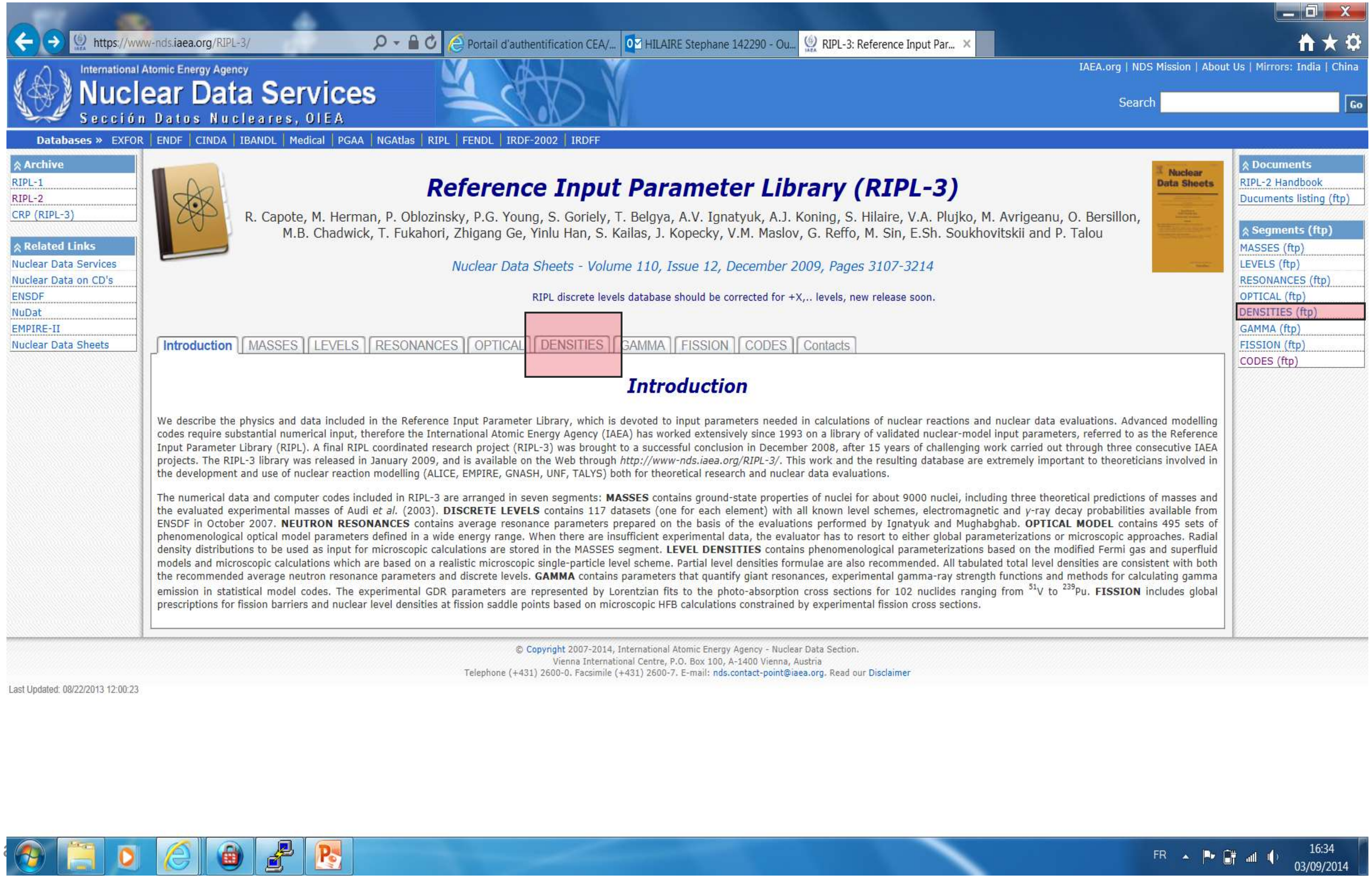
Last Updated: 08/22/2013 12:00:23

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 pre-equilibrium model : RIPL inputs



Content

- Introduction

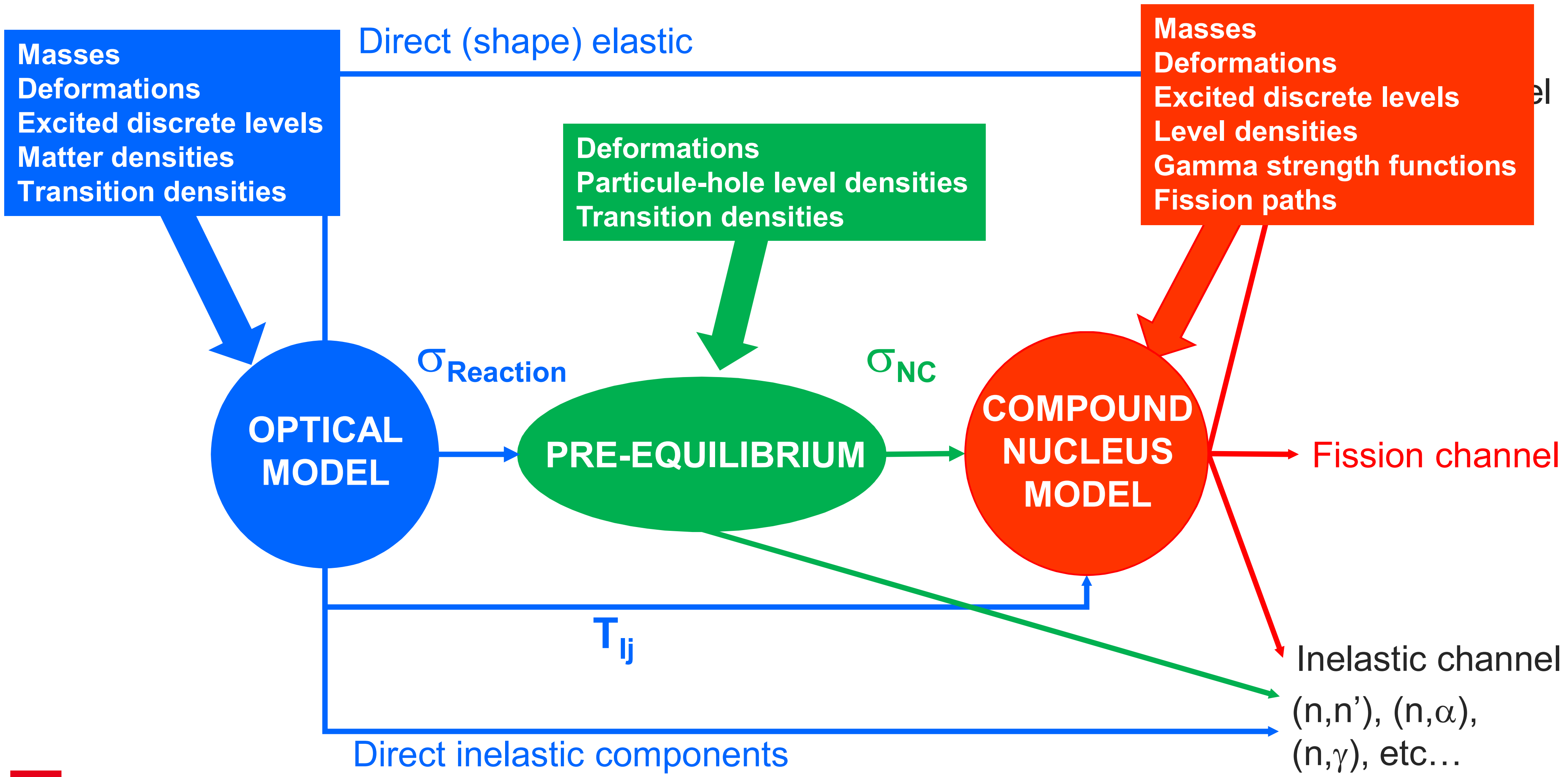
- General features about nuclear reactions

  - 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**

Models sequence and required ingredients



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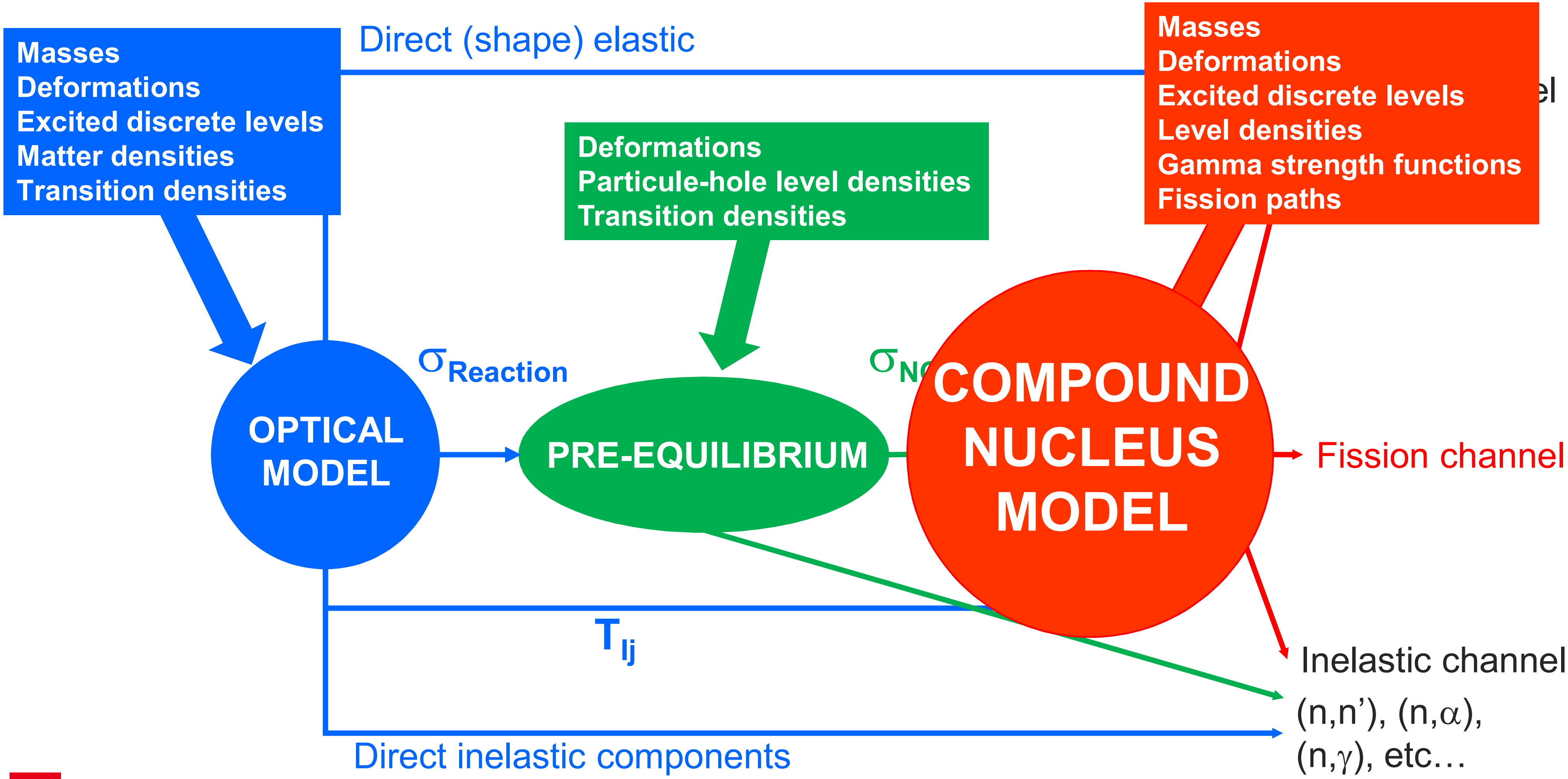
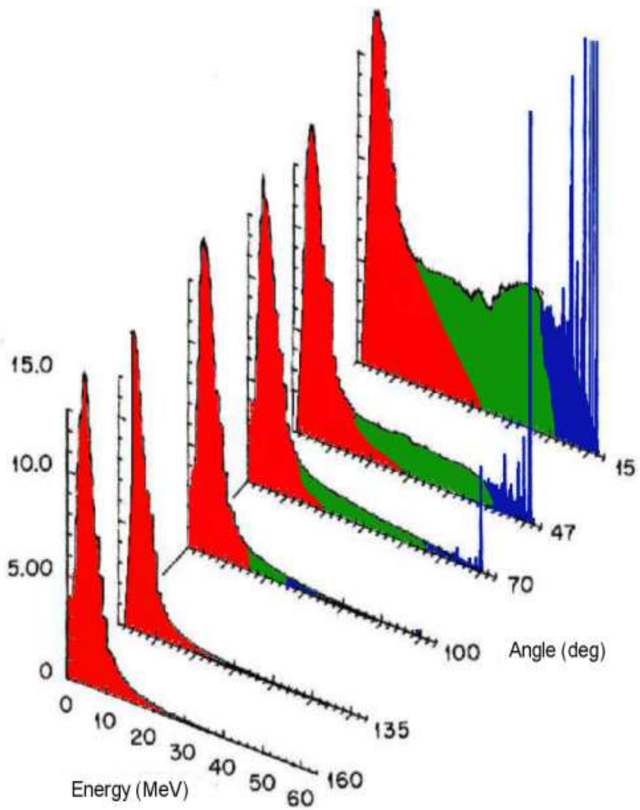


Typical spectrum shape

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



3 regions :

- **Red : « evaporation » peak**
  always present and low outgoing energy

- Green : « flat » intermediate region
  width increases with incident energy

- Blue : « discrete » peaks
  outgoing energy close to incident energy

The compound nucleus model : initial population

After direct and pre-equilibrium emission

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

The compound nucleus model : initial population

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

N_0
Z_0
E^*_0
J_0

The compound nucleus model : initial population

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

N_0	$N_0\text{-}dN_D$
Z_0	$Z_0\text{-}dZ_D$
E^*_0	$E^*_0\text{-}dE^*_D$
J_0	$J_0\text{-}dJ_D$

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N_0	$N_0\text{-}dN_D$	$N_0\text{-}dN_D\text{-}dN_{PE}$	$= N$
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	$J_0\text{-}dJ_D$	$J_0\text{-}dJ_D\text{-}dJ_{PE}$	$= J$

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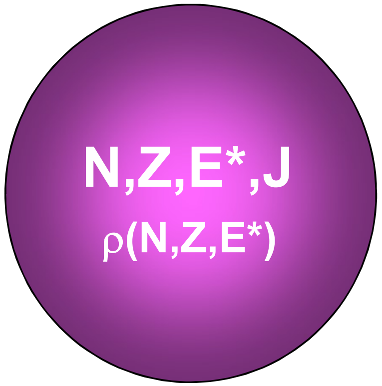

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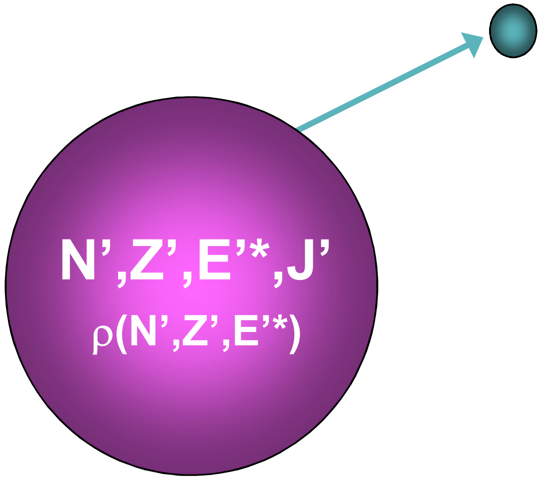
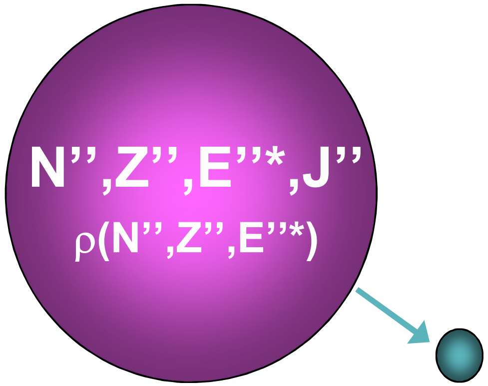


The compound nucleus model : initial population

After direct and pre-equilibrium emission

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

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



After direct and pre-equilibrium emission

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

N_0	$N_0 - dN_D$	$N_0 - dN_D - dN_{PE} = N$
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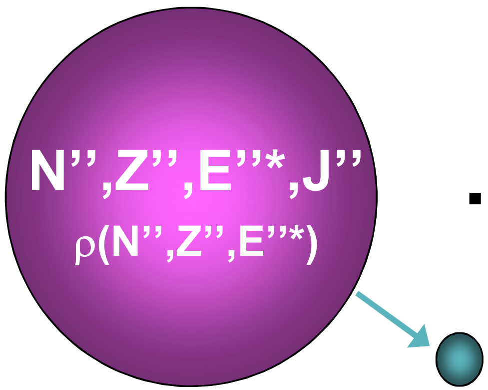

…

The compound nucleus model : basic formalism

Compound nucleus hypothesys

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

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

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

Compound nucleus hypothesys

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

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

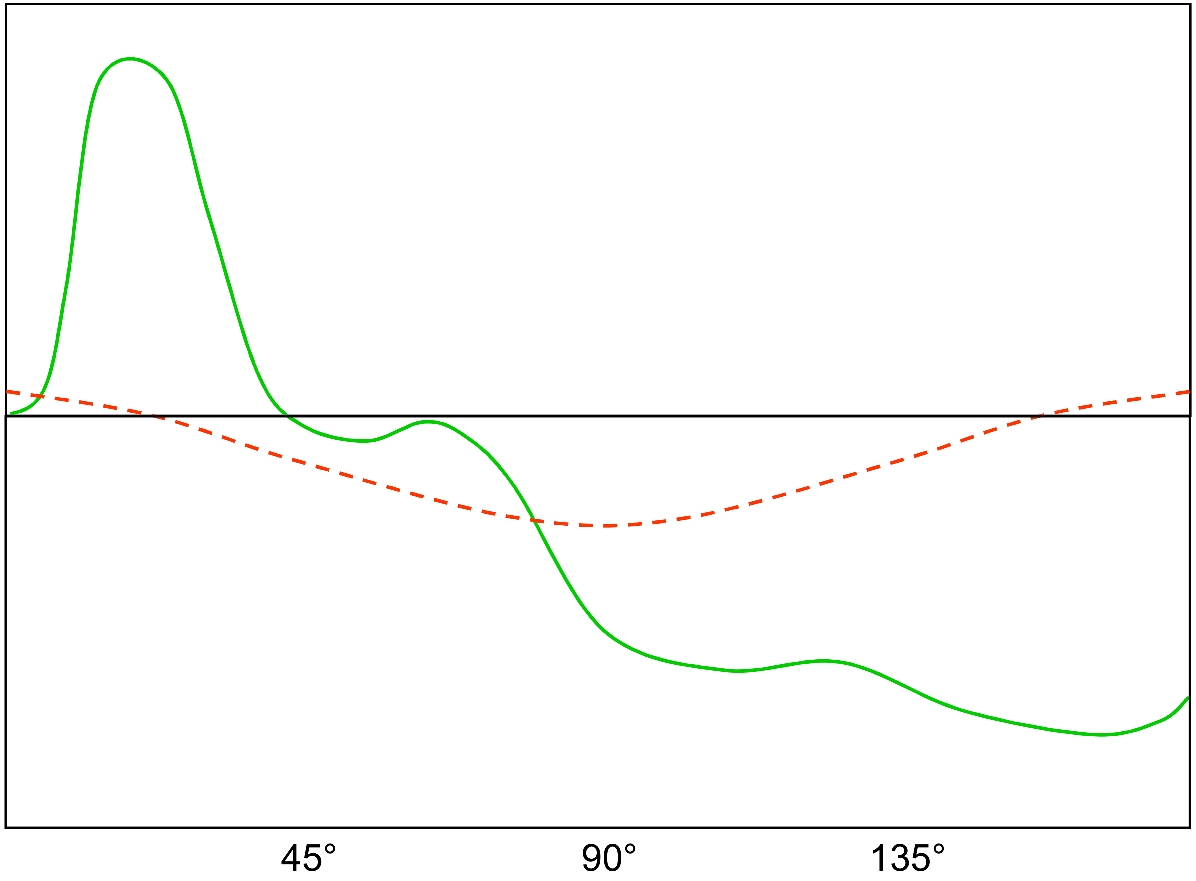
$$\sigma_a^{(CN)} = \frac{\pi}{k_a^2} T_a \qquad\qquad P_b = \frac{T_b}{\sum_c T_c}$$

$\Rightarrow$ **Hauser- Feshbach formula**

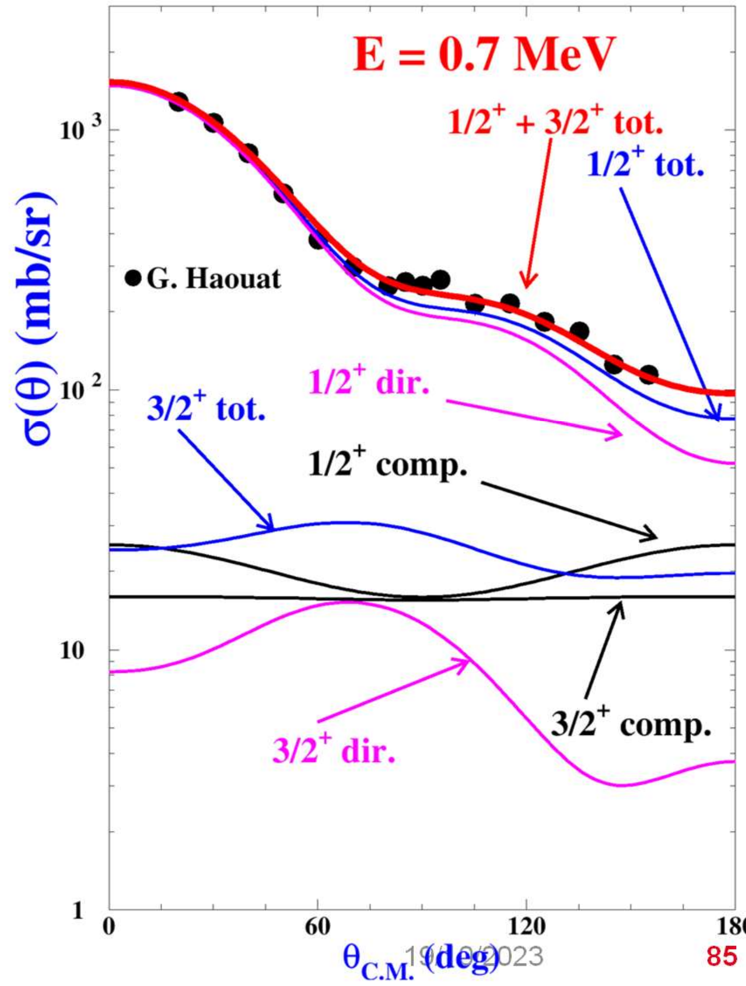
$$\sigma_{ab} = \frac{\pi}{k_a^2} \frac{T_a T_b}{\sum_c T_c}$$

The compound nucleus model : qualitative feature

Compound angular distribution & **direct** angular distributions



^{239}Pu(n,n')



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 : basic formalism

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

$$\sigma_{ab} =$$

The compound nucleus model : basic formalism

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

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

The compound nucleus model : basic formalism

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Given by OMP

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

The compound nucleus model : basic formalism

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

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

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

$$\sigma_{ab} = \frac{\pi}{k_a^2} \sum_{J=|I_A - s_a|}^{I_A + s_a + l_a^{max}} \sum_{\pi=\pm} \frac{(2J+1)}{(2I_A+1)(2s_a+1)} \sum_{j_a=|J-I_A|}^{J+I_A} \sum_{l_a=|j_a-s_a|}^{j_a+s_a} \sum_{j_b=|J-I_B|}^{J+I_B} \sum_{l_b=|j_b-s_b|}^{j_b+s_b} \delta_\pi(a)\,\delta_\pi(b) \frac{T^{J\pi}_{a,l_a,j_a}\, T^{J\pi}_{b,l_b,j_b}}{\sum_c T^{J\pi}_{c,l_c,j_c}}$$

Parity selection rules (→ $\delta_\pi(a)\,\delta_\pi(b)$)

The compound nucleus model : basic formalism

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

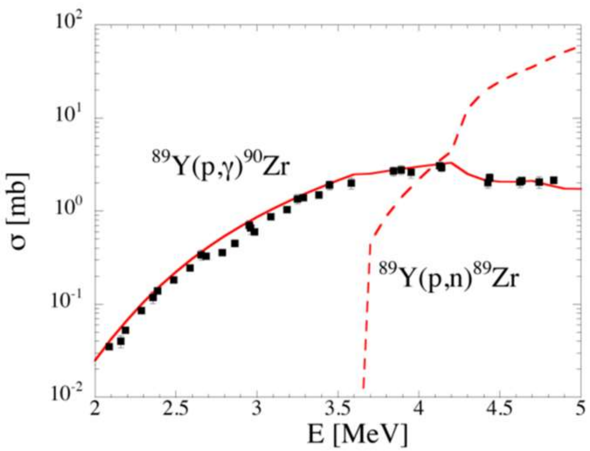
$$\sigma_{ab} = \frac{\pi}{k_a^2} \sum_{J=|I_A - s_a|}^{I_A + s_a + l_a^{max}} \sum_{\pi=\pm} \frac{(2J+1)}{(2I_A+1)(2s_a+1)}$$

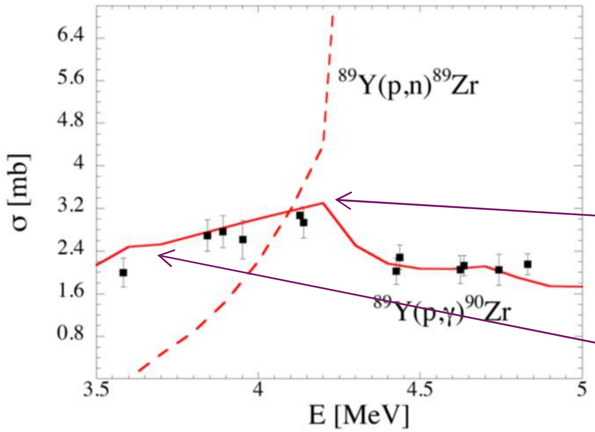
$$\sum_{j_a=|J-I_A|} \quad \sum_{l_a=|j_a - s_a|} \quad \ldots \quad \sum_{l_b=|j_b - s_b|}$$

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

Width fluctuation correction factor to account for deviations from independance hypothesis

The compound nucleus model : quantum numbers rule





^{89}Y Ground state : $1/2^+$

^{89}Y (p,n) ^{89}Zr threshold = 3,65 MeV

$$\vec{I}_{CN} = \vec{I}_{target} + \vec{\ell} + \vec{½} \Rightarrow$$

Transmission coefficients incident proton at 4.5 MeV :

60 % ℓ=0 ⇒ CN spin 0^+, 1^+

35 % ℓ=1 ⇒ CN spin 0^-, 1^-, 2^-

$$\vec{I}_{CN} = \vec{I}_{residual} + \vec{\ell} + \vec{½} \Rightarrow$$

Transmission coefficients outgoing neutron at 1.0 MeV :

70 % ℓ=1 ⇒ residual spin $1/2^-$, $3/2^-$, $5/2^-$, $1/2^+$, $3/2^+$, $5/2^+$, $7/2^+$

25 % ℓ=0 ⇒ residual spin $1/2^-$, $3/2^-$, $5/2^-$, $1/2^+$, $3/2^+$

^{89}Zr Level scheme

$3/2^-$	1.094 MeV
$1/2^-$	0.587 MeV
$9/2^+$	0.0 MeV

⇒ (p,γ) decreases when (p,n) decay to the $1/2^-$ level opens because the (p,n) decay to $9/2^+$ is too weak for low energies du to too low transmission coefficients

The compound nucleus model : width fluctuation

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

The compound nucleus model : width fluctuation

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

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

The compound nucleus model : width fluctuation

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

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

The compound nucleus model : main methods for WFCF

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- Tepel method

  Simplified iterative method

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Elastic enhancement with respect to the other channels

The compound nucleus model : main methods for WFCF

- Tepel method

  Simplified iterative method

- Moldauer method

  Simple integral

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  « exact » result

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

The compound nucleus model : GOE triple integral

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

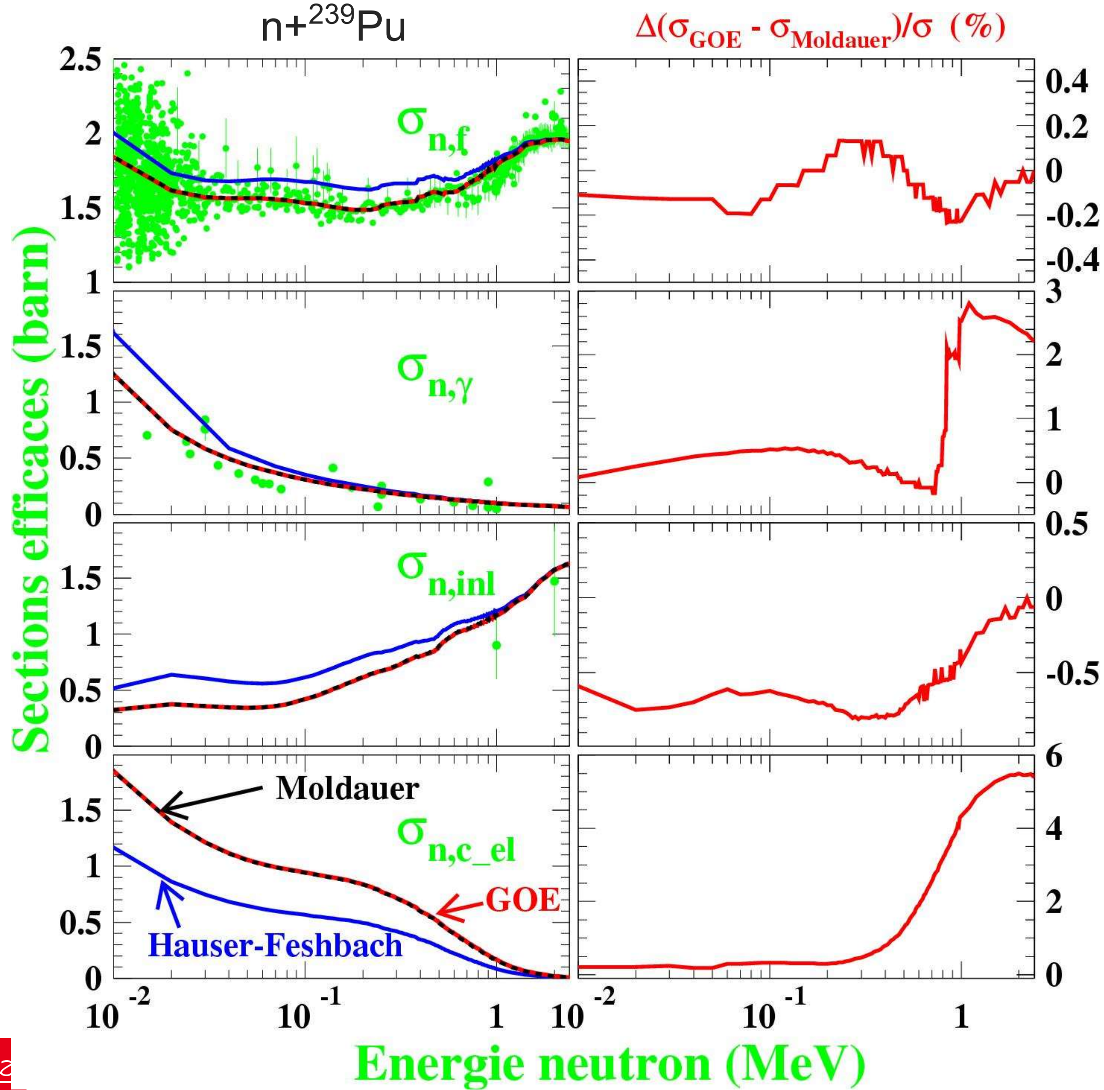
$$\prod_c \frac{(1-\lambda T^J_{c,l_c,j_c})}{\sqrt{(1+\lambda_1 T^J_{c,l_c,j_c})(1+\lambda_2 T^J_{c,l_c,j_c})}} \quad \Bigg\{ \delta_{ab}(1 - T^J_{a,l_a,j_a})$$

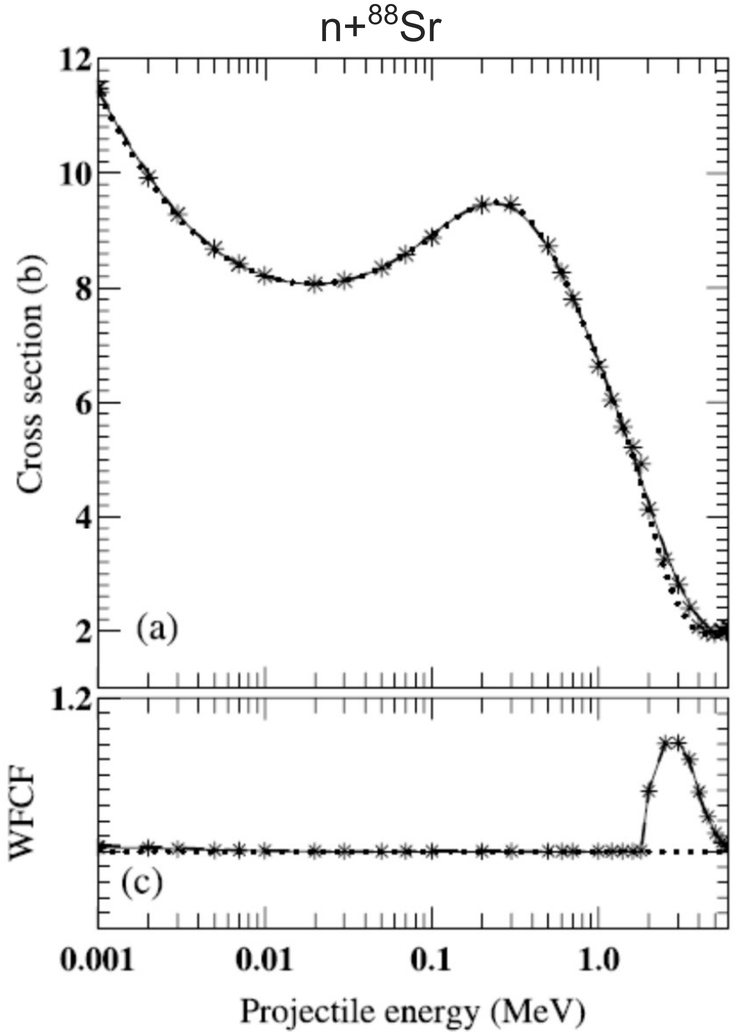
$$\left[\frac{\lambda_1}{1+\lambda_1 T^J_{a,l_a,j_a}} + \frac{\lambda_2}{1+\lambda_2 T^J_{a,l_a,j_a}} + \frac{2\lambda}{1-\lambda T^J_{a,l_a,j_a}}\right]^2 + (1+\delta_{ab})$$

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

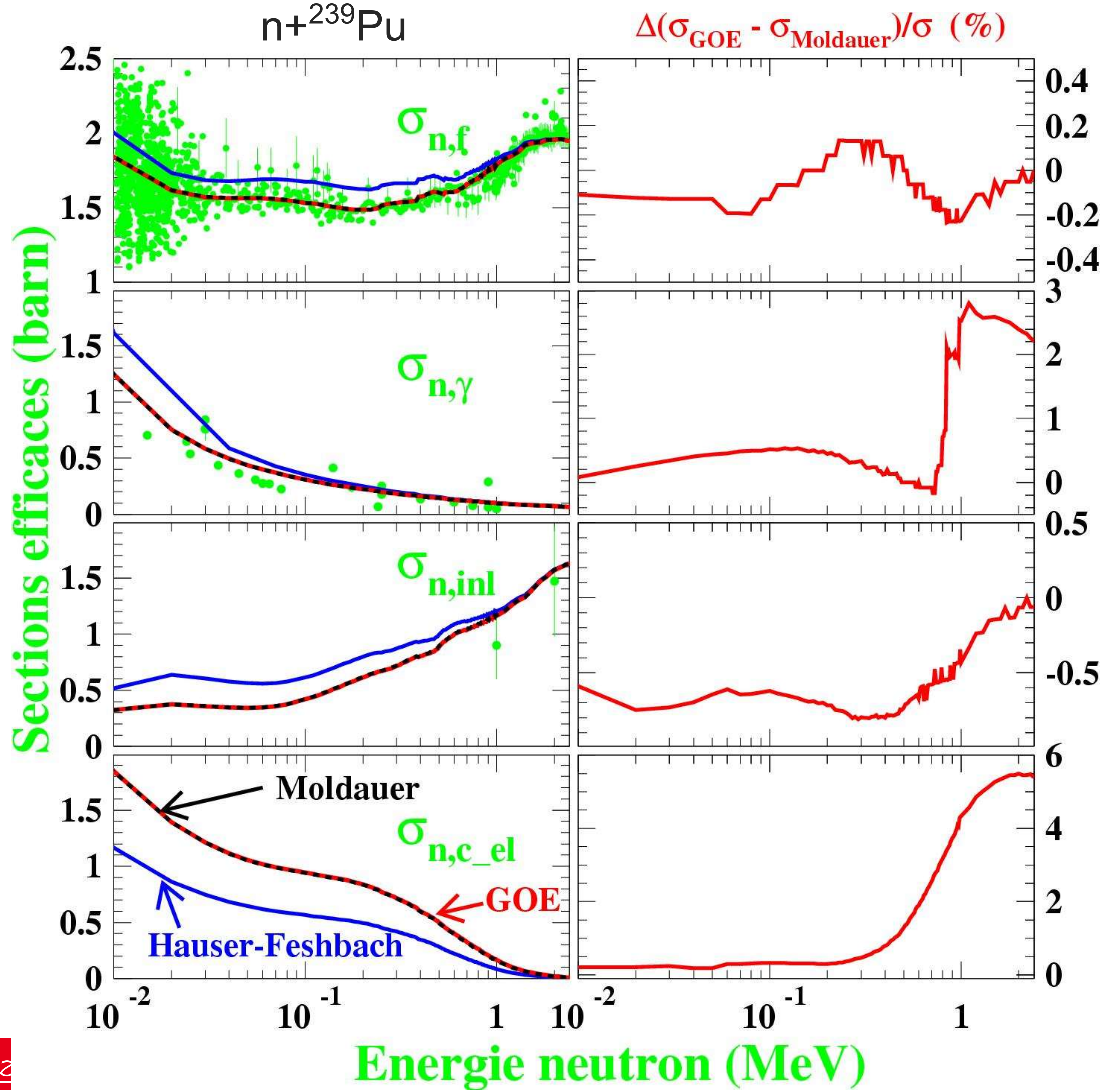
$$\left. + \frac{2\lambda(1-\lambda)}{(1-\lambda T^J_{a,l_a,j_a})(1-\lambda T_{b,l_b,j_b})}\right]\Bigg\}$$

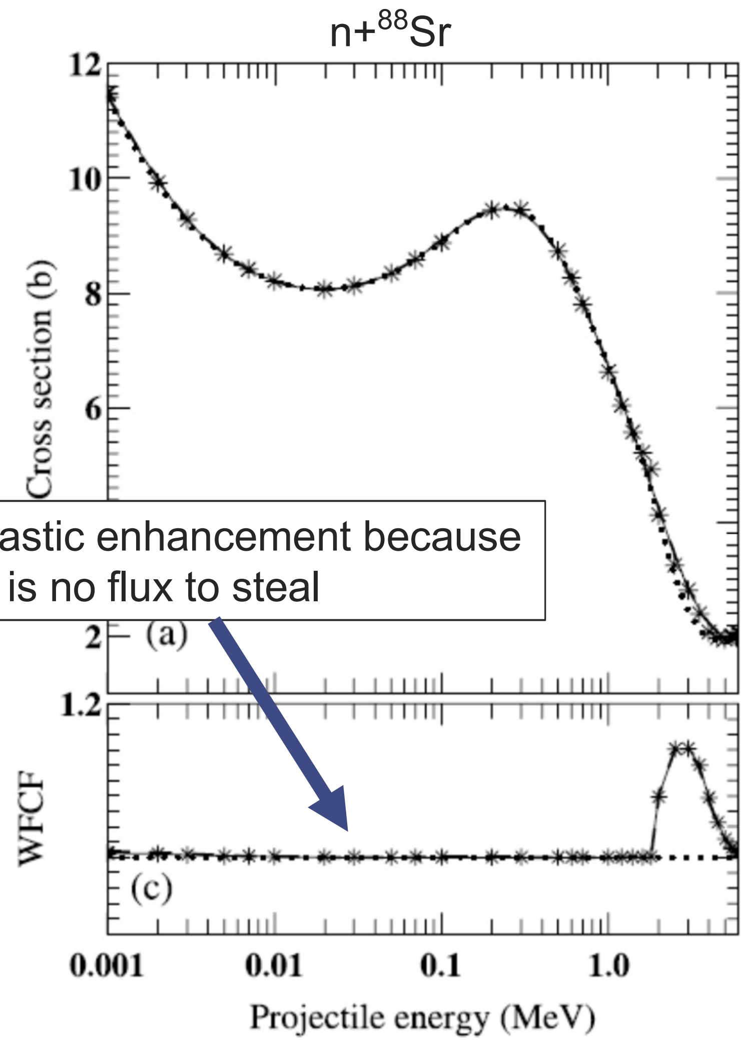
The compound nucleus model : WFCF flux redistribution





The compound nucleus model : WFCF flux redistribution





No elastic enhancement because there is no flux to steal

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

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

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

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

$$\prod_c \frac{(1-\lambda T^J_{c,l_c,j_c})}{\sqrt{(1+\lambda_1 T^J_{c,l_c,j_c})(1+\lambda_2 T^J_{c,l_c,j_c})}} \qquad \left\{ \delta_{ab}(1 - T^J_{a,l_a,j_a}) \right.$$

Using OMP transmission coefficients is OK for a diagonal S matrix (no coupled channels) but not correct if off-diagonal S matrix elements are significant

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

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

The compound nucleus model : Engelbrecht-Weidenmuller transformation

More details in Kawano T., Phys. Rev. C 94, 014612 (2016)

1. One defines $P \equiv \mathbb{I} - SS^\dagger$
2. One diagonalize P and computes the U matrix such that $UPU^\dagger = D_p$
3. Then $A = USU^T$ is diagonal
4. Using $\tilde{T}_\alpha \equiv 1 - |A_{\alpha\alpha}|^2$ one gets the analogous of the usual $T_\alpha \equiv 1 - |S_{\alpha\alpha}|^2$
5. Finally

$$\begin{aligned}\sigma_{ab} &= \sum_\alpha |U_{\alpha a}|^2 |U_{\alpha b}|^2 \tilde{\sigma}_{\alpha\alpha} + \sum_{\alpha\neq\beta} U^*_{\alpha a} U^*_{\beta b} (U_{\alpha a} U_{\beta b} + U_{\beta a} U_{\alpha b}) \tilde{\sigma}_{\alpha\beta} \\ &+ \sum_{\alpha\neq\beta} U^*_{\alpha a} U^*_{\alpha b} U_{\beta a} U_{\beta b} \langle A_{\alpha\alpha} A_{\beta\beta} \rangle\end{aligned}$$

where $\tilde{\sigma}_{\alpha\beta} = \frac{\tilde{T}_\alpha \tilde{T}_\beta}{\sum_\gamma \tilde{T}_\gamma} \tilde{W}_{\alpha\beta}$ and $\tilde{W}_{\alpha\beta}$ are calculed with ……

The compound nucleus model : GOE triple integral

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

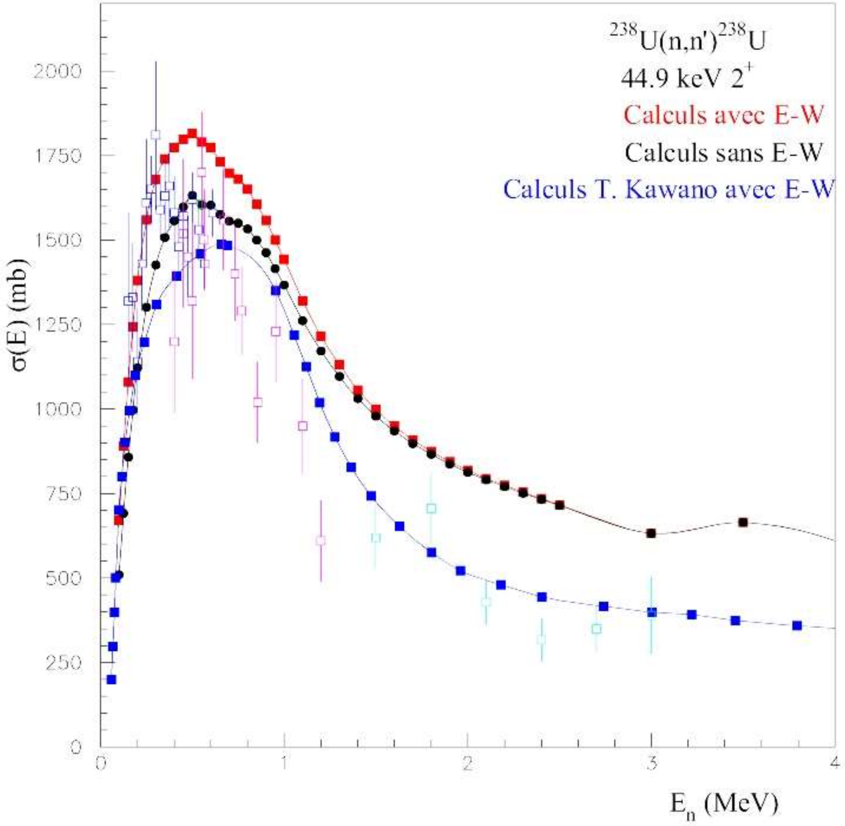
$$\prod_c \frac{(1-\lambda T^J_{c,l_c,j_c})}{\sqrt{(1+\lambda_1 T^J_{c,l_c,j_c})(1+\lambda_2 T^J_{c,l_c,j_c})}} \quad \Bigg\{ \delta_{ab}(1 - T^J_{a,l_a,j_a})$$

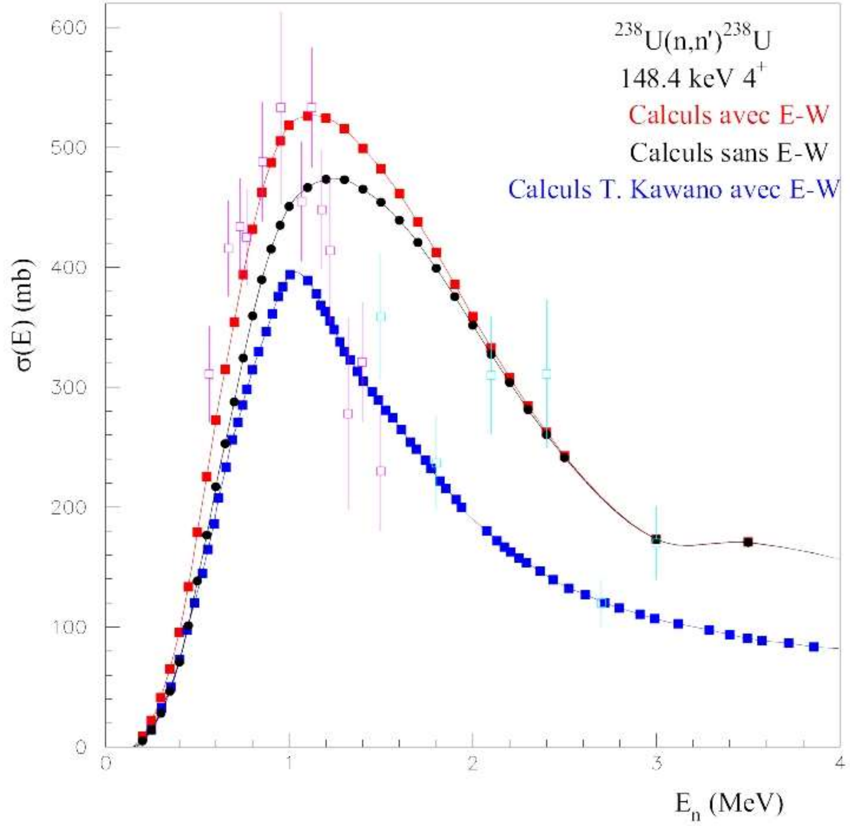
$$\left[\frac{\lambda_1}{1+\lambda_1 T^J_{a,l_a,j_a}} + \frac{\lambda_2}{1+\lambda_2 T^J_{a,l_a,j_a}} + \frac{2\lambda}{1-\lambda T^J_{a,l_a,j_a}} \right]^2 + (1+\delta_{ab})$$

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

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

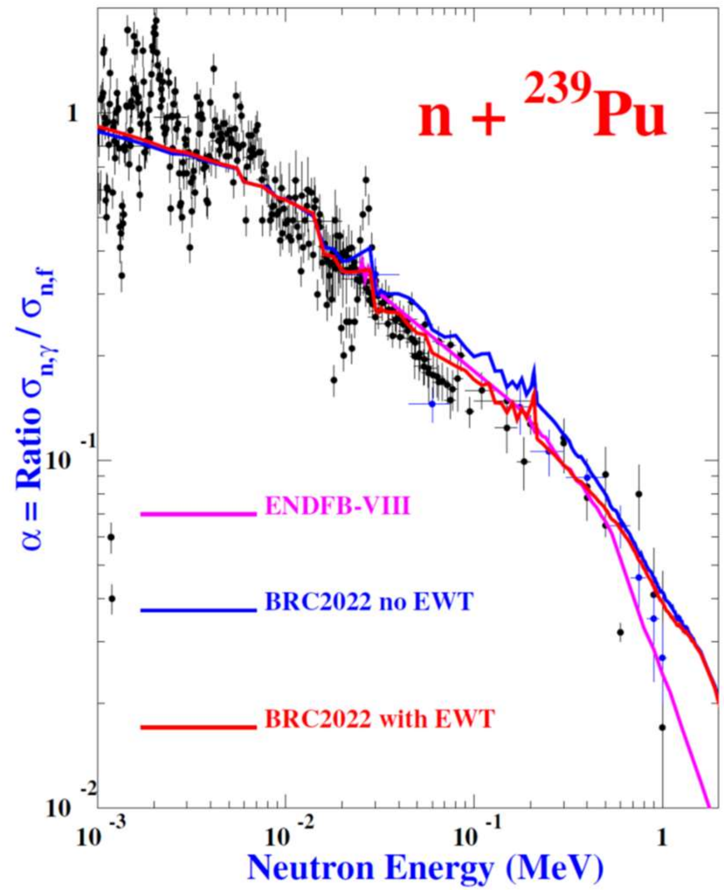
The compound nucleus model : Engelbrecht-Weidenmuller transformation





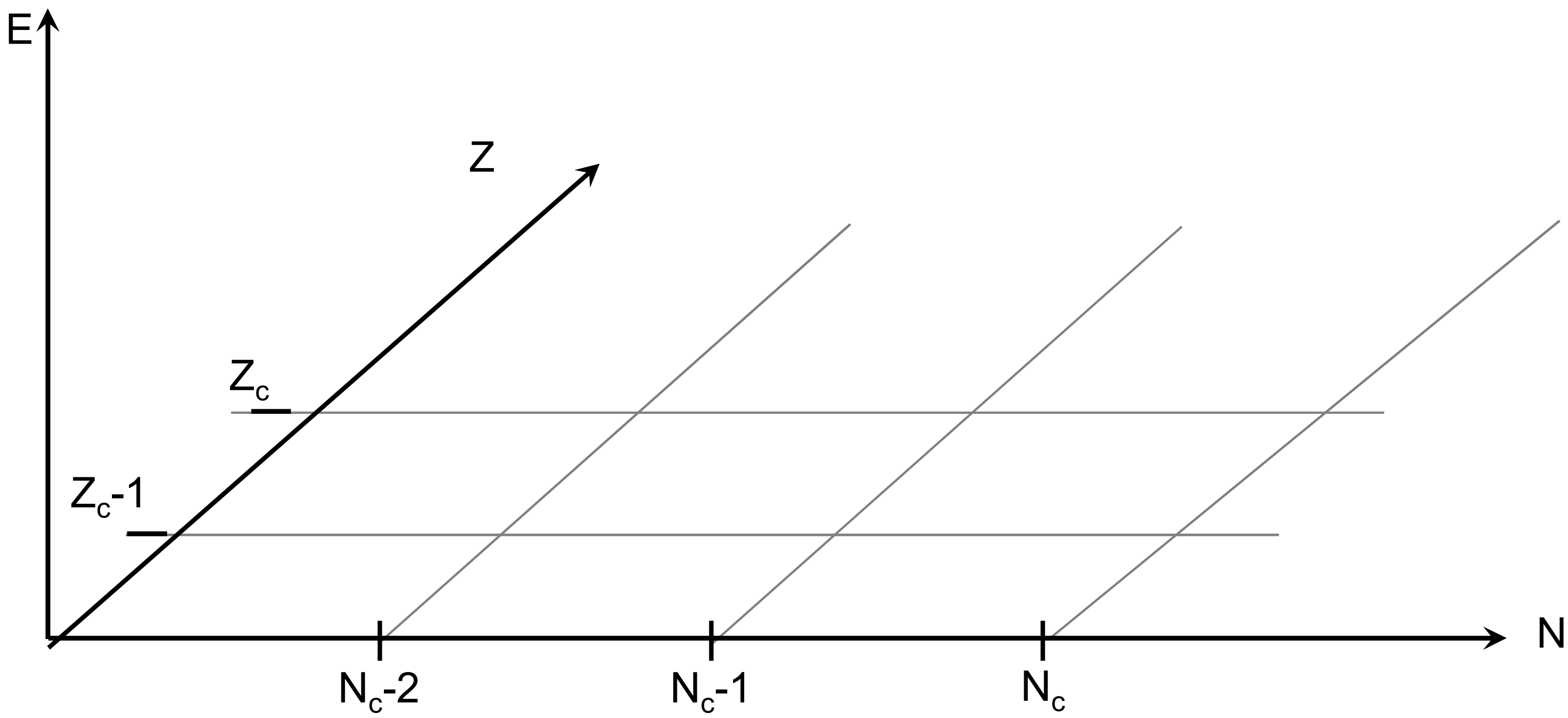
$\Rightarrow$ Optical model re-optimisation required !

The compound nucleus model : Engelbrecht-Weidenmuller transformation

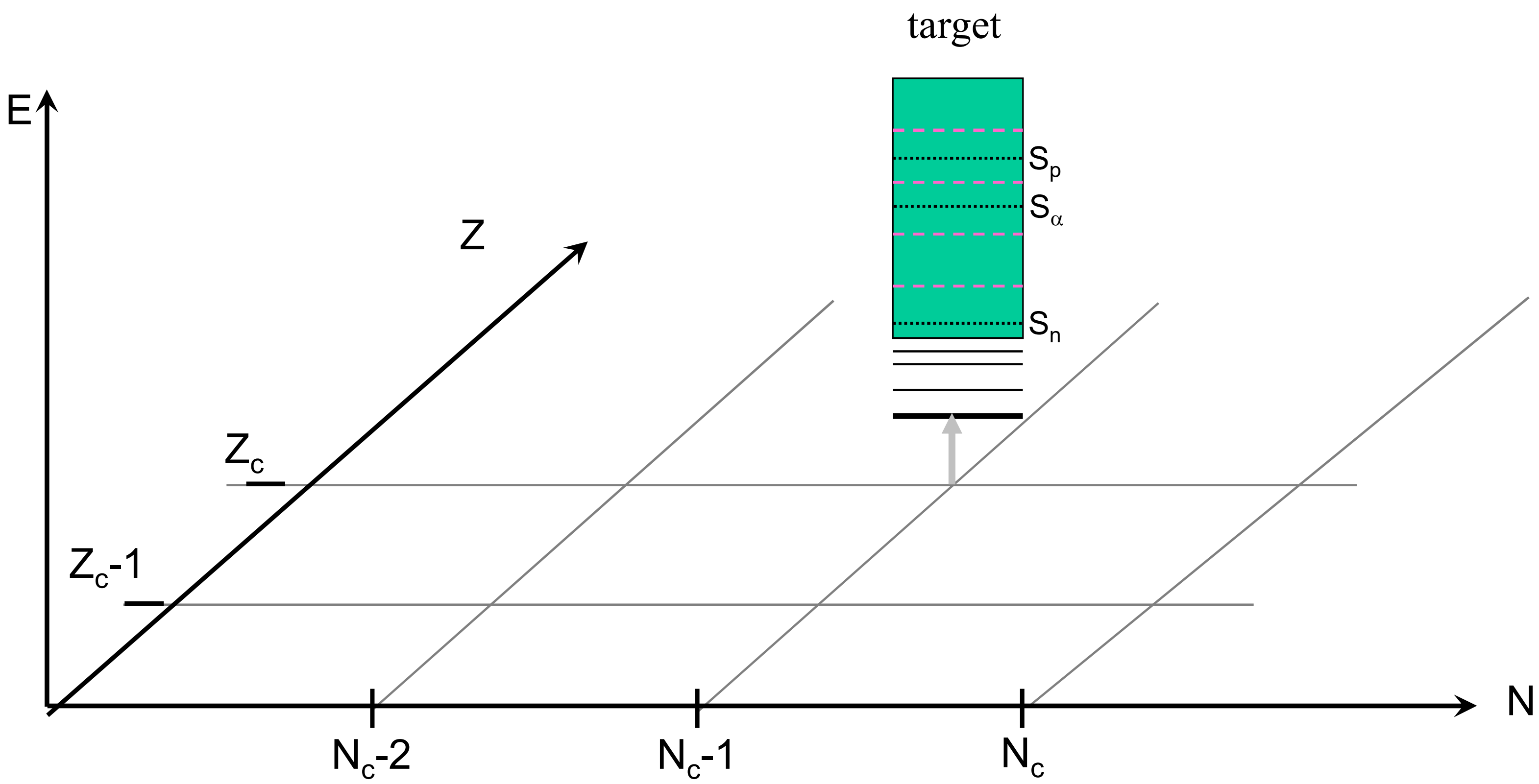


Capture cross section shape modified

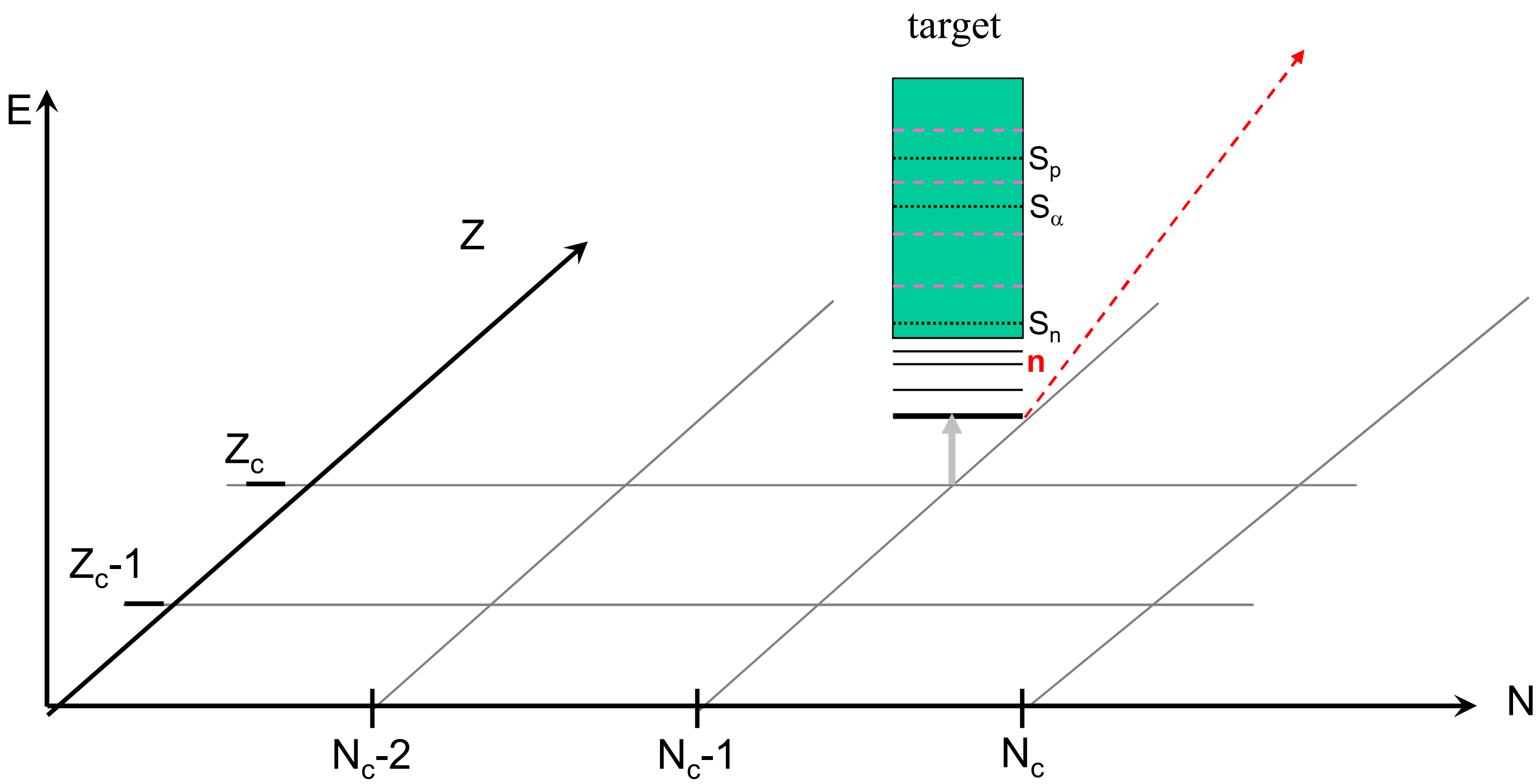
The compound nucleus model : multiple emission



The compound nucleus model : multiple emission



The compound nucleus model : multiple emission



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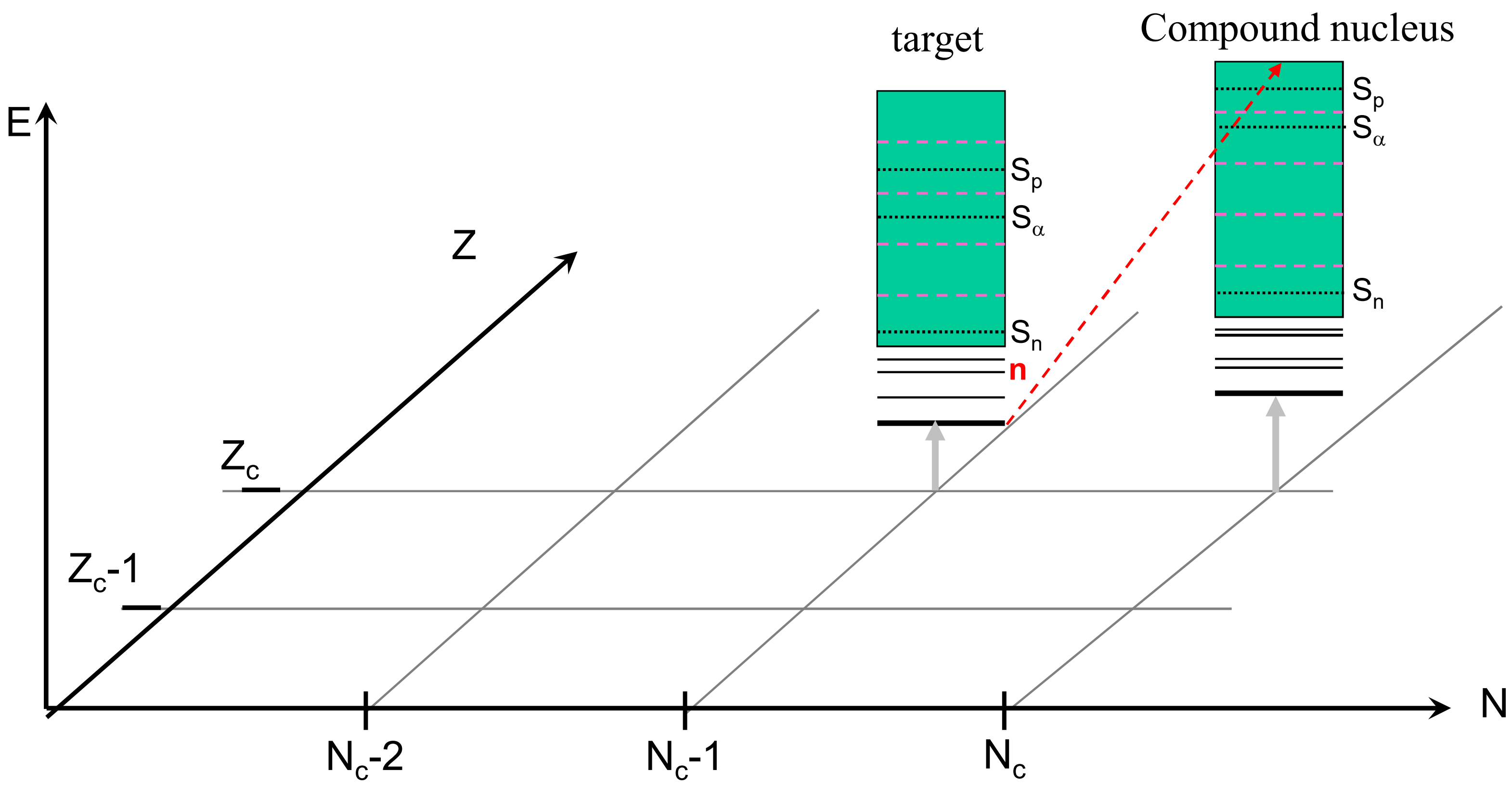

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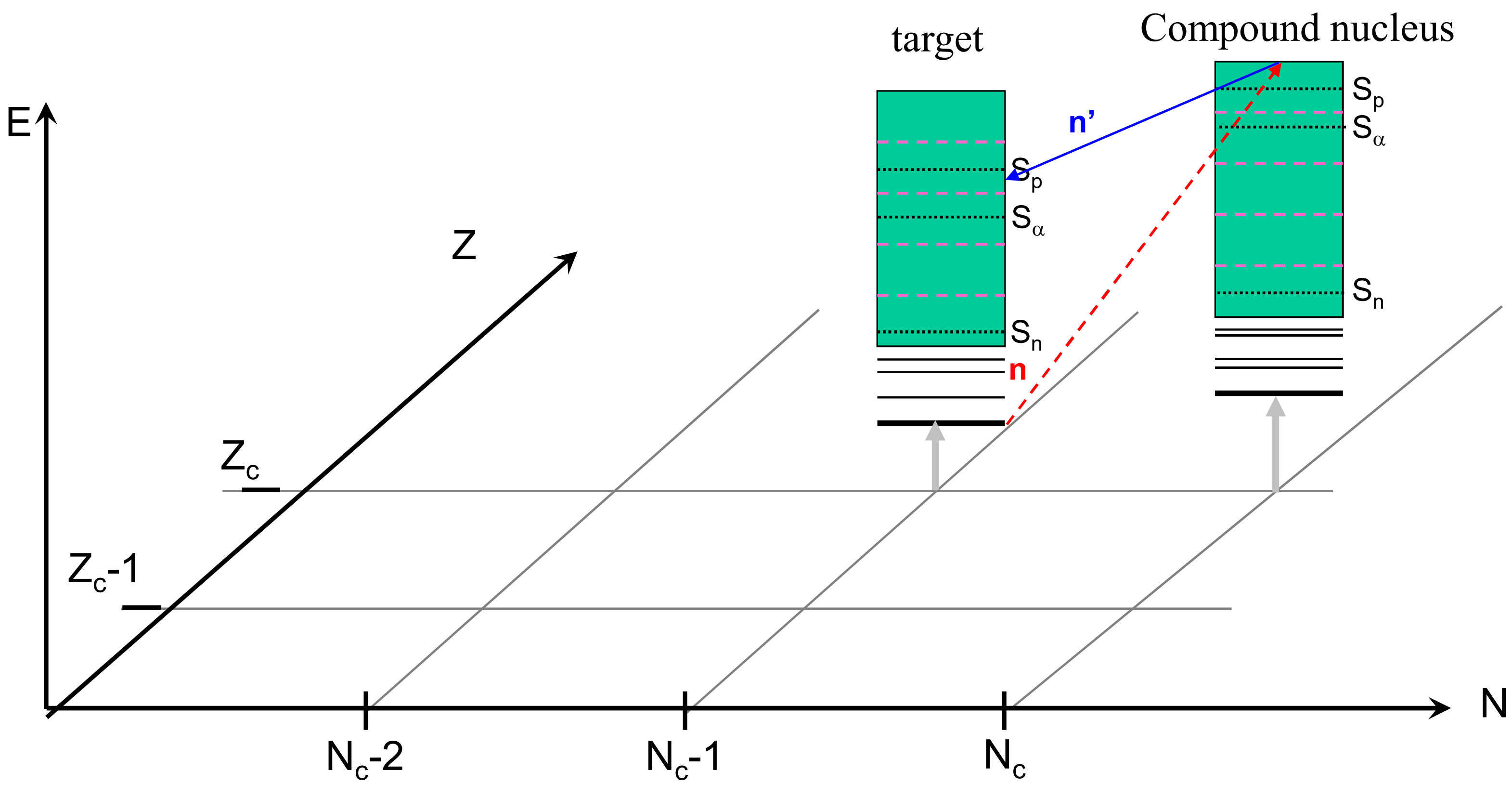

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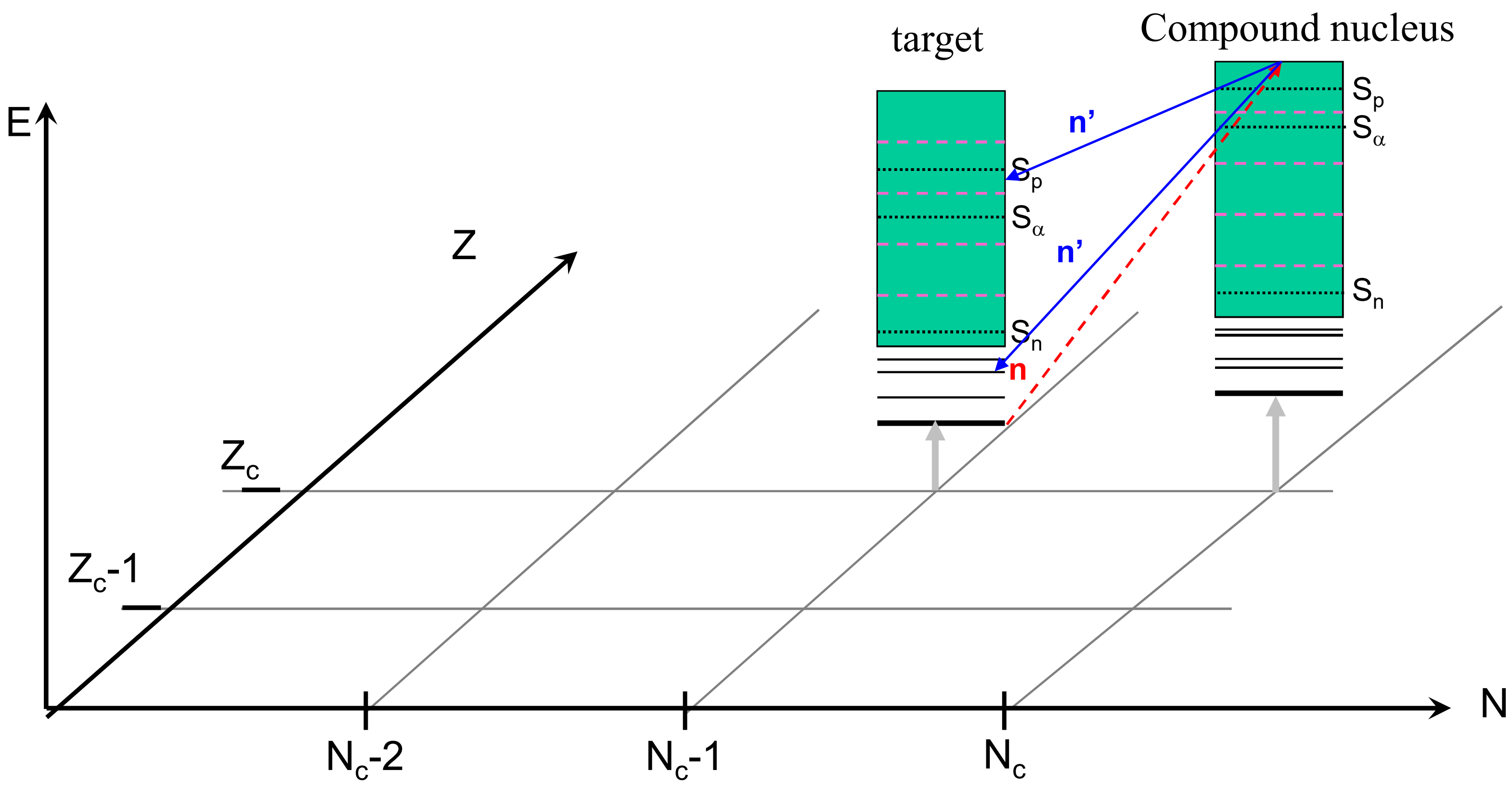

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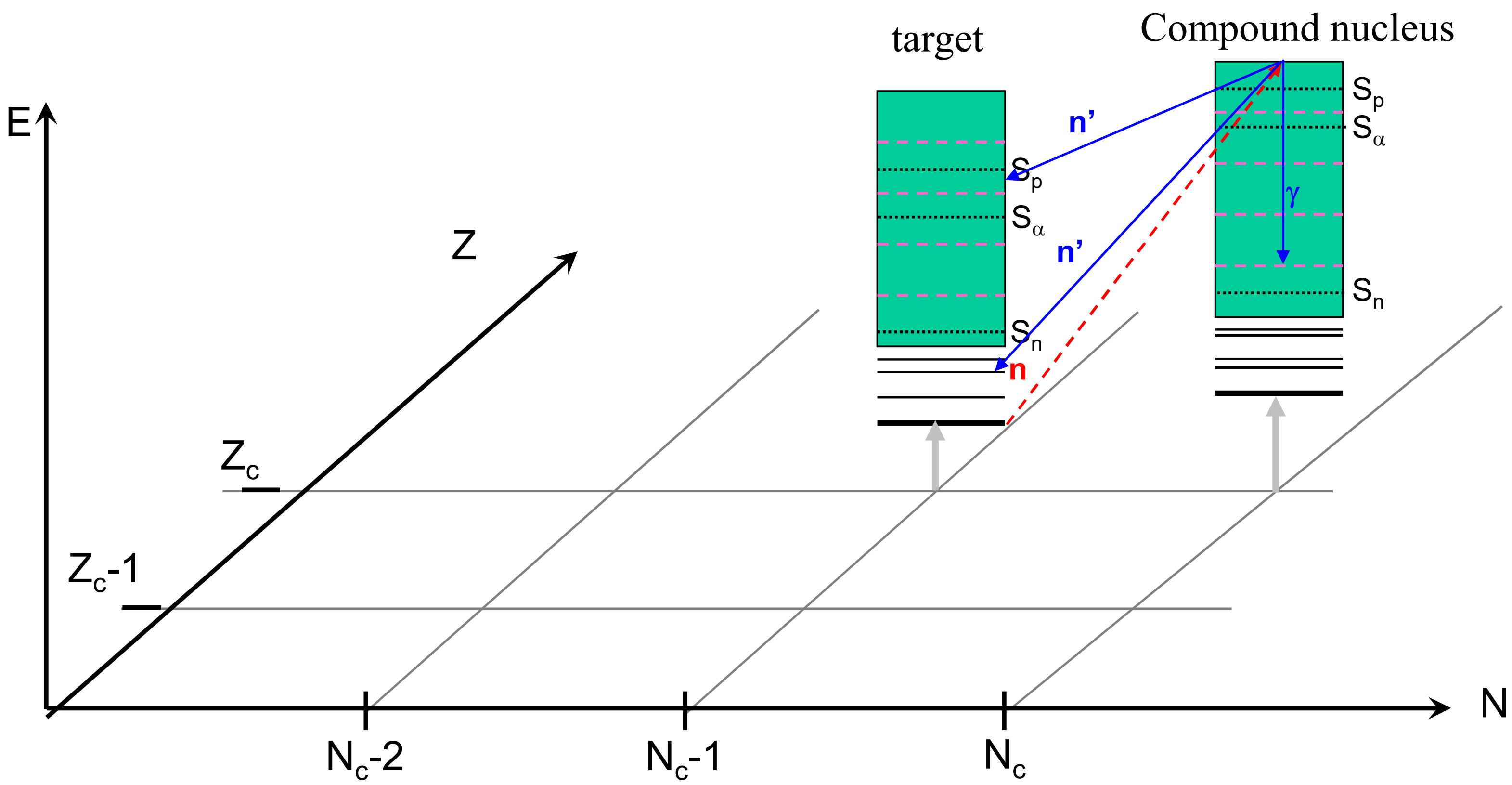

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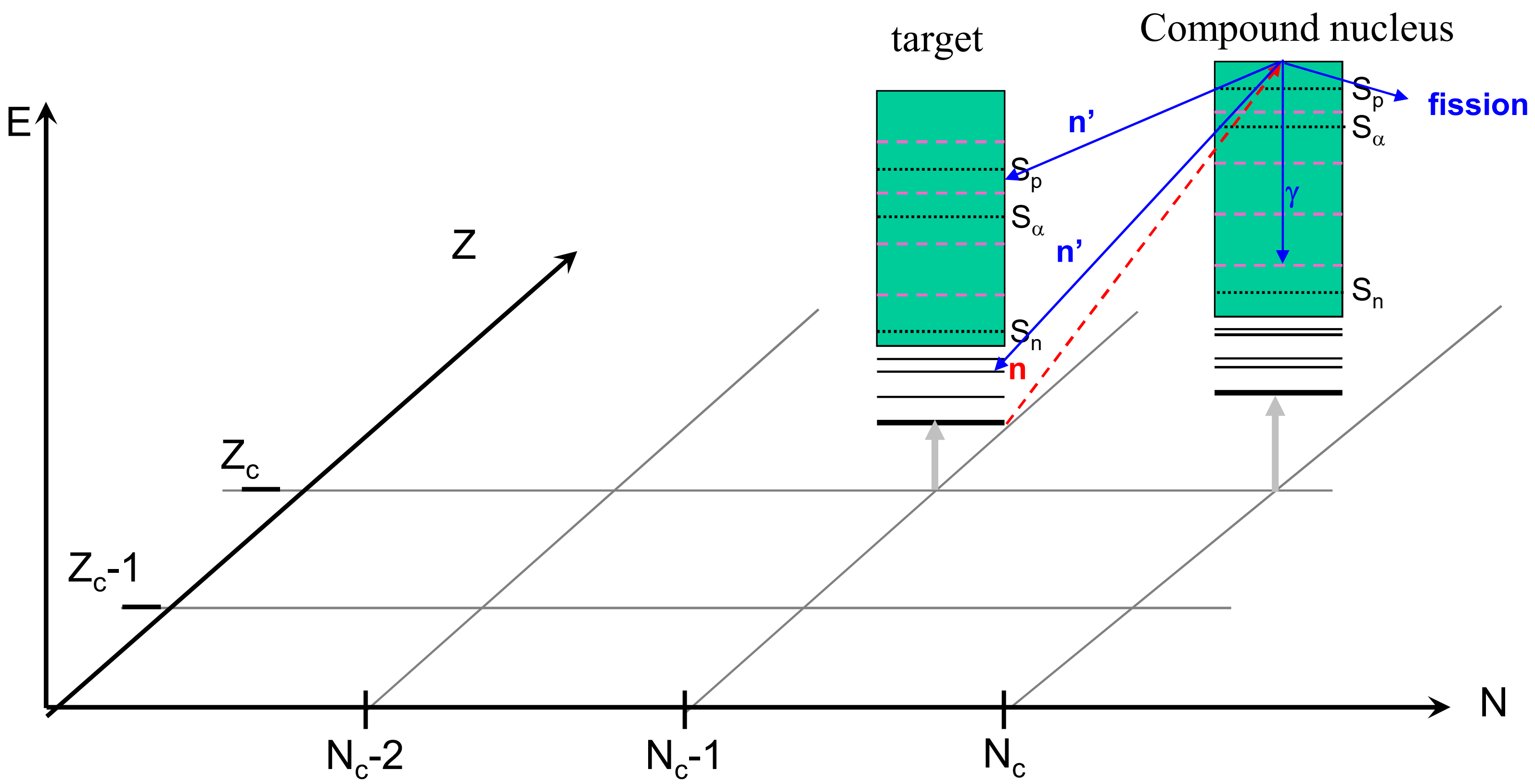

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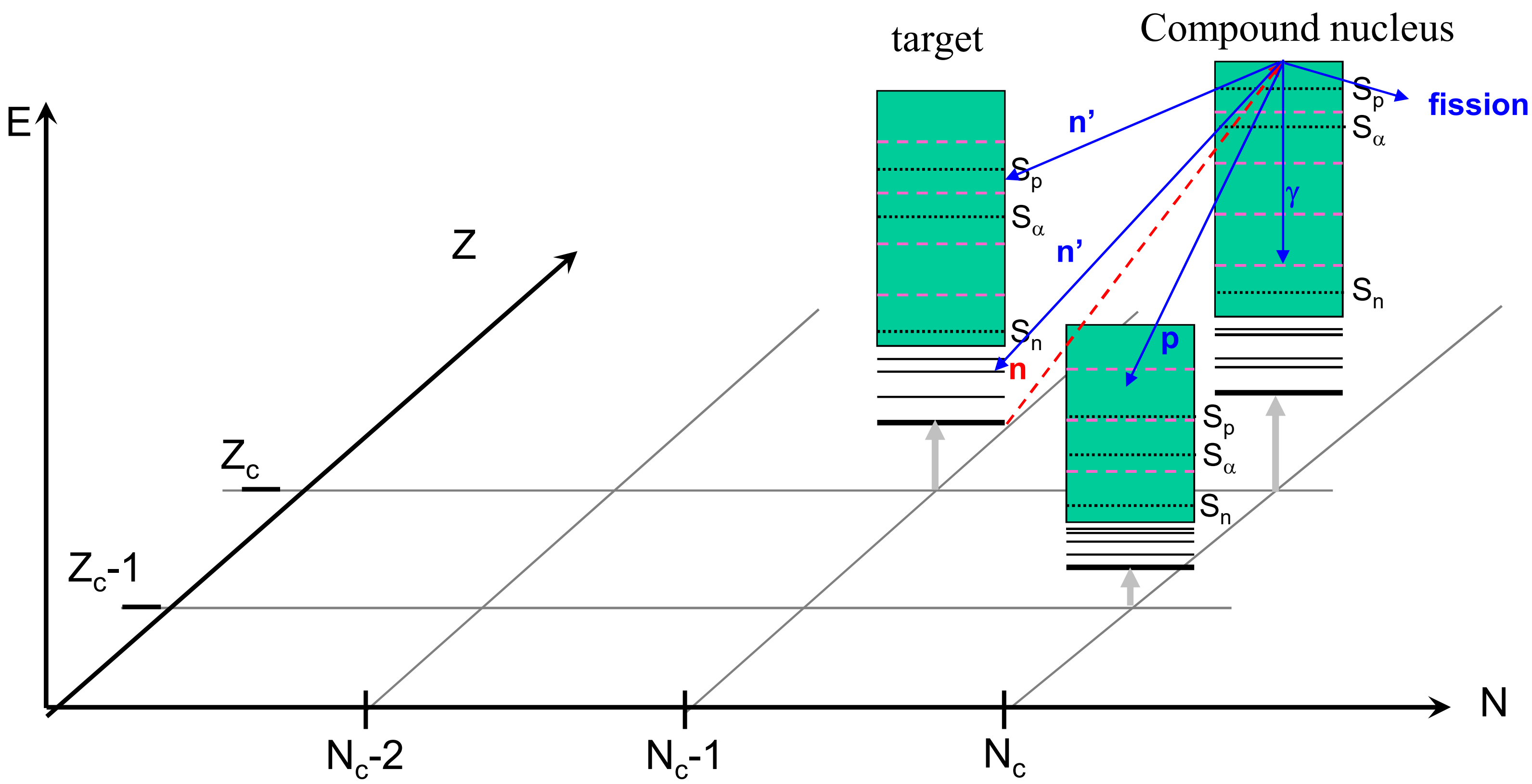

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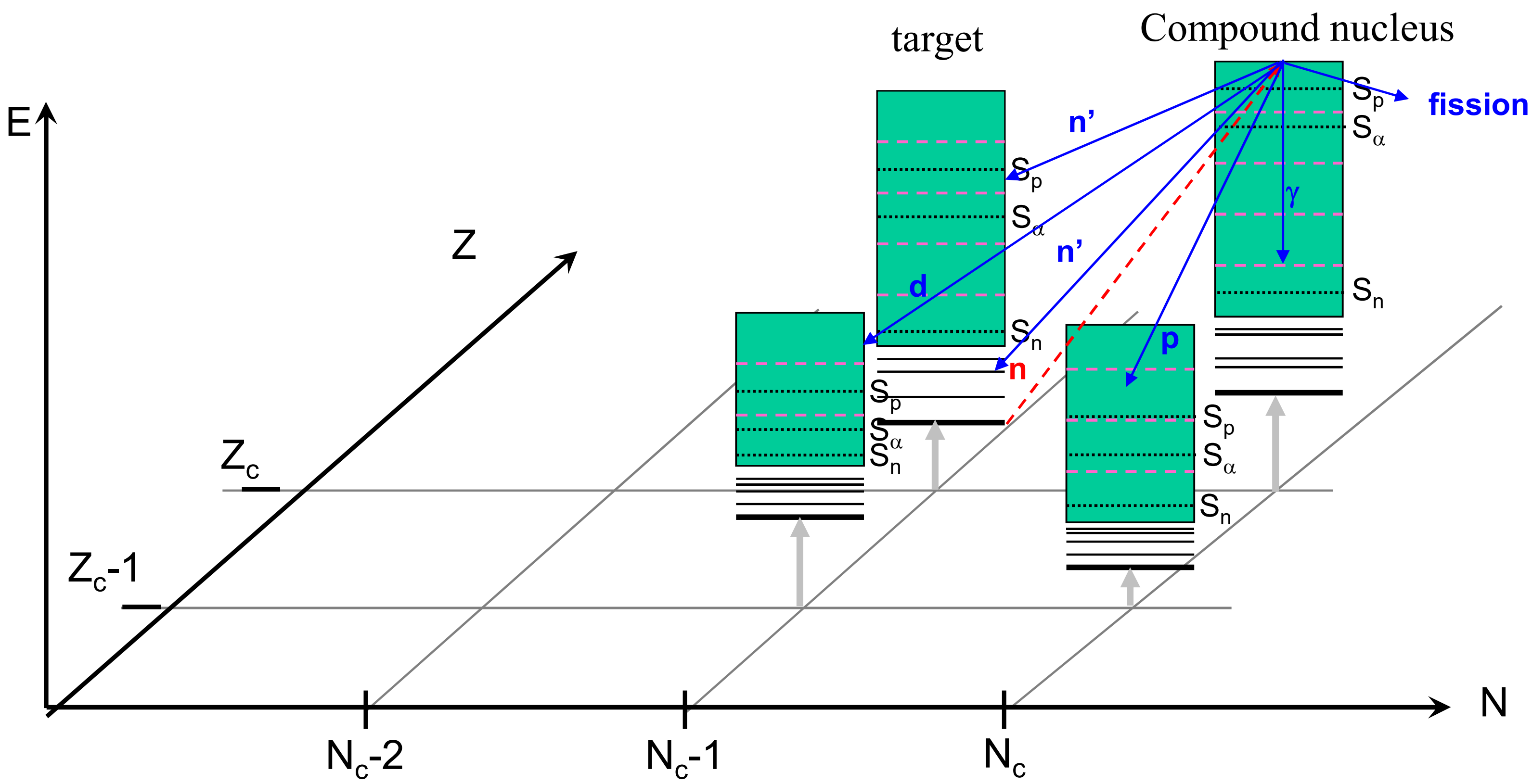

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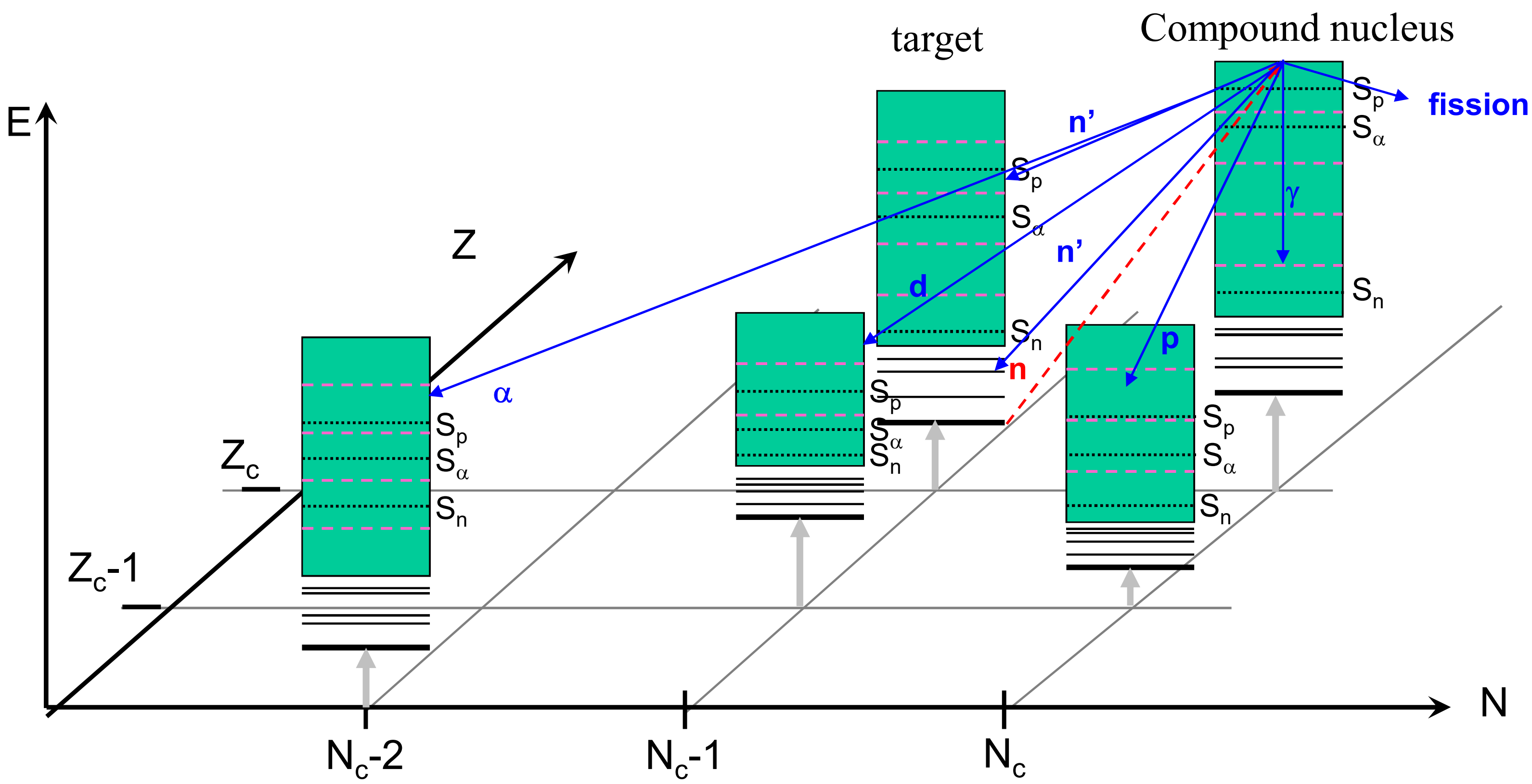

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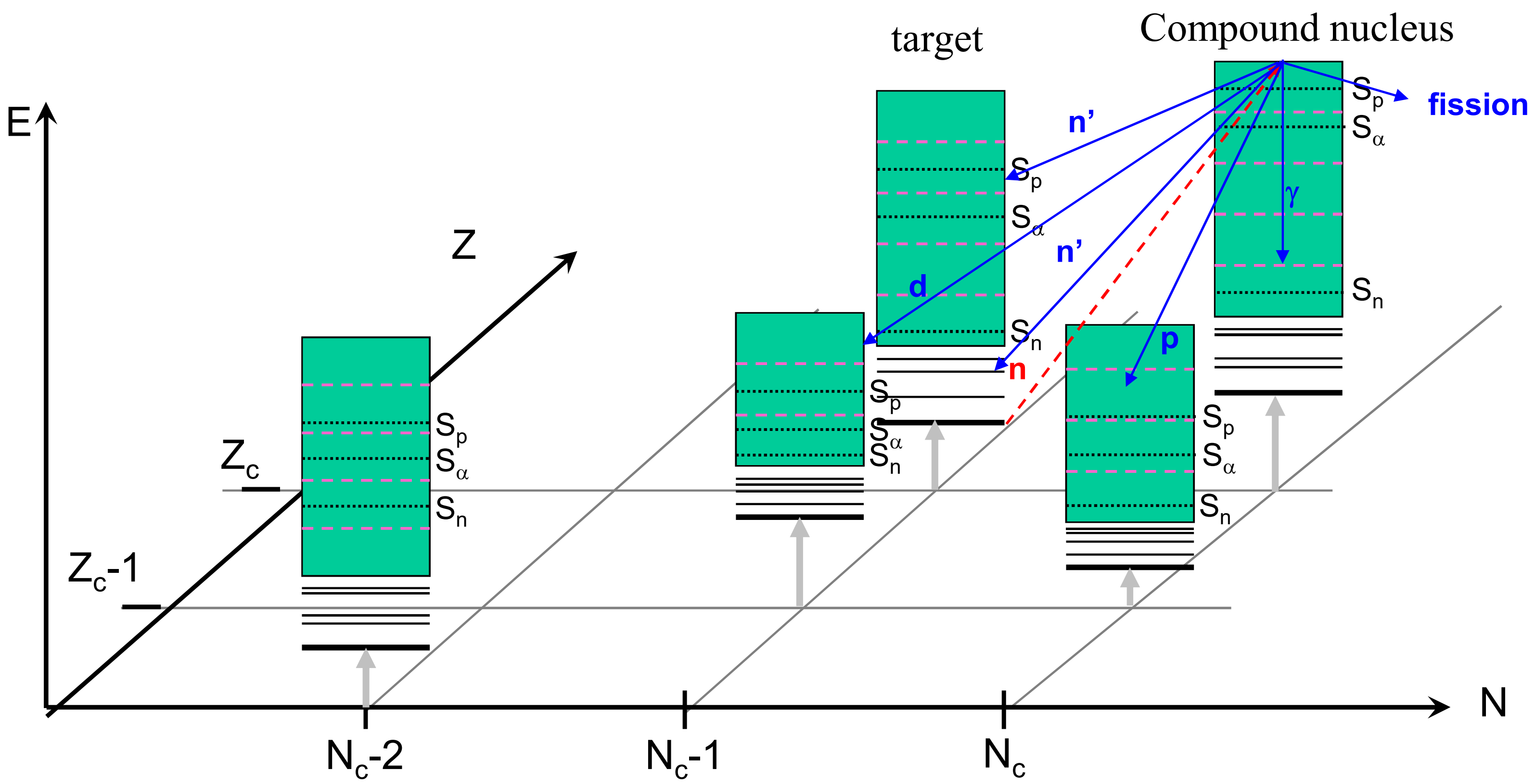

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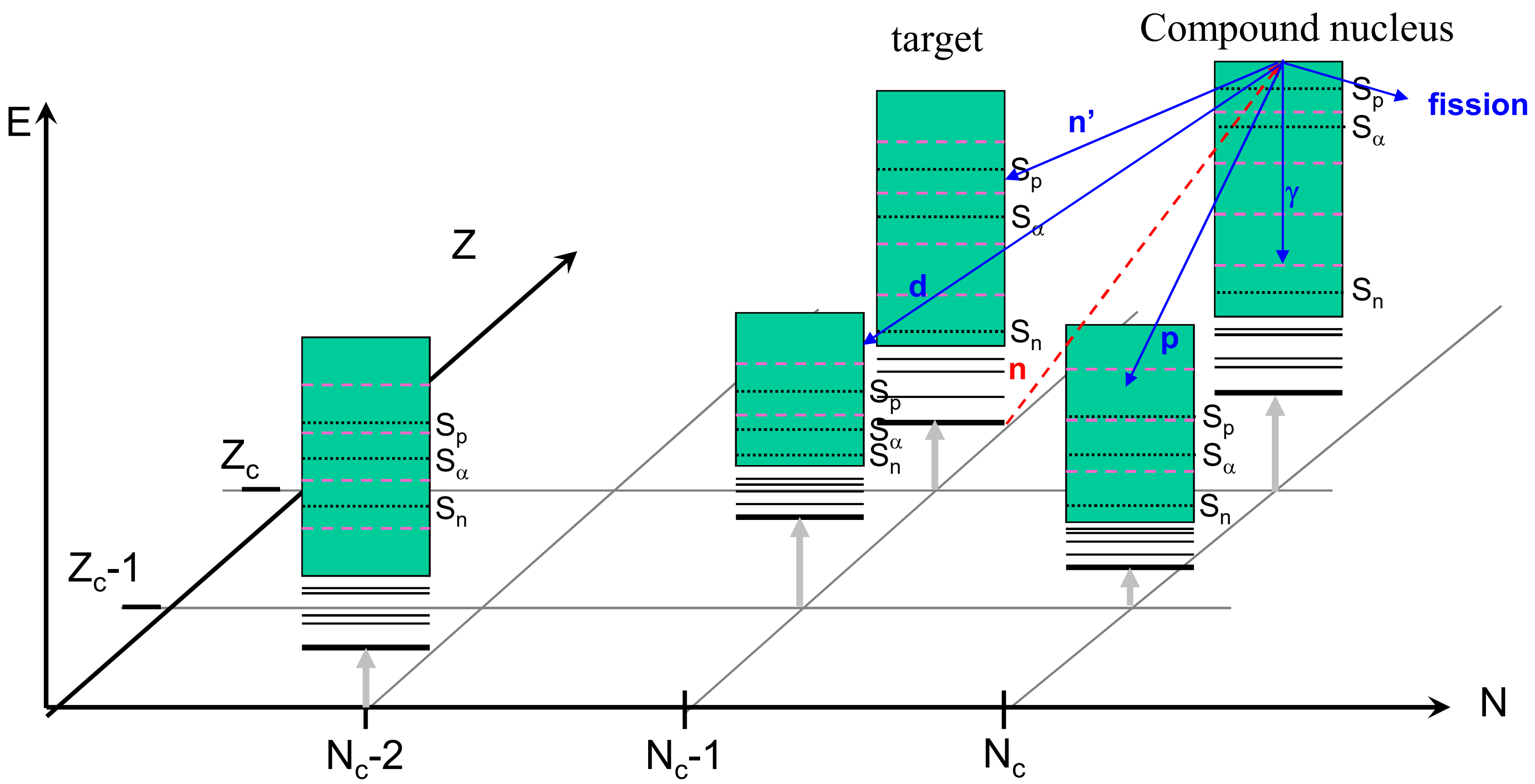

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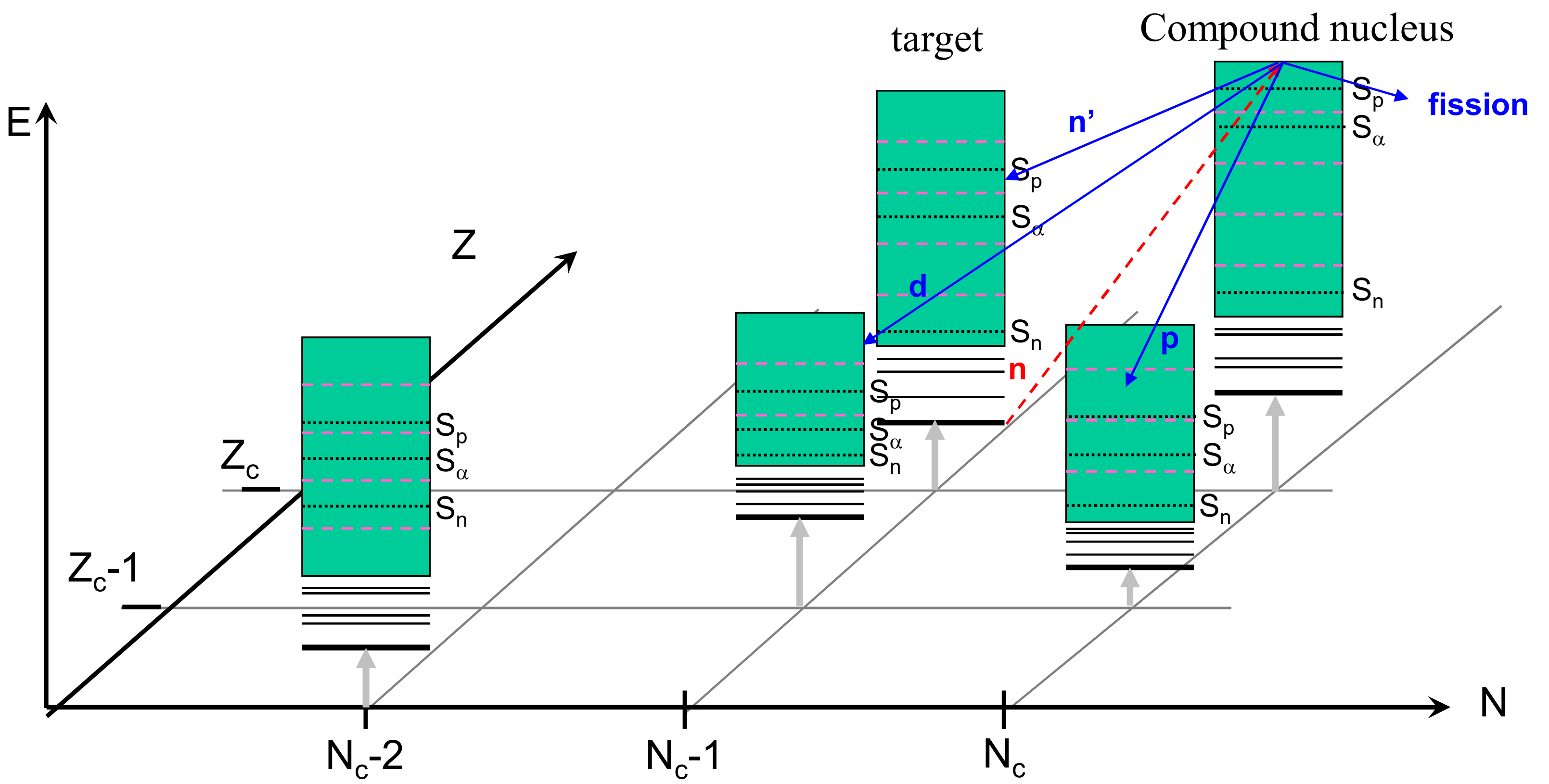

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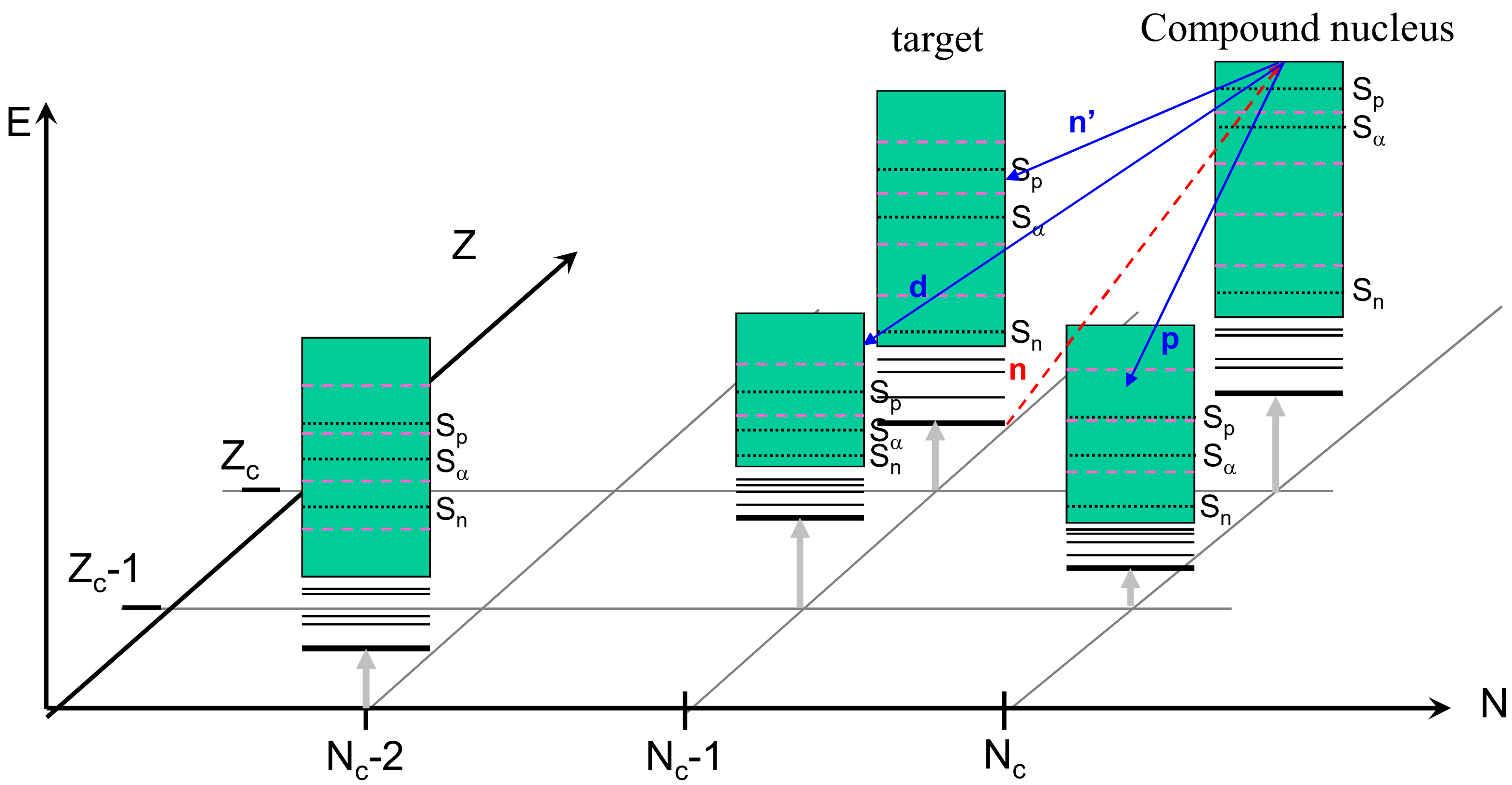

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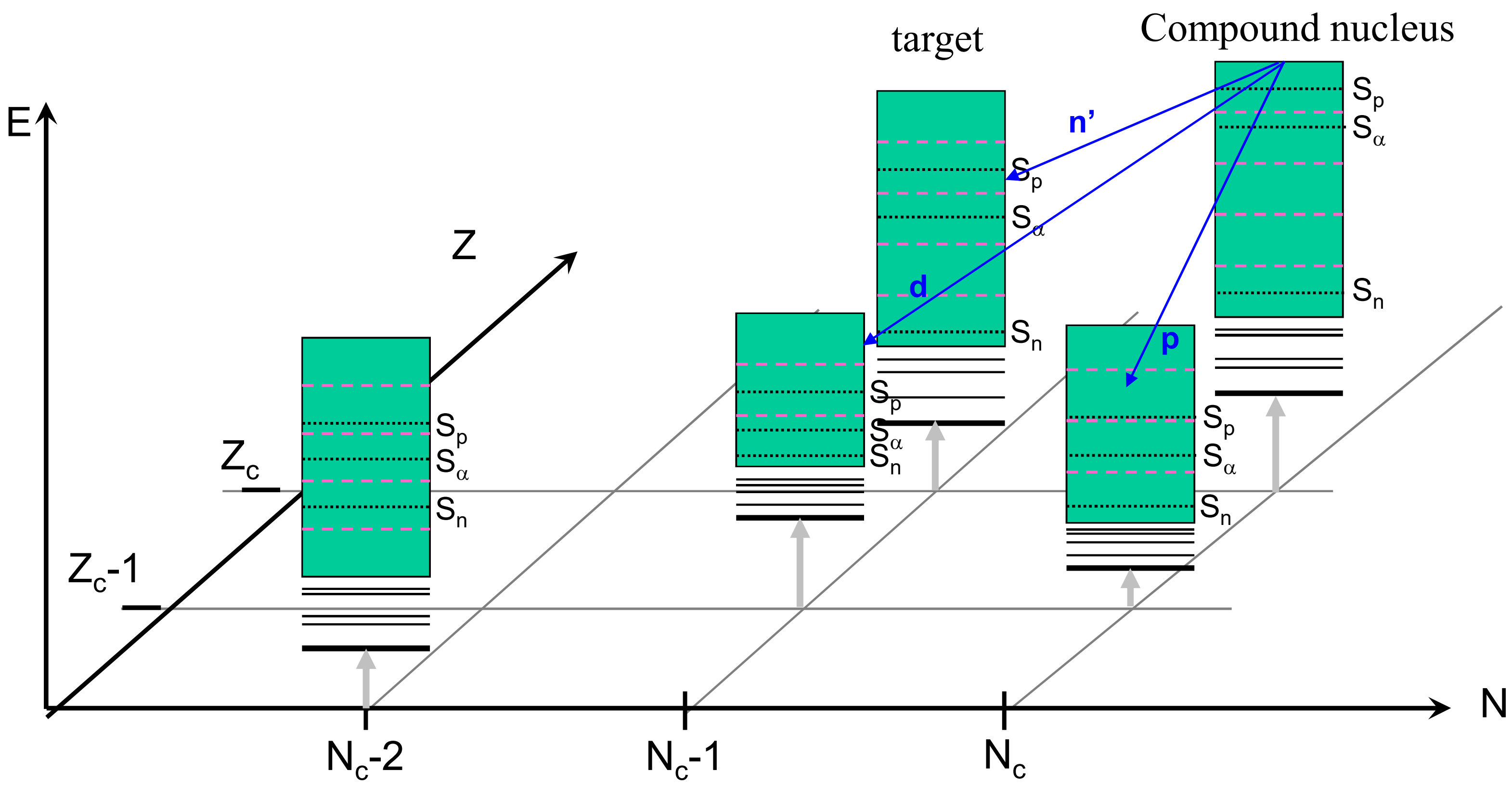

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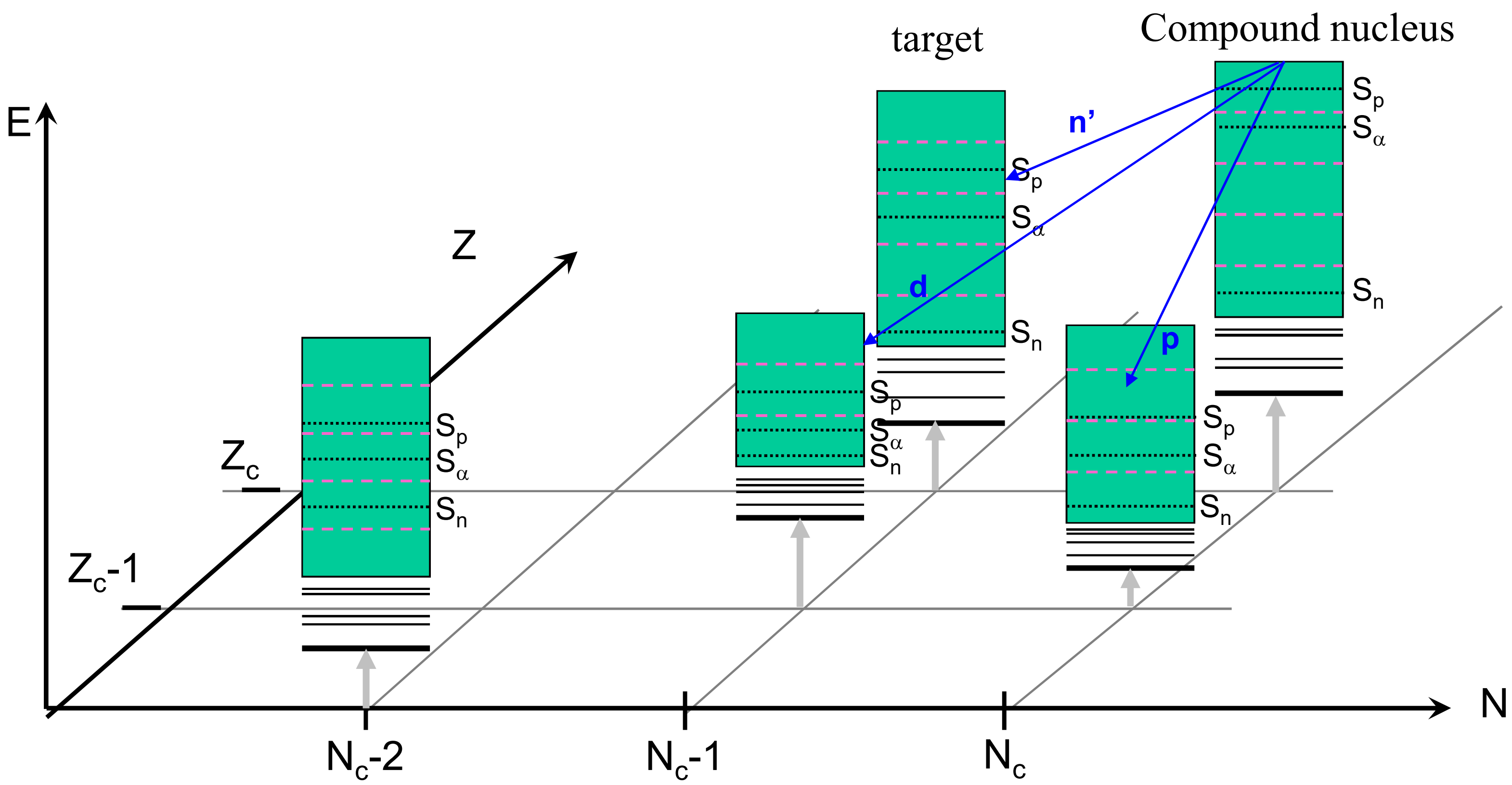

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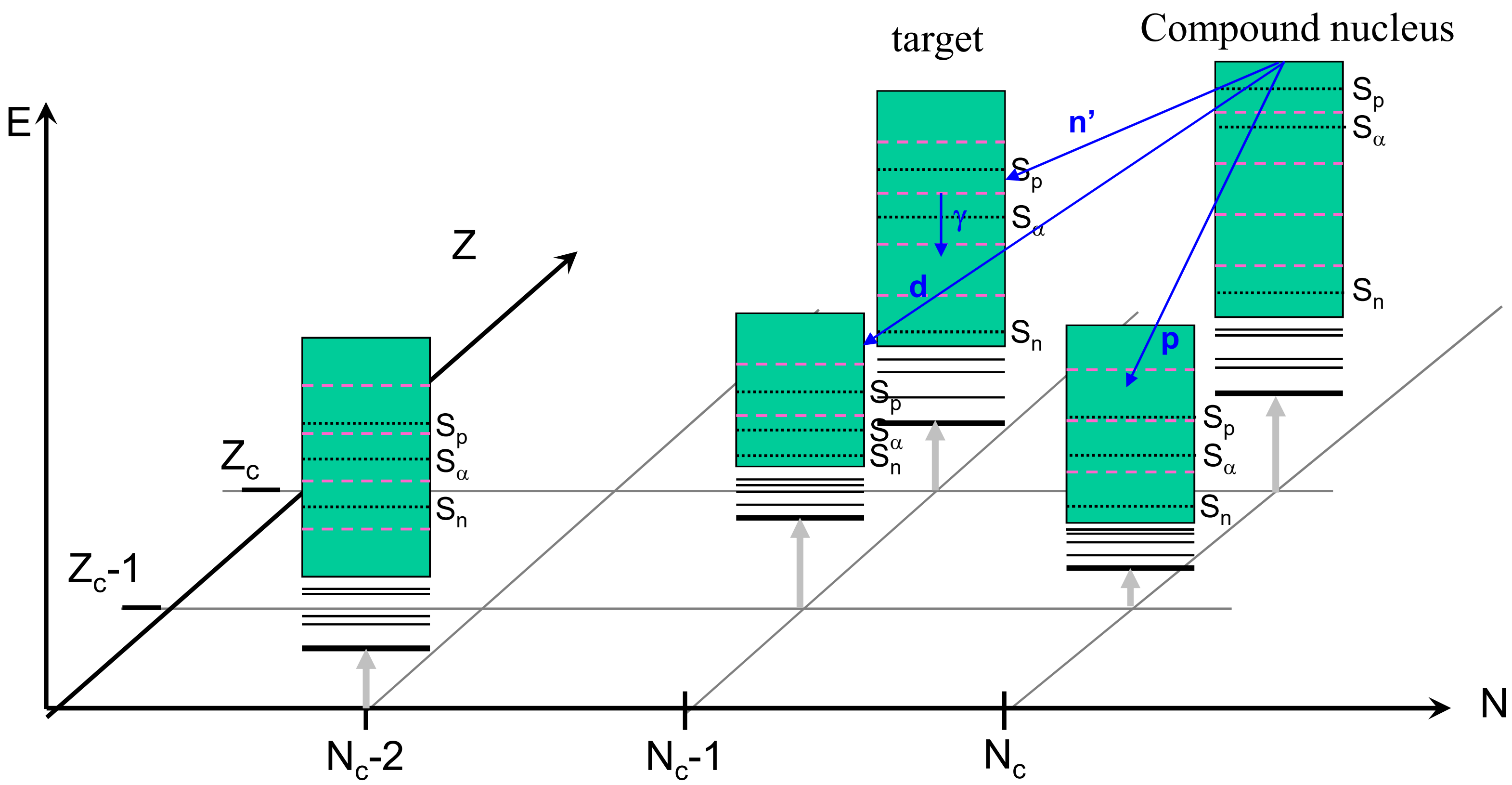

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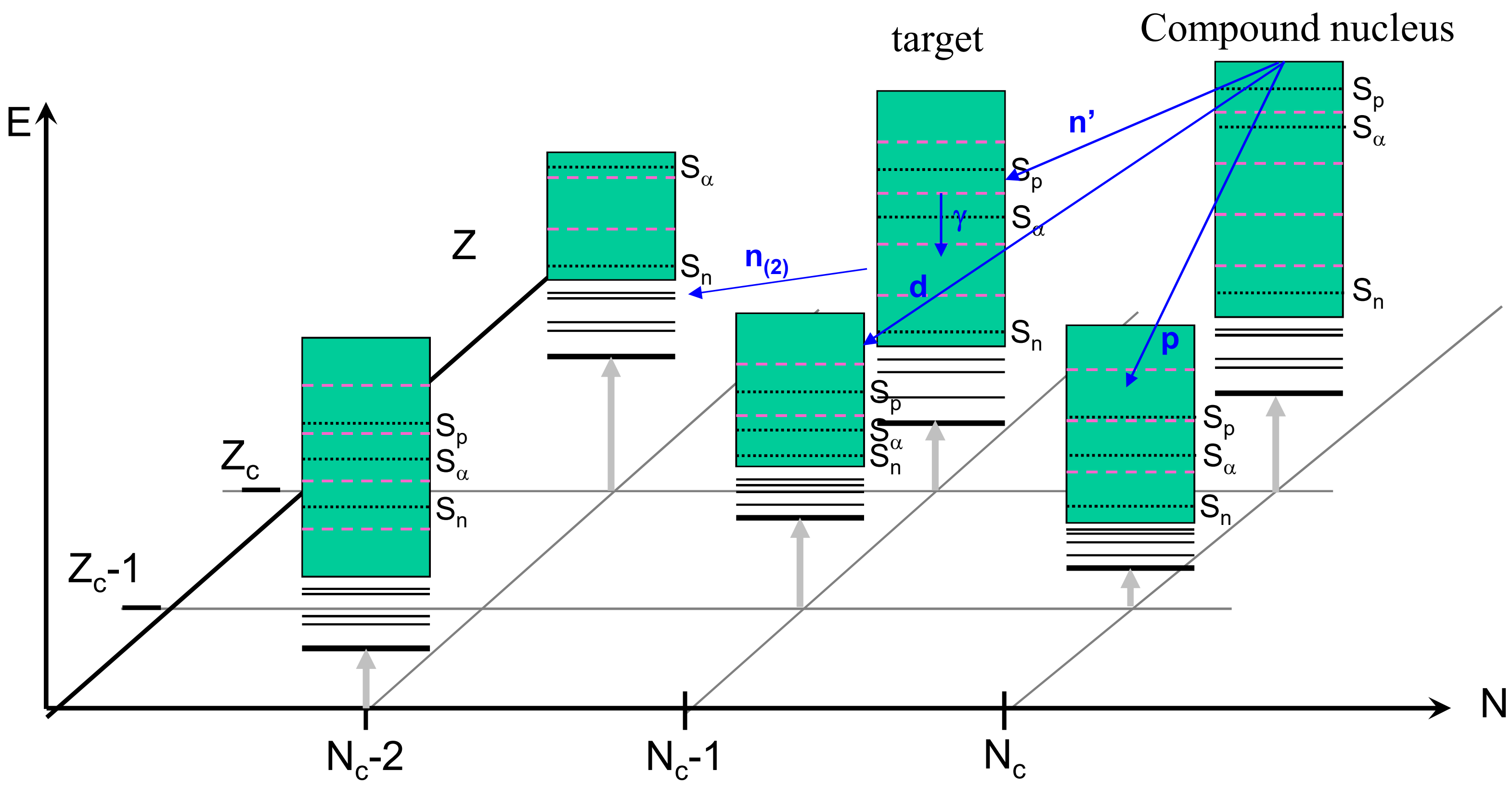

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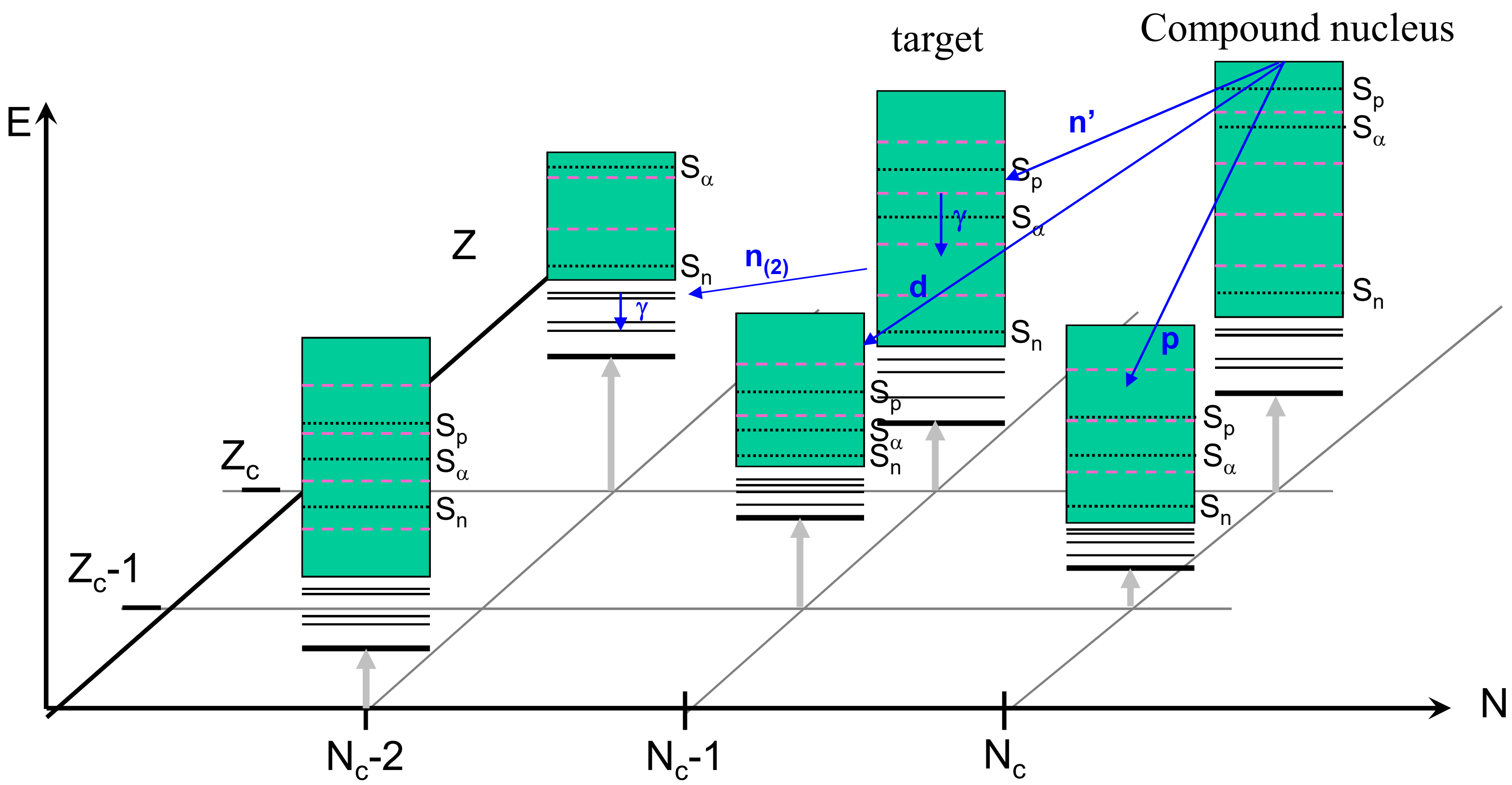

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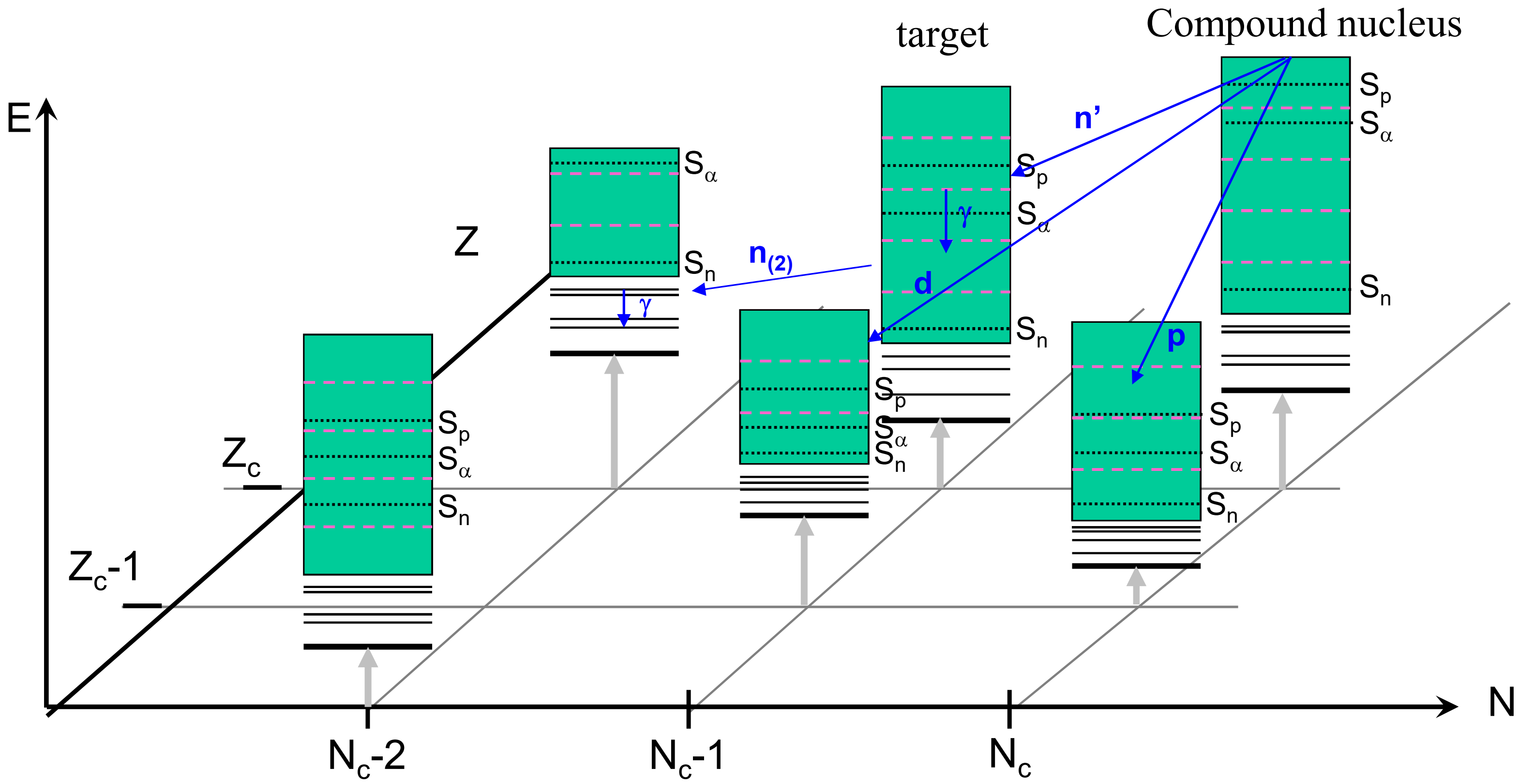

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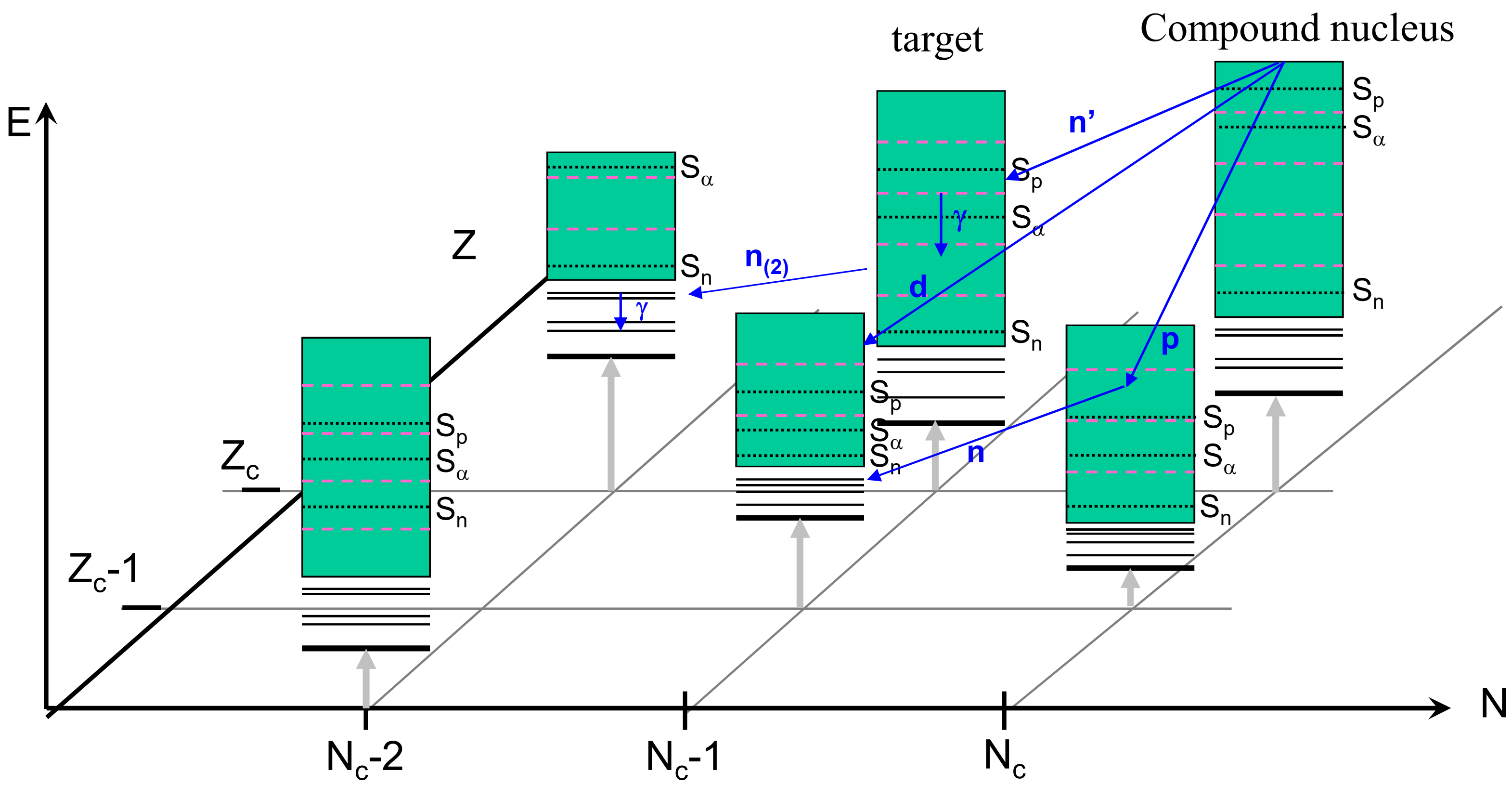

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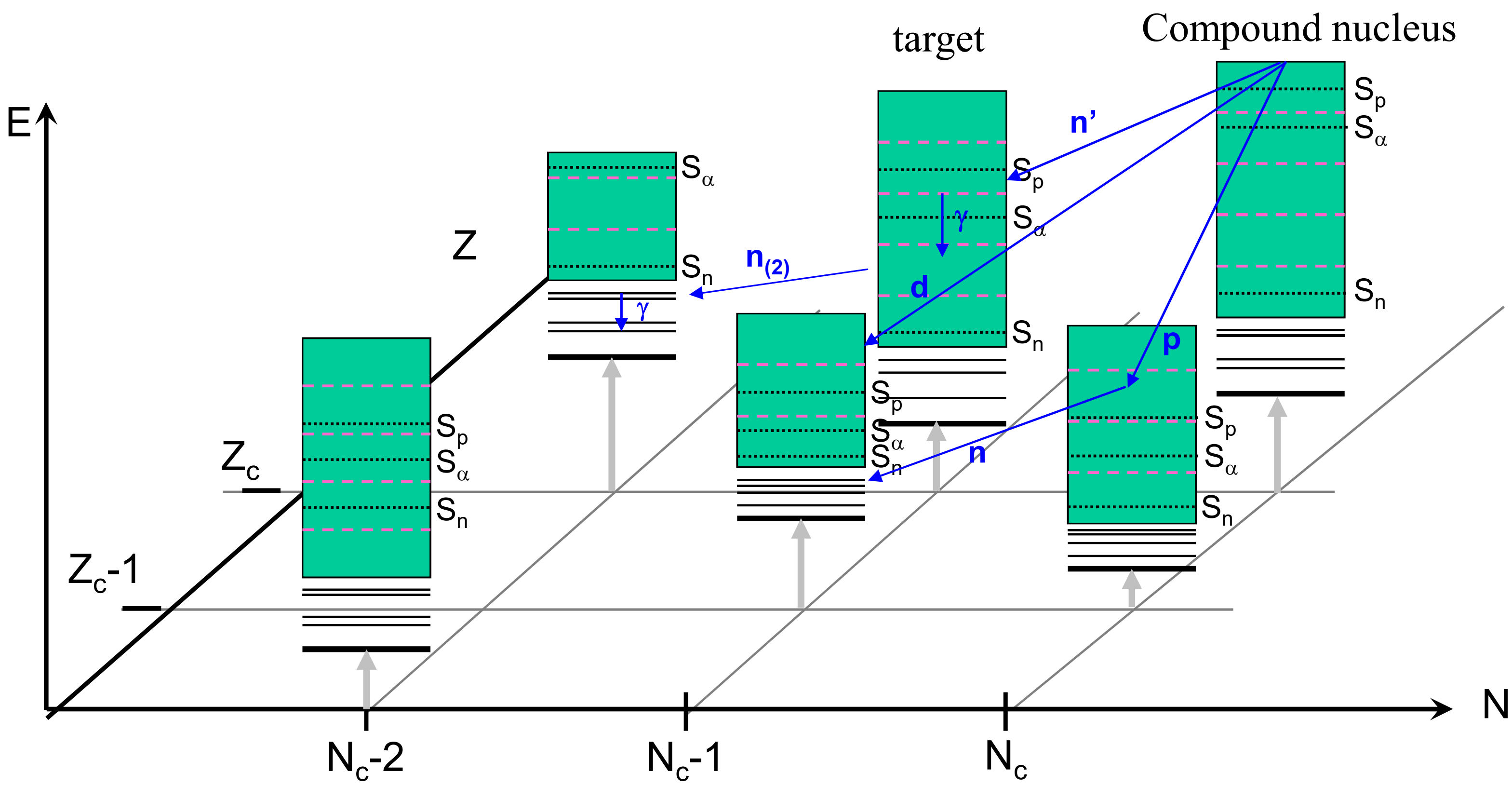
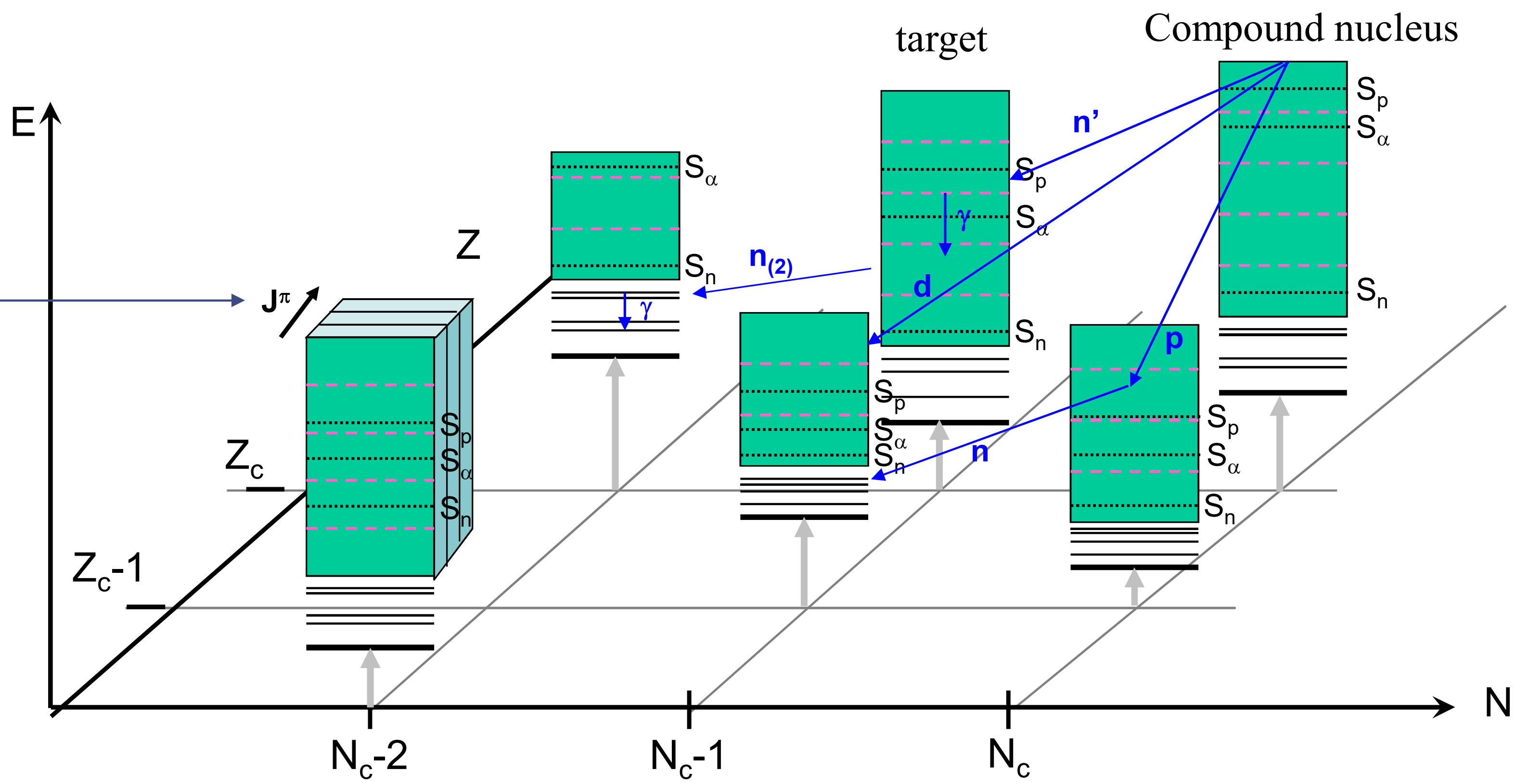
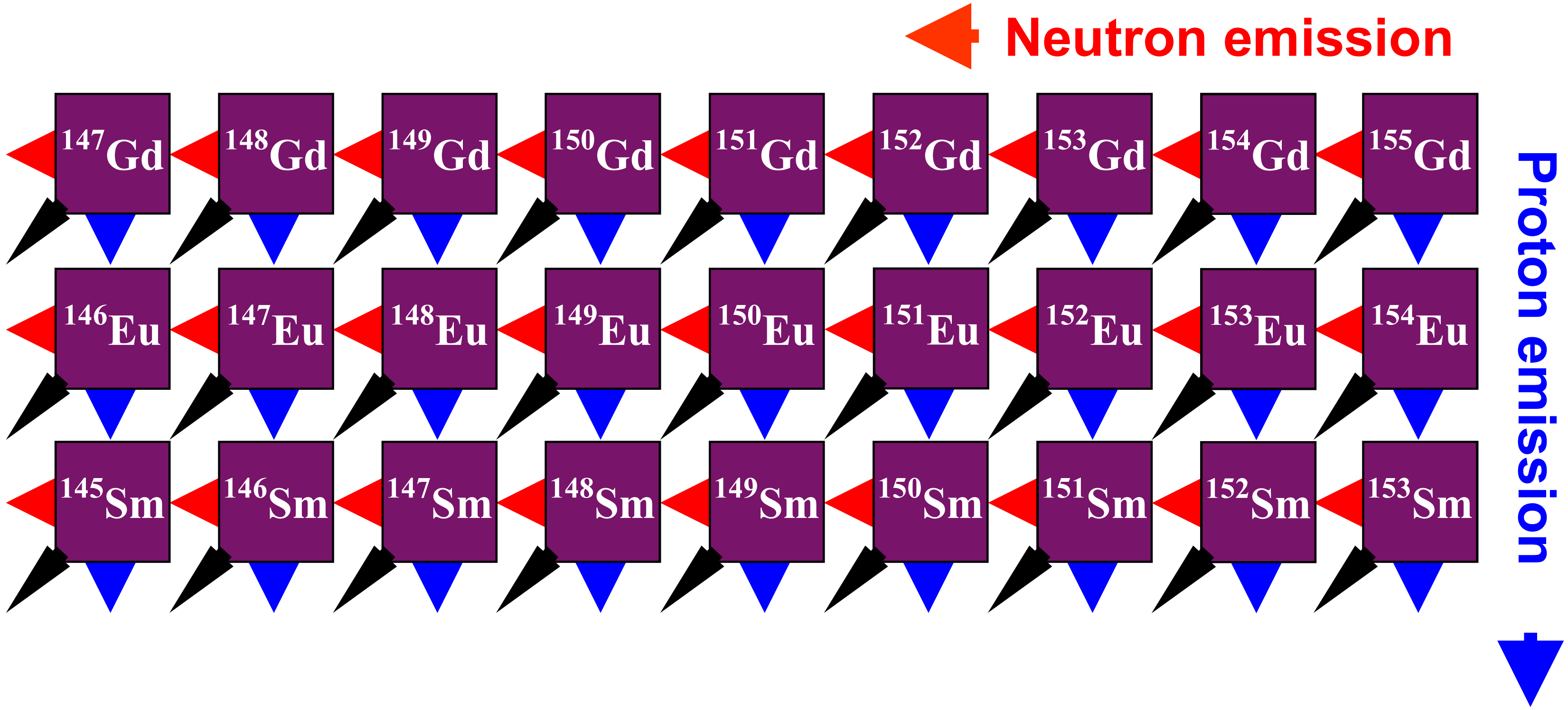


The compound nucleus model : multiple emission

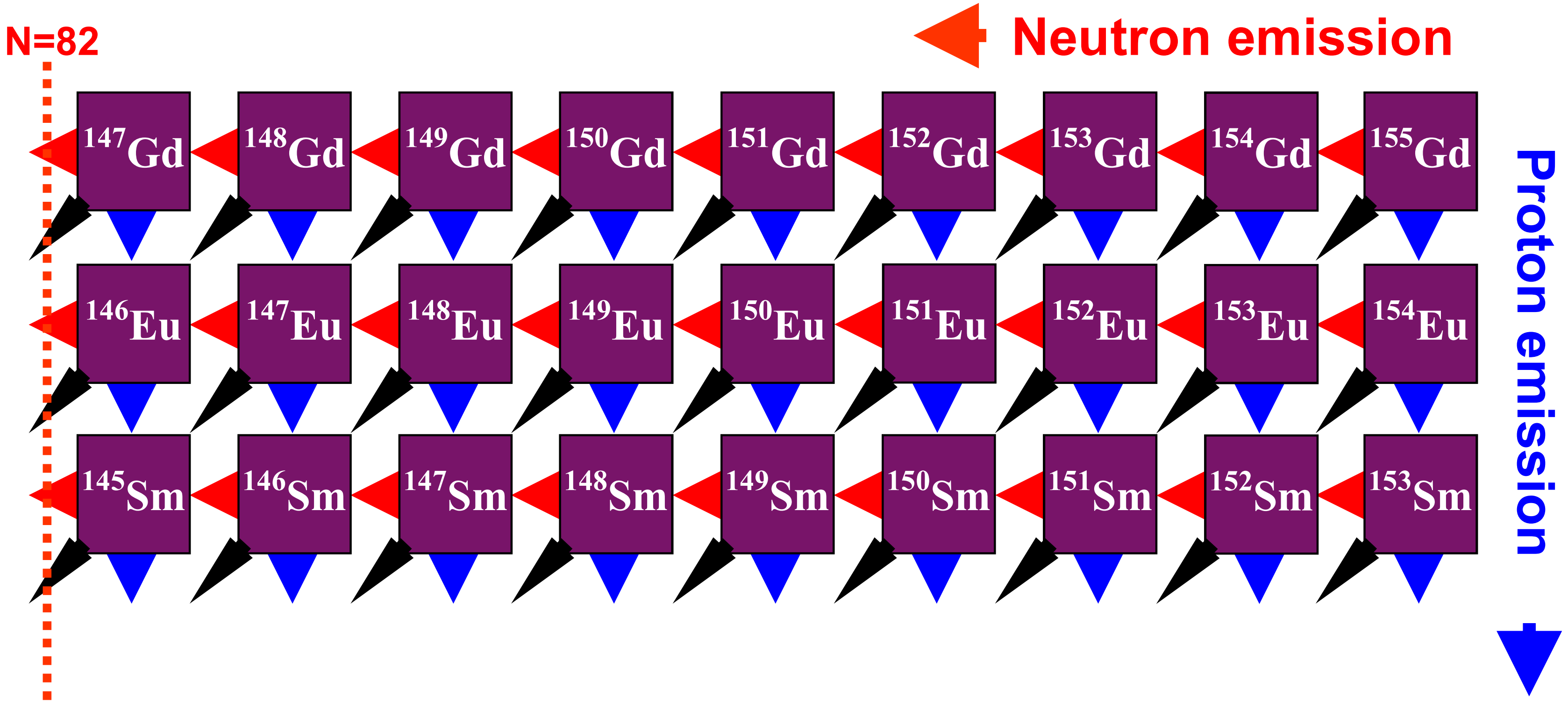
+ loop over compound nucleus spins and parities



The compound nucleus model : changing OMP within decay



The compound nucleus model : changing OMP within decay



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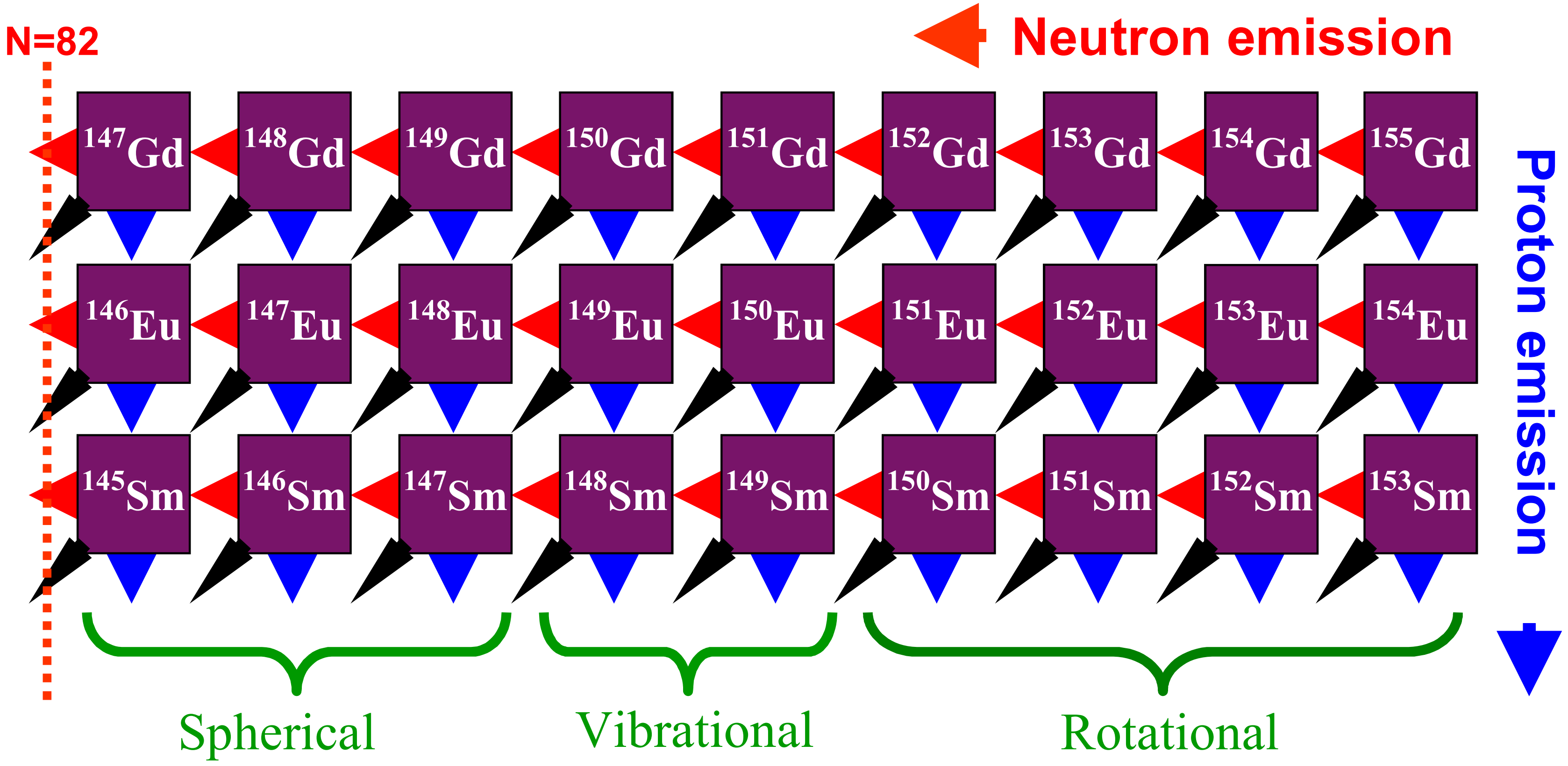

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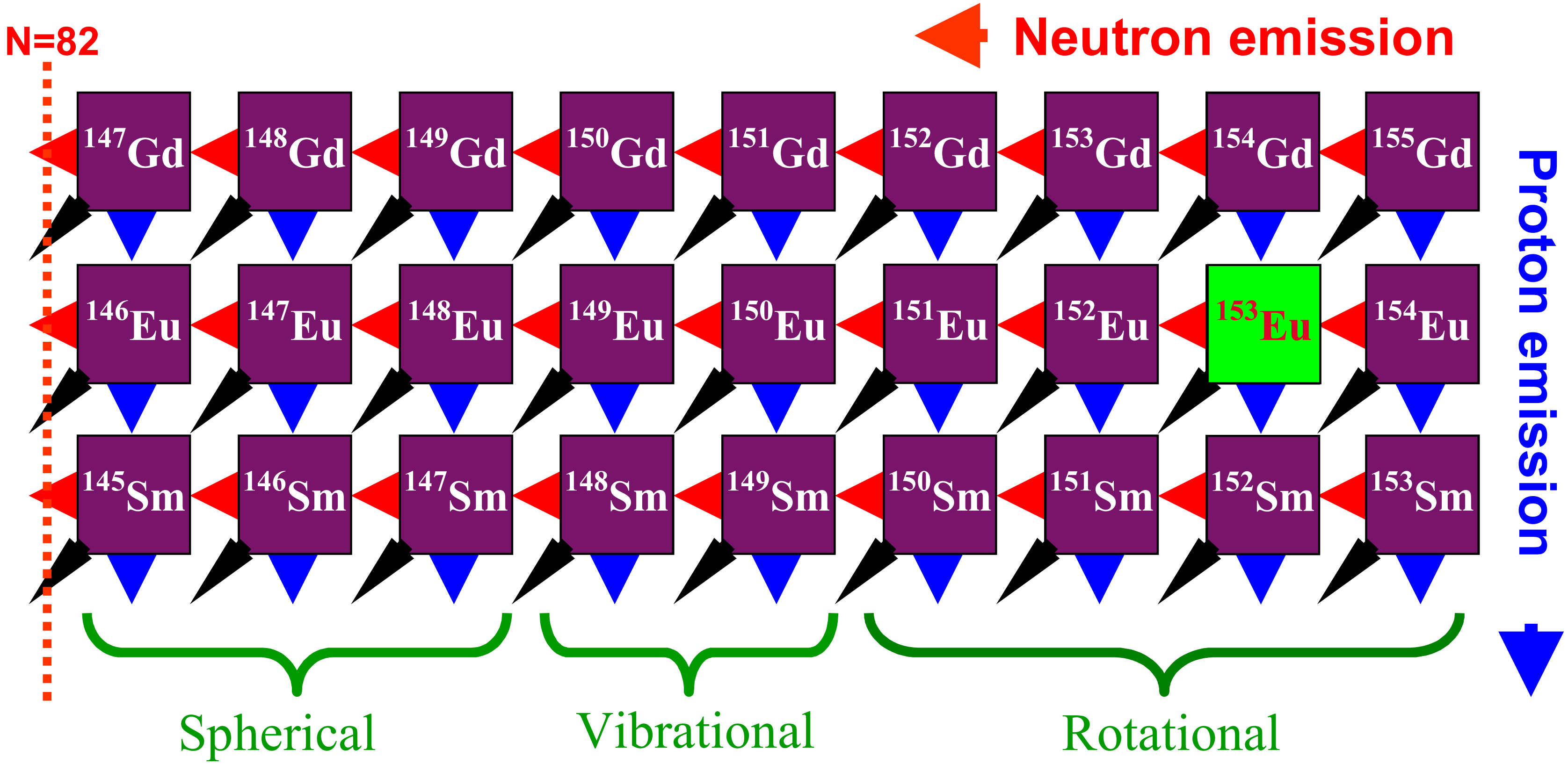

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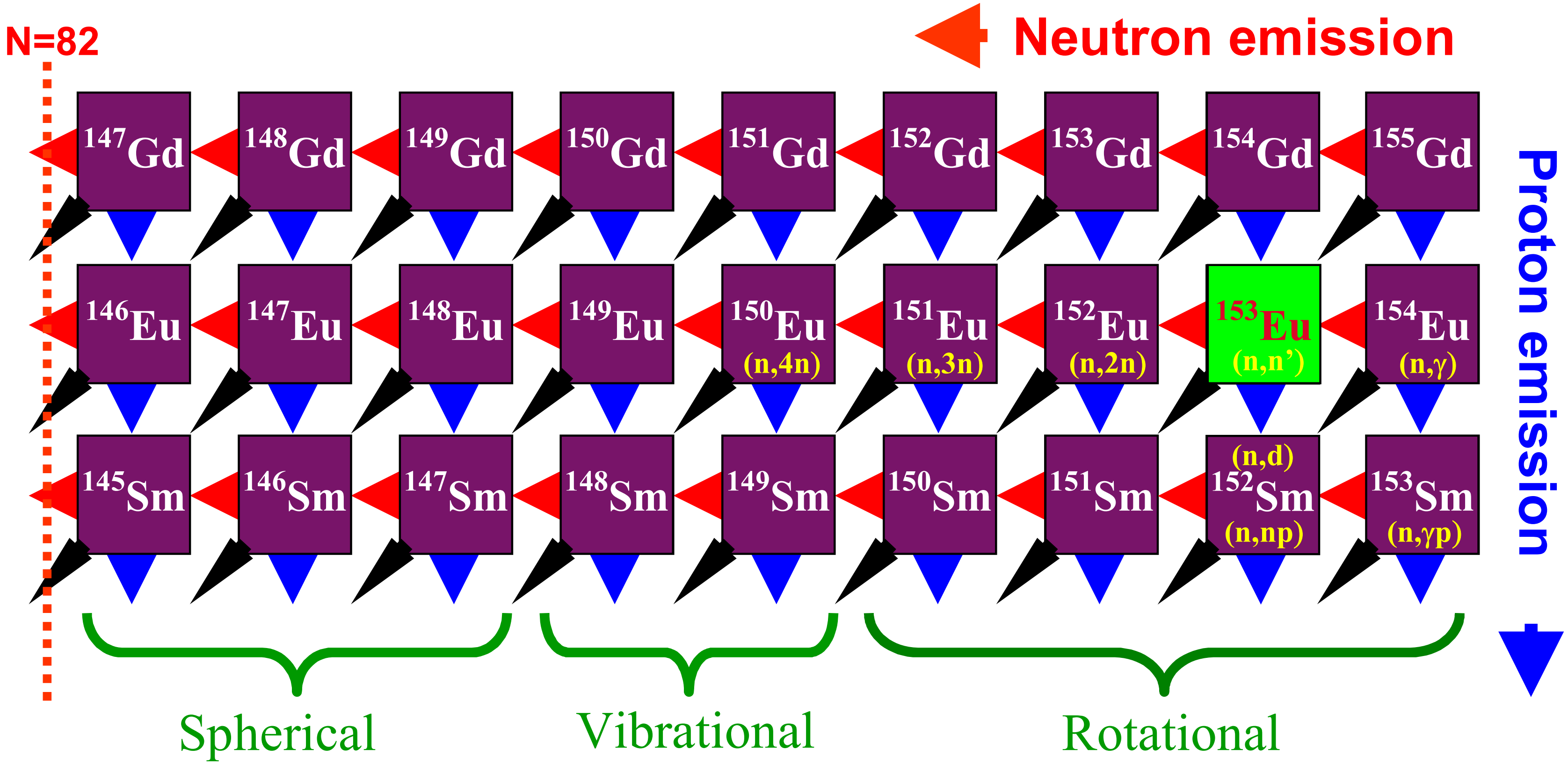
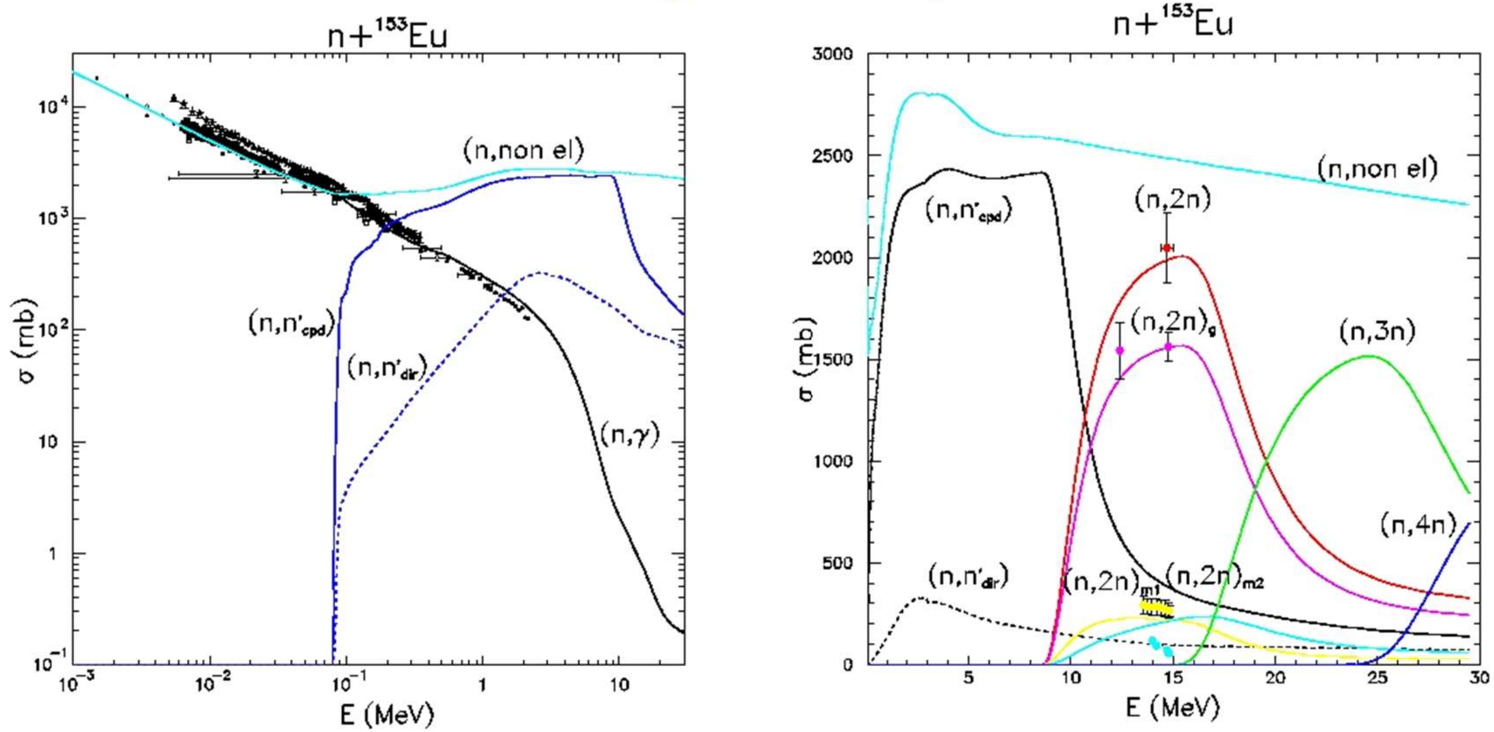


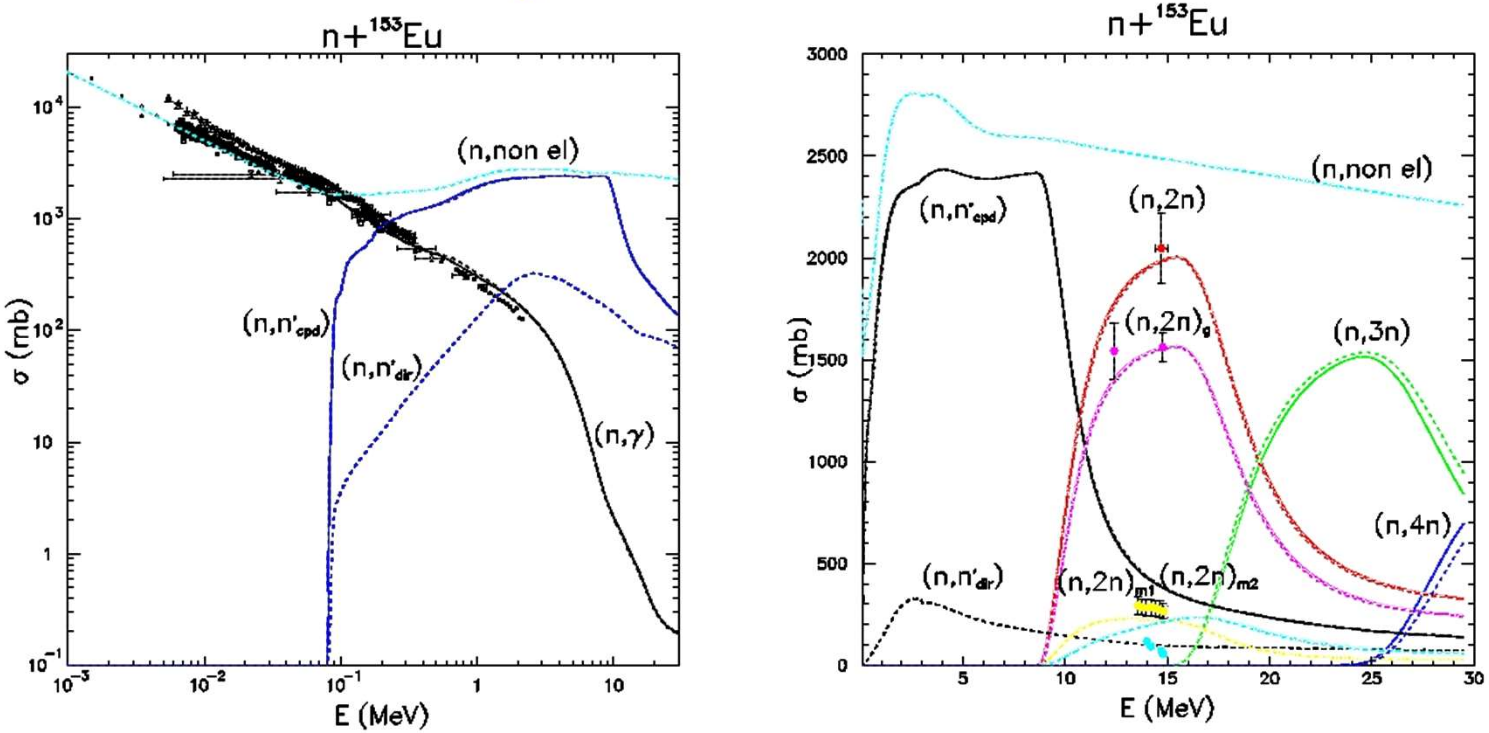
The compound nucleus model : changing OMP within decay

Target's OMP only



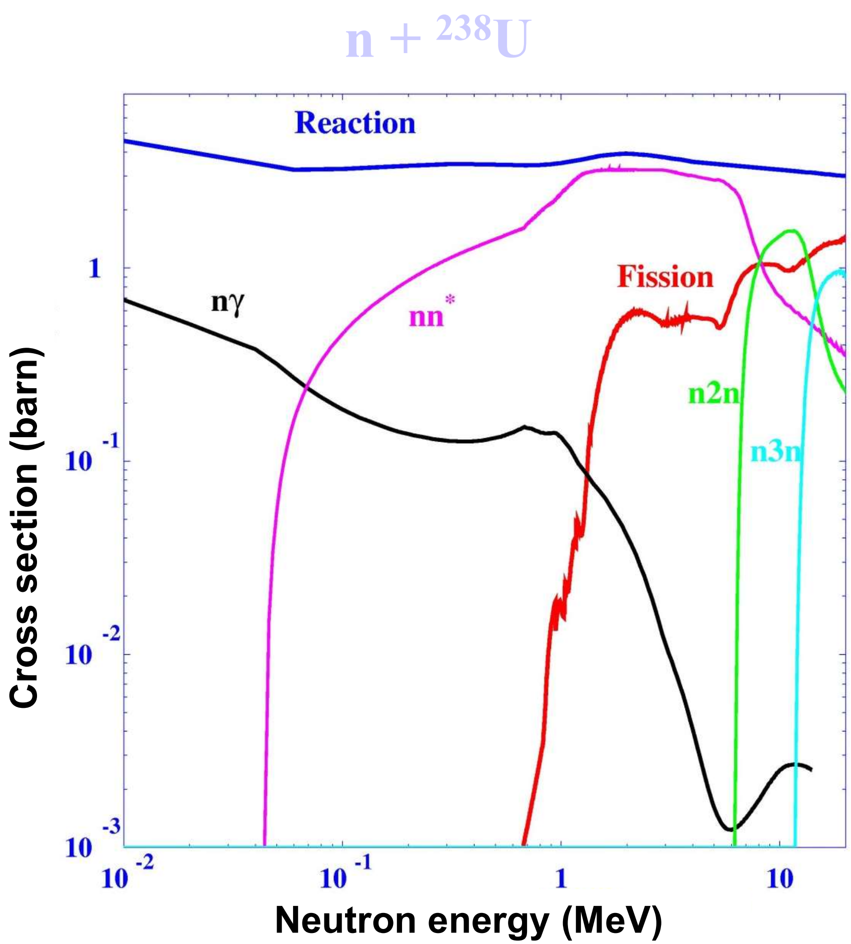
The compound nucleus model : changing OMP within decay

Target's and residuals' OMP



⇒ Little impact compared to investment

The compound nucleus model : summary



Optical model

+

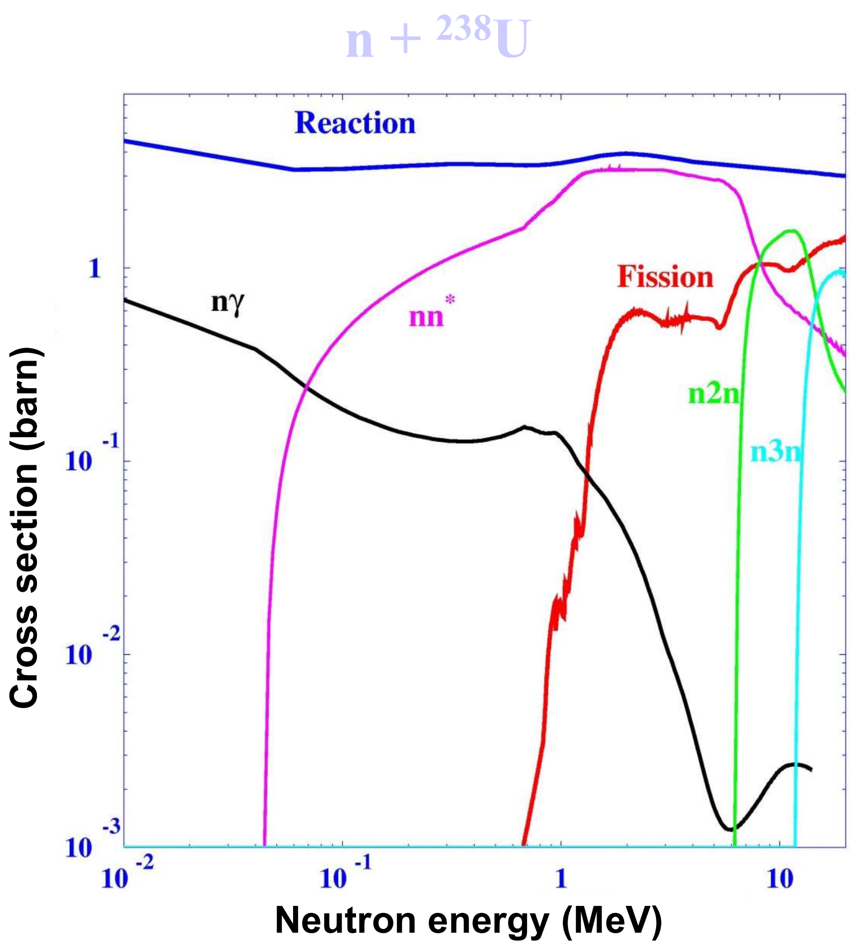
Statistical model

+

Pre-equilibrium model

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

The compound nucleus model : summary



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

$$\sigma_{NC} = \sum_b \sigma_{ab} \quad \text{where } b = \gamma \text{ , n, p, d, t, …, fission}$$

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

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

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- Emission to a discrete level with energy E_d

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

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

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- Emission of photons, fission

Specific treatment