BRC neutron evaluations of actinides with the TALYS code

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What is a neutron evaluation ?

energie atomique • energies alternatives

A set of cross sections … :

$\sigma_T(E)$, $\sigma_{n,n'}(E)$, $\sigma_{n,2n}(E)$, $d\sigma/d\Omega$, $d^2\sigma/dEd\Omega$, …(also $\sigma_{n,f}$ **(E)** for actinides)

given : on an energy mesh

in a specific format (ENDF)

In order to be used by computing codes
for different studies and nuclear applications

how to get them ?

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In our approach
at
BRuyères-le-Châtel (BRC) :
we have chosen
the

FULL MODEL

approach

using TALYS code

cea

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TALYS

adventures in wonderland
(of cross sections)

« railways » :
the new fission path

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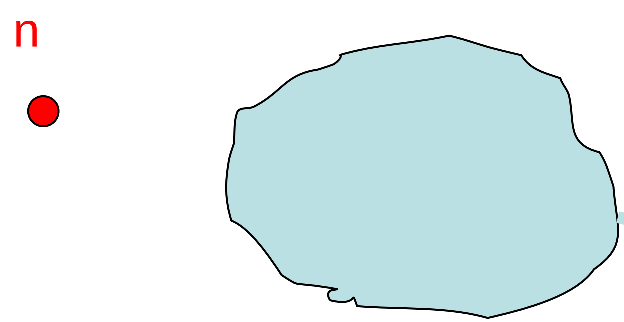
Optical Model

(able to describe : potential scattering)

or shape elastic

n



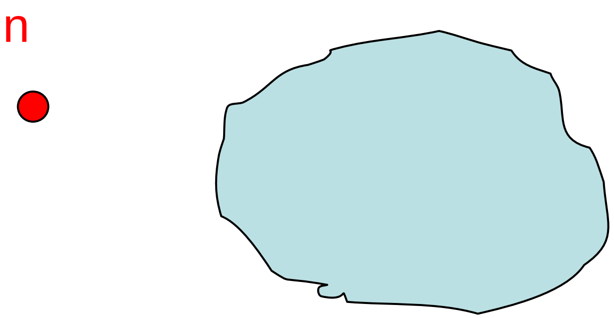
INTERACTING ZONE
(mean field)
=
potential created by
the A nucleons
of the target nucleus

$$E\,|\Psi\rangle = (\,T \boxed{+\,V\,)}\;|\Psi\rangle$$
$$= H\,|\Psi\rangle$$

BUT ….

(unable to describe :)

n



n,2n

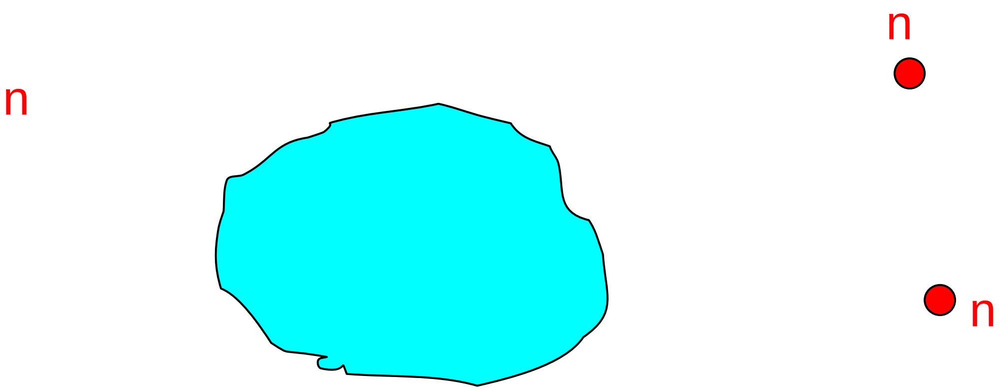
n

INTERACTING ZONE
(mean field)
=
potential created by
the A nucleons
of the target nucleus

$$E\,|\Psi> \;= (\,T \;\boxed{+\,V\,)}\; |\Psi>$$
$$= H\,|\Psi>$$

BUT ….

(unable to describe :)



n,2n

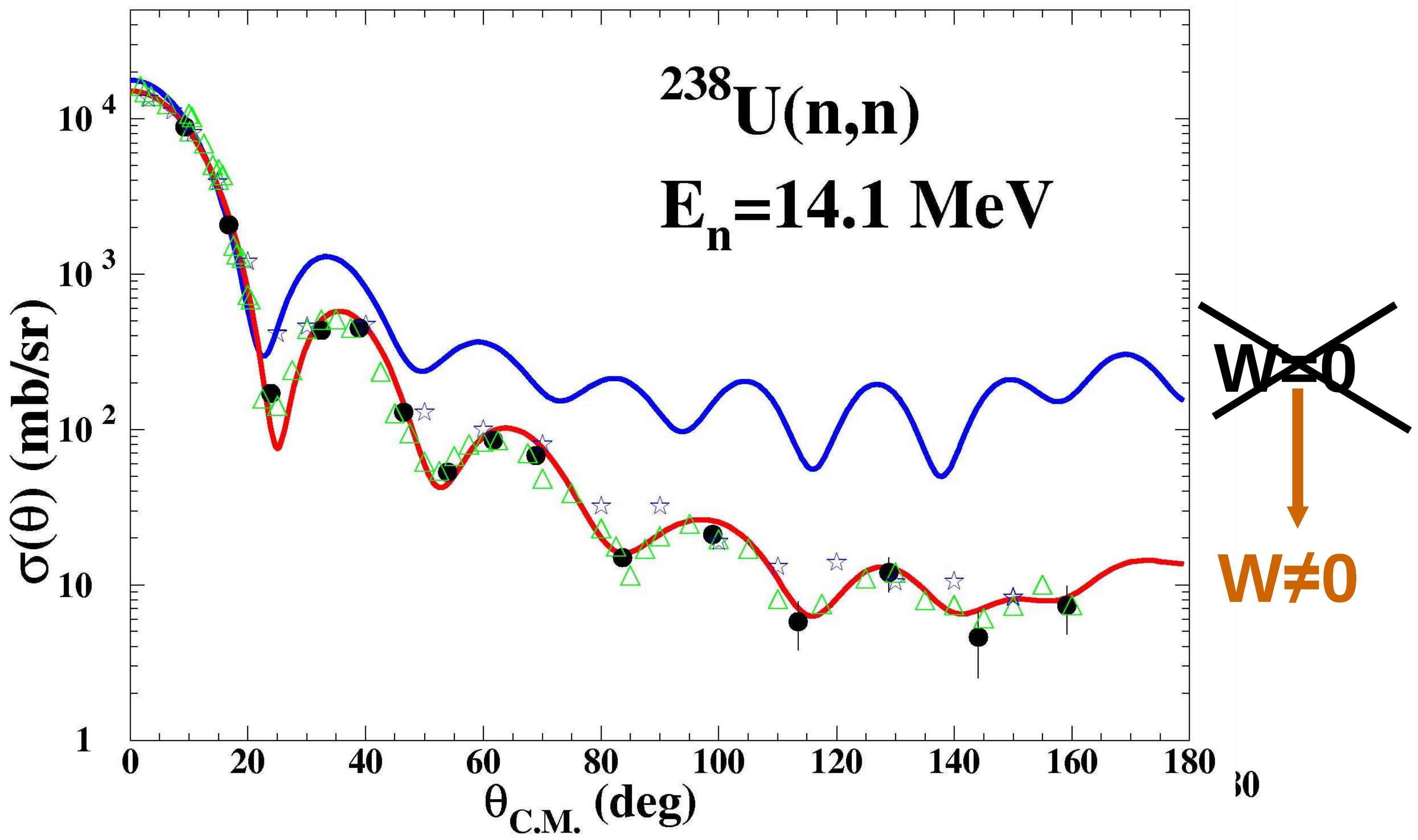
INTERACTING ZONE
(mean field)
=
potential created by
the A nucleons
of the target nucleus

$$E\,|\Psi\rangle = (T + U)\,|\Psi\rangle = H\,|\Psi\rangle$$

$$U = V + i\,W$$

U *: optical potential (depends of the target)*

$U = V + i\,W$: *optical potential*



W : *remove flux from elastic channel*

$U = V + i\,W$: *optical potential*

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W : to quantify the *absorption*

W : gives $\sigma_R \leftarrow T_\ell$

It must have the « right dimension »

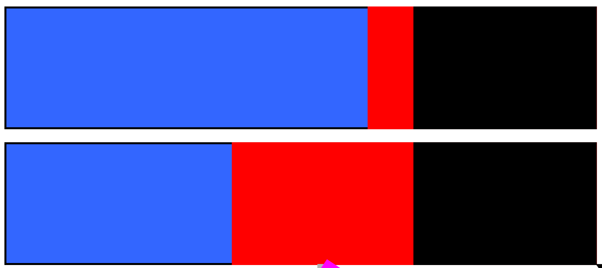
σ_{Tank}

$\sigma_R = \Sigma_\ell (2\ell+1) T_\ell$

Evaluation only from Models

Optical Model

$$\sigma_{tot} = \sigma_{SE} + \sigma_R \quad , \quad T_l$$



Statistical Model

+

Pre-equilibrium

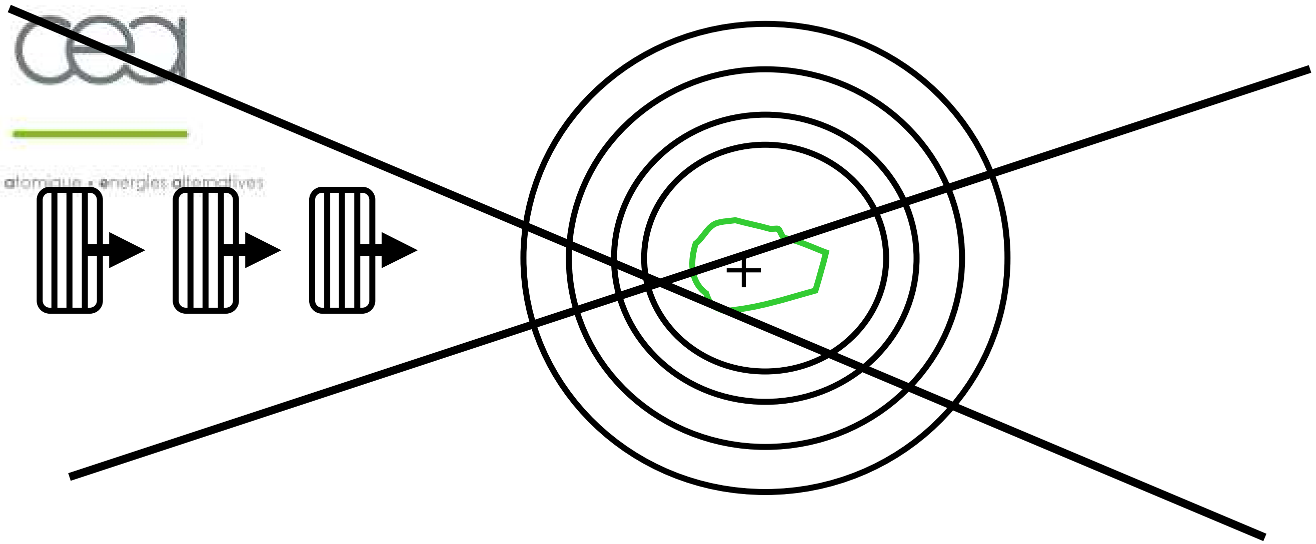
$$\sigma_R = \sigma_{CN} + \sigma_{PE} + \sigma_{DIrect}$$

time scale

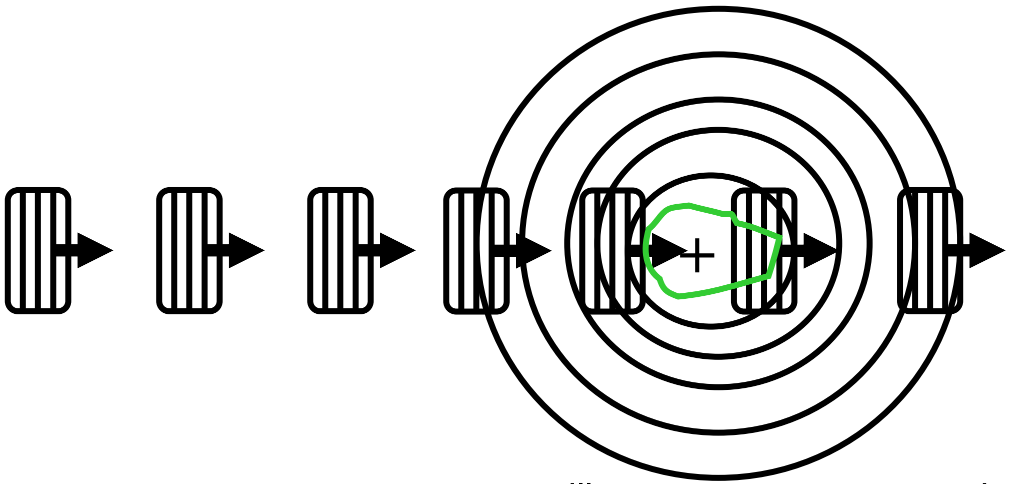
Optical Model

Dispersive Optical Model

(Dispersion relations $\Leftarrow$ causality principle)



Causality principle: the scattered wave cannot be emitted before the incident wave has reached the target.



Pour notre problème de diffusion :

Causality principle : *causes preceding effects*

===> Dispersion Relations

$$\Delta V(E) = Re(U_{dyn}(E)) = \frac{1}{\pi} P \int \frac{Im(U_{dyn}(E'))}{E' - E} dE'$$

additional constraint when adjusting absorption

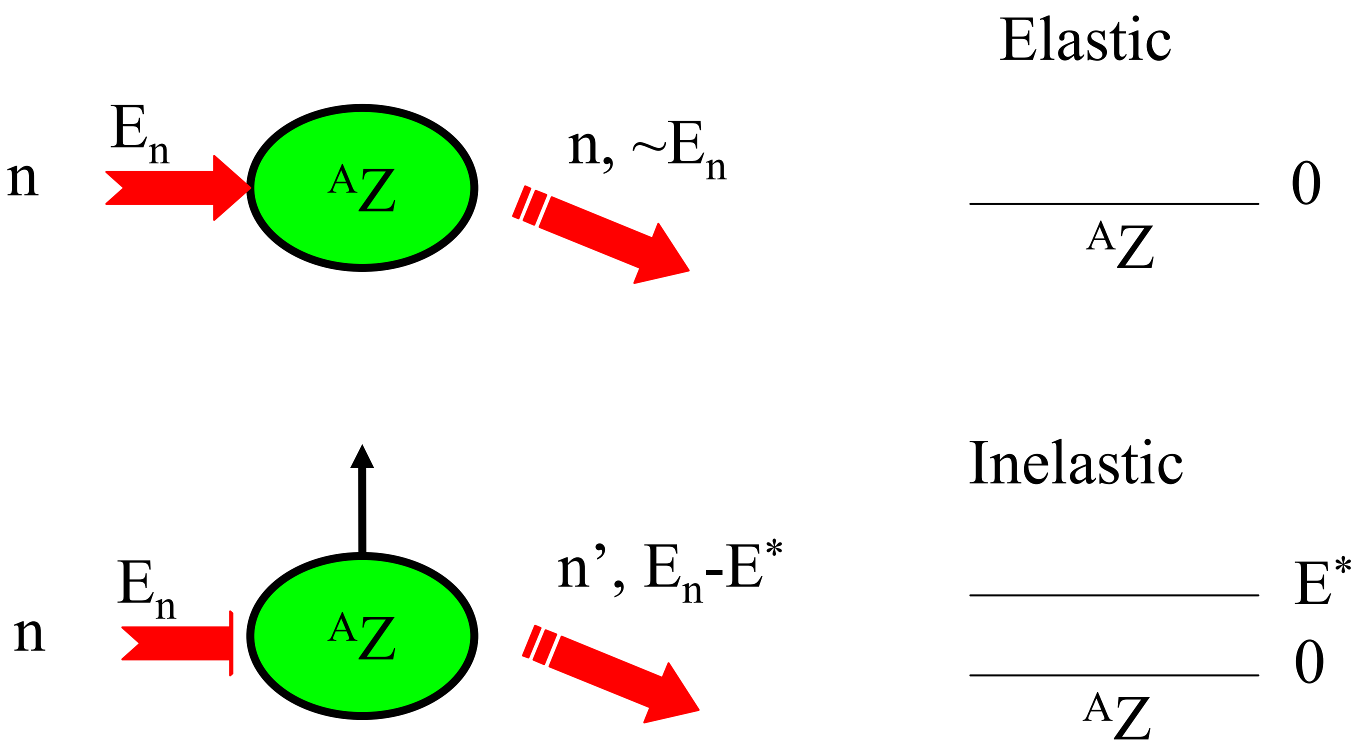
Coupled Channel Calculations
(ECIS)

(As everybody knows for
deformed nuclei in their g.s.)

énergie atomique • énergies alternatives

Direct Interaction

rapid Process   t ~ 10^{-21} s



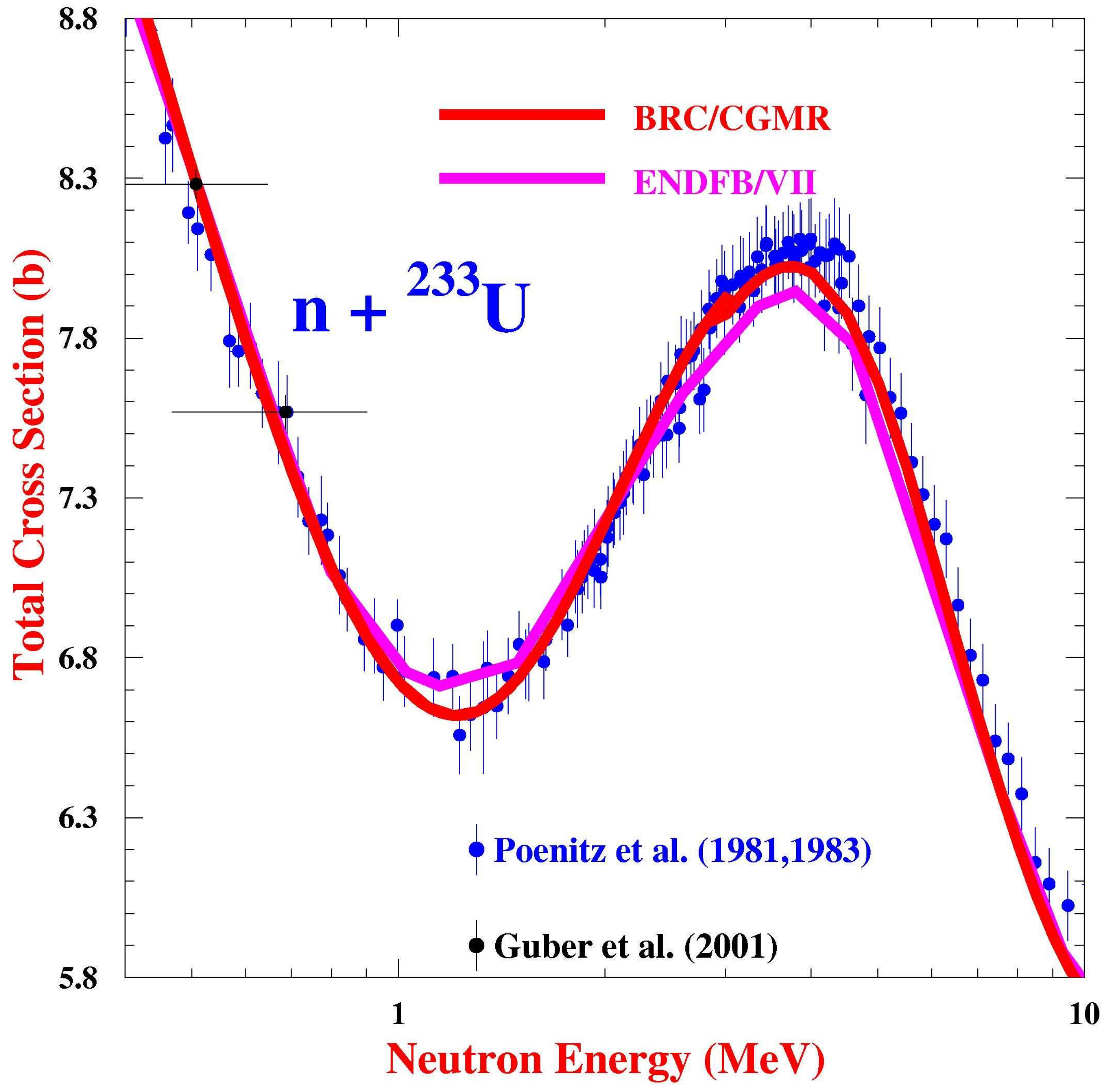
Coupled Channel Calculations
(ECIS)

(As everybody knows for deformed nuclei in their g.s.)

Moreover for actinides a coupling† to the lowest octupolar band is needed.

† *(This idea originated from a previous work of V. Maslov in 1998 on the system n + ^{238}U)*

(implies a new repartition between DI ↗ and CN ↘ processes)



8.8
8.3
7.8
7.3
6.8
6.3
5.8
Total Cross Section (b)
BRC/CGMR
ENDFB/VII
n + ^{233}U
Poenitz et al. (1981,1983)
Guber et al. (2001)
1
10
Neutron Energy (MeV)

Evaluation only from Models

Optic

$$+\ \sigma_R \quad , \quad T_l$$

Statistical Model

+

Pre-equilibrium

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

time scale

Statistical Model ***(GNASH - TALYS - EMPIRE ...)***

All open channel are simultaneously treated

$$a + A \longrightarrow C^* \longrightarrow b + B$$

entrance channel **exit channel**

$$\sigma_{ab} = \underbrace{\sigma_{CN}}_{\sigma_{CN} = \sum_b \sigma_{ab}} \frac{T^J_b}{\sum_c T^J_c} W_{ab}$$

GNASH - TALYS EMPIRE built around this equation

fission slow process via CN

(n,f) **(n,γ)** **(n,xn)** **(n,p)** **(n,α)**

Kopecky Uhl model

optical model

for fission the transmision coefficients come from a penetration barrier model

Transmission coefficients are the keys used to open the compound nucleus cross section σ_{CN} **TANK**

(we need one key per emitted type of particle)

n,p,d,t,α ⇔ keys built at **optical potential machine**

related to σ_{CN} (b+B où b=n,p,d,t,α)

$\boxed{C^* \longleftarrow \mathbf{b} + B}$

γ ⇔ keys bought at the **GDR supermarket**

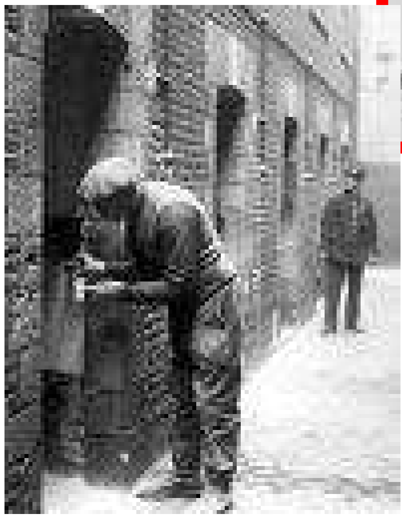
fission ⇔ keys or pass-keys ??????

(keys built at optical potential machine)

exit channel

C* → b + B

b



key / entrance

C*

C*

entrance channel

C* ← b + B

(study inverse reaction)

key / exit

B

Transmission coefficients are the keys used to open the compound nucleus cross section σ_{CN} **TANK**

(we need one key per emitted type of particule)

n,p,d,t,α ⇔ keys built at **optical potential machine**

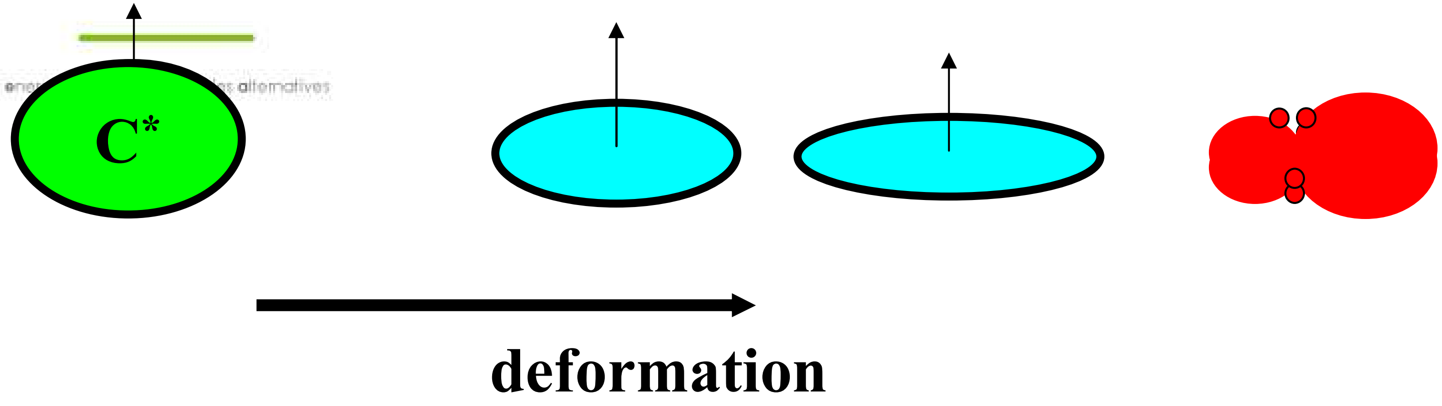
related to σ_{CN} (b+B où b=n,p,d,t,α)

$\boxed{C^* \leftarrow \mathbf{b} + B}$

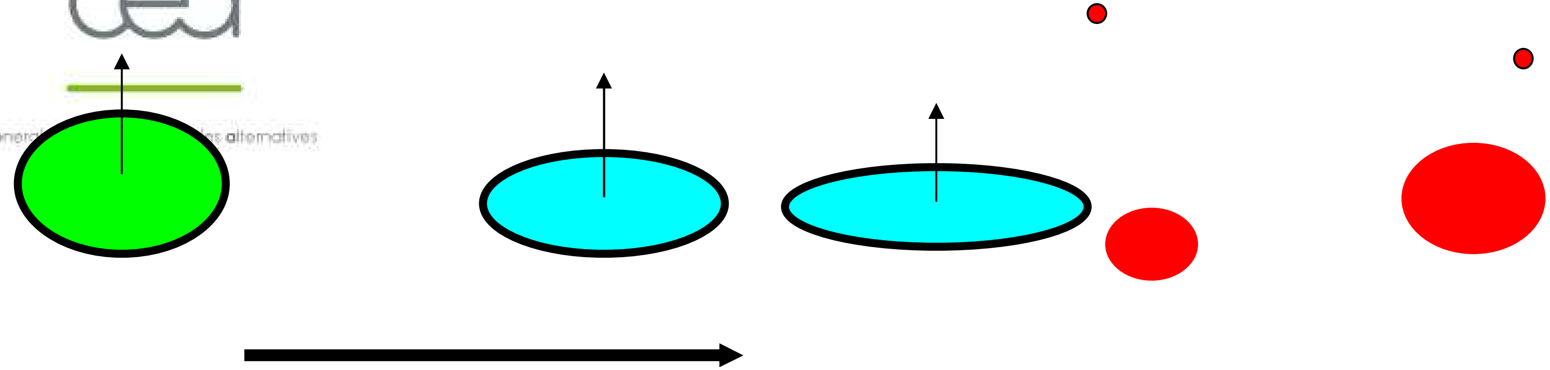
γ ⇔ keys bought at the **GDR supermarket** related to the **photo**-absorption cross section

fission ⇔ keys or pass-keys ??????

not easily related to fusion cross section b+B, especially too much couples b+B fragments!!!!!!!



inverse mecanism ???



deformation

<u>many sets</u> of fragments

<u>moreover</u>

fragments **more or less <u>excited</u>** and **<u>deformed</u>**

<u>AND</u>

emitted neutrons with velocities distributions

<u>AND</u>

etc, etc …

and then !!!

But we can drink it

Transmission coefficients are the keys used to open the compound nucleus cross section σ_{CN} **TANK**

(we need one key per emitted type of particle)

n,p,d,t,α ⇔ keys built at **optical potential machine**

reliées à σ_{CN} (b+B où b=n,p,d,t,α)

$C^* \leftarrow$ **b** + B

γ ⇔ keys bought at the **GDR supermarket** .

related to the **photo**-absorption cross section

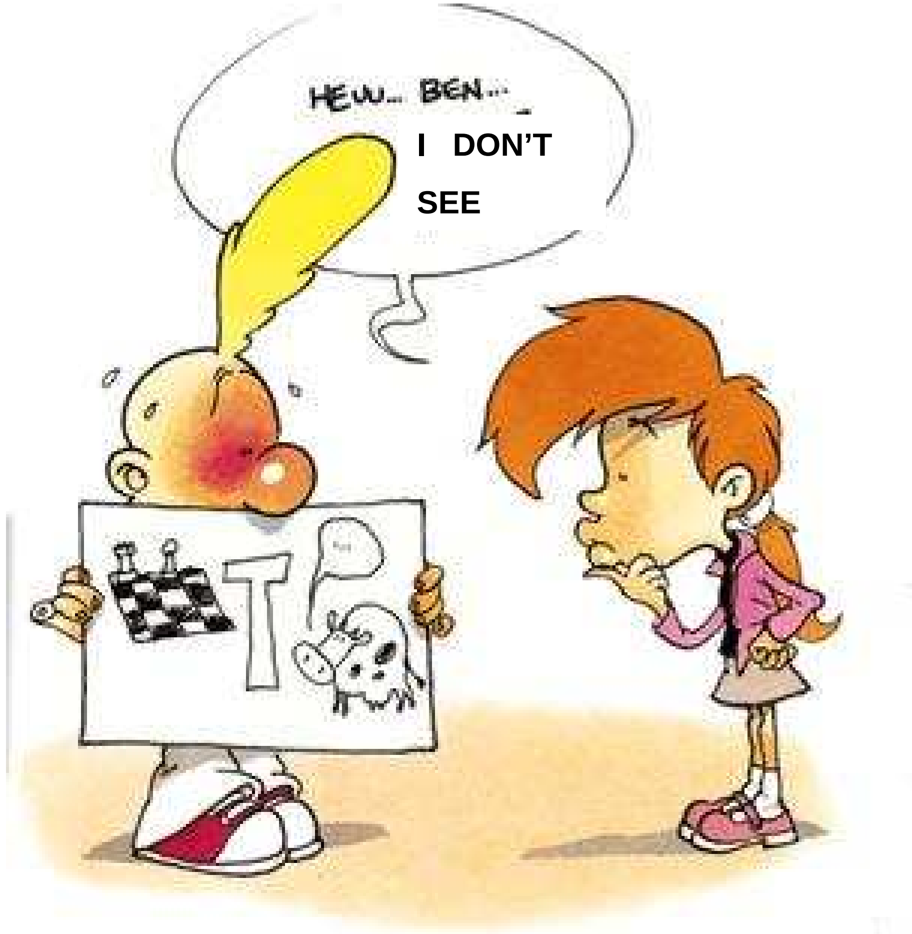
fission ⇔ keys or pass-keys ??????

not related to fusion cross section b+B,

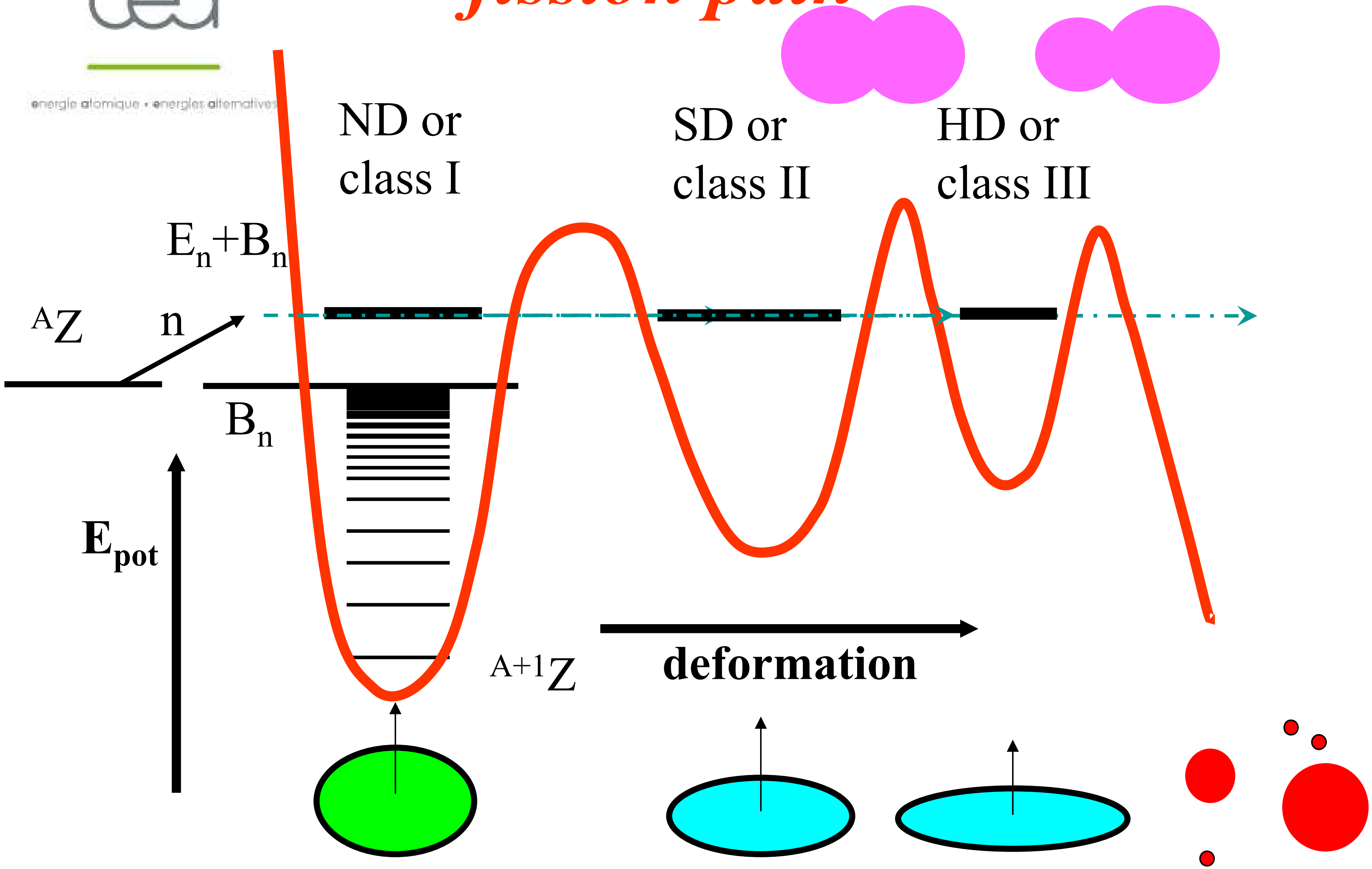
especially that many couples b+B fragments!!!!!!!

keys built on line

adjust with Statistical Model

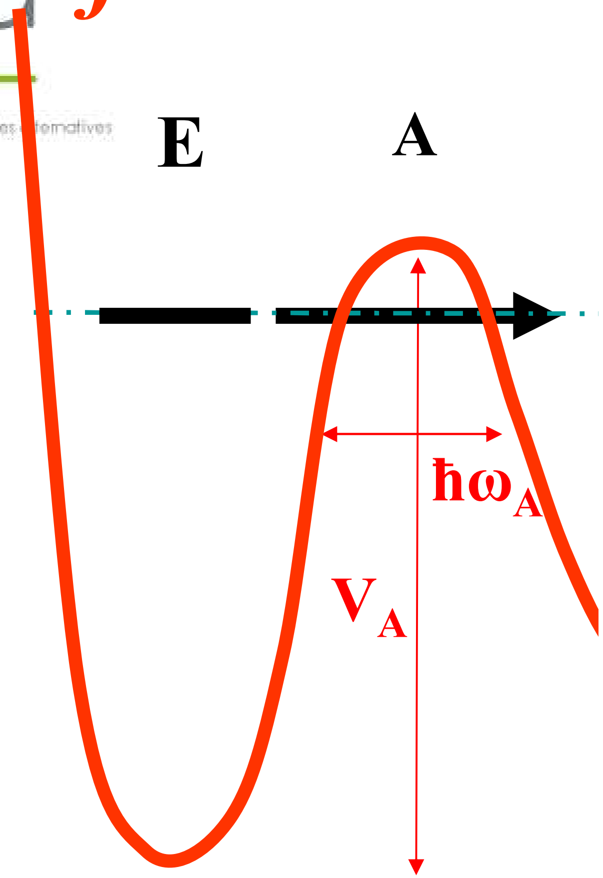

HEUU... BEN...
I DON'T
SEE

fission path



 key or pass-key ??

fission barrier with 1 hump



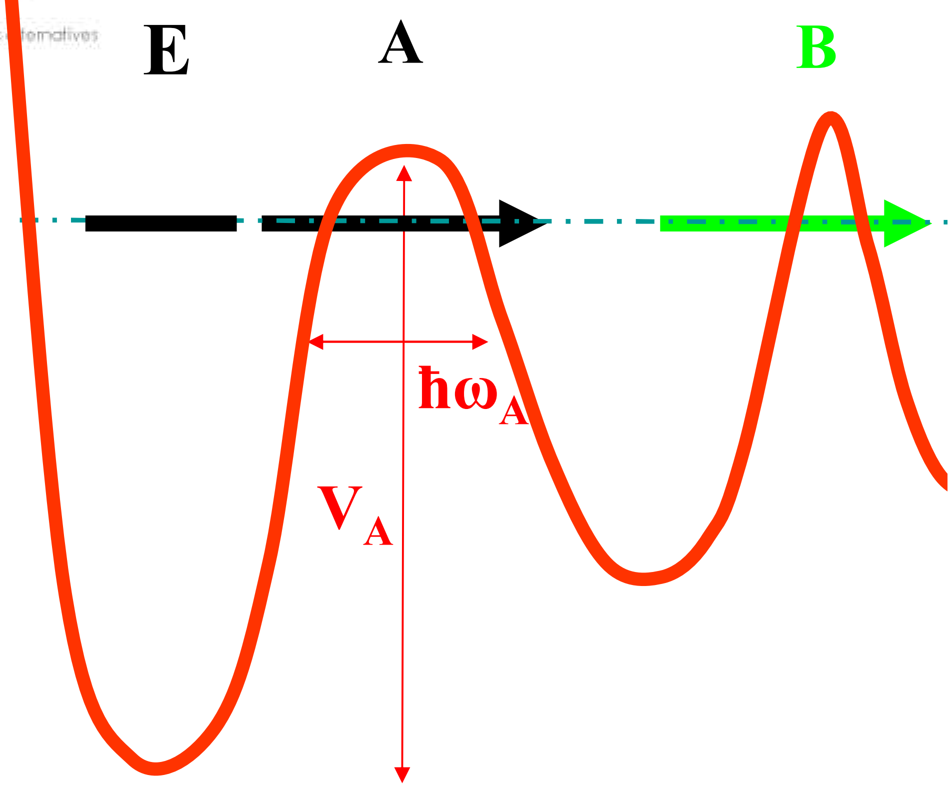
$$T_f = T_A$$

$T_i = 1/[1 + \exp(2\pi(V_i\text{-}E)/\hbar\omega_i)]$

Hill-Wheeler

deformation

fission barrier with 2 humps



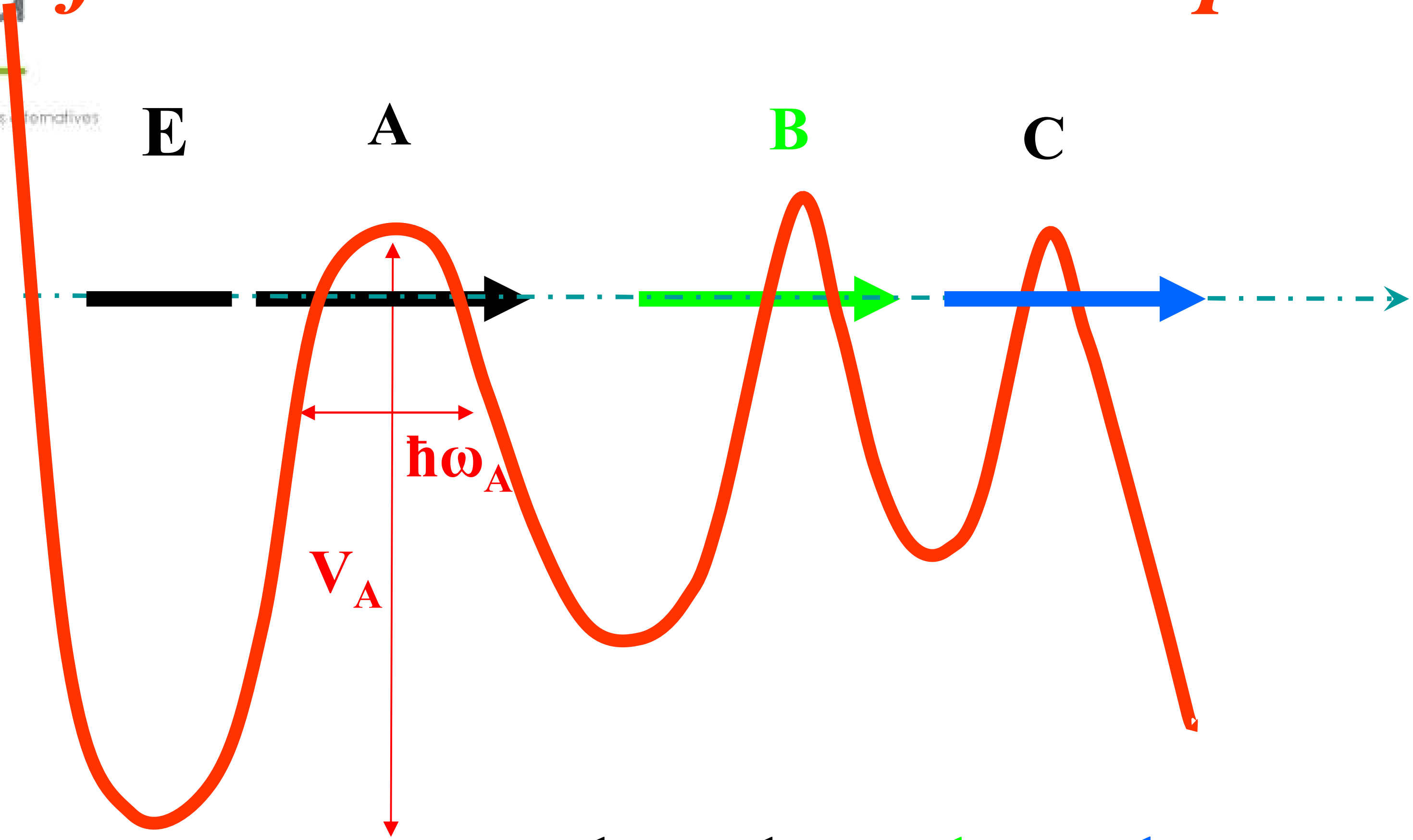
$$T_f = T_A \frac{T_B}{T_A + T_B}$$

$$T_i = 1/[1 + \exp(2\pi(V_i - E)/\hbar\omega_i)]$$

Hill-Wheeler

deformation

fission barrier with 3 humps



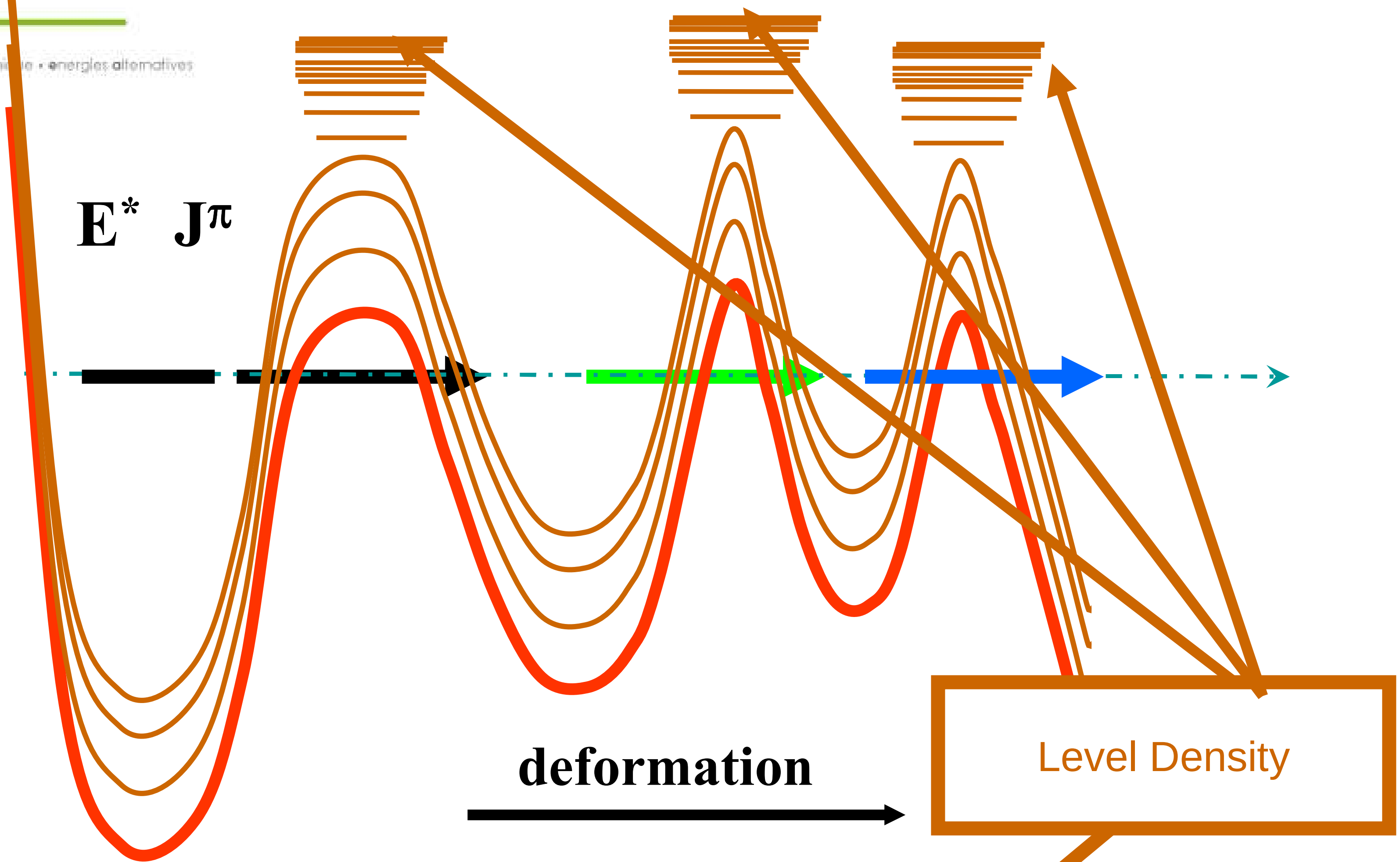
$$\frac{1}{T_f} = \frac{1}{T_A} + \frac{1}{T_B} + \frac{1}{T_C}$$

$$T_i = 1/[1 + \exp(2\pi(V_i - E)/\hbar\omega_i)]$$

Hill-Wheeler

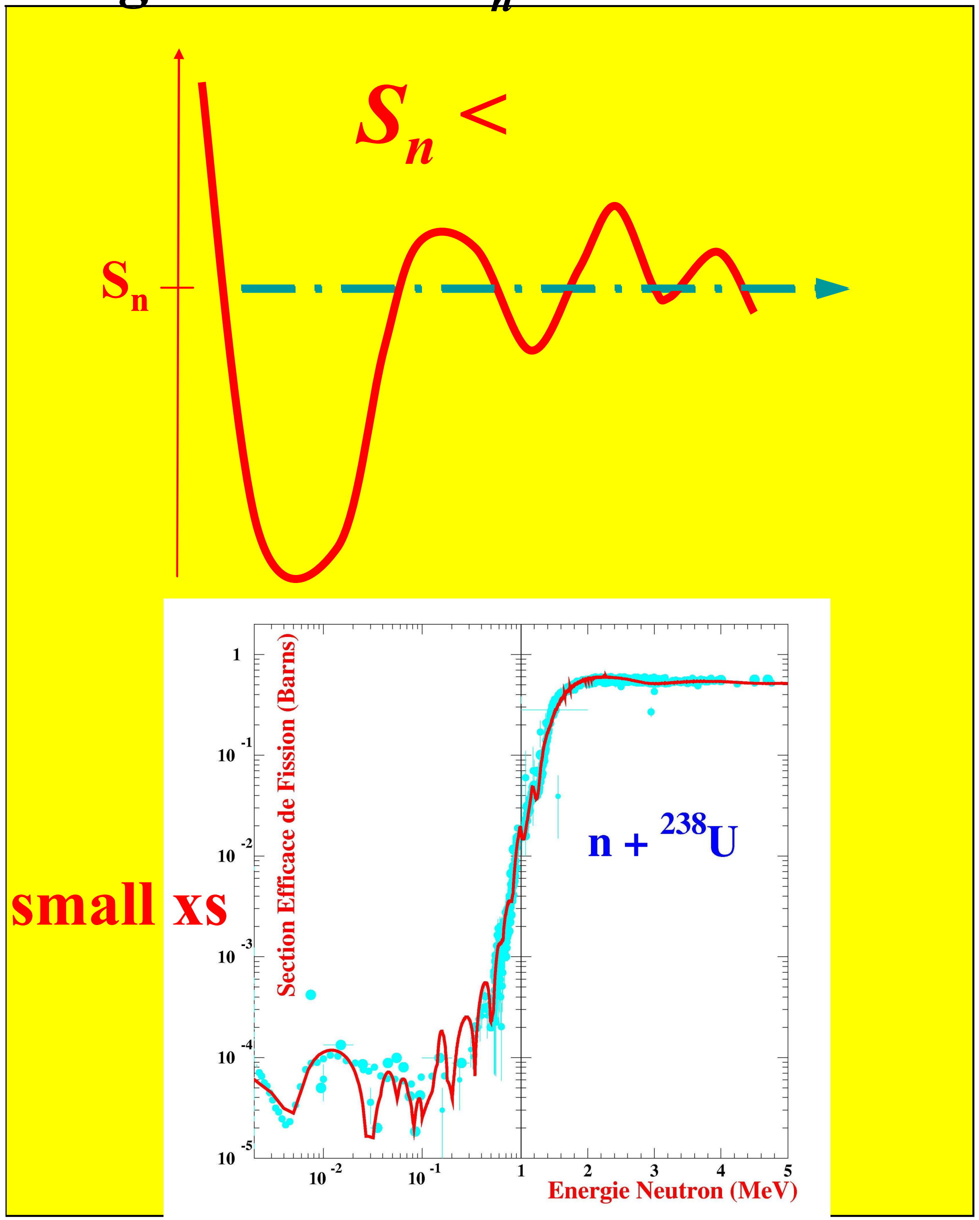
deformation

Transition States



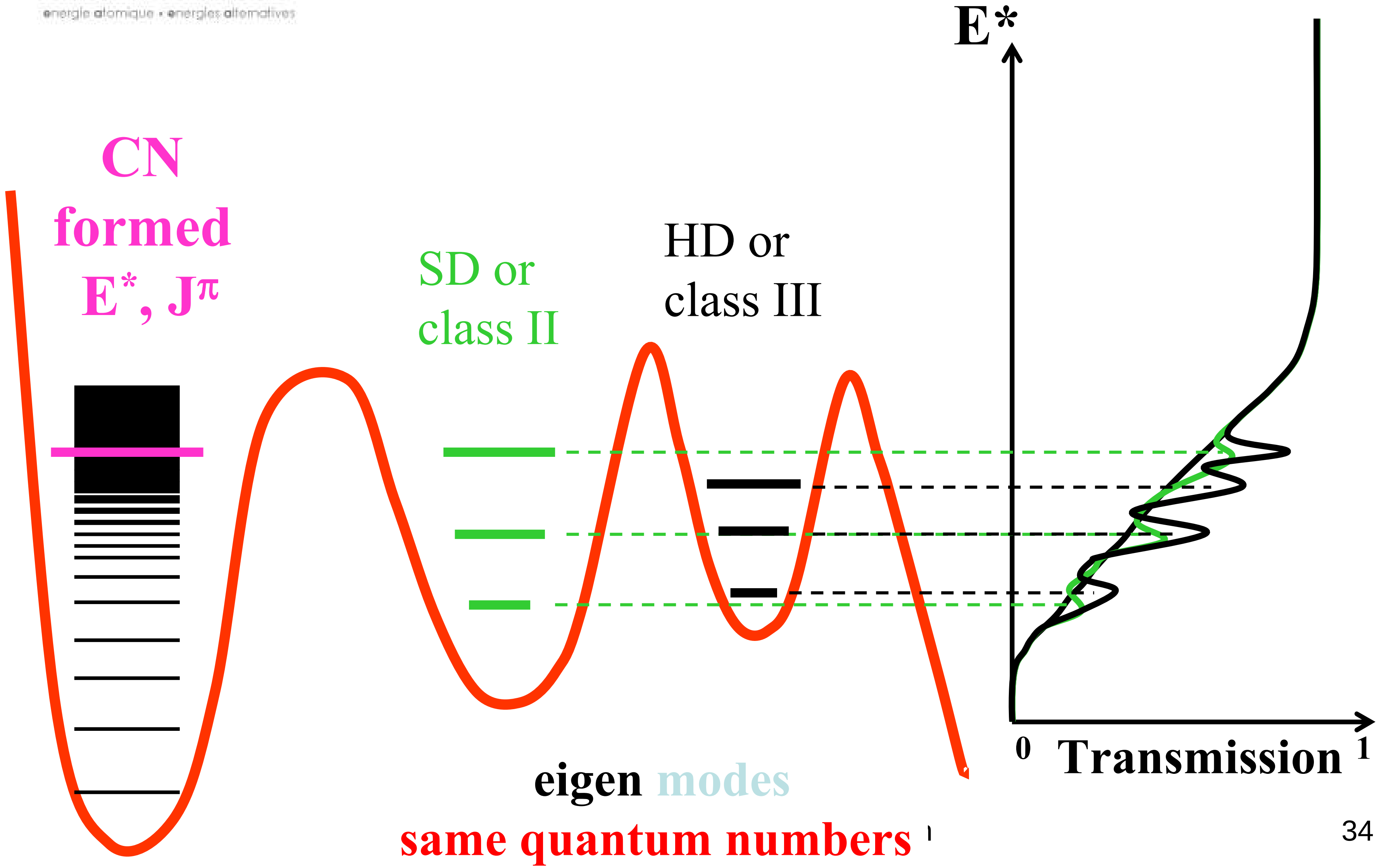
$$T_i^{J^\pi}(E^*) = \sum_k T_i^k(E^*, \varepsilon_i^k) + \int \rho_i(\varepsilon_i^x, J^\pi) T_i^x(E^*, \varepsilon_i^x) d\varepsilon_i^x \, .$$

At low neutron incident energies, CN is formed at excitation energies close to S_n.

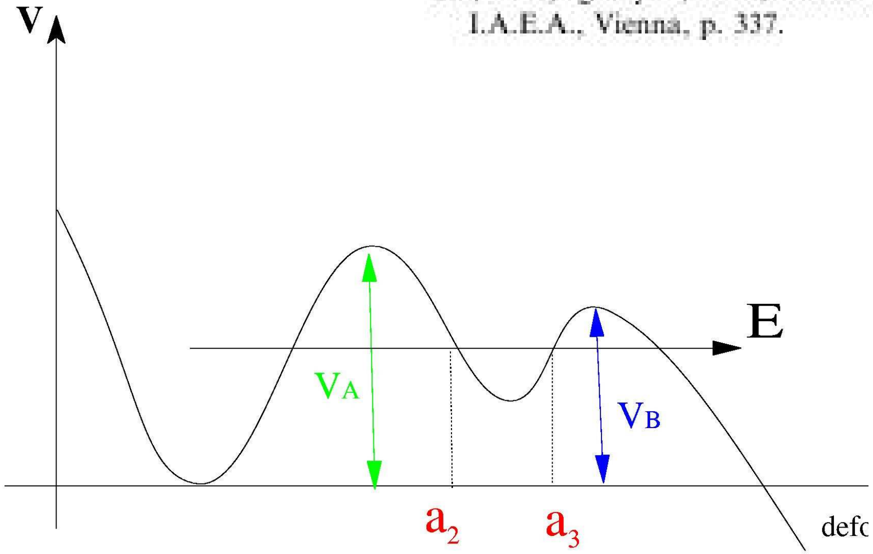


energie atomique • energies alternatives

Resonant Transmission



Gai, E.V., Ignatyuk, A.V., Rabotnov, N.S., Smirenkin, G.N., 1969. Physics and Chemistry of Fission. I.A.E.A., Vienna, p. 337.



$$T_{moy}(E) = \frac{1}{\pi}\int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} \frac{\frac{T_A T_B}{4}}{\cos^2\phi + (\frac{T_A+T_B}{4})^2 \sin^2\phi} d\phi$$

average

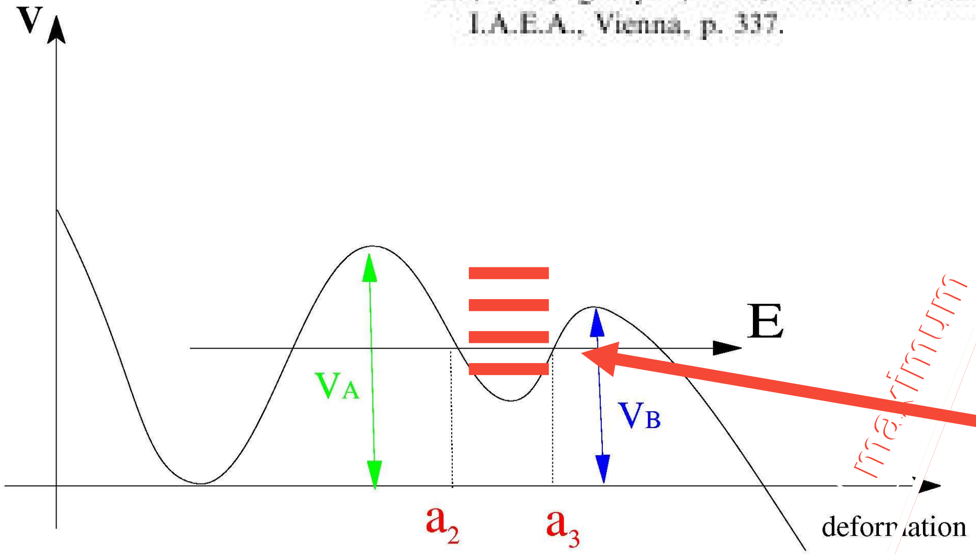
this leads to

$$T_{moy}(E) = \frac{T_A T_B}{T_A + T_B}$$

Academic model

$$T(E) \approx \frac{\frac{T_A T_B}{4}}{\cos^2\phi + (\frac{T_A+T_B}{4})^2 \sin^2\phi}$$

Gai, E.V., Ignatyuk, A.V., Rabotnov, N.S., Smirenkin, G.N., 1969. Physics and Chemistry of Fission. I.A.E.A., Vienna, p. 337.



$$T_{max}(E) = \frac{4T_A T_B}{(T_A + T_B)^2}$$

when :

$$\phi(E) = \int_{a_2}^{a_3} K(x)dx = \pi(E - E_{II})/\hbar\omega_{II} = (2n+1)\frac{\pi}{2}$$

assuming V(x) well oscillator

$$E - E_{II} = (n + \frac{1}{2})\hbar\omega_{II}$$

Academic model

$$T(E) \approx \frac{\frac{T_A T_B}{4}}{\cos^2\phi + (\frac{T_A + T_B}{4})^2 \sin^2\phi}$$

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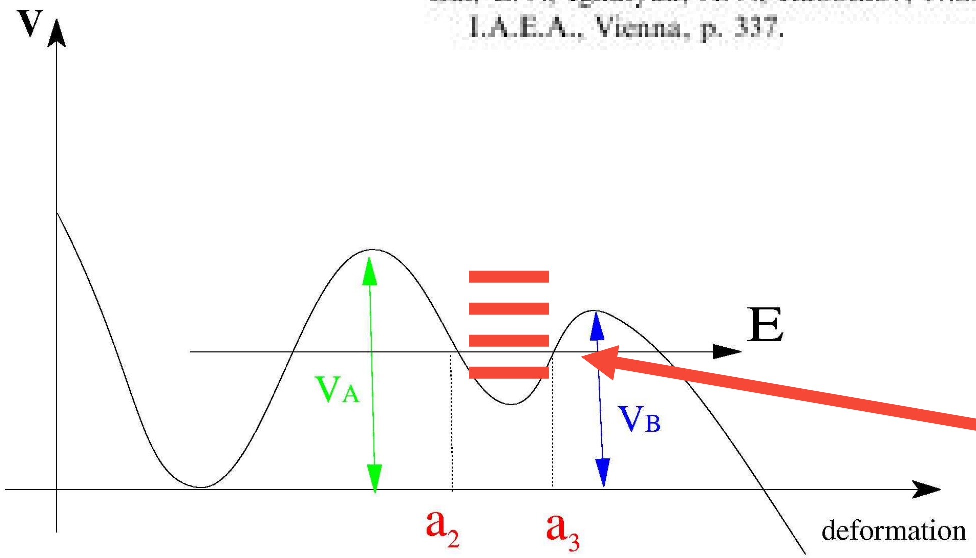

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assuming V(x) well oscillator

$$E - E_{II} = (n + \frac{1}{2})\hbar\omega_{II}$$

Resonant transmission

Academic model

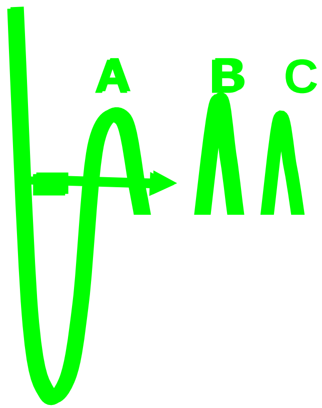
$${}^{R}T_2 = \frac{T_A \times T_B}{T_A + T_B} \times \boxed{\frac{4}{T_A + T_B}}$$

$$= \frac{4T_A^{J^\pi} T_B^{J^\pi}}{(T_A^{J^\pi} + T_B^{J^\pi})^2}$$

Enhancement factor for transmission that we will now apply to our simplified model for fission channel

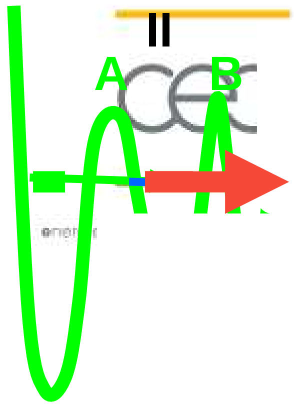
Extension
to a
Simplified model
and
generalization

{like in previous **GNASH** code (1996)}



Inverse parabola

Hill – Wheeler formula : $T_A(E) = \dfrac{1}{1 + \exp[\frac{-2\pi}{\hbar\omega}(E - V_A)]}$

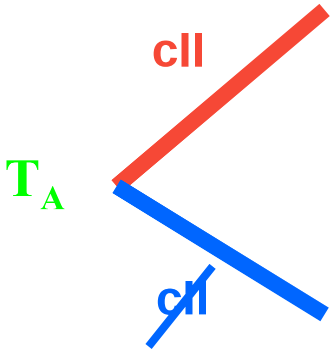


Double humped barrier → cII

double hump

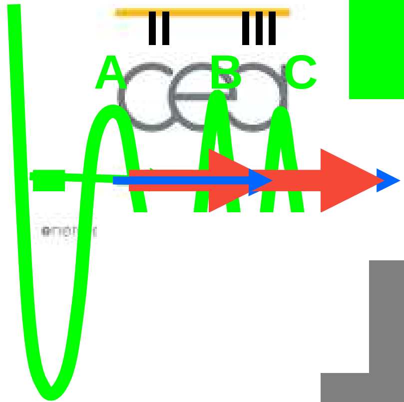
$$ {}^{R}T_2 = \frac{T_A \times T_B}{T_A + T_B} \times \boxed{\frac{4}{T_A + T_B}} $$

$$ = \frac{4 T_A^{J^\pi} T_B^{J^\pi}}{\left(T_A^{J^\pi} + T_B^{J^\pi}\right)^2} $$



$$ T_2 = \frac{T_A \times T_B}{T_A + T_B} = \frac{T_A^{J^\pi} T_B^{J^\pi}}{\left(T_A^{J^\pi} + T_B^{J^\pi}\right)} $$

Ann. Nucl. Energy ***32***, *195 (2005)*



Triple humped barrier → cII and cIII

double hump

T_A

cII

$${}^{R}T_2 = \frac{T_A \times T_B}{T_A + T_B} \times \frac{4}{T_A + T_B} = \frac{4T_A^{J^\pi} T_B^{J^\pi}}{\left(T_A^{J^\pi} + T_B^{J^\pi}\right)^2}$$

~~cII~~

$$T_2 = \frac{T_A \times T_B}{T_A + T_B} = \frac{T_A^{J^\pi} T_B^{J^\pi}}{\left(T_A^{J^\pi} + T_B^{J^\pi}\right)}$$

triple hump

cIII

$$\frac{{}^{R}T_2 \times T_C}{{}^{R}T_2 + T_C} \times \frac{4}{{}^{R}T_2 + T_C} = \frac{16 T_A^{J^\pi} T_B^{J^\pi} T_C^{J^\pi} \left(T_A^{J^\pi} + T_B^{J^\pi}\right)^2}{\left(4T_A^{J^\pi} T_B^{J^\pi} + T_C^{J^\pi}\left(T_A^{J^\pi} + T_B^{J^\pi}\right)^2\right)^2}.$$

~~cIII~~

$$\frac{{}^{R}T_2 \times T_C}{{}^{R}T_2 + T_C} = \frac{4 T_A^{J^\pi} T_B^{J^\pi} T_C^{J^\pi}}{4T_A^{J^\pi} T_B^{J^\pi} + T_C^{J^\pi}\left(T_A^{J^\pi} + T_B^{J^\pi}\right)^2}.$$

cIII

$$\frac{T_2 \times T_C}{T_2 + T_C} \times \frac{4}{T_2 + T_C} = \frac{4 T_A^{J^\pi} T_B^{J^\pi} T_C^{J^\pi}\left(T_A^{J^\pi} + T_B^{J^\pi}\right)}{\left(T_A^{J^\pi} T_B^{J^\pi} + T_A^{J^\pi} T_C^{J^\pi} + T_B^{J^\pi} T_C^{J^\pi}\right)^2}.$$

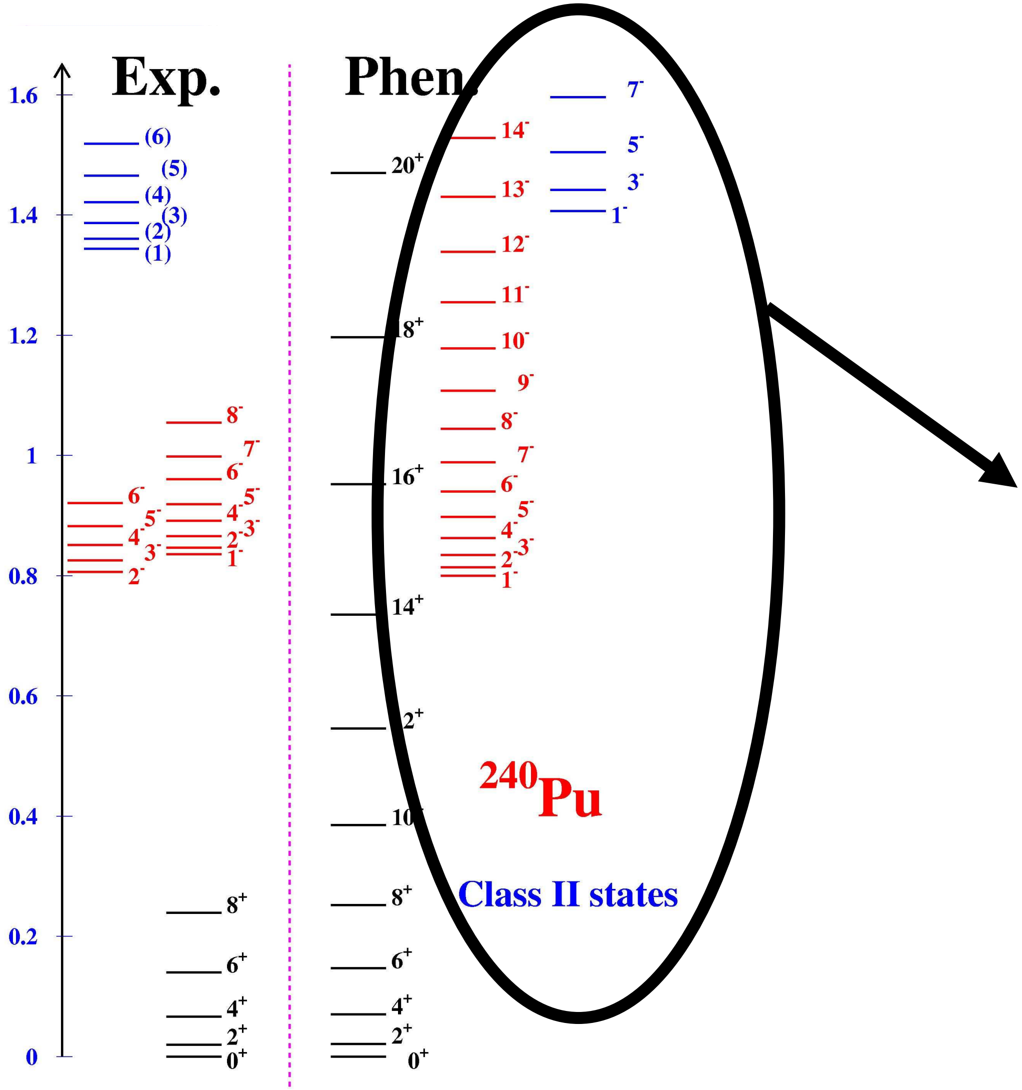
~~cIII~~

$$\frac{T_2 \times T_C}{T_2 + T_C} = \frac{T_A^{J^\pi} T_B^{J^\pi} T_C^{J^\pi}}{T_A^{J^\pi} T_B^{J^\pi} + T_A^{J^\pi} T_C^{J^\pi} + T_B^{J^\pi} T_C^{J^\pi}}.$$

Ann. Nucl. Energy ***32****, 195 (2005)*

B. Morillon H. Duarte P. Roma

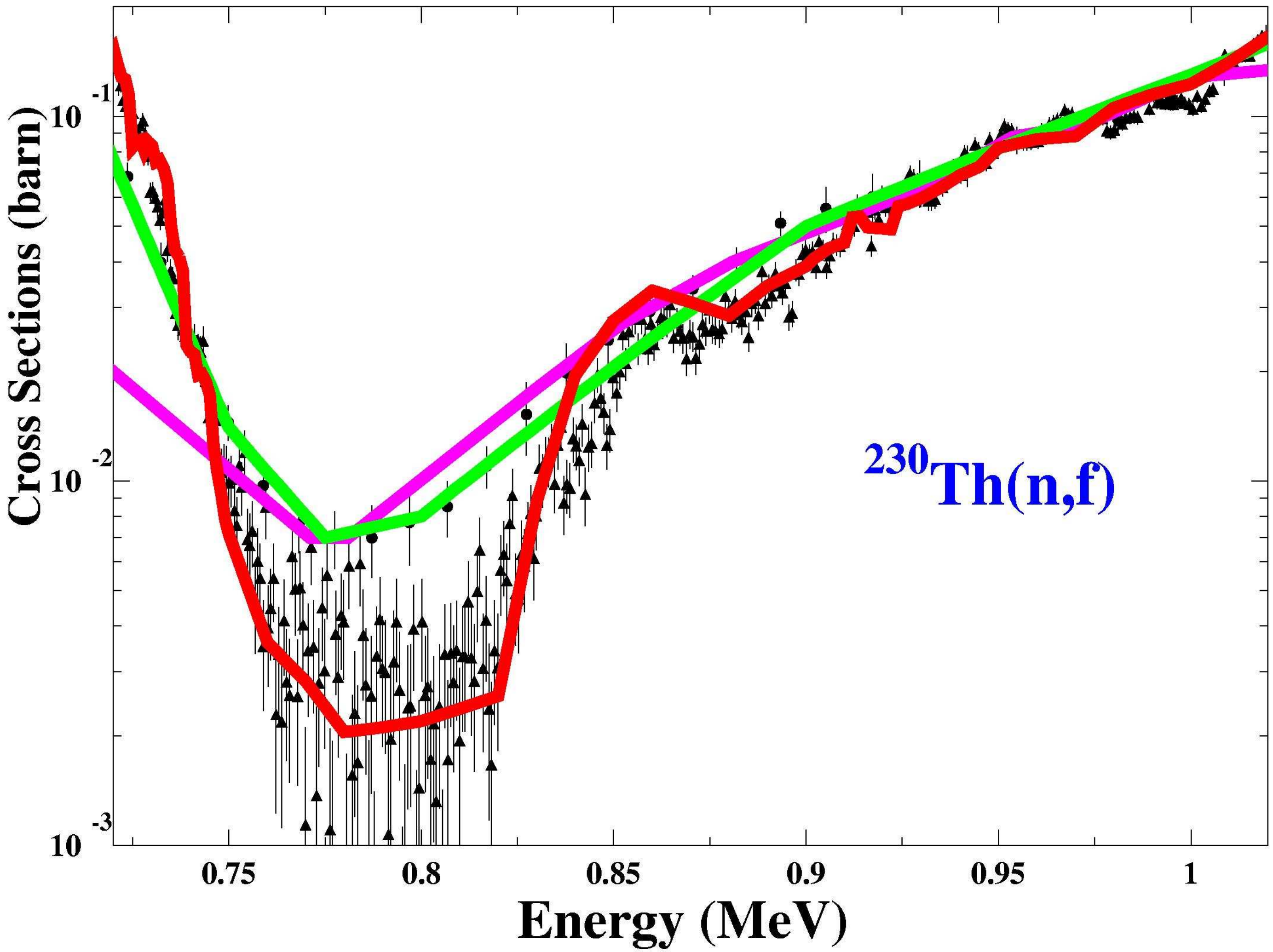
In this simplified model we have only to adjust (to find E_i and J^π) cII and cIII quantum number in order to reproduce (fit) the first chance fission cross sections



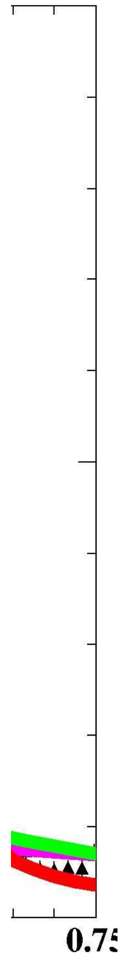
Results of our adjustments without knowing experiment

TEST of our model on ^{230}Th

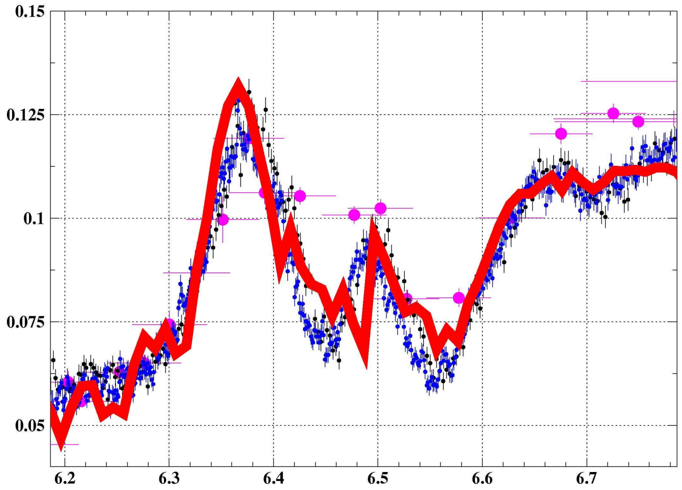
Z = 90



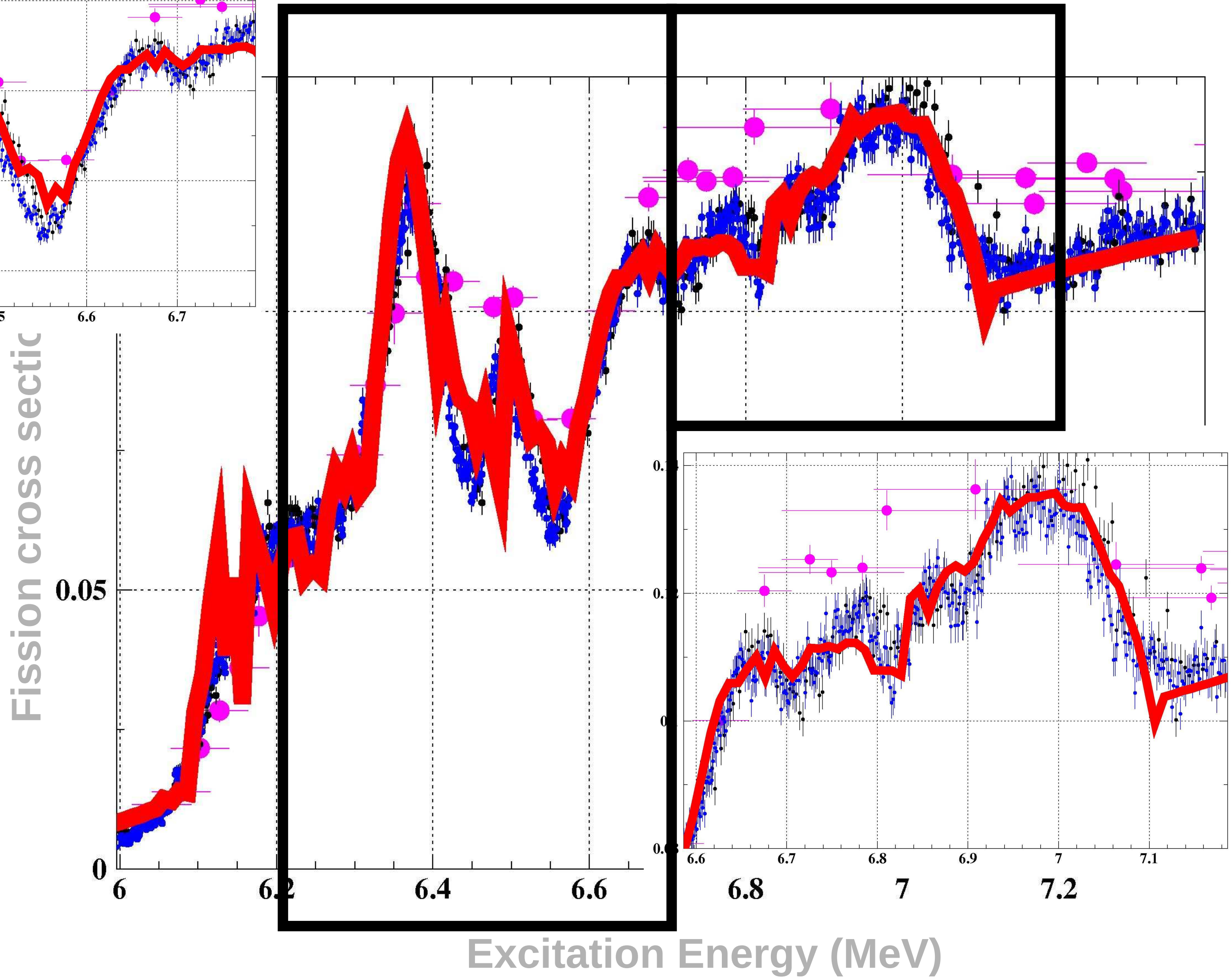
Cross Sections (barn)
10^-1
10^-2
10^-3
0.75
0.8
0.85
0.9
0.95
1
Energy (MeV)
230Th(n,f)



0.75


0.15
0.125
0.1
0.075
0.05
6.2
6.3
6.4
6.5
6.6
6.7

n + ^{232}Th

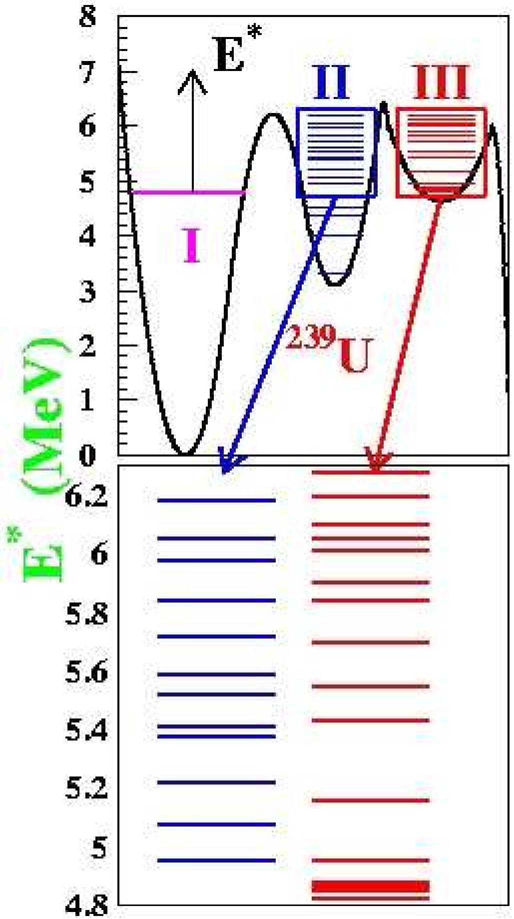

Fission cross sectic
0.05
0
6
6.2
6.4
6.6
6.8
7
7.2
Excitation Energy (MeV)
6.6
6.7
6.8
6.9
7
7.1

TEST of our model on

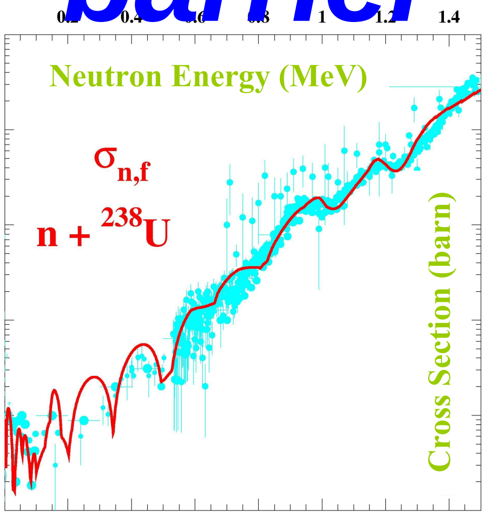
Z = 92

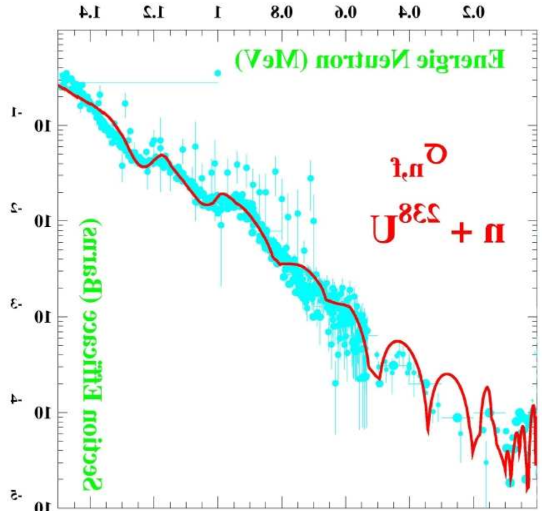
^{239}U : Triple-humped fission barrier

Resonant transmission



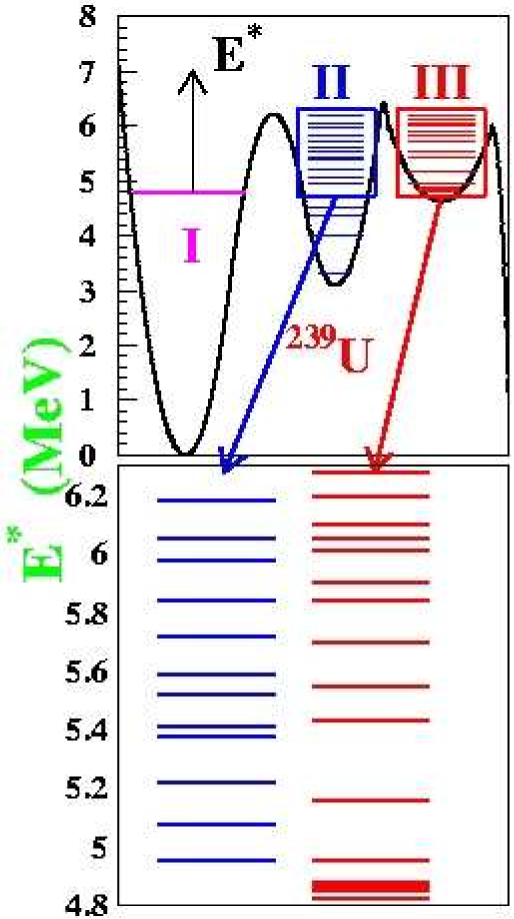
Bandhead states



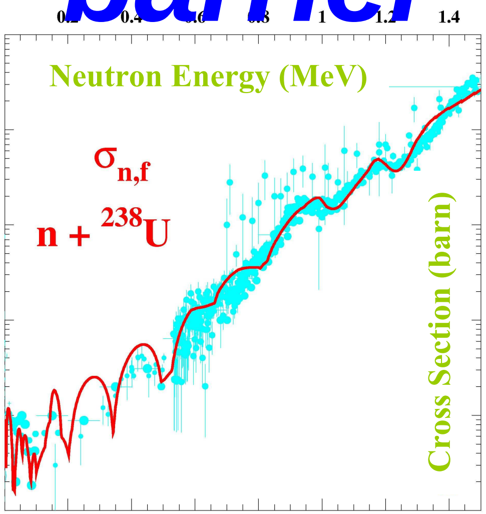


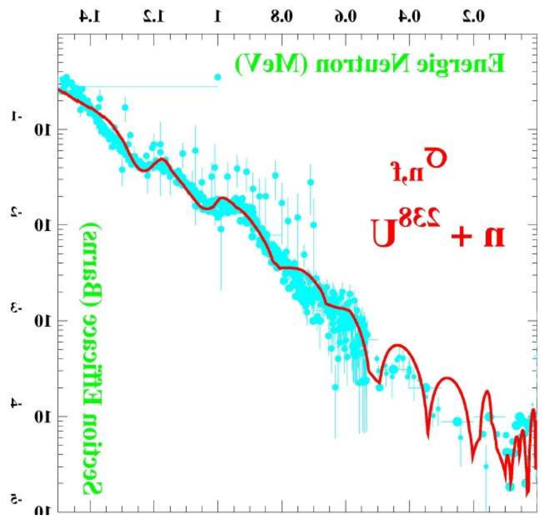
^{239}U : Triple-humped fission barrier

Resonant transmission



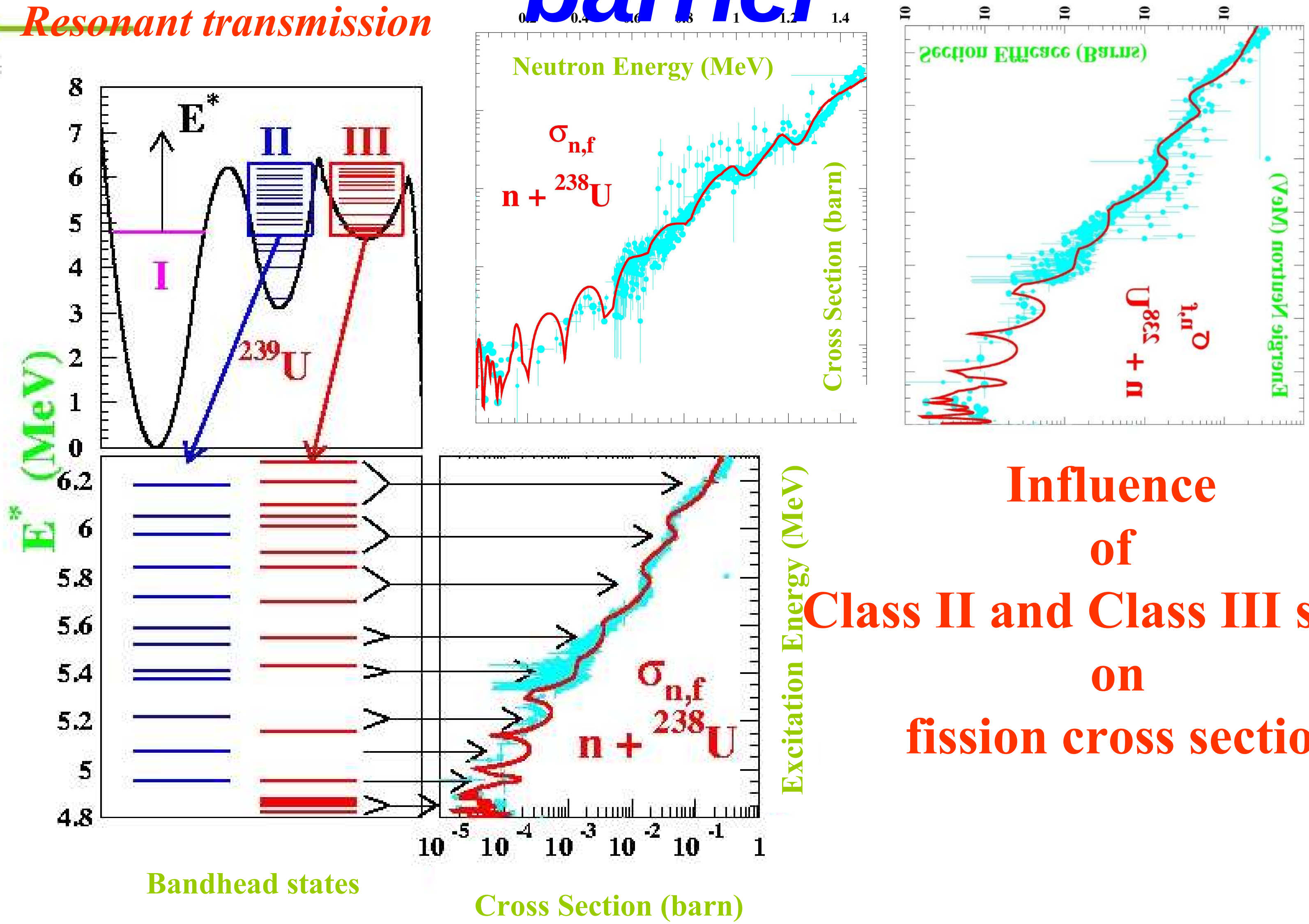
Bandhead states





^{239}U : Triple-humped fission barrier

Resonant transmission



Influence of Class II and Class III states on fission cross section

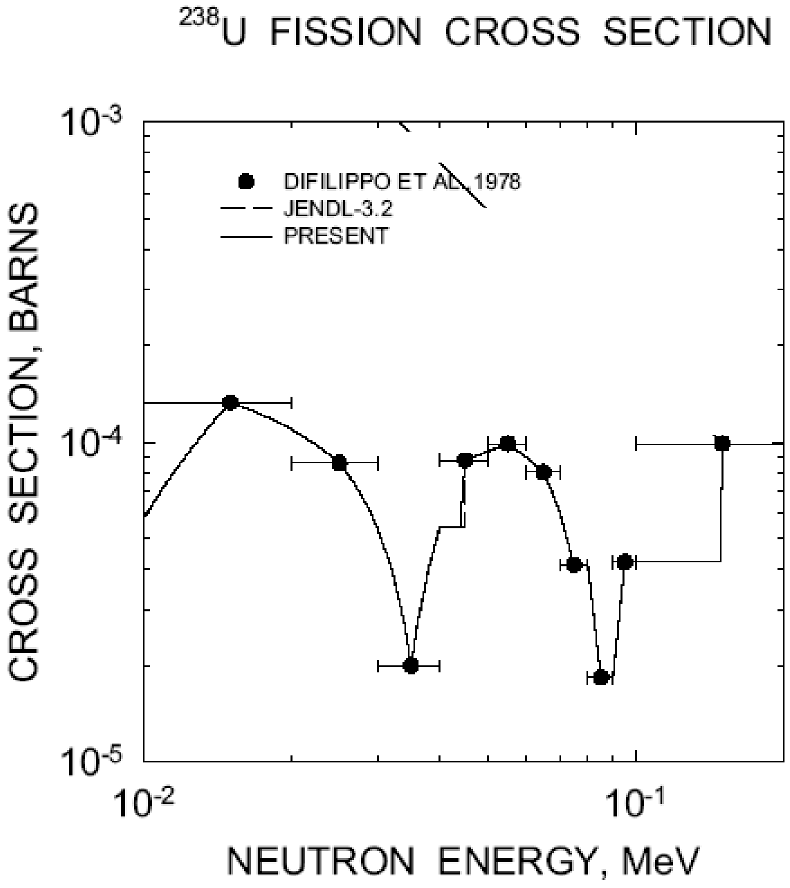
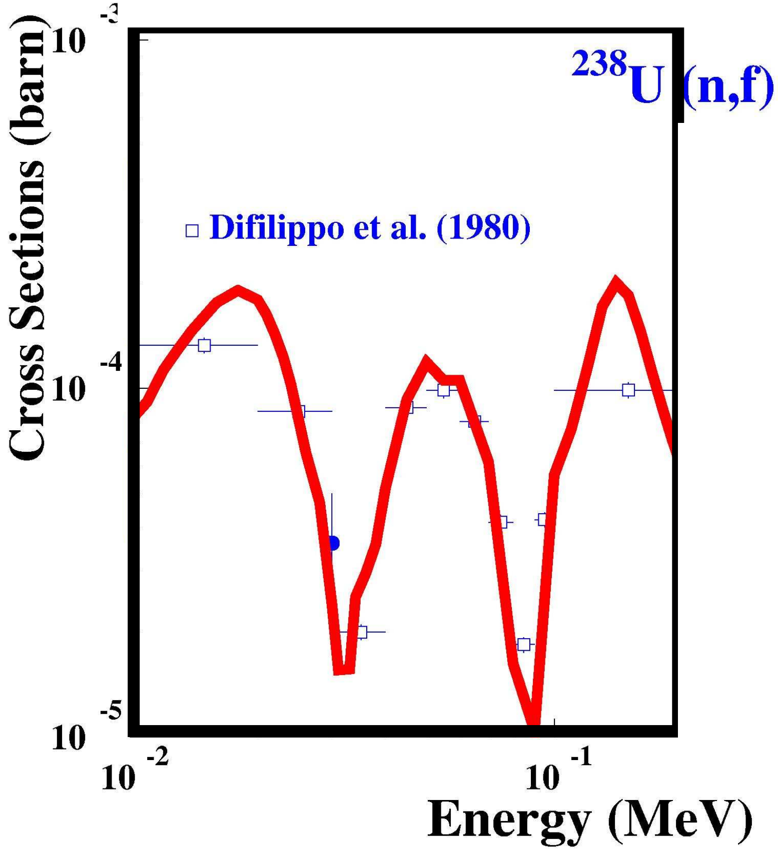


FIG. 10



V. MASLOV INDC(BLR)-014

INTERNATIONAL ATOMIC ENERGY AGENCY

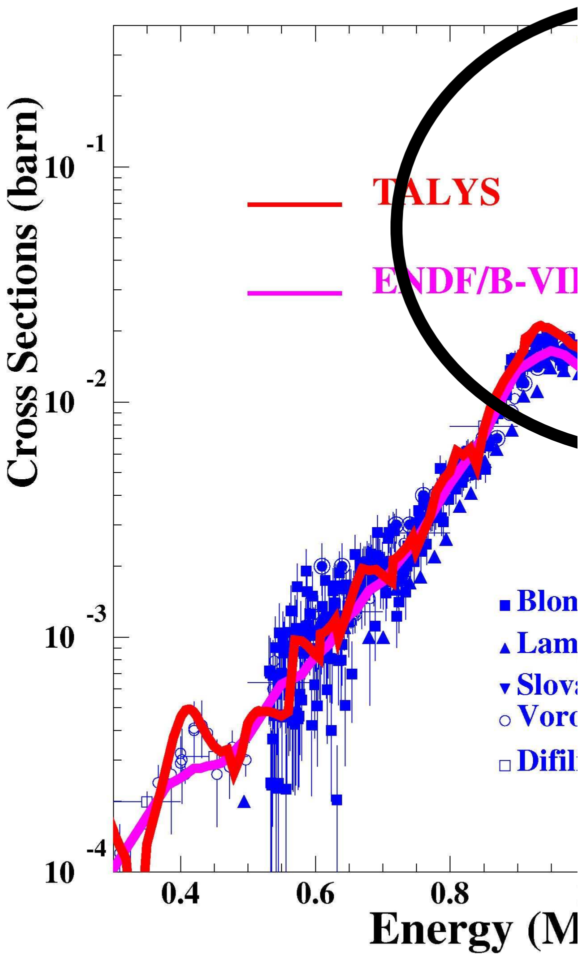
INDC(BLR)-014
Distr. J+TU/EL

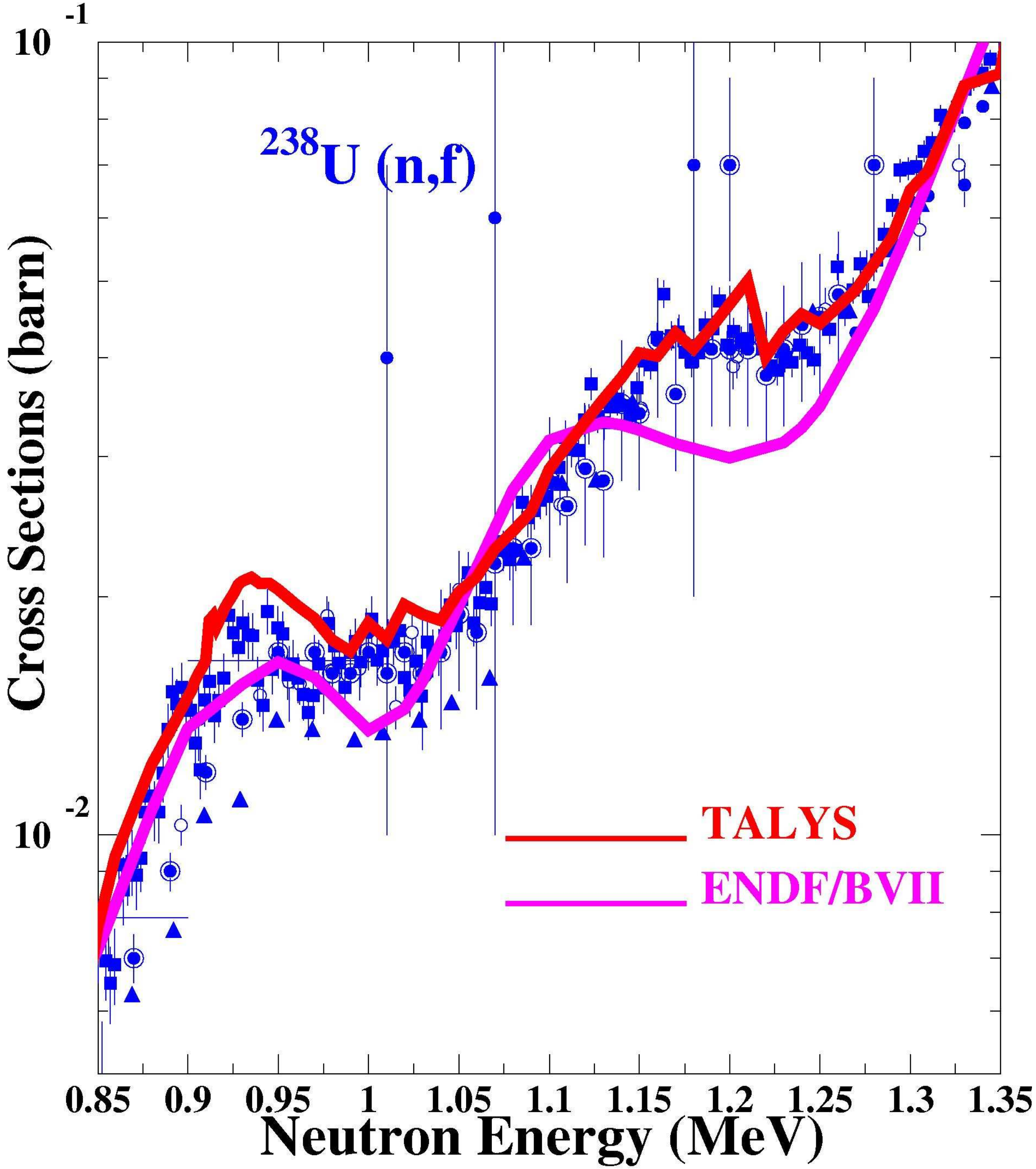
INDC INTERNATIONAL NUCLEAR DATA COMMITTEE

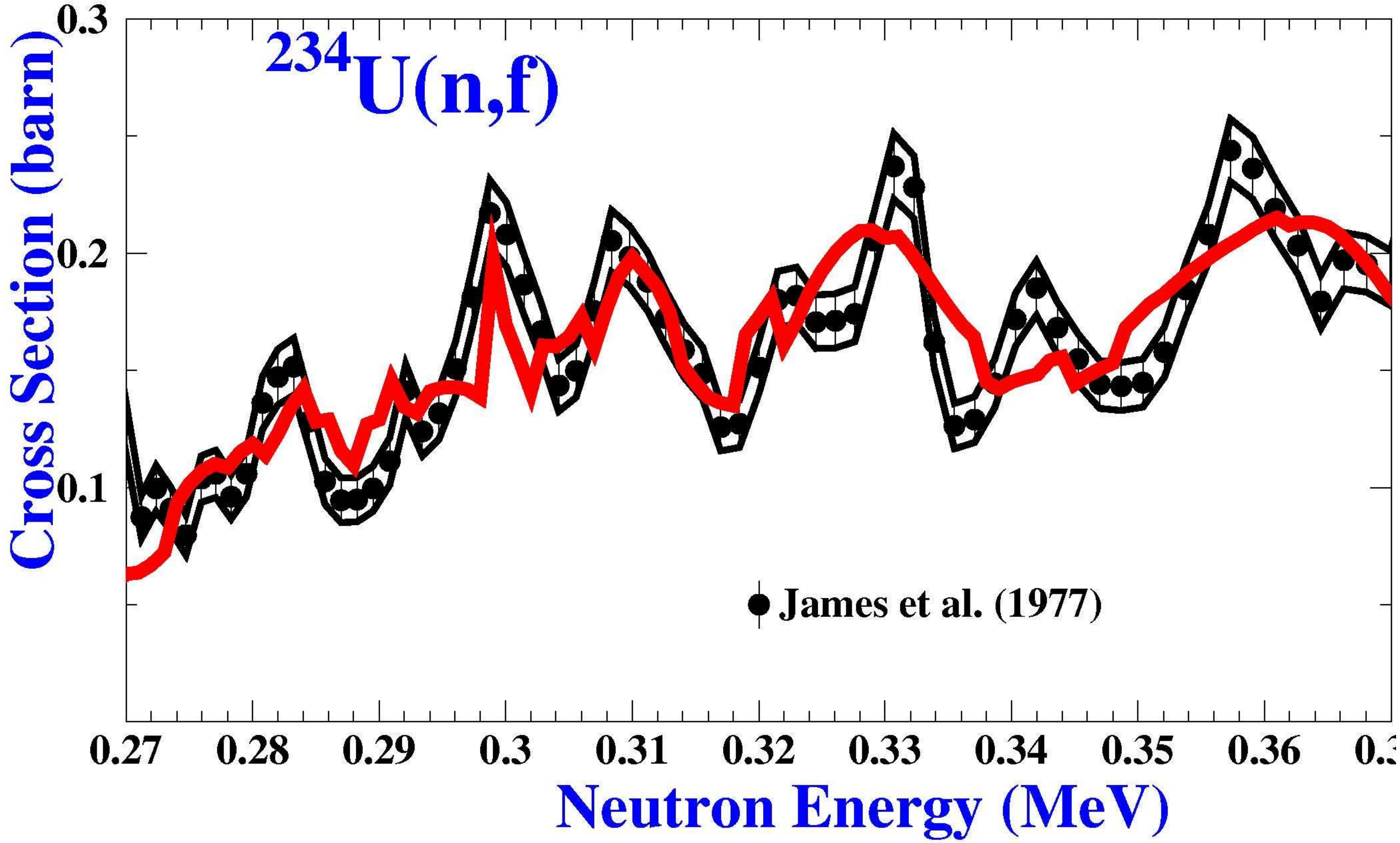
H. Duarte P. Romain

TALYS

TALYS = BRC2008

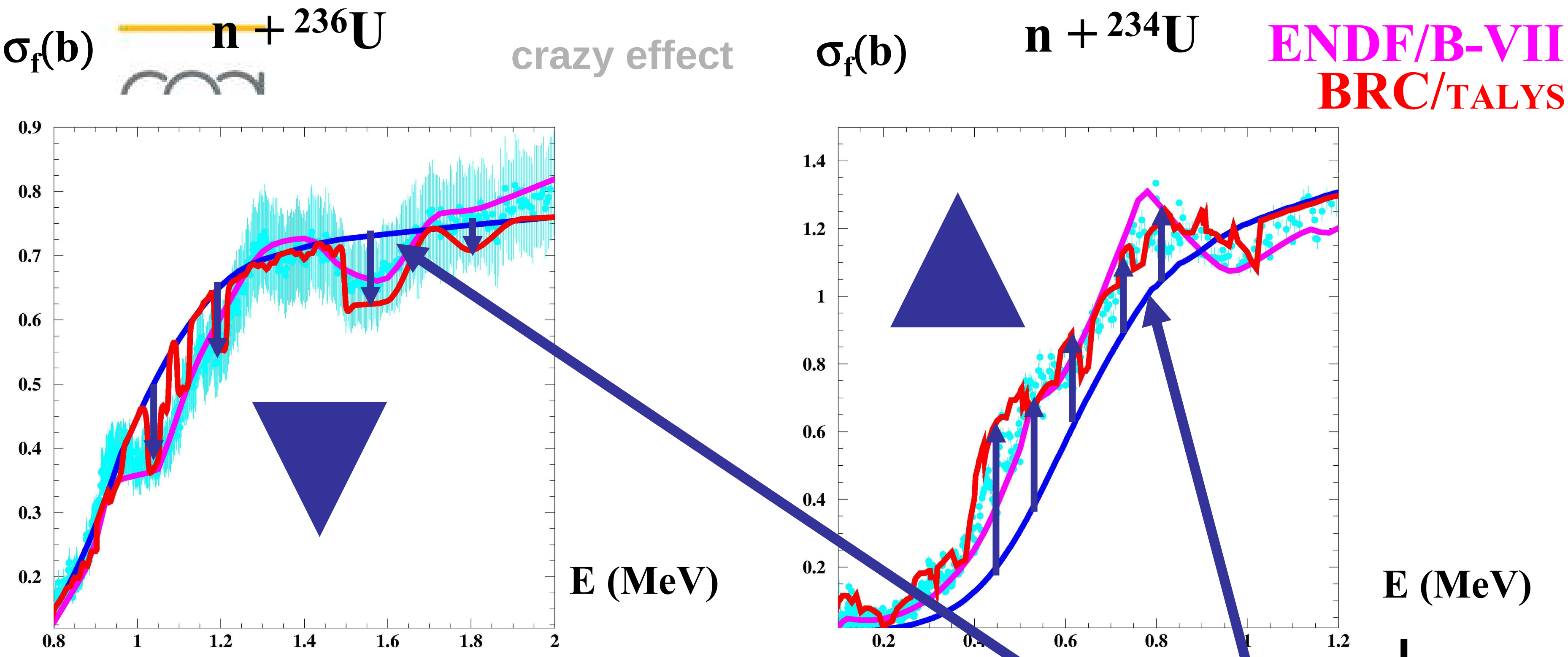




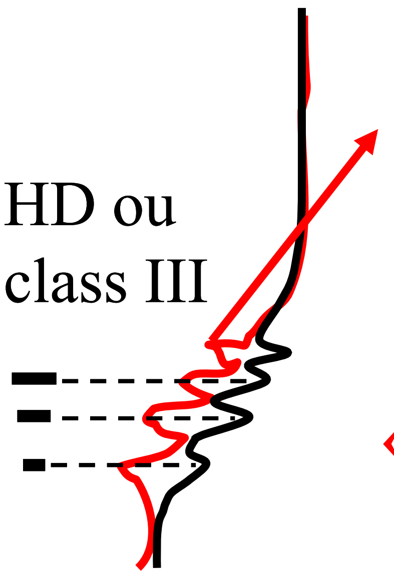


$^{234}U(n,f)$
Cross Section (barn)
0.3
0.2
0.1
James et al. (1977)
0.27
0.28
0.29
0.3
0.31
0.32
0.33
0.34
0.35
0.36
Neutron Energy (MeV)

TALYS



HD ou
class III



antiresonance

antiresonant circuit
= circuit bouchon
(frenchy speaking)

« bouchonance »

B. Morillon H. Duarte P. Ro

M.J. López-Jiménez

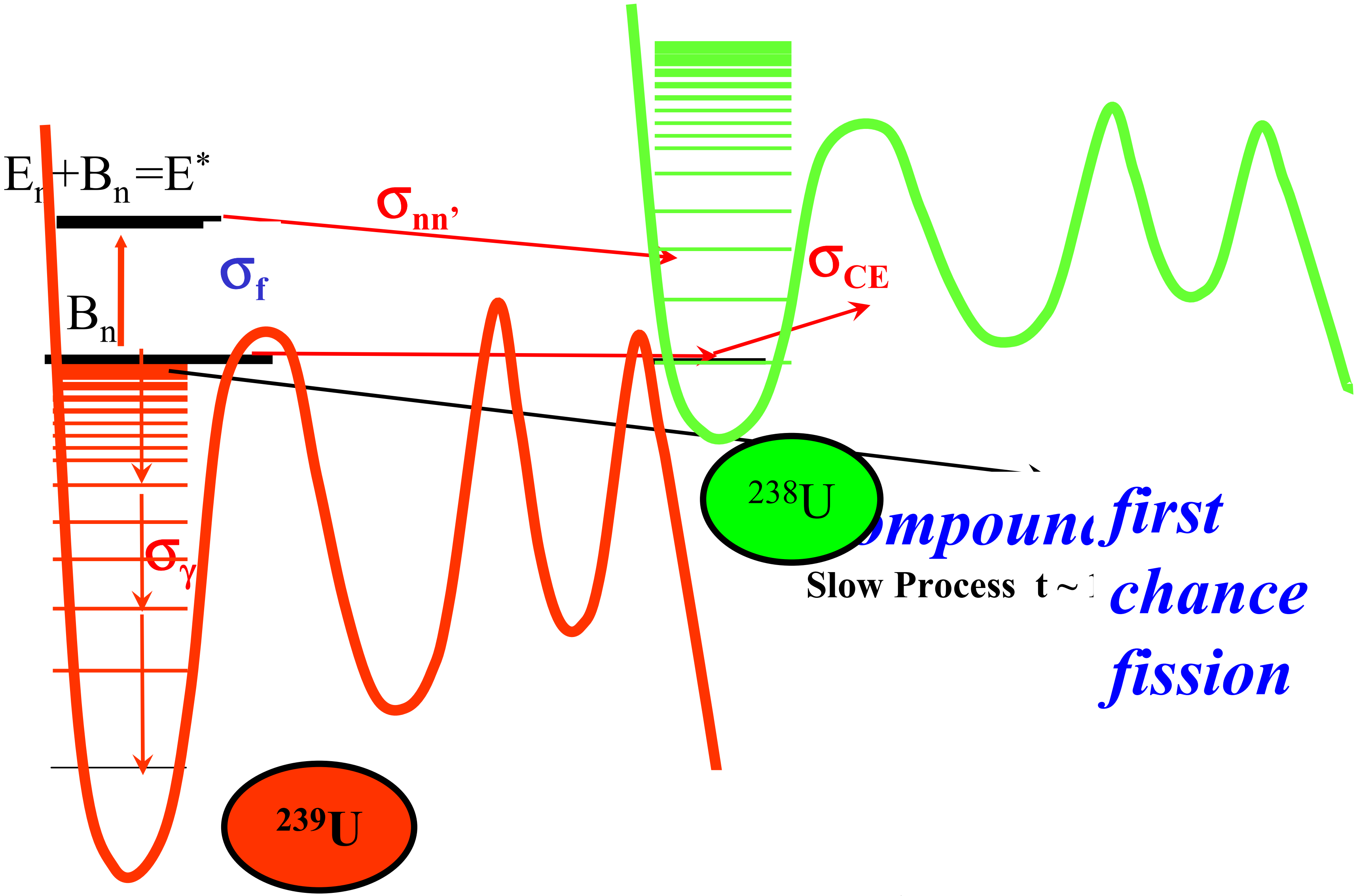
Post doc 2001-2003

at SPN

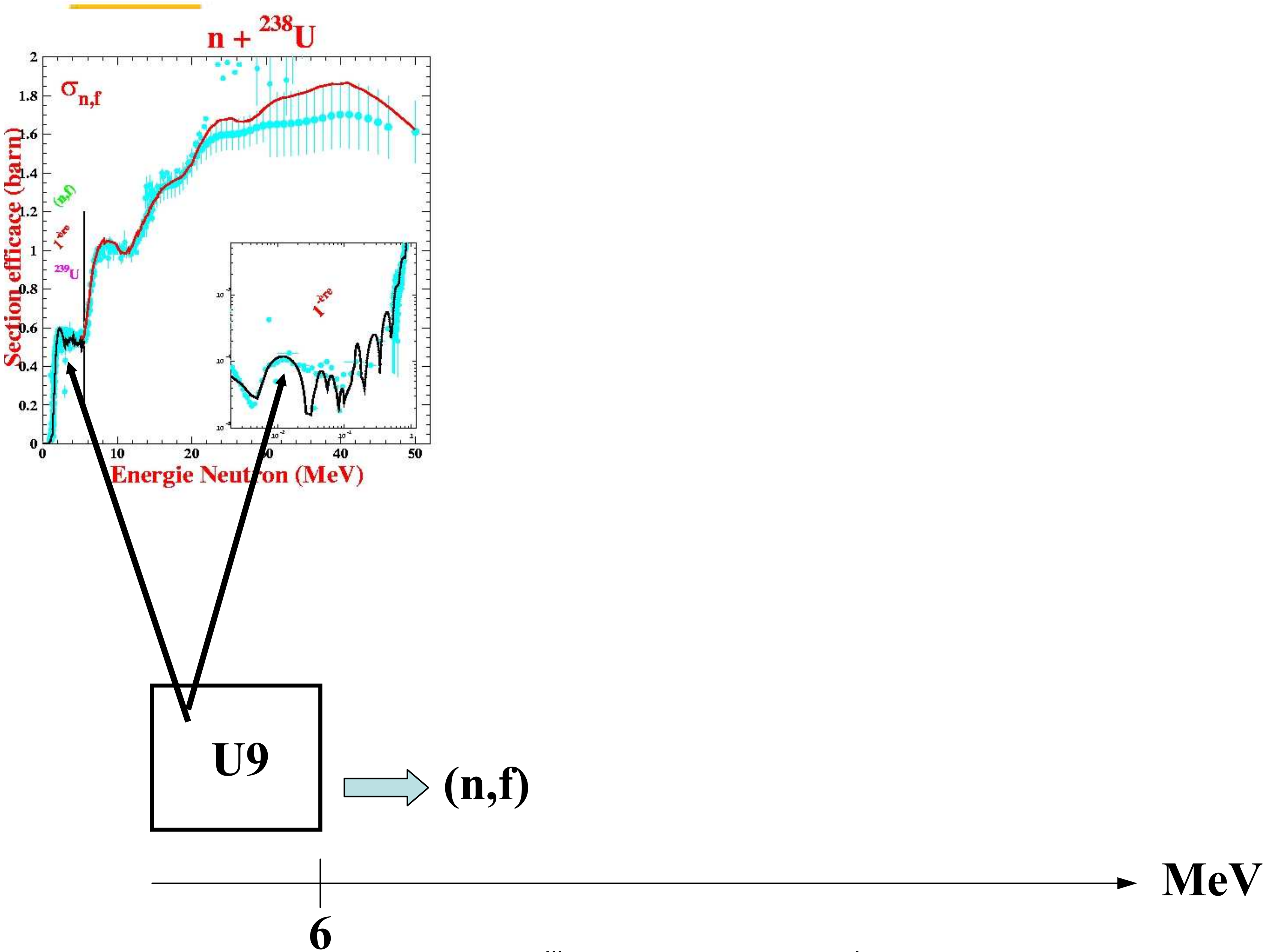
energie atomique • energies alternatives

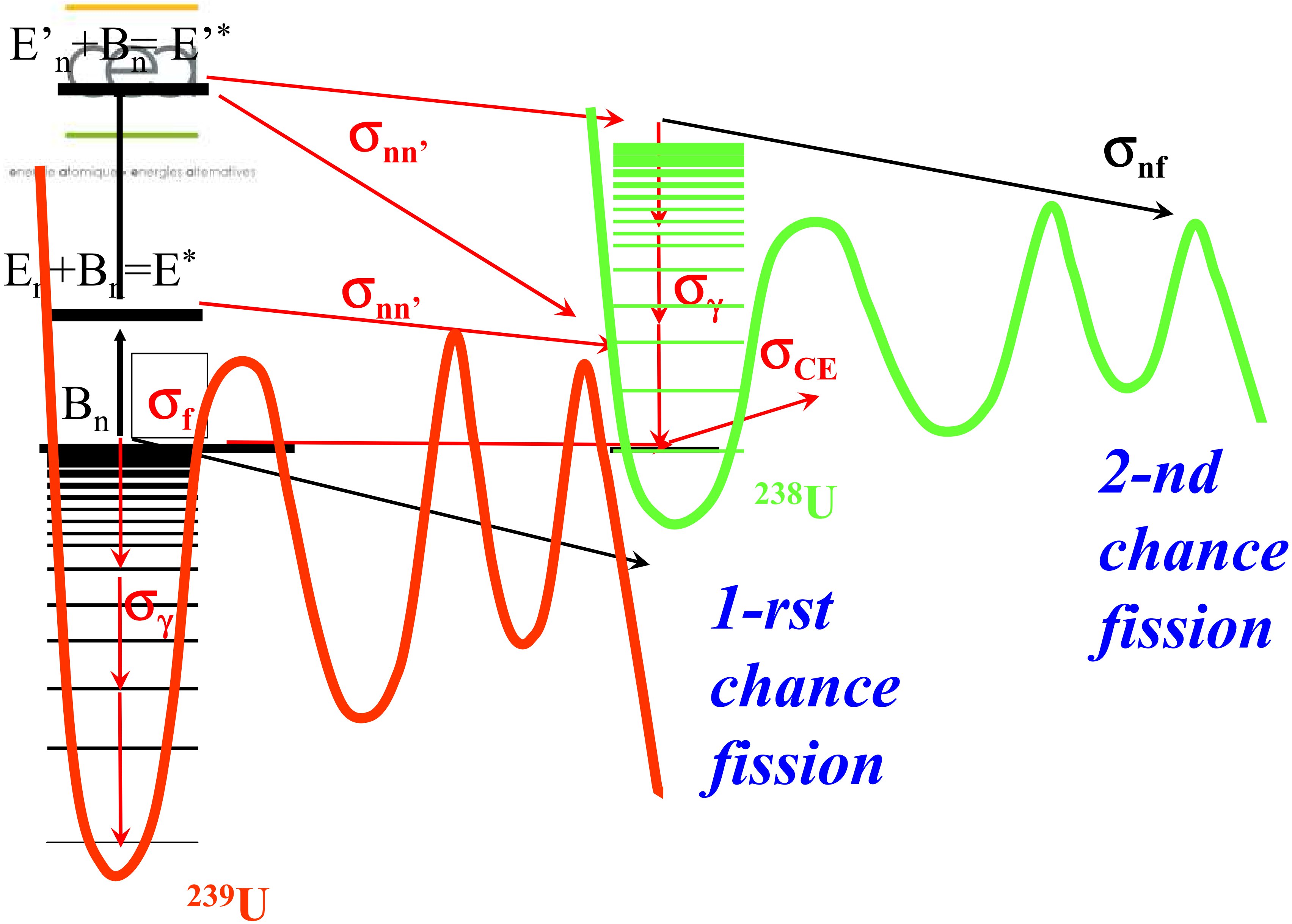
And now when neutron incident energy increases

methodology

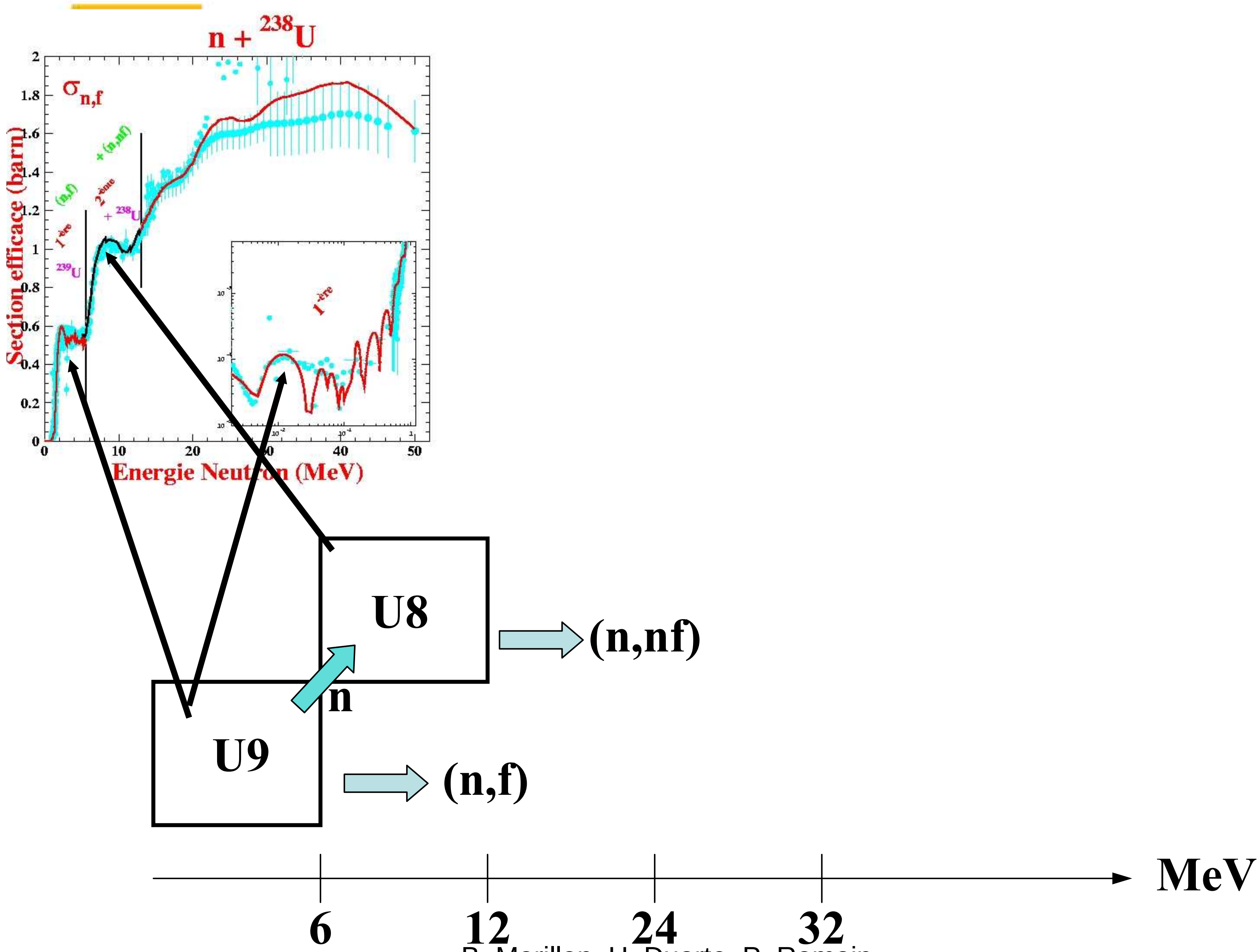


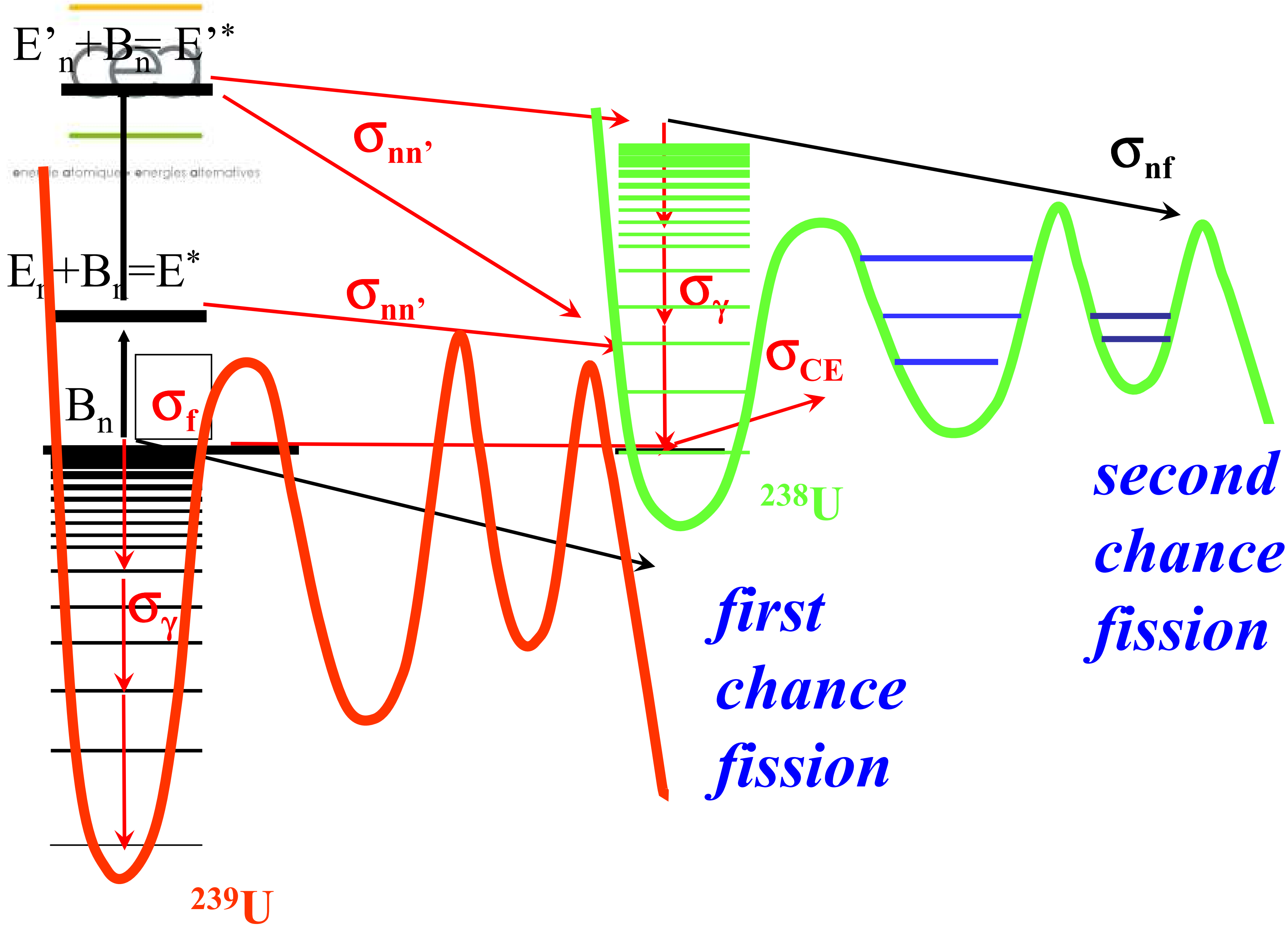
first chance fission


n + 238U
σn,f
Section efficace (barn)
Energie Neutron (MeV)
(n,f)
1ère
239U
U9
(n,f)
MeV
6

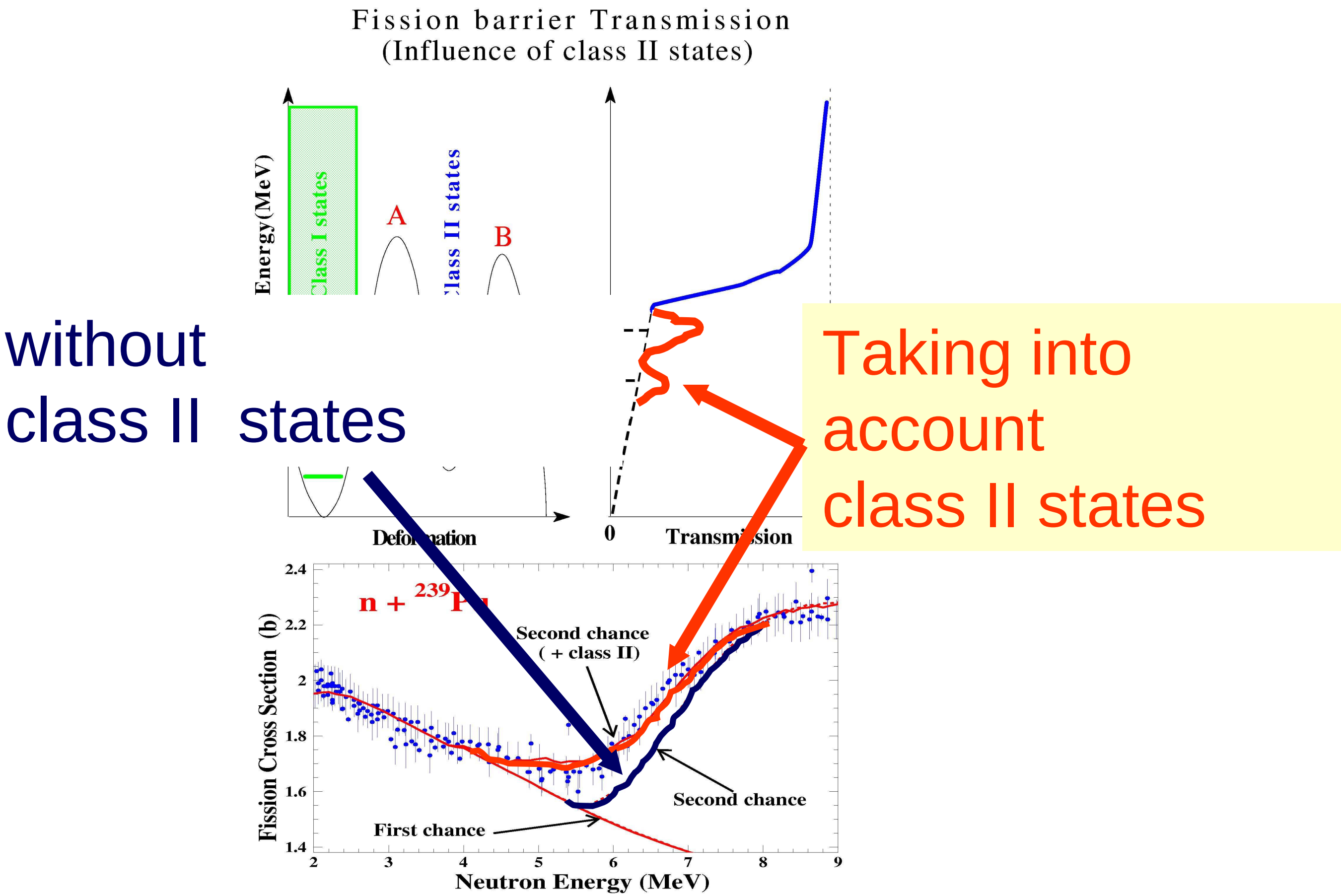


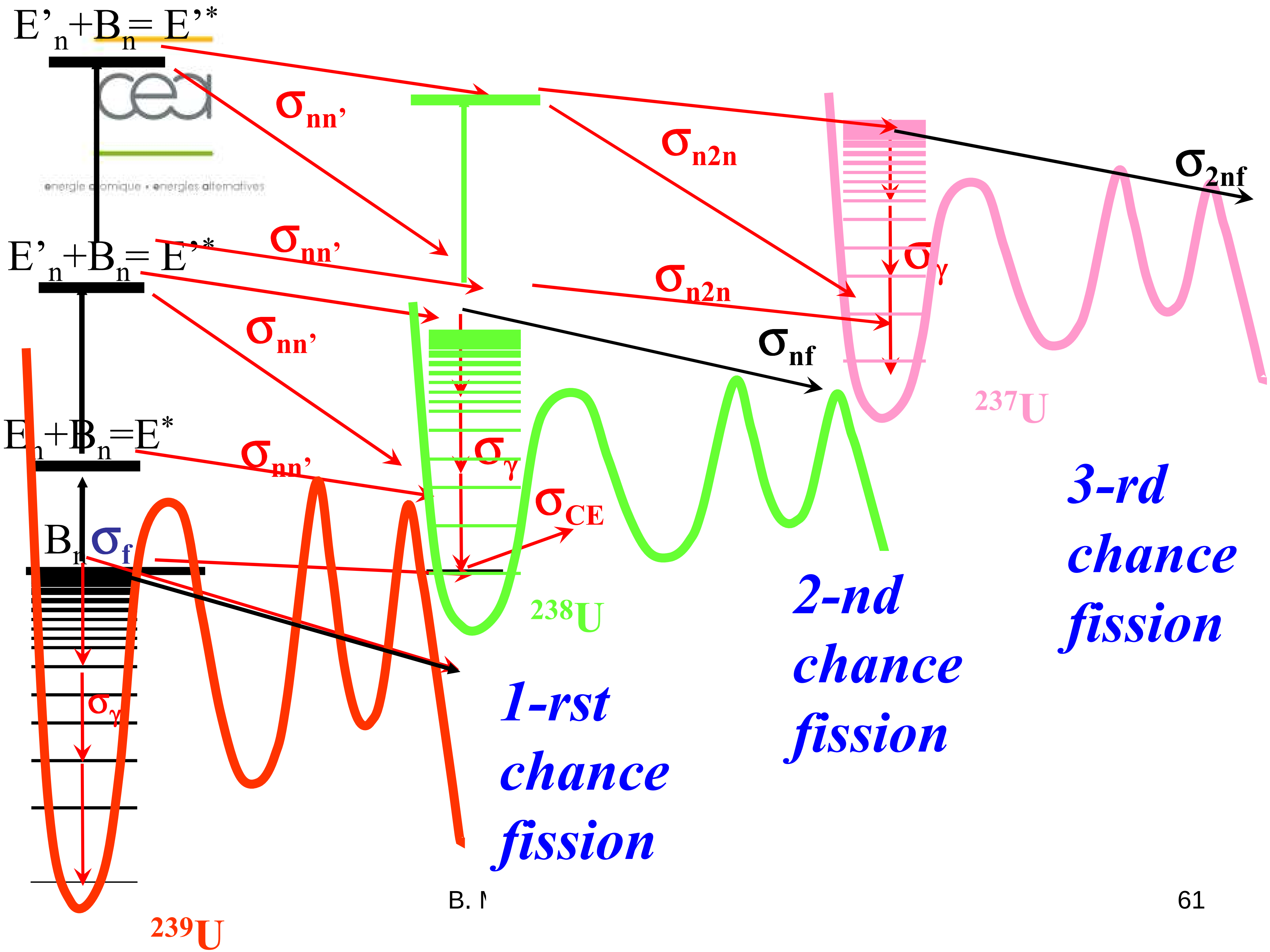
E'n+Bn=E'*
En+Bn=E*
σnn'
σnn'
σnf
σγ
σCE
Bn
σf
σγ
238U
239U
1-rst chance fission
2-nd chance fission

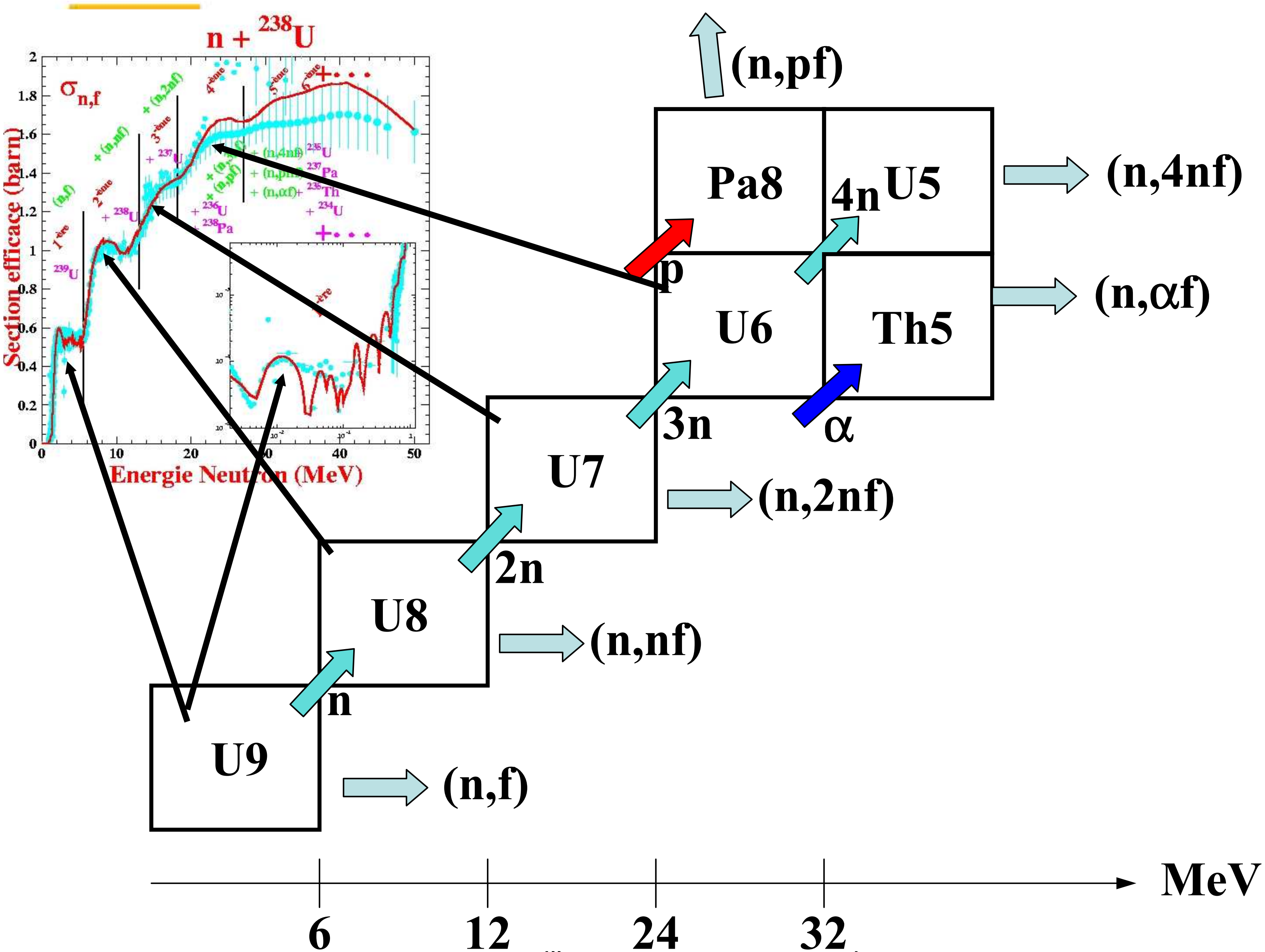

n + 238U
σn,f
Section efficace (barn)
Energie Neutron (MeV)
(n,f)
+ (n,nf)
U8
U9
n
(n,nf)
(n,f)
MeV
6
12
24
32


E'n+Bn=E'*
En+Bn=E*
Bn
σf
σnn'
σnn'
σγ
σγ
σCE
σnf
238U
239U
first chance fission
second chance fission

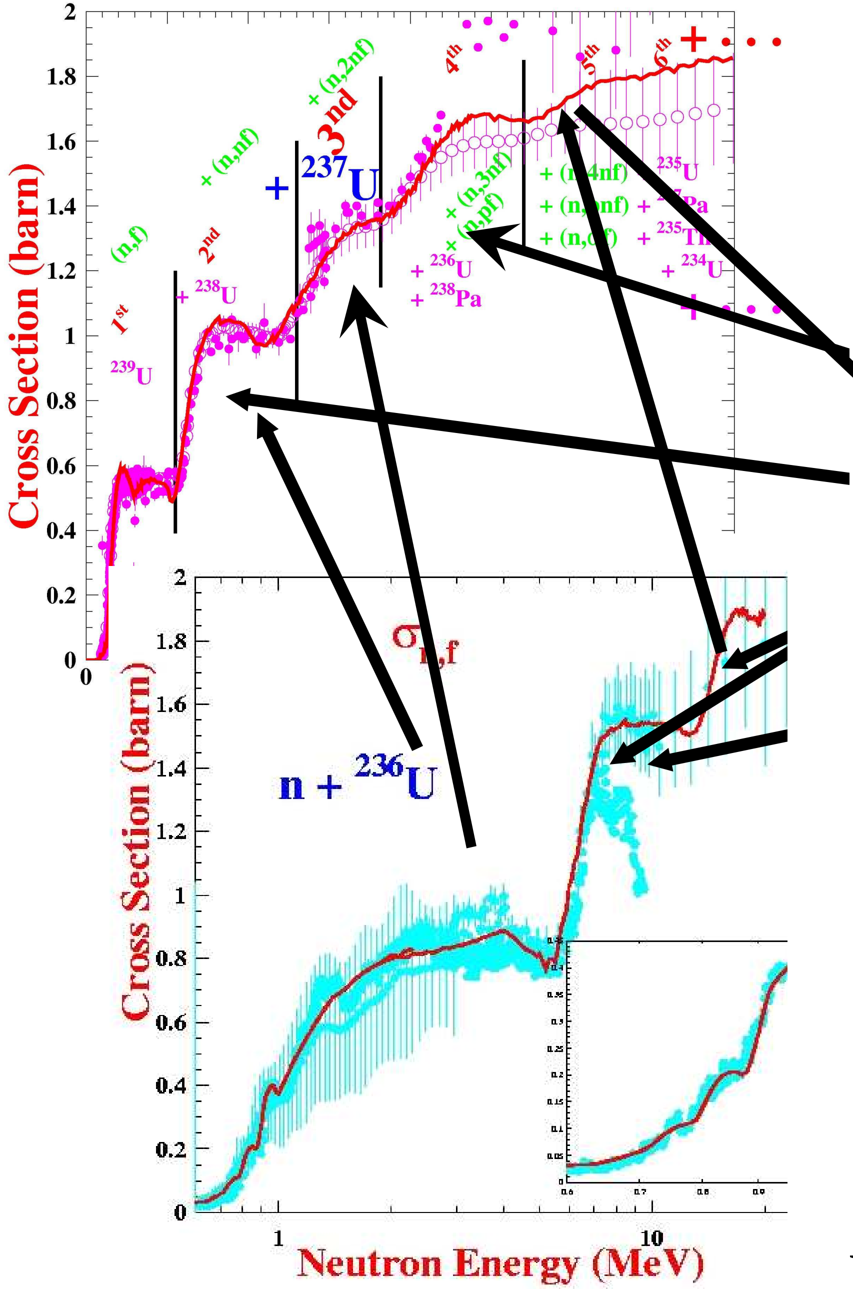
Effects of class II states on opening of second chance fission

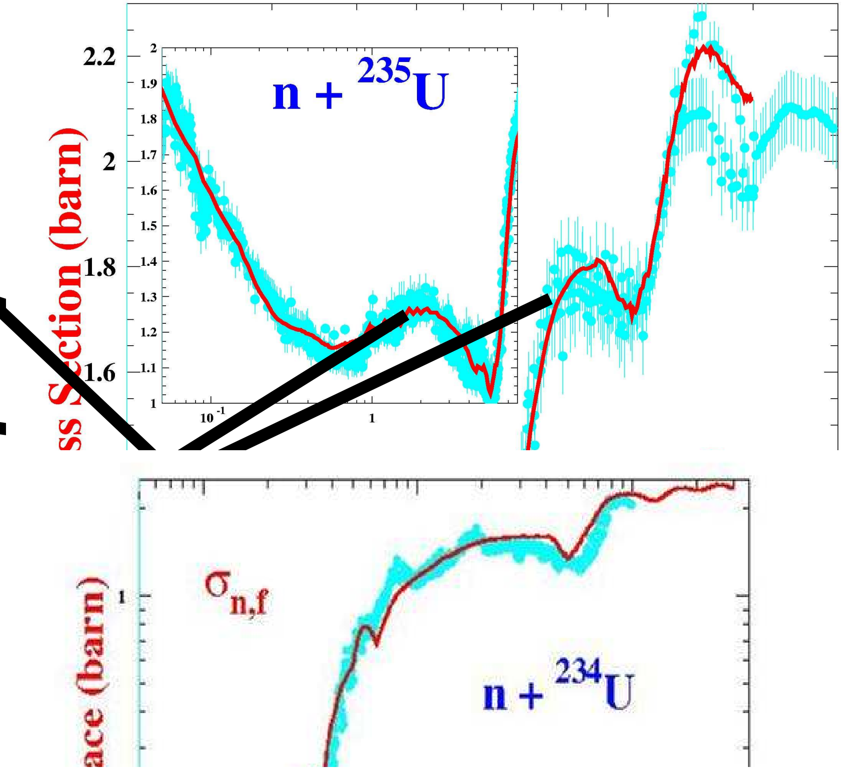



E'ₙ+Bₙ= E'*
σnn'
σn2n
σ2nf
E'ₙ+Bₙ= E'*
σnn'
σnn'
σn2n
σnf
σγ
237U
Eₙ+Bₙ=E*
σnn'
σγ
σCE
3-rd chance fission
Bₙ σf
238U
2-nd chance fission
σγ
1-rst chance fission
239U



n + 238U
σn,f
Section efficace (barn)
Energie Neutron (MeV)
(n,pf)
Pa8
4n
U5
(n,4nf)
p
U6
Th5
(n,αf)
3n
α
U7
(n,2nf)
2n
U8
(n,nf)
n
U9
(n,f)
MeV
6
12
24
32





Avec le même passe-partout ^{238}U

on visite plusieurs réservoirs :

σ_{CN} (n+^{238}U) ➔n,nf

σ_{CN} (n+^{237}U) ➔n,f

σ_{abs} (γ+^{238}U) ➔γ,f

In our approach
at
BRuyères-le-Châtel (BRC) :

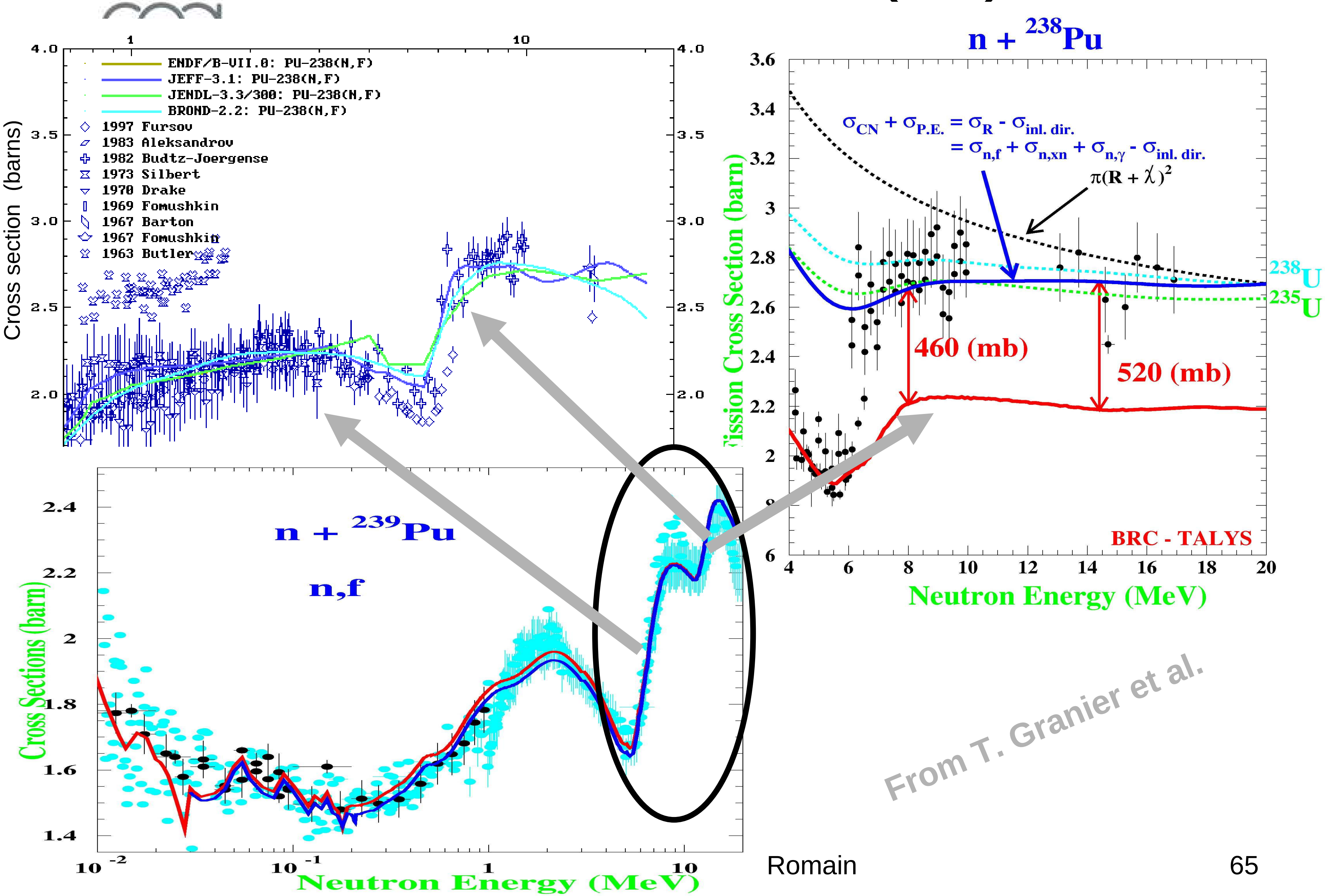
FULL MODEL

approach

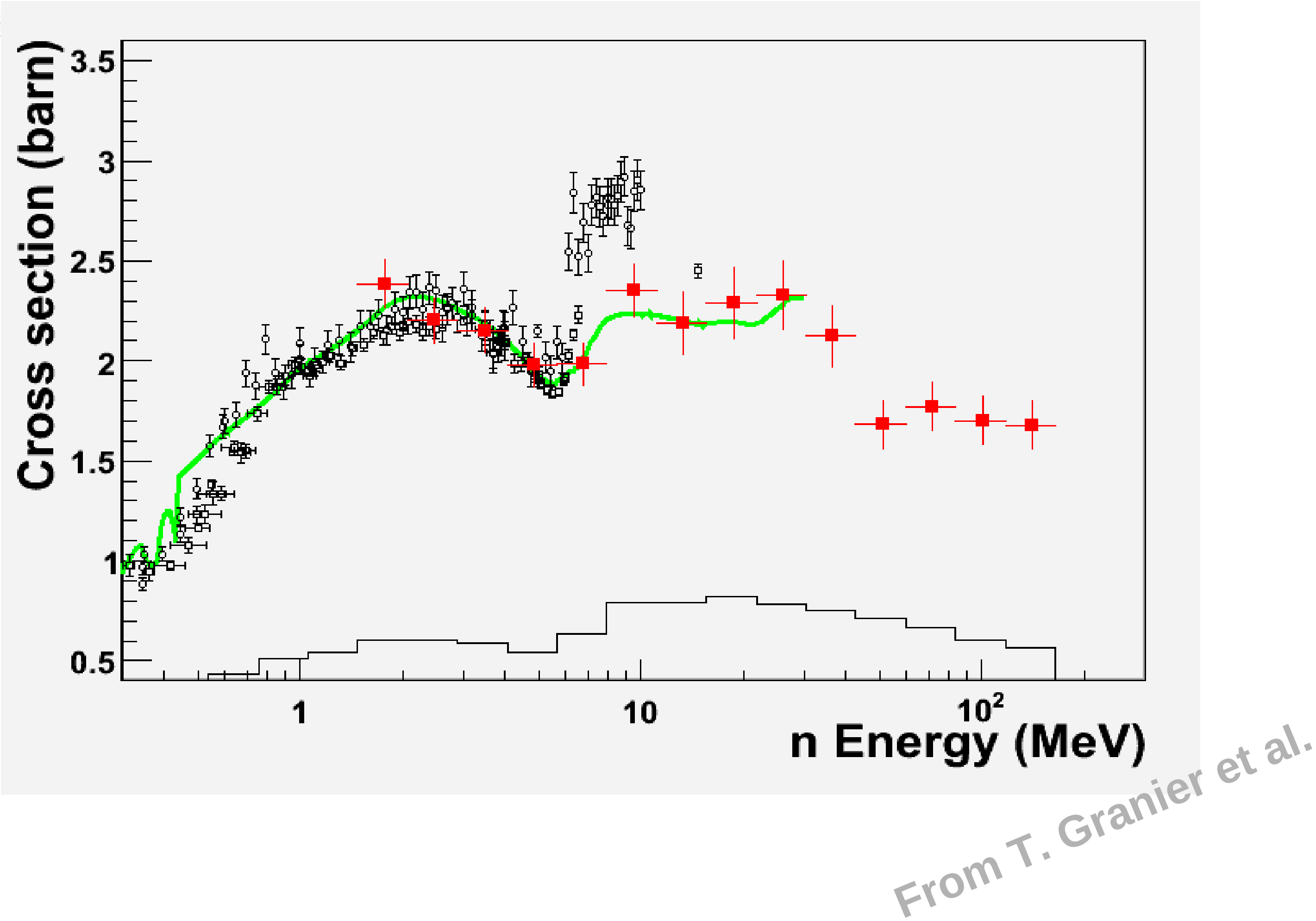
=

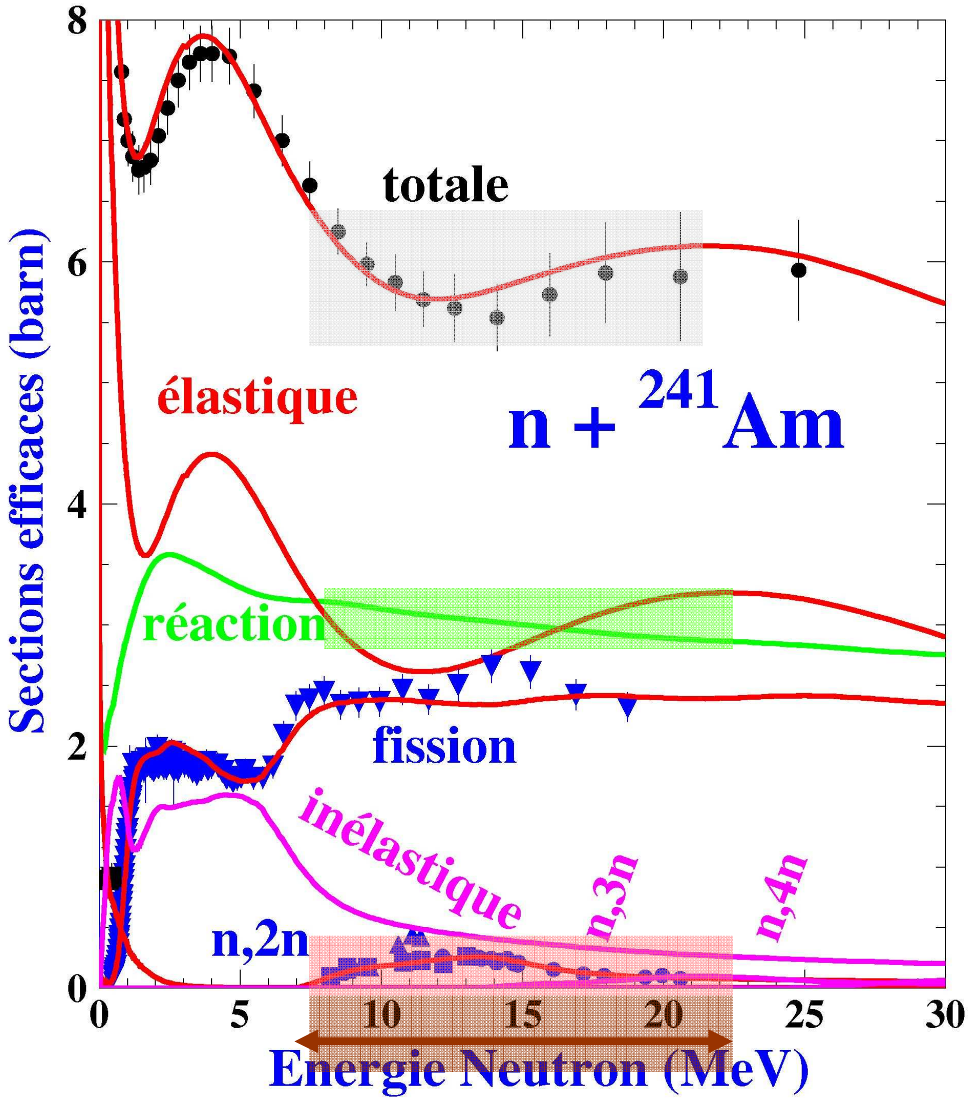
consistency

Problem in $^{238}Pu(n,f)$



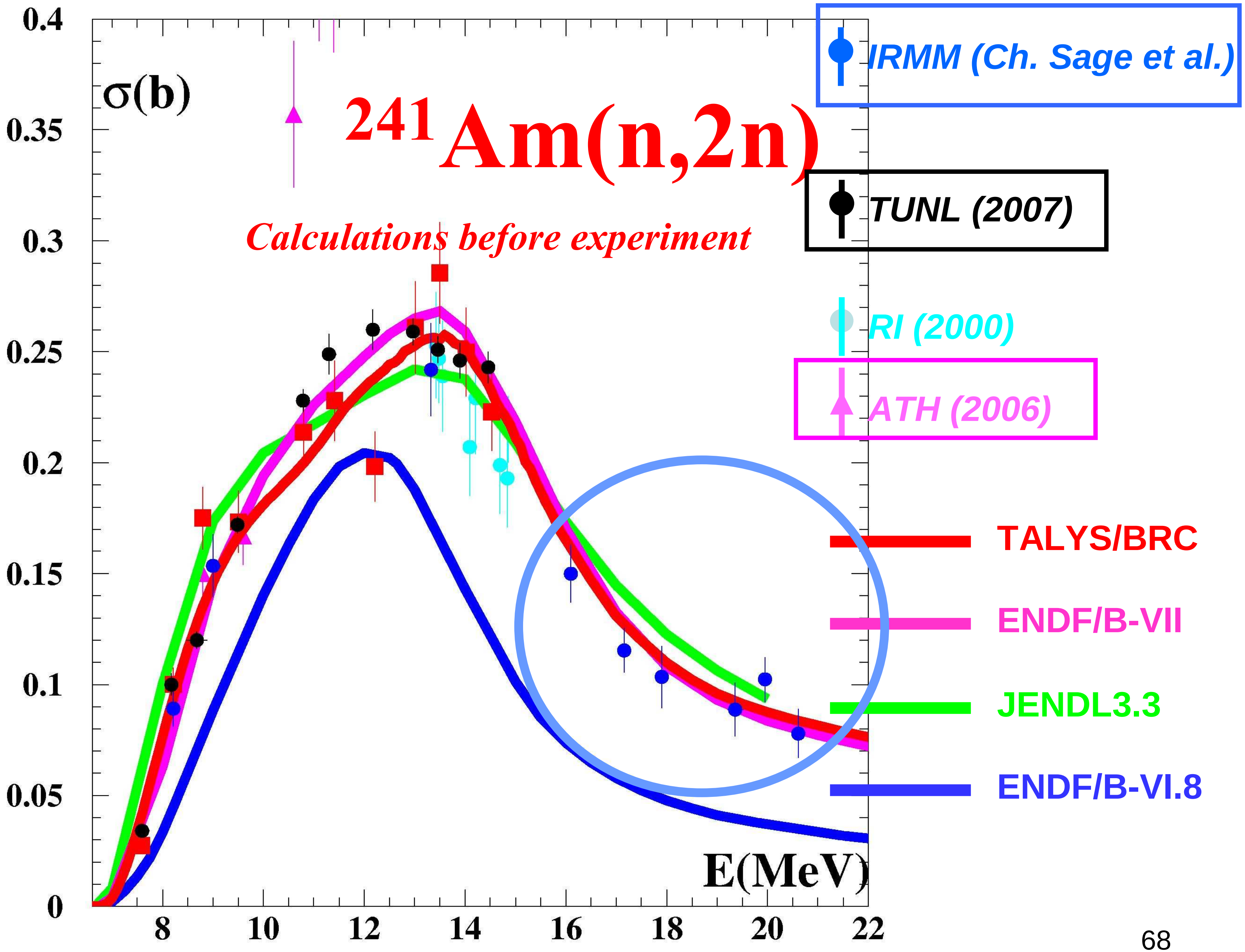
Preliminary results (T. Granier *et al.*)





≈ 4.5 % de σ_{tot}

≈ 8.5 % de σ_R



σ(b)
241Am(n,2n)
Calculations before experiment
IRMM (Ch. Sage et al.)
TUNL (2007)
RI (2000)
ATH (2006)
TALYS/BRC
ENDF/B-VII
JENDL3.3
ENDF/B-VI.8
E(MeV)
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
8
10
12
14
16
18
20
22

TALYS
adventures
in
wonderland

The End

THANKS