

Workshop NACRE "Bilan et perspectives -2023"

22-23 janvier 2024, IPHC Strasbourg



Advances in (n,xn) and (n,xng) reaction modeling

DE LA RECHERCHE À L'INDUSTRIE

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AIEA Vienna**

Commissariat à l'énergie atomique et aux énergies alternatives - www.cea.fr

Reaction mechanisms / observables

I

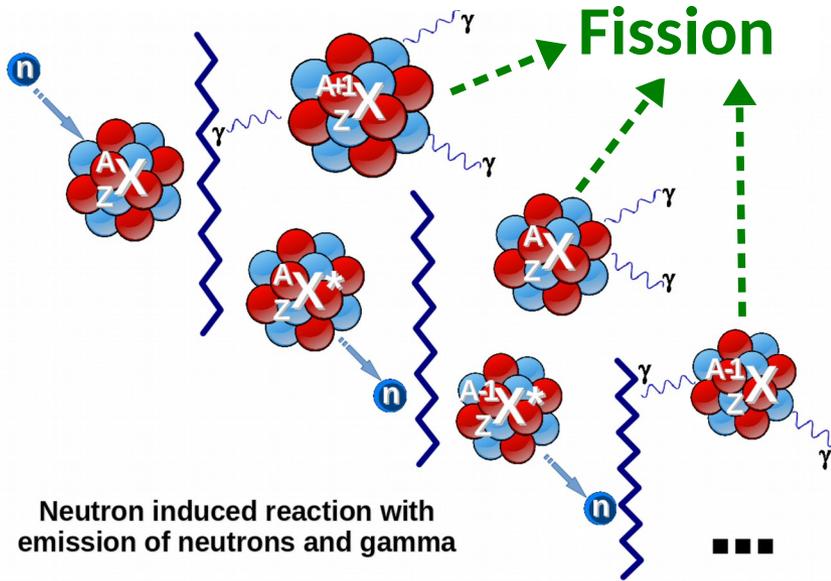
Modeling (n, x_n) and (n, x_{ng})
Pre-equilibrium and (n, x_n) reactions

II

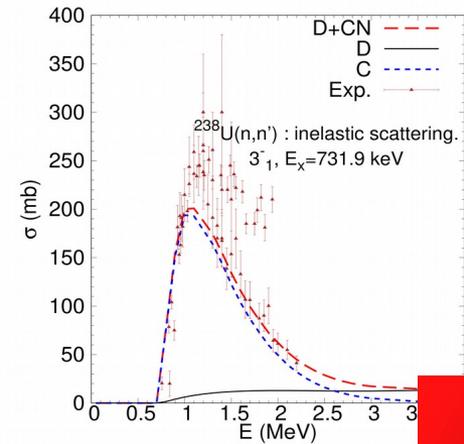
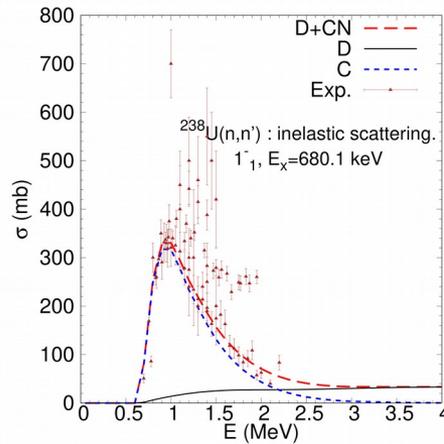
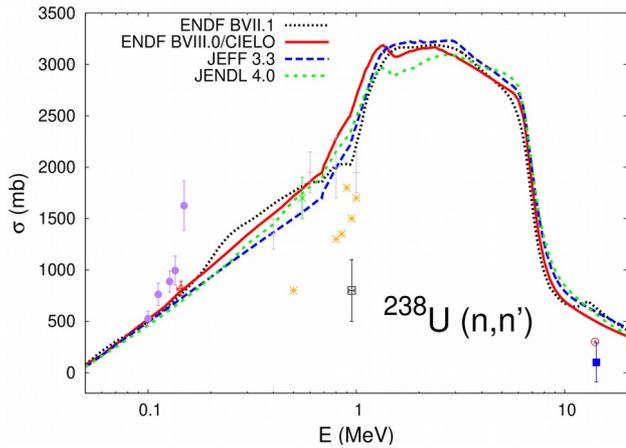
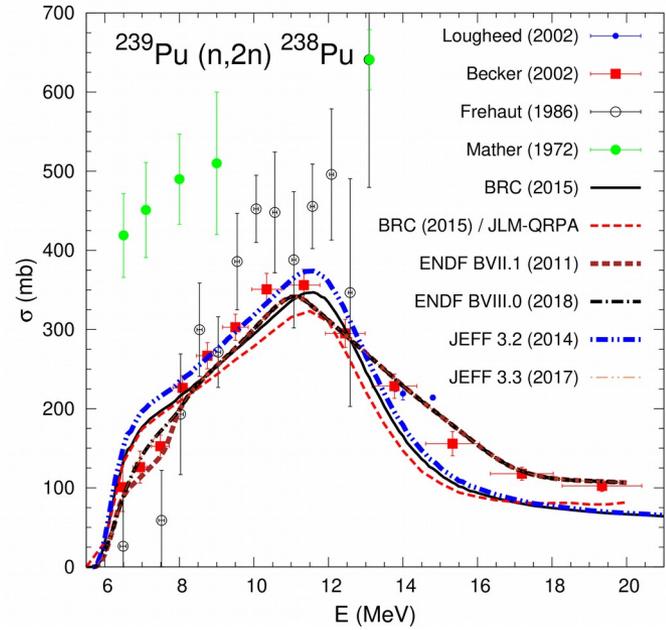
Details of (n, x_{ng}) modeling
How (n, x_{ng}) data can help improve models

Conclusions and perspectives

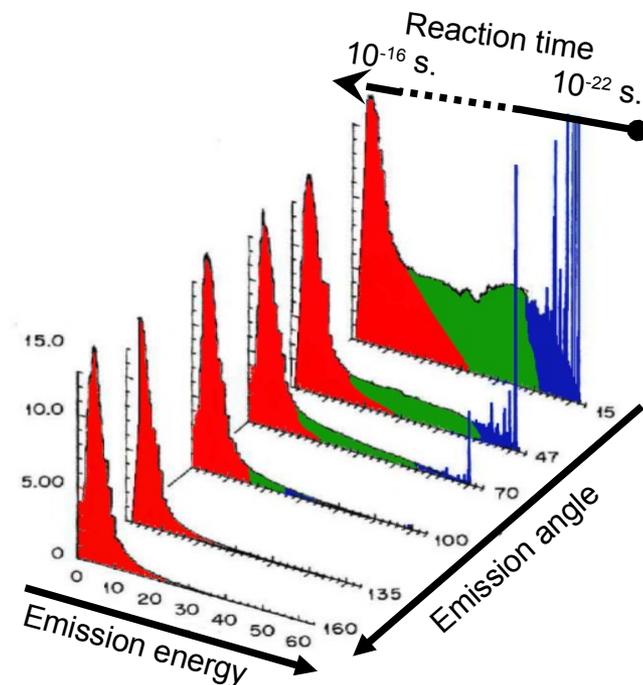
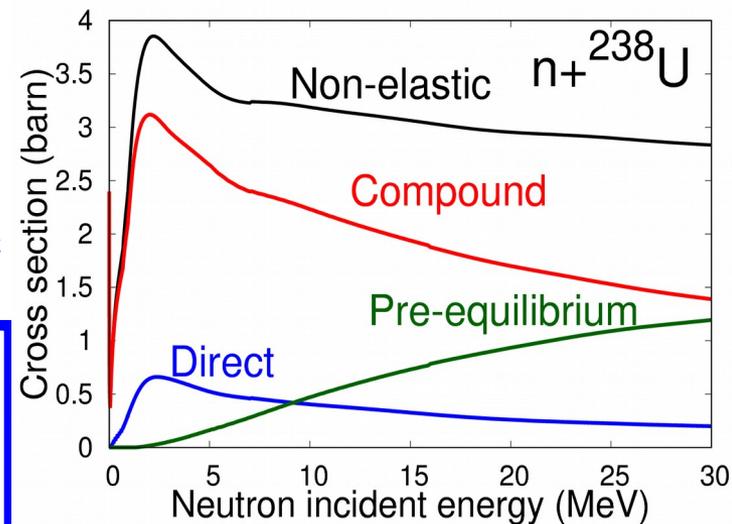
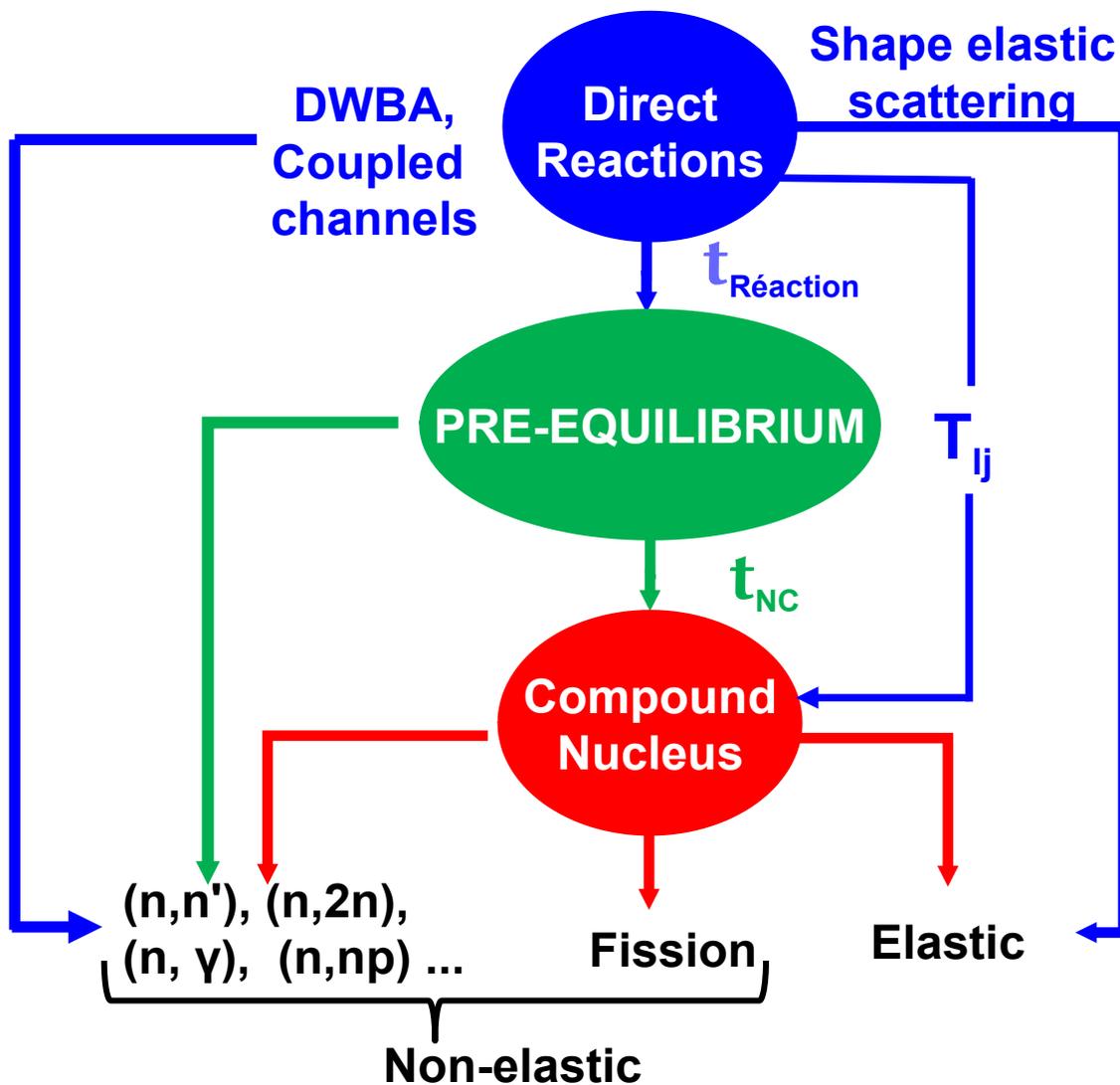
Neutron induced reactions



Neutron induced reaction with emission of neutrons and gamma



Reactions mechanisms



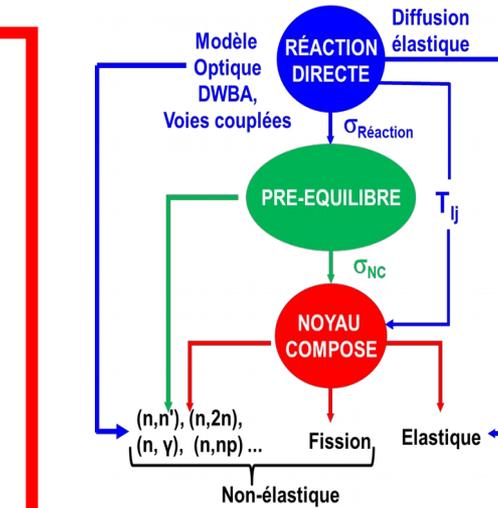
Reactions mechanisms

EVAPORATION DU NOYAU COMPOSÉ

Diffusion élastique et inélastique vers niveaux discrets et du continuum,
Émission multiple
Émission gamma
Fission

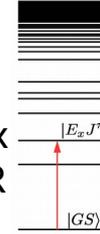
Approche :
Hauser-Feshbach
Fluctuations de largeur de voie

Potentiel Optique



RÉACTION DIRECTE

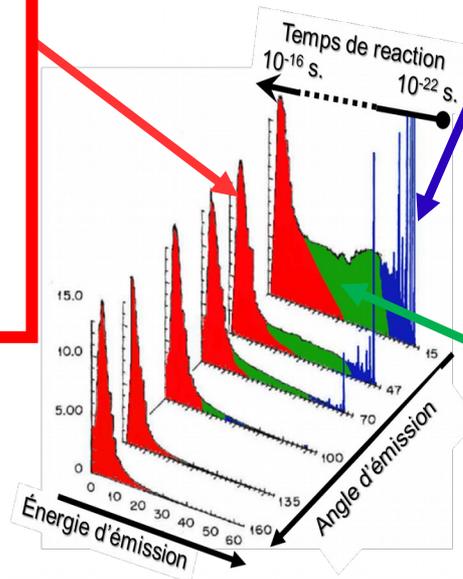
Diffusion élastique
Inélastique vers niveaux discrets, GR
Transfert



Potentiel Optique

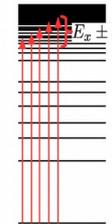
Voies couplées, DWBA

Sensibilité aux détails de structure (densités de matière)



PRE-EQUILIBRE

Diffusion Inélastique vers niveaux du continuum,
Émission multiple



Approches :

- Phénoménologiques : (excitons, hybrides)
- Semi-classiques (cascade intra-nucléaire)
- **Quantiques**

Reactions mechanisms

EVAPORATION DU NOYAU COMPOSÉ

Diffusion élastique et inélastique vers niveaux discrets et du continuum,

Émission multiple

Émission gamma

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INFORMATIONS DE STRUCTURE NUCLÉAIRE

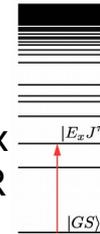
- **Masses**
- **Déformations**
- **Niveaux discrets**
- **Densités de niveaux**
- **Densités de matière**
- **Fonctions de force- γ**
- **Paramètres de fission**
- ...

RÉACTION DIRECTE

Diffusion élastique

Inélastique vers niveaux discrets, GR

Transfert



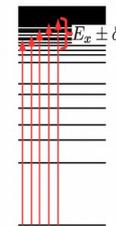
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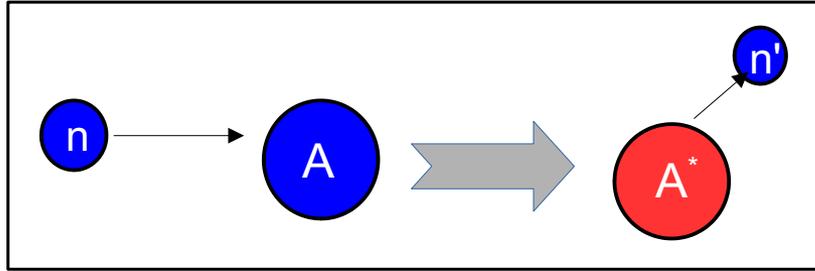
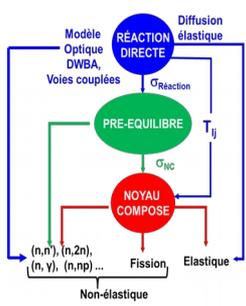
Diffusion élastique vers niveaux du continuum, Émission multiple



Approches :

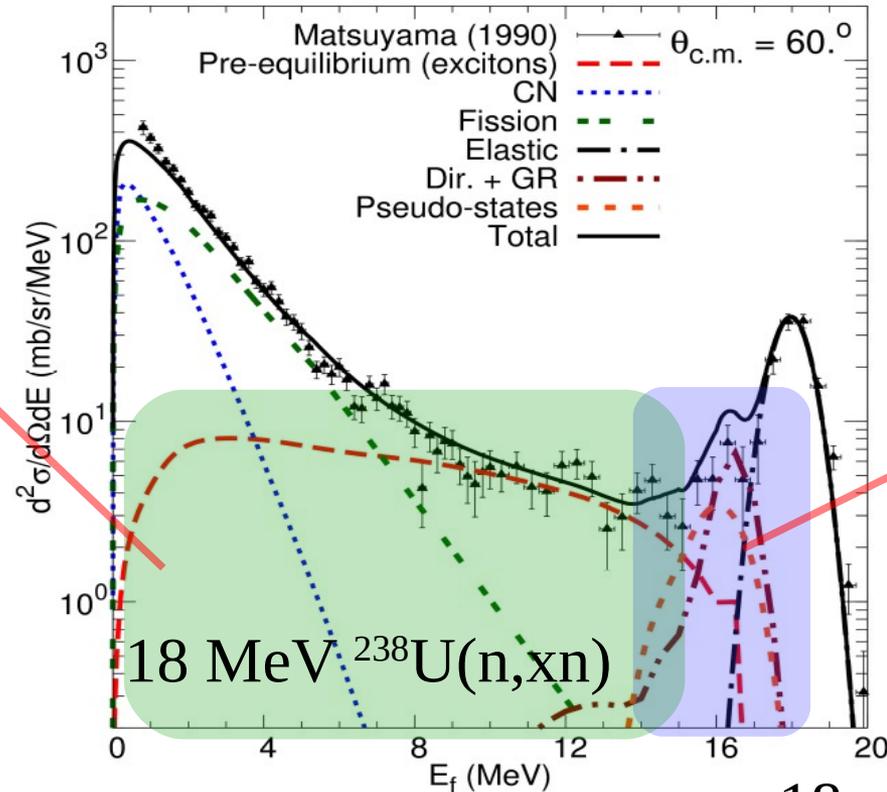
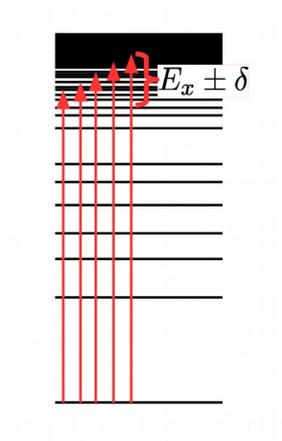
- **Phénoménologiques :** (excitons, hybrides)
- **Semi-classiques** (cascade intra-nucléaire)
- **Quantiques**

Pre-equilibrium: first emission = inelastic scattering to the continuum

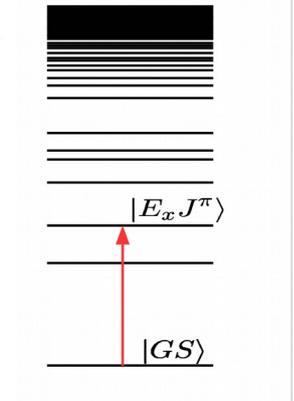


“Fast” inelastic scattering (no intermediate compound system)

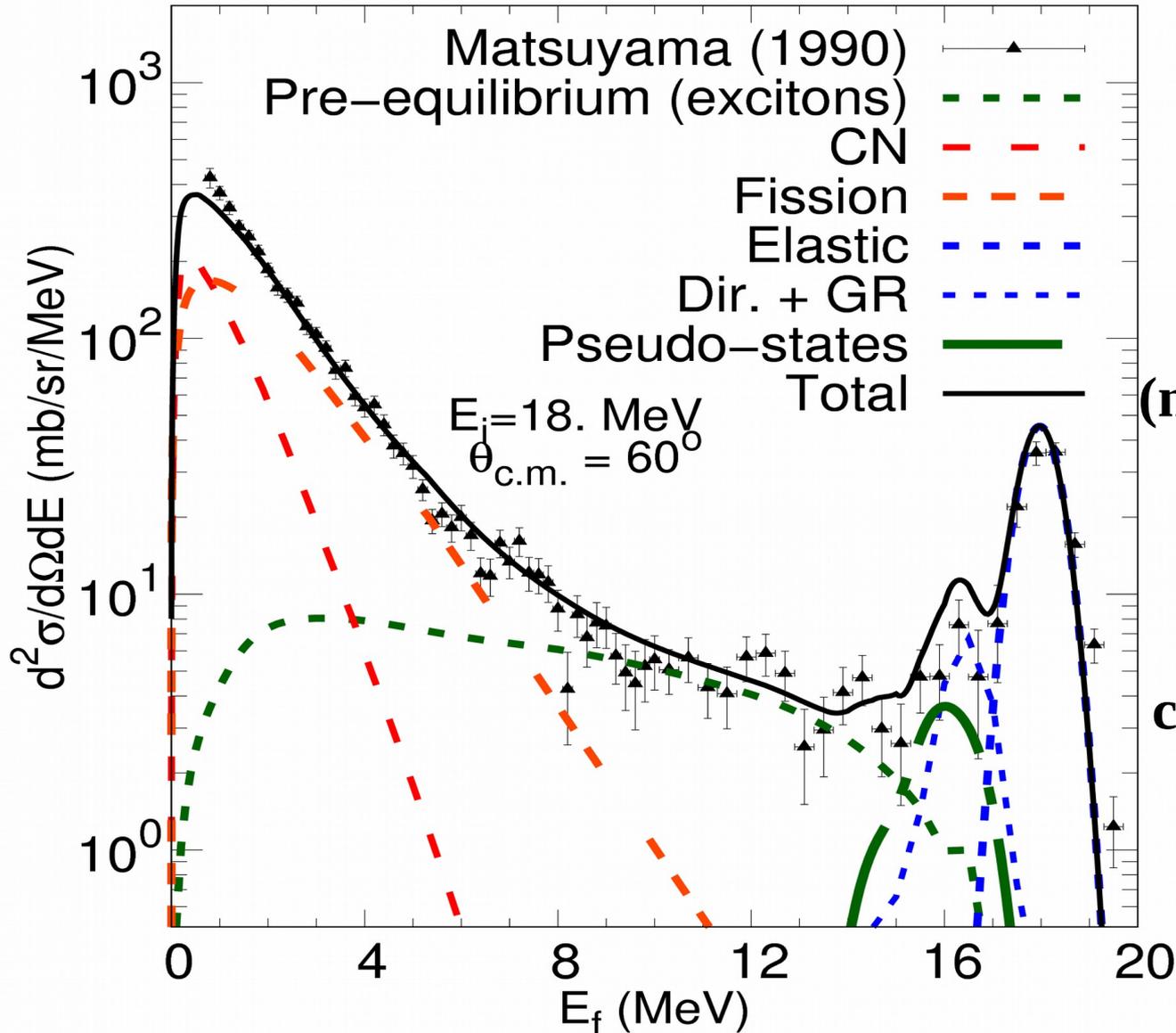
to the continuum : pre-equilibrium



to low energy discrete excitations

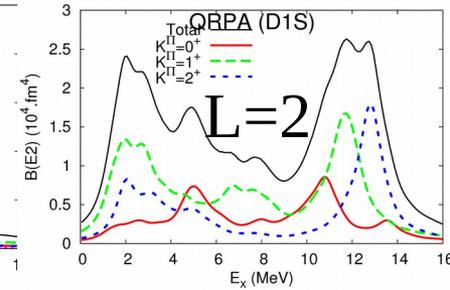
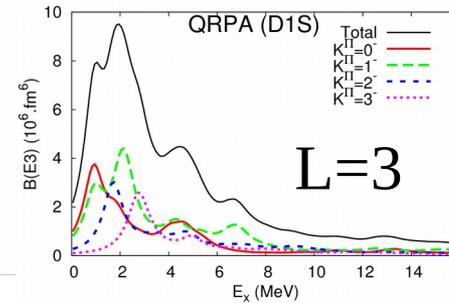
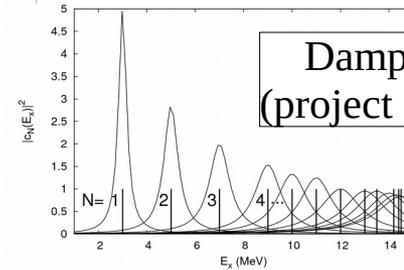
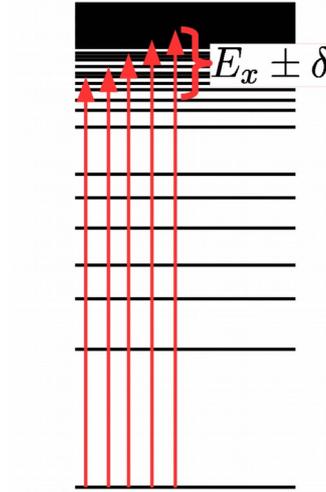
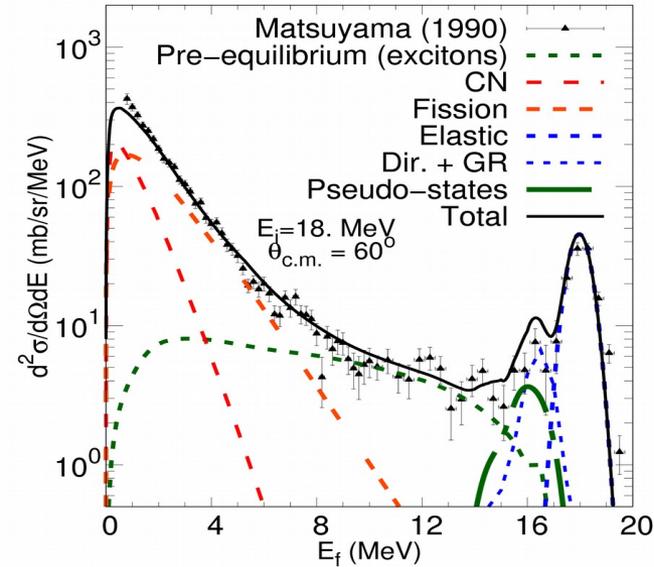


Inelastic scattering to the continuum : (n,xn)



Problem :
(n,xn) cross sections:
High energy
emission
 \rightarrow **pseudo-states:**
emperical
collective vibration
contributions

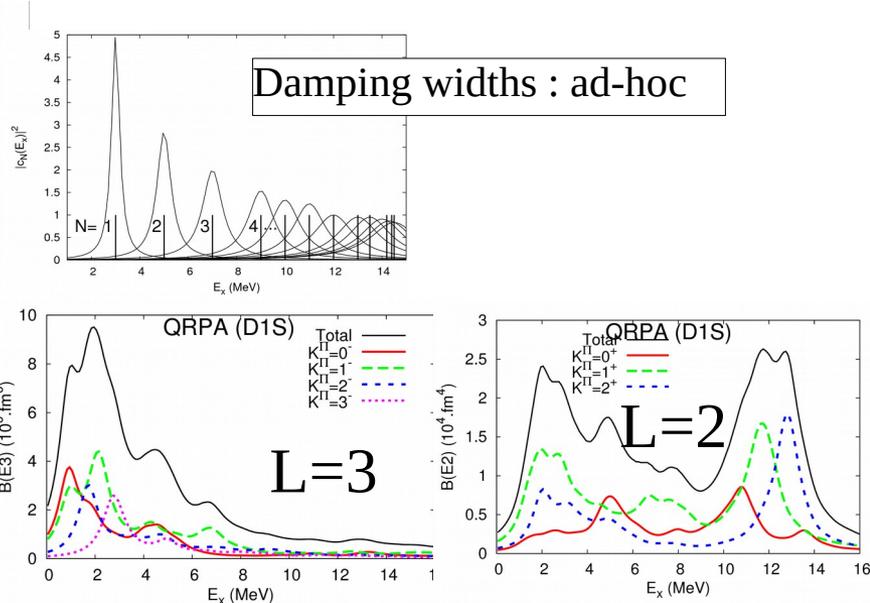
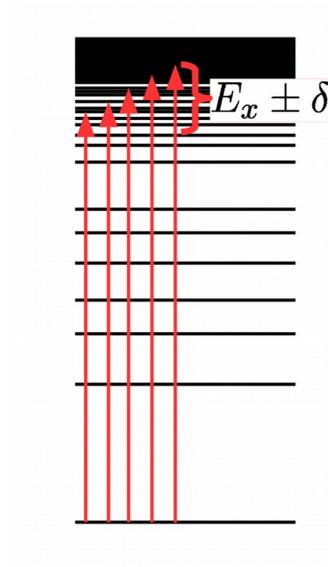
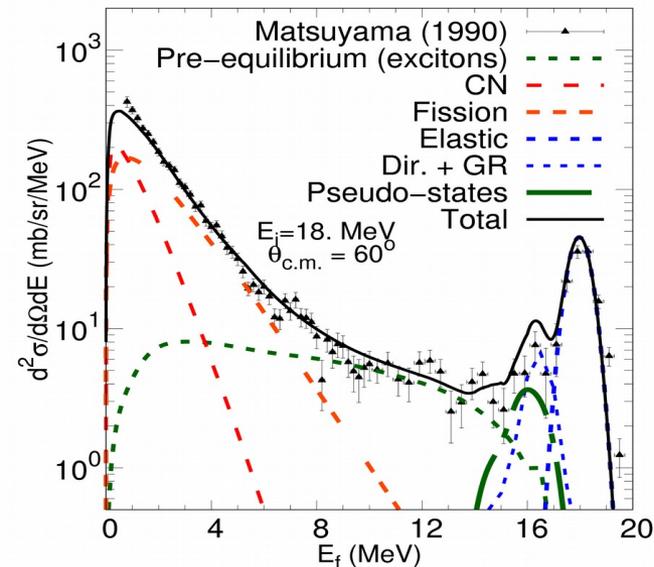
Inelastic scattering to the continuum : (n,xn)



Problem :
 (n,xn) cross sections :
 High energy emission
 → pseudo-states

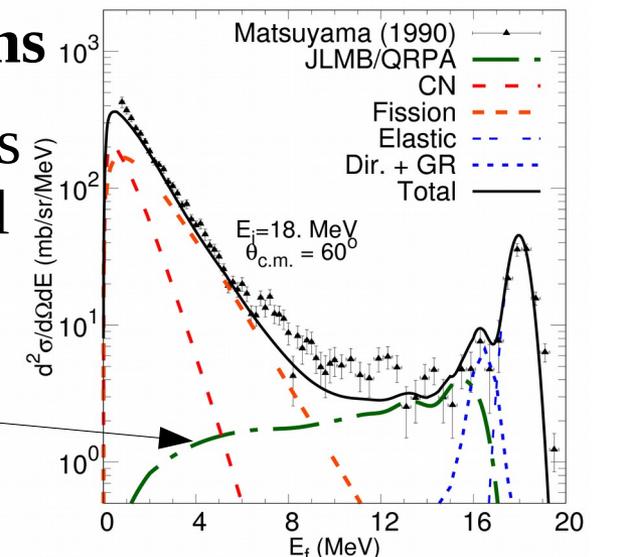
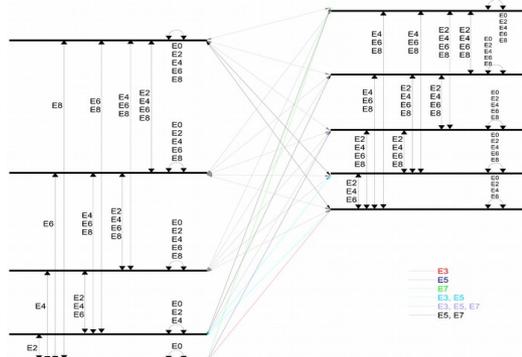
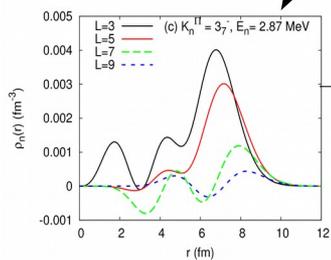
Solution : Consider all QRPA
 one-phonon excitations

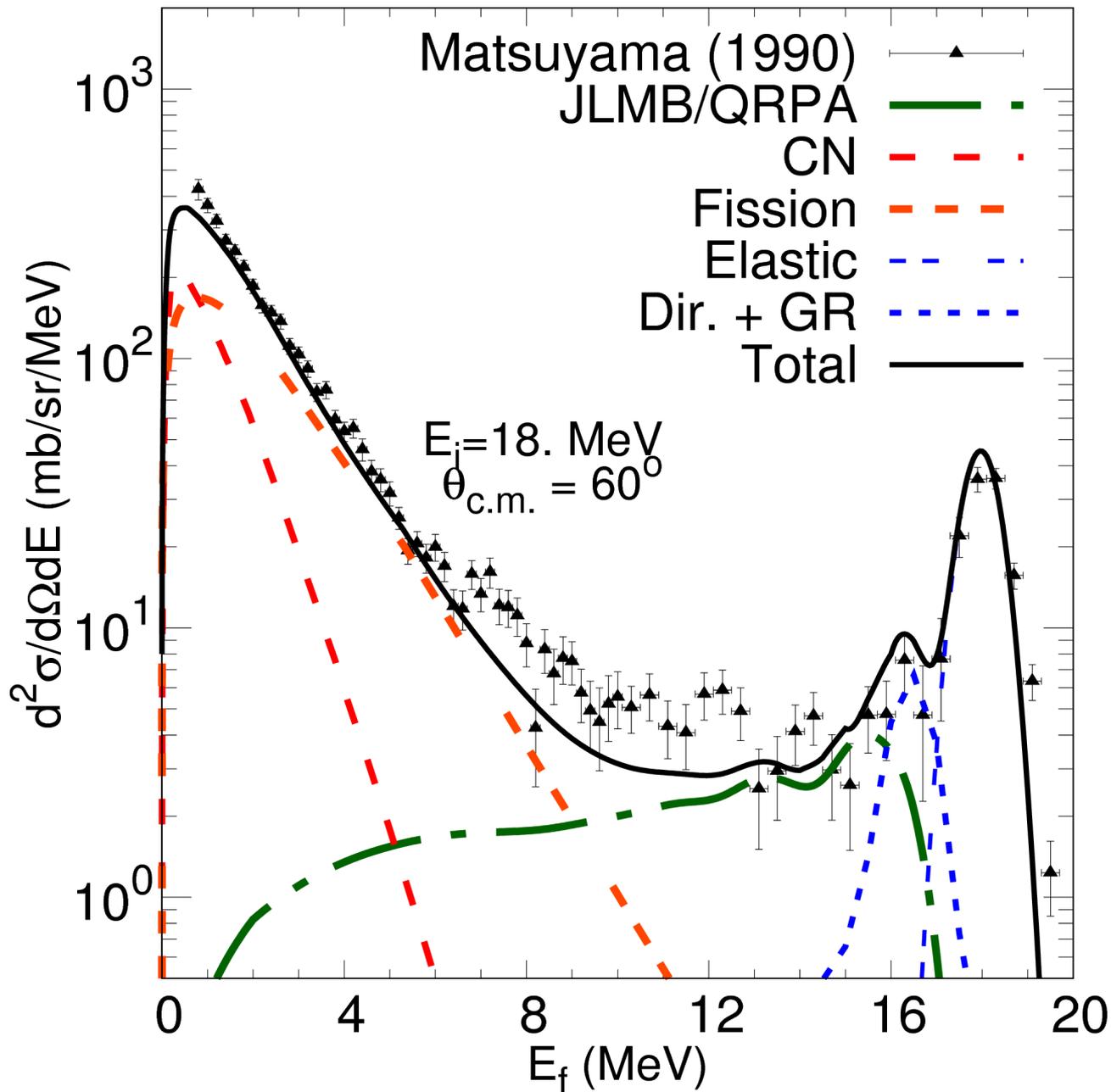
Inelastic scattering to the continuum : (n,xn)



Problem :
 (n,xn) cross sections :
 High energy emission
 → pseudo-states

Consider all QRPA
 one-phonon excitations
 Individual cross sections
 calc. within JLM model



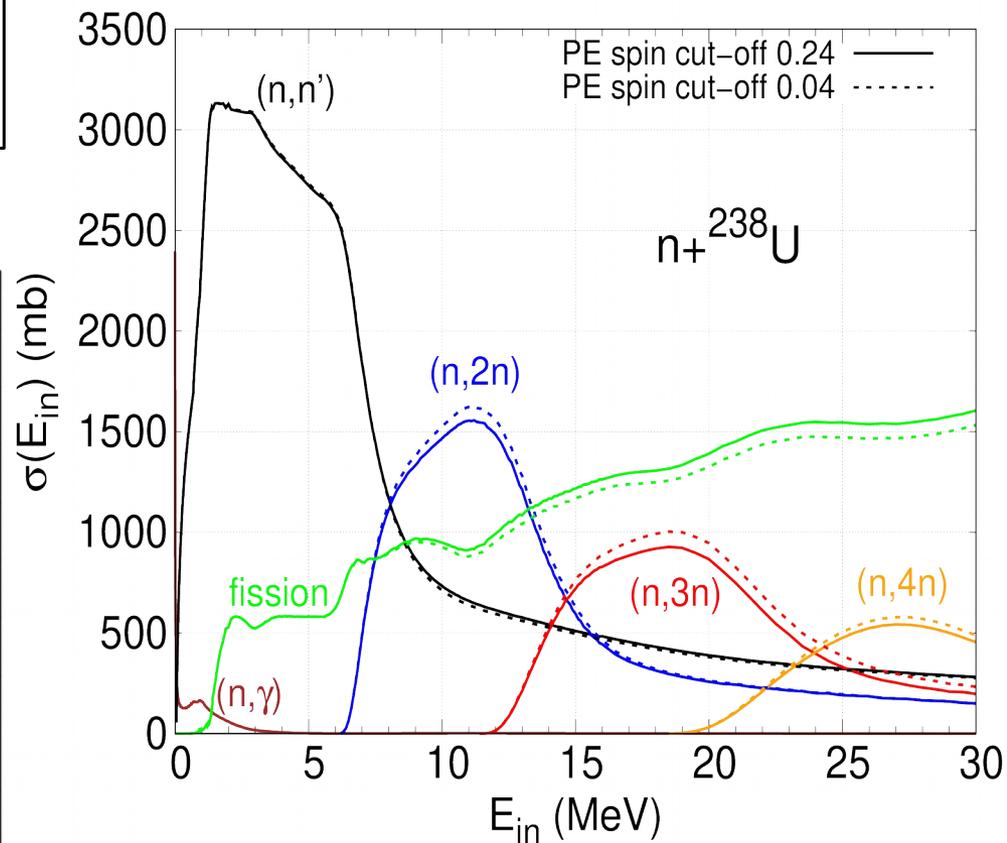
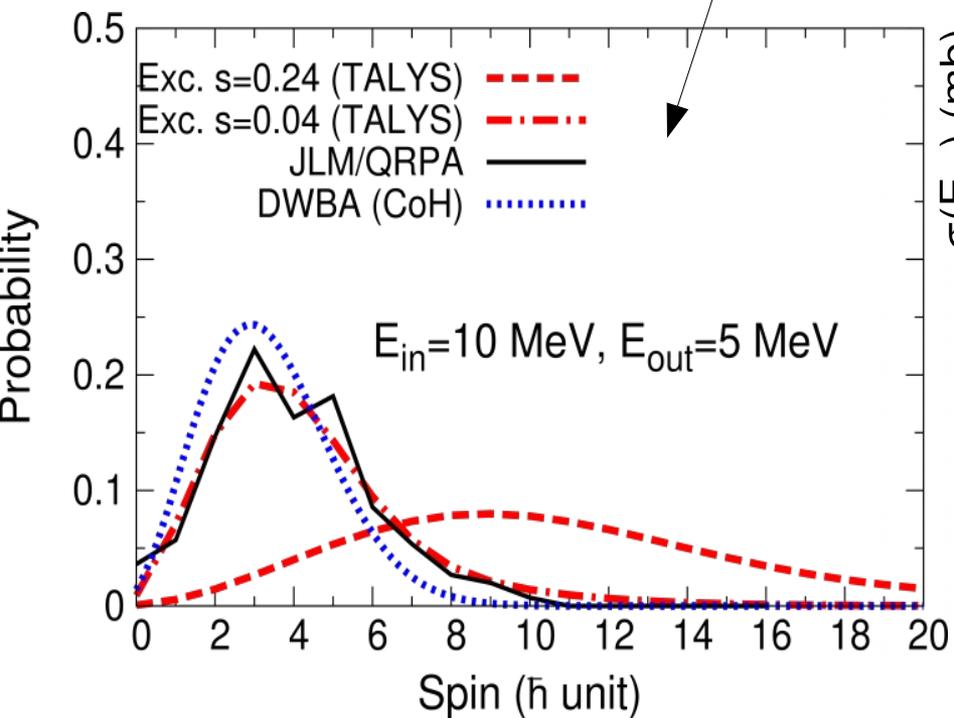
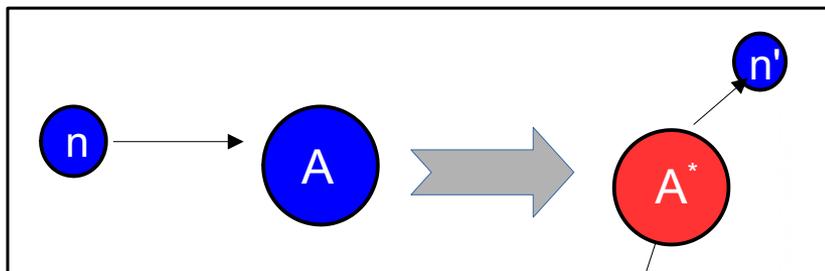


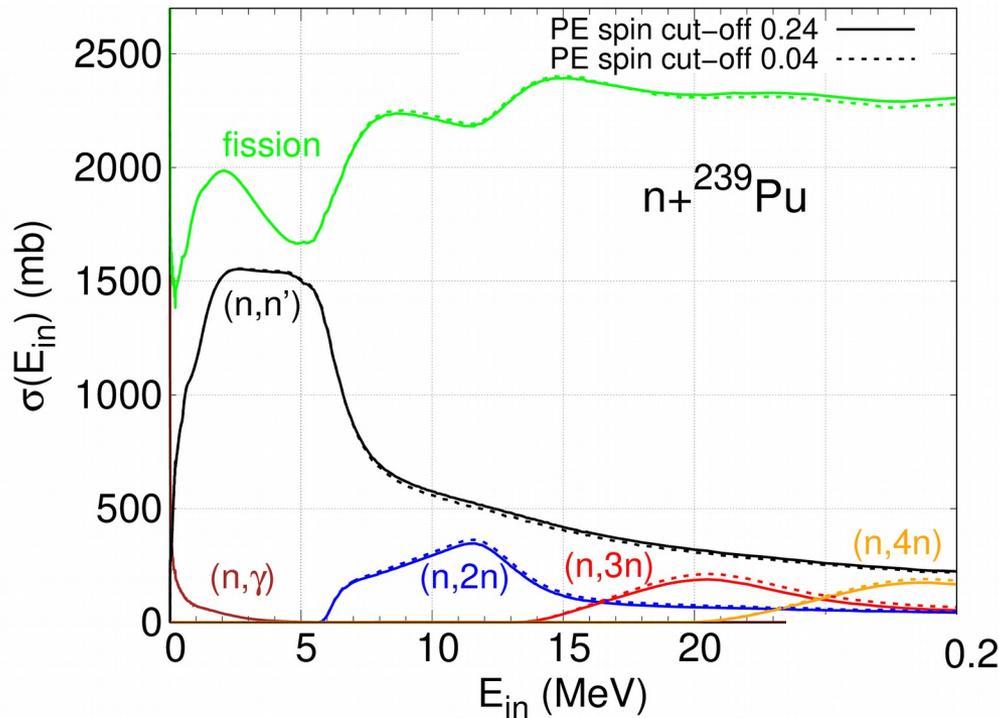
Alt. approach :

Excitons
 +
 emulation of coll.
 Excitations with
 Effective level
 density :

M.R. Mumpower et
 al., PRC107 (2023)

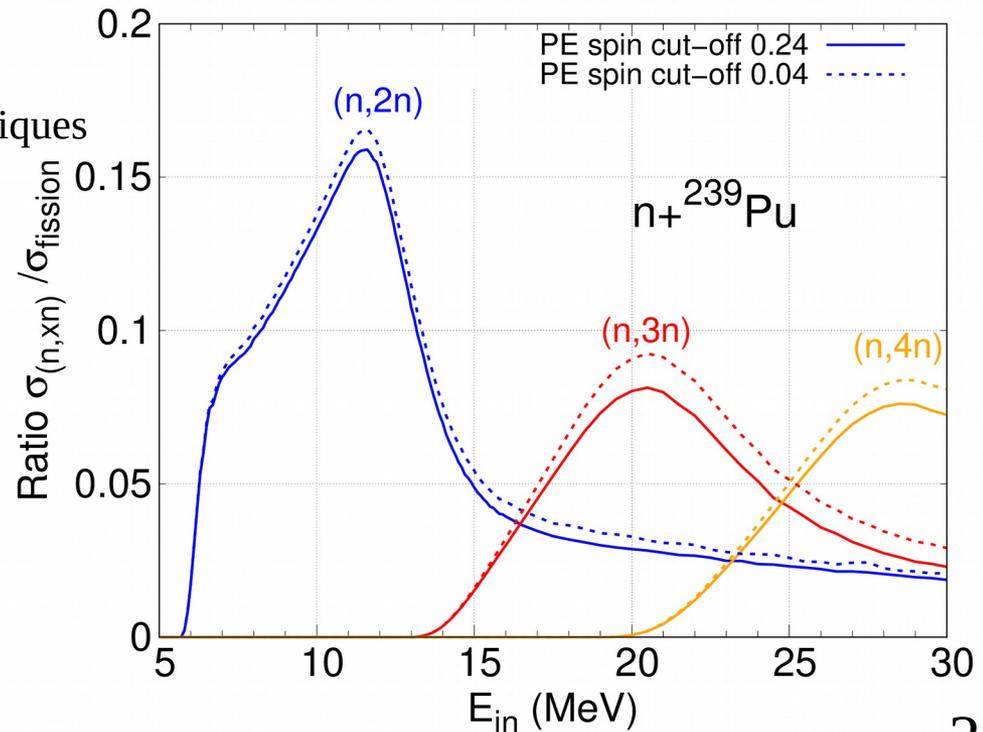
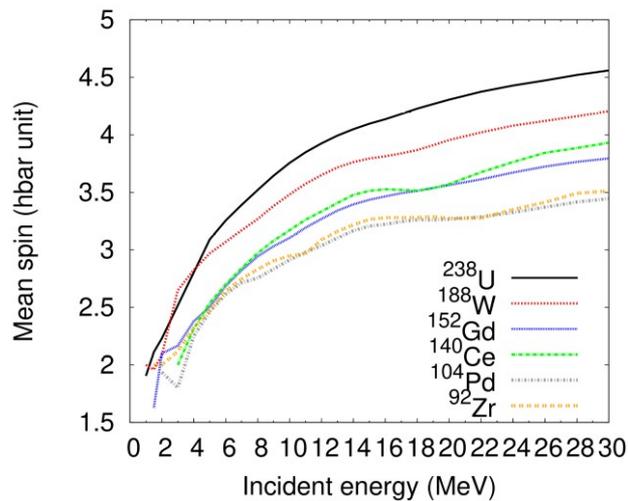
Spin distribution



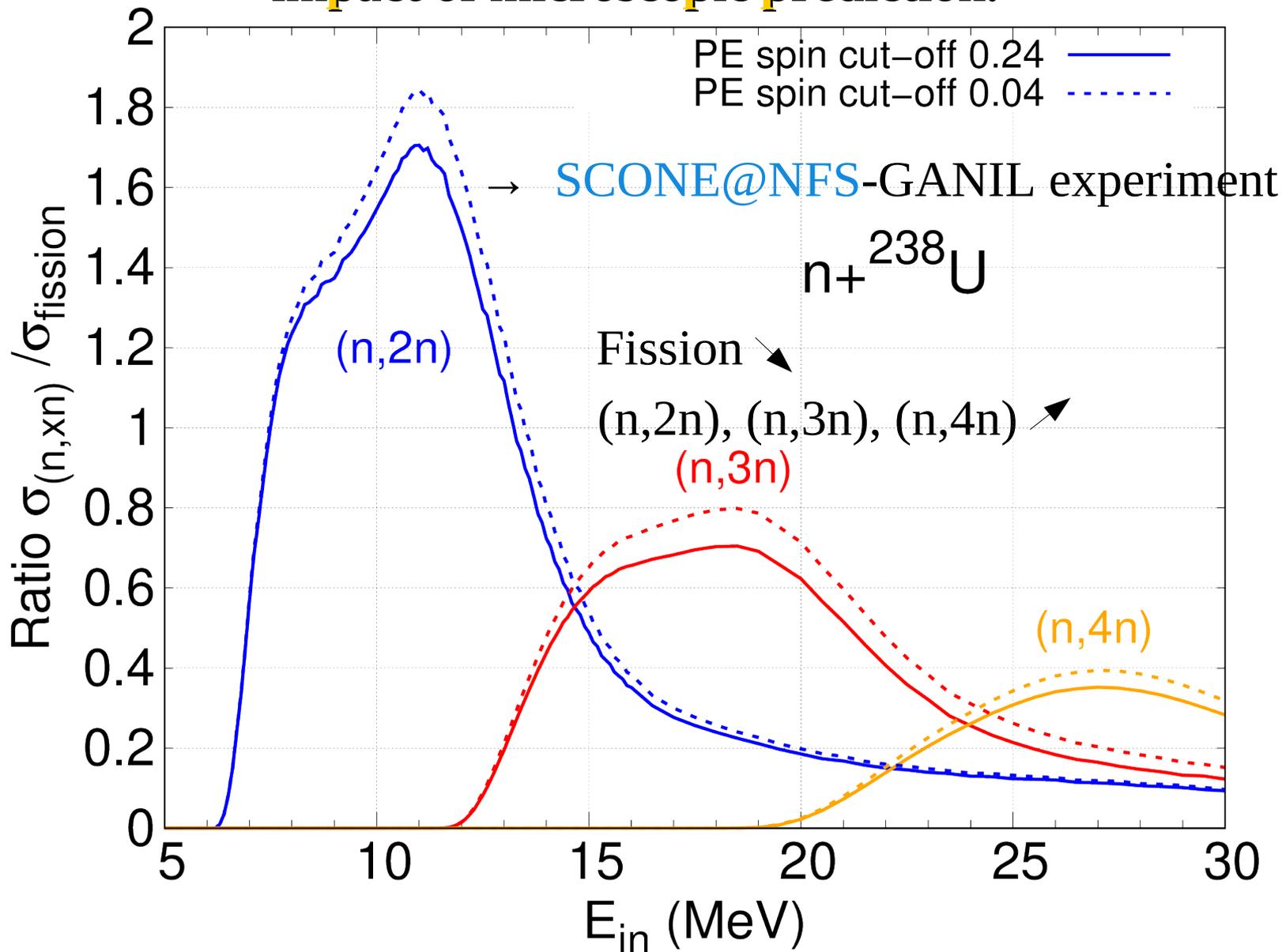


Spin cut-off in the residual nucleus after pre-eq. Emission : impact of microscopic prediction.

Systematic calculation, $A=16-240$: P(J) microscopiques



Spin cut-off in the residual nucleus after pre-eq. Emission : impact of microscopic prediction.



(n,n'g) modeling

Test améliorations récentes des modèles

Discriminer certaines données de structure / choix de paramètres

Meilleures totales à partir des partielles

Terrain de jeu :

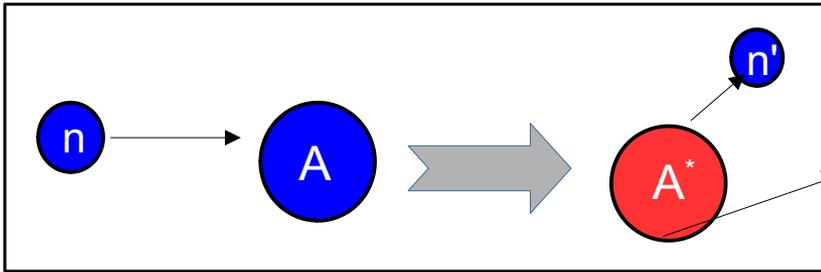
→ données (n,xng) IPHC @ GELINA EC-JRC-Geel

→ ^{238}U , ^{232}Th ,

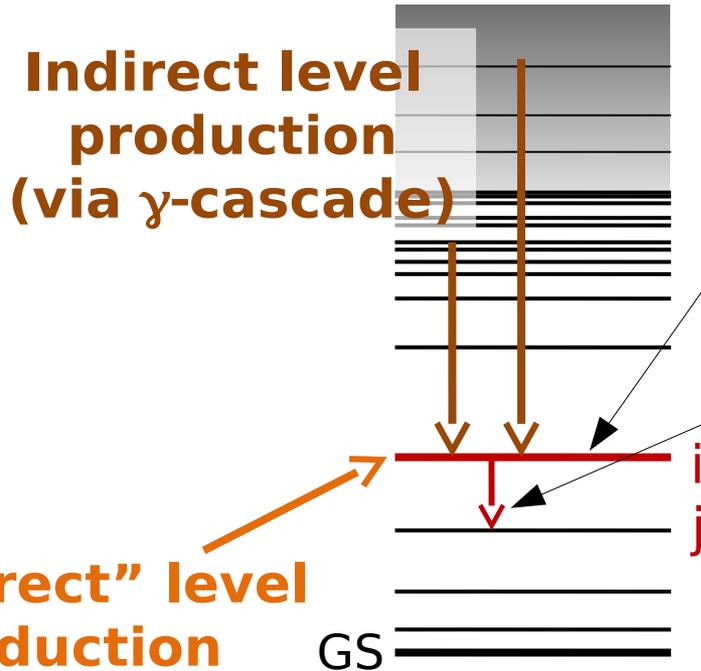
→ $^{182,184,186}\text{W}$

→ Code de calcul : Talys (1,96) [+ Empire et Coh]

(n,n'g) modeling



After inelastic scattering, the residual nucleus is left in an excited state.



Production of level i

$$\sigma(n, n'_i) =$$

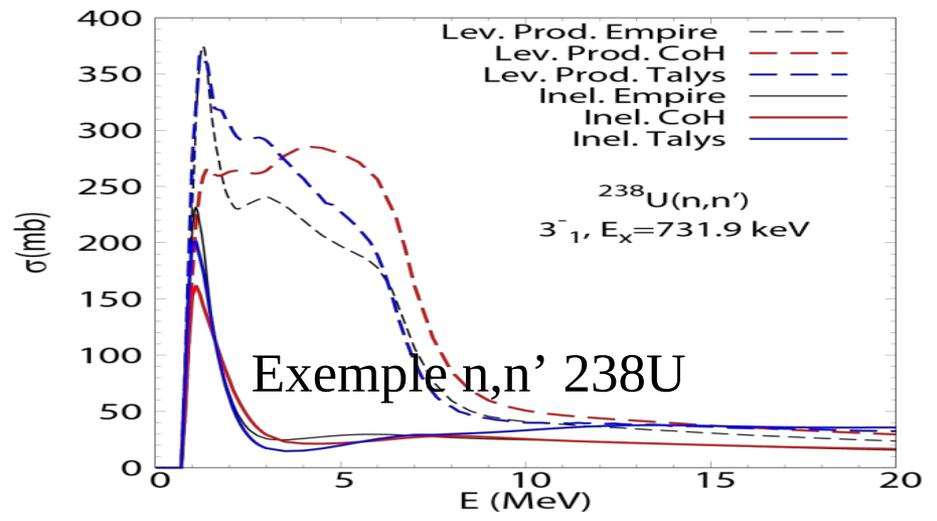
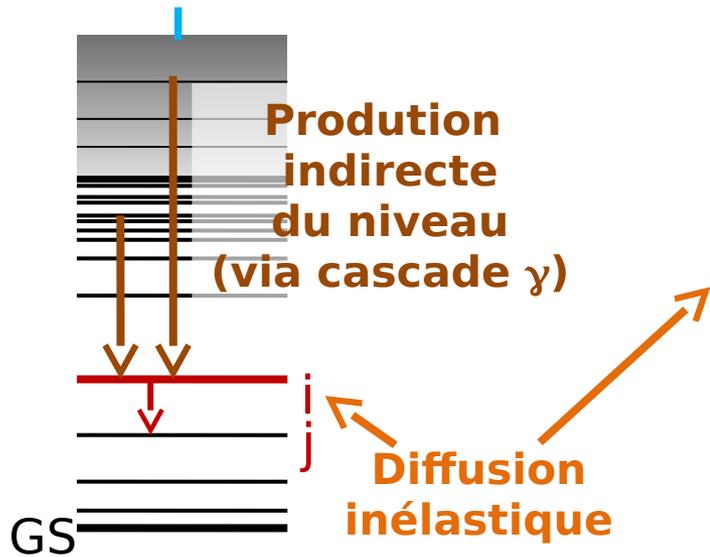
(feeding of the level i)

γ production for transition $i \rightarrow j$

$$\sigma(n, n' \gamma_{i \rightarrow j}) =$$

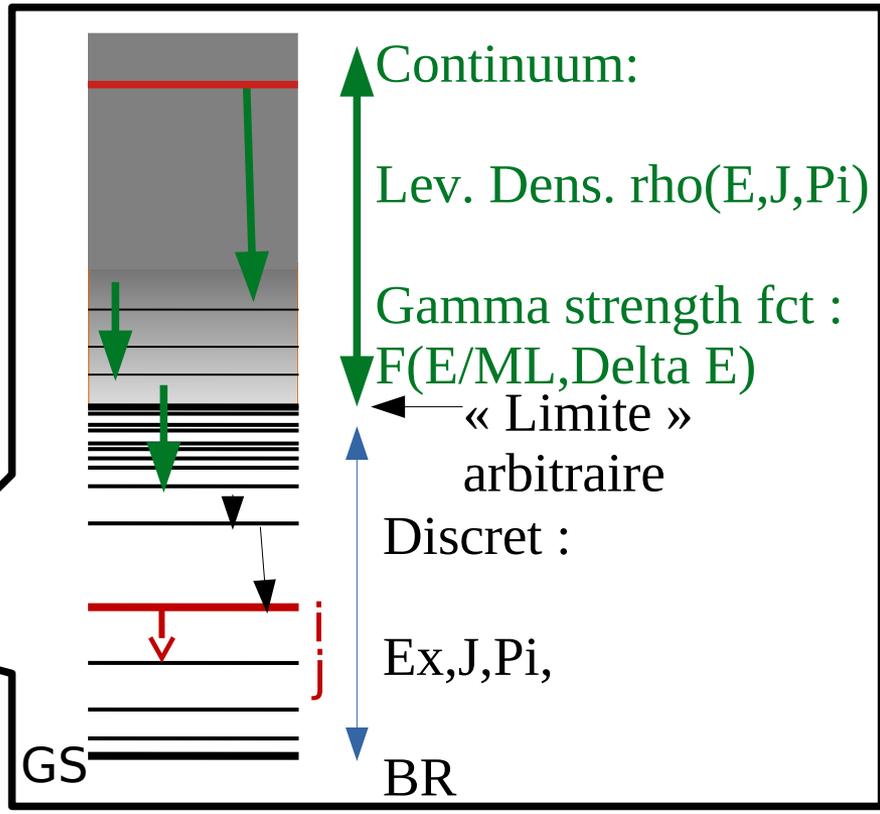
(feeding of the level i) * $BR_{\gamma}^{i \rightarrow j}$

“Direct” level
Production
(via inelastic
scattering)

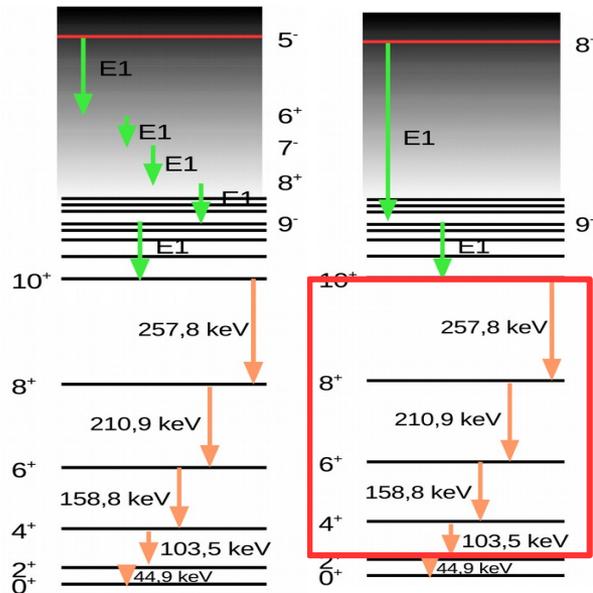
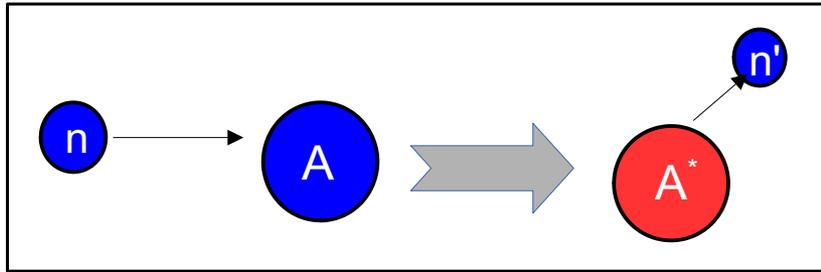


Production du niveau i

"Alimentation directe" =
 diffusion inélastique vers le niveau i
 +
 "Alimentation indirecte" :
 décroissance du niveau i

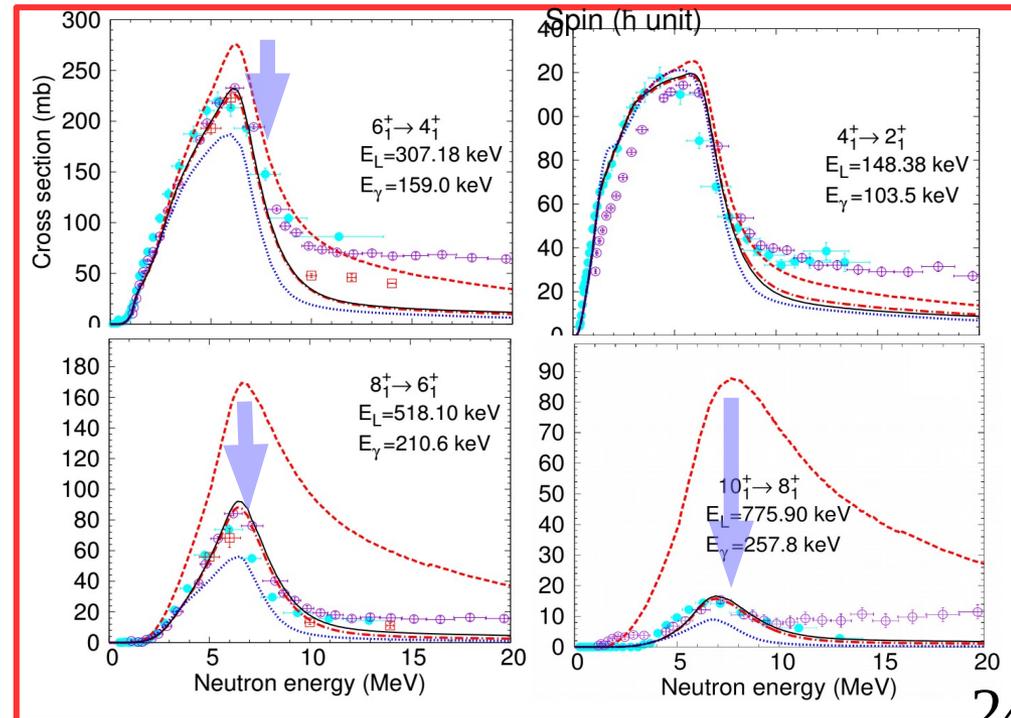
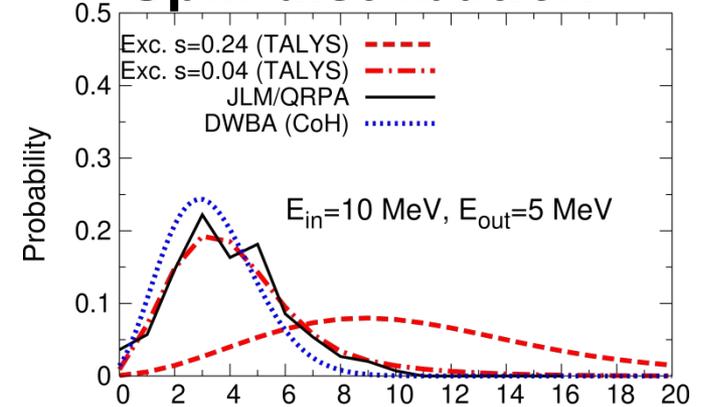


Inelastic to the continuum : $(n,n'\gamma)$

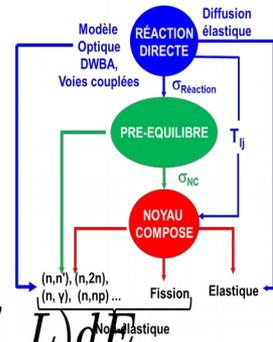


M. Kerveno et al.,
 Phys.Rev. C 104, 044605 (2021)

Spin distribution



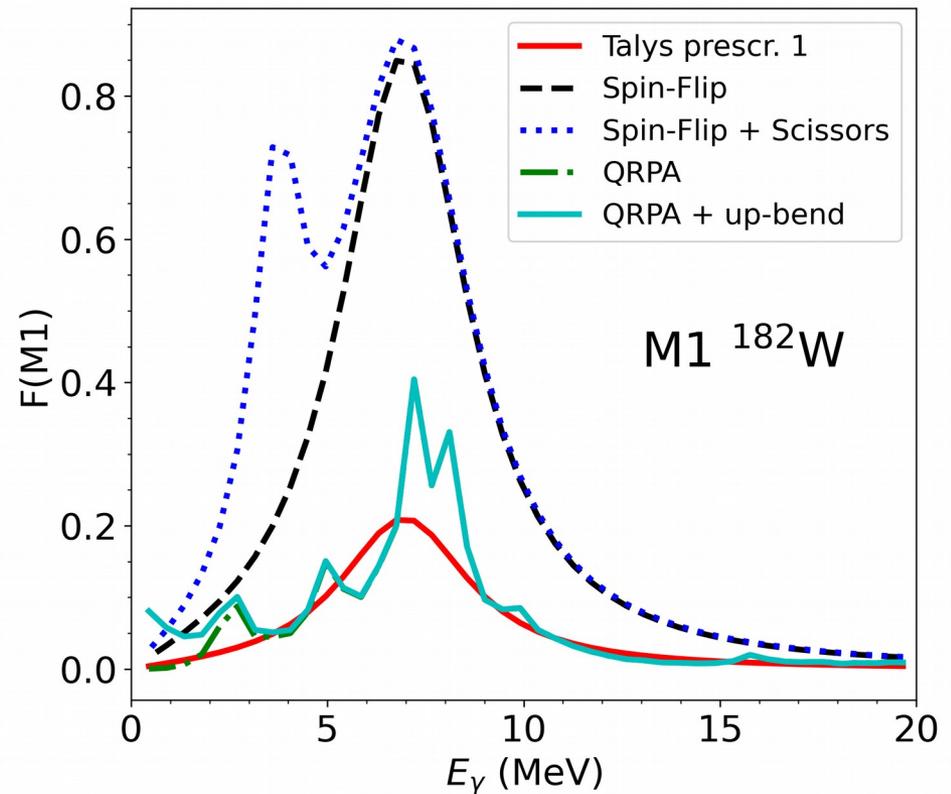
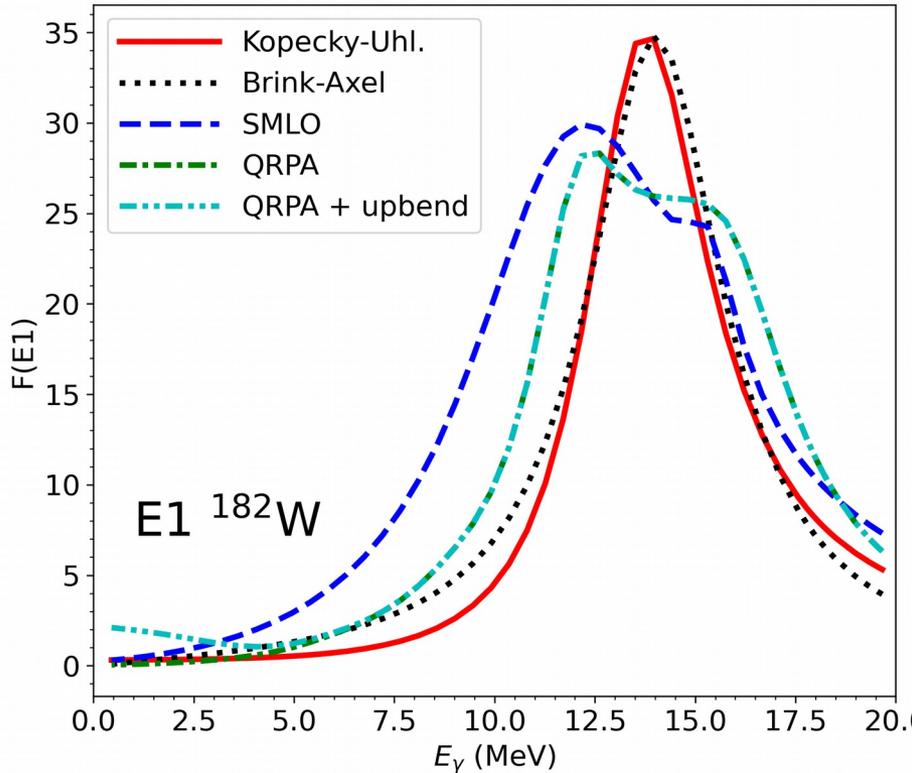
Compound nucleus decay from continuum



Fonctions de force gamma

$$\frac{2\pi\Gamma_\gamma}{D_0} = \sum_{J\Pi; I'\Pi'} \sum_{X=E/M; L} \int_0^{S_n} \underbrace{2\pi F_{E/ML}(E_\gamma) E_\gamma^{2L+2}}_{T_{E_r/M_r}(E_\gamma)} \rho(S_n - E_\gamma, I', \Pi') F(E/M, \Pi', L) dE_\gamma$$

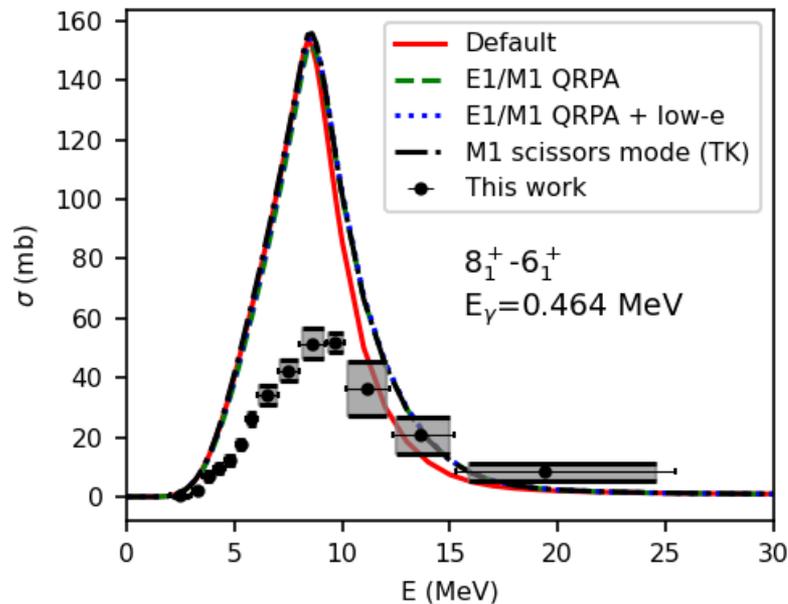
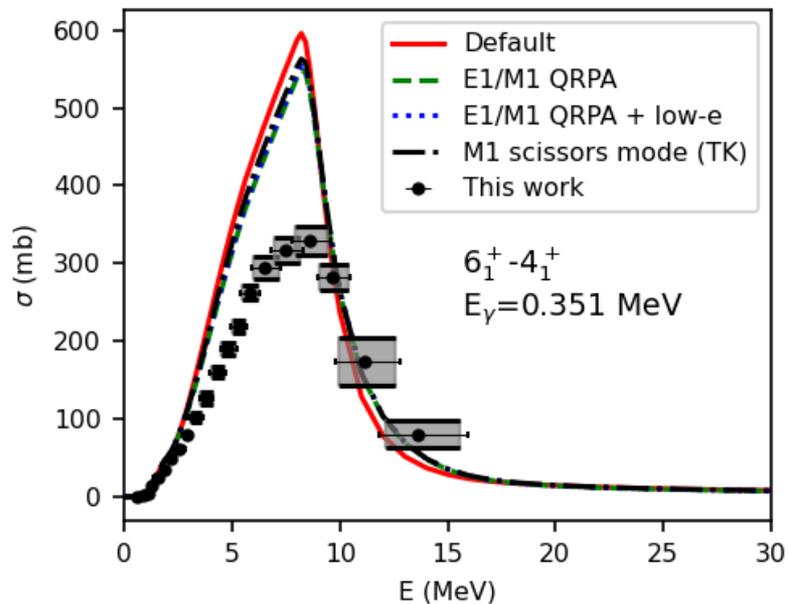
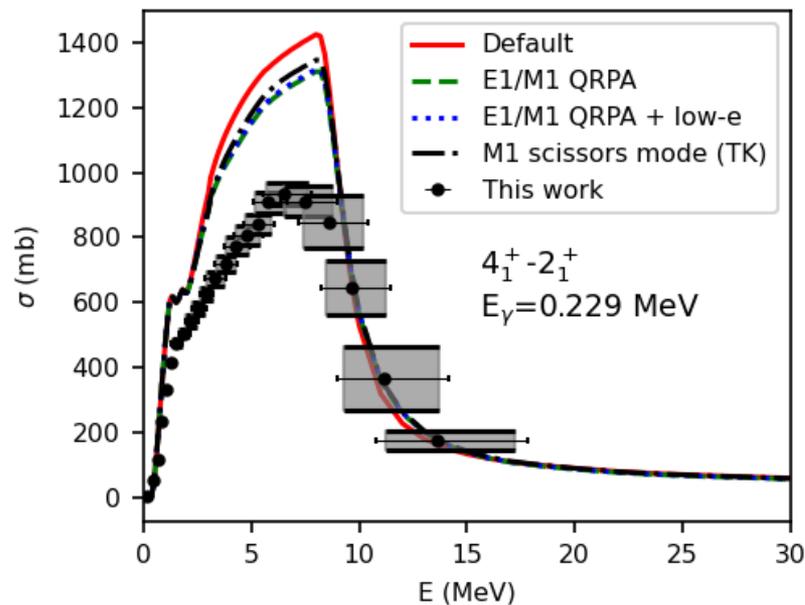
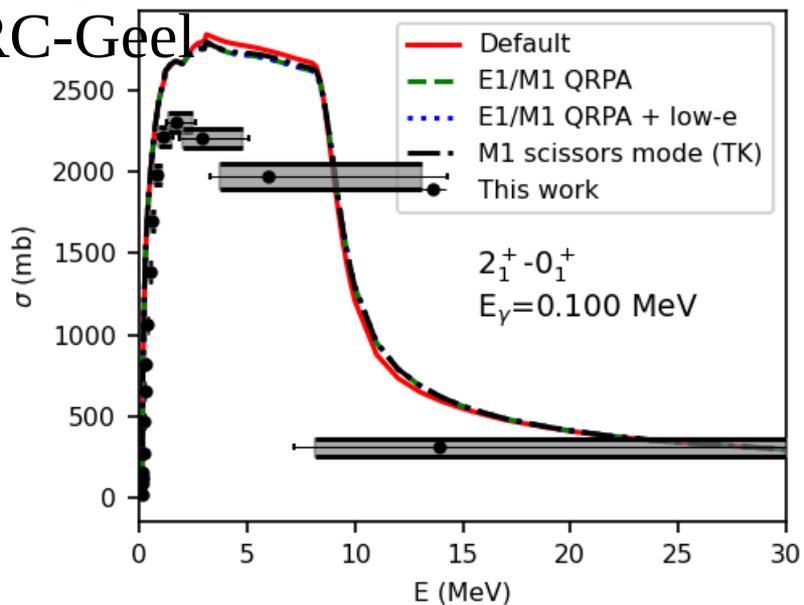
Densités de niveaux



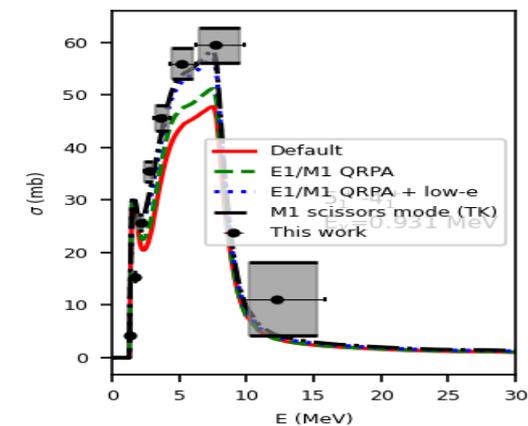
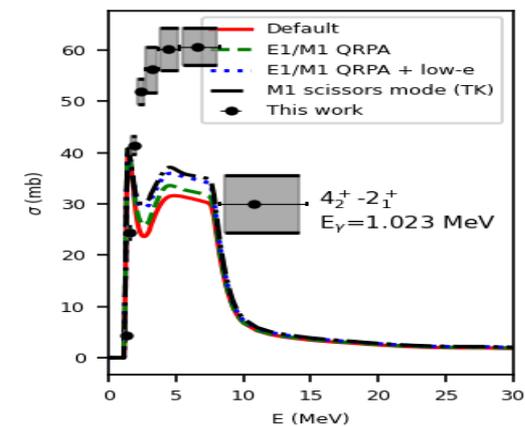
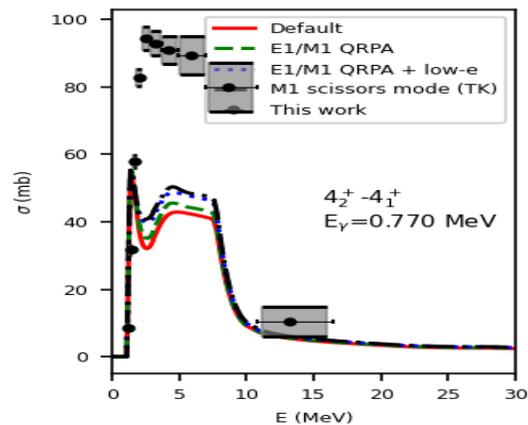
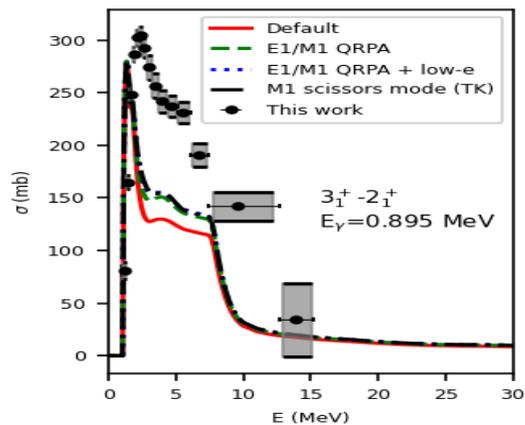
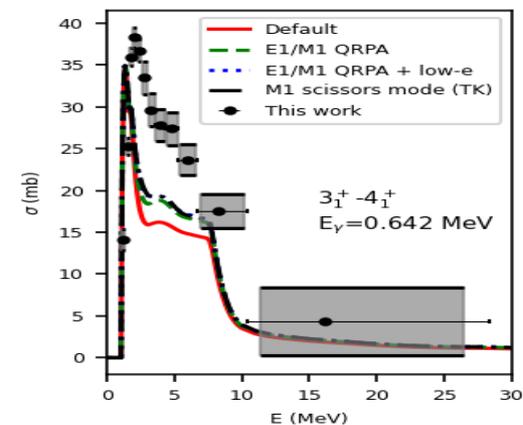
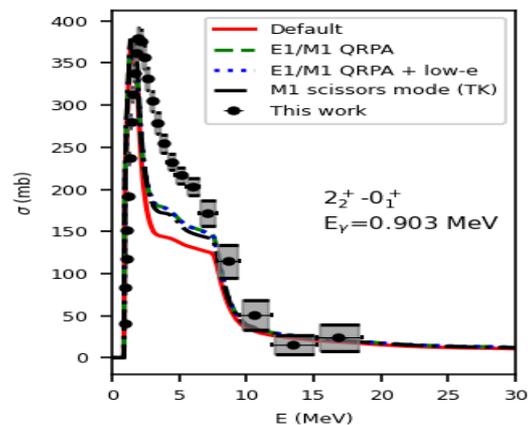
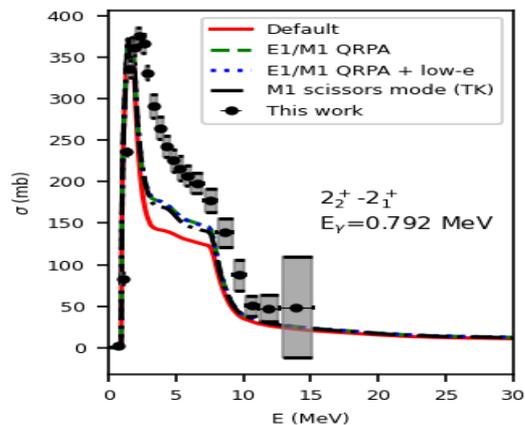
This work
= IPHC @ GELINA

$^{182}\text{W}(n,n'\gamma)$, band 1

EC-JRC-Geel

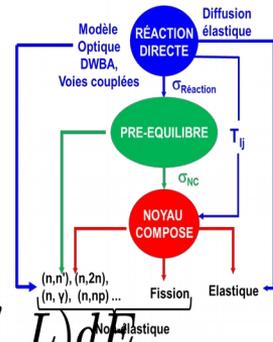


$^{184}\text{W}(n,n'\gamma)$, band 2



This work
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EC-JRC-Geel

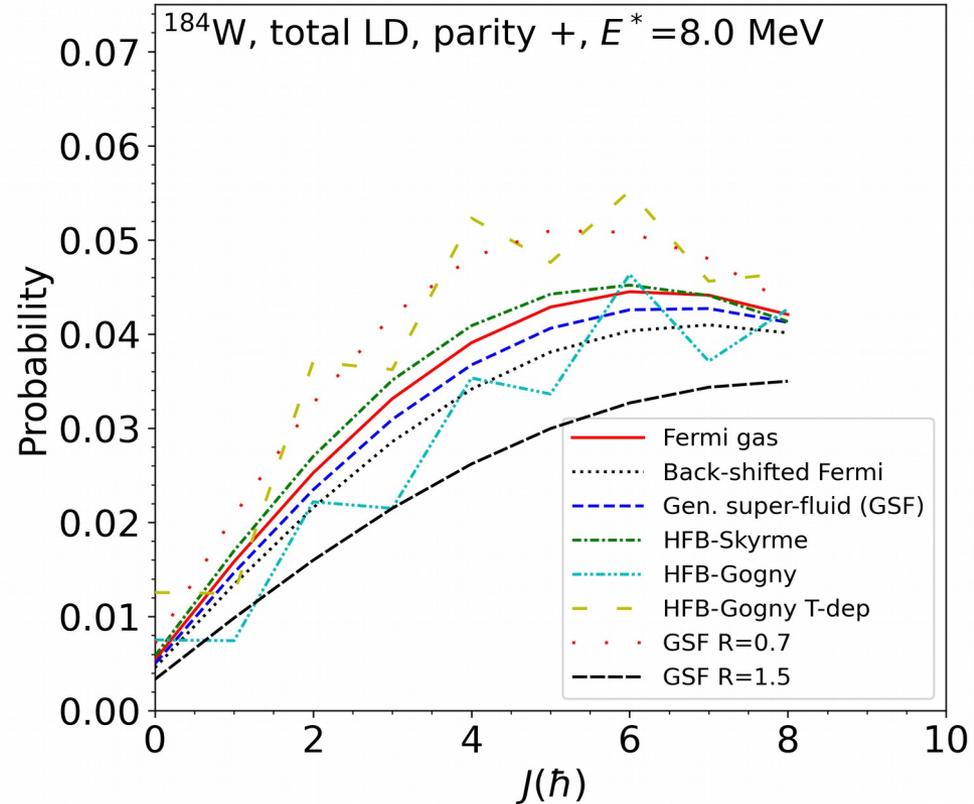
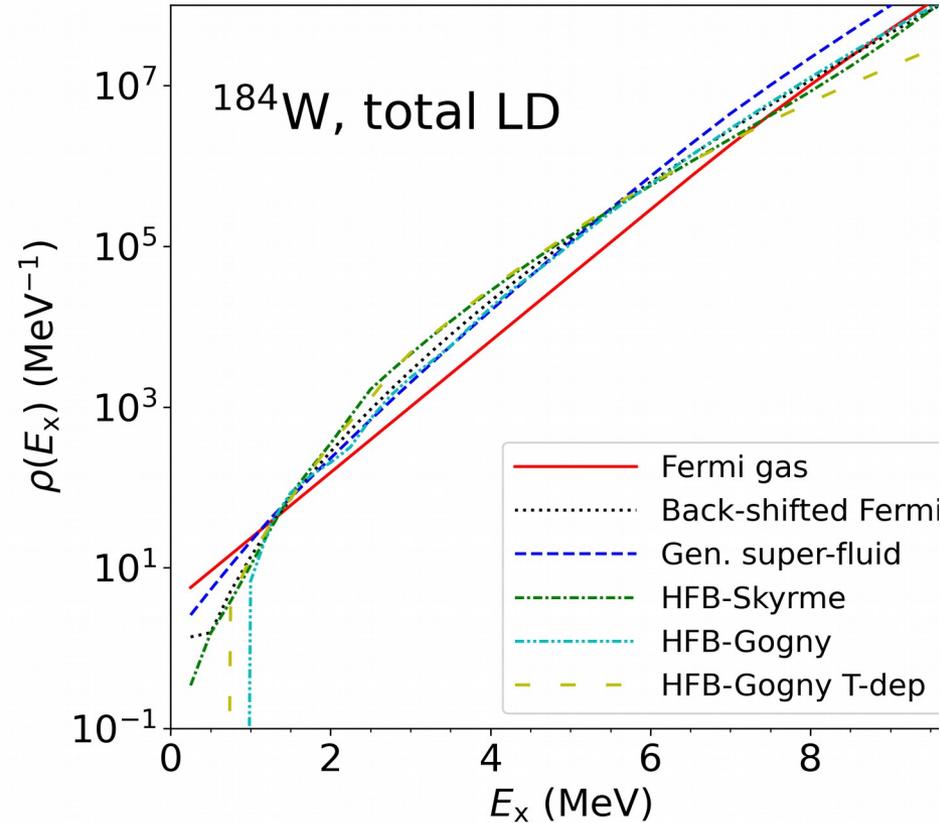
Compound nucleus decay from continuum



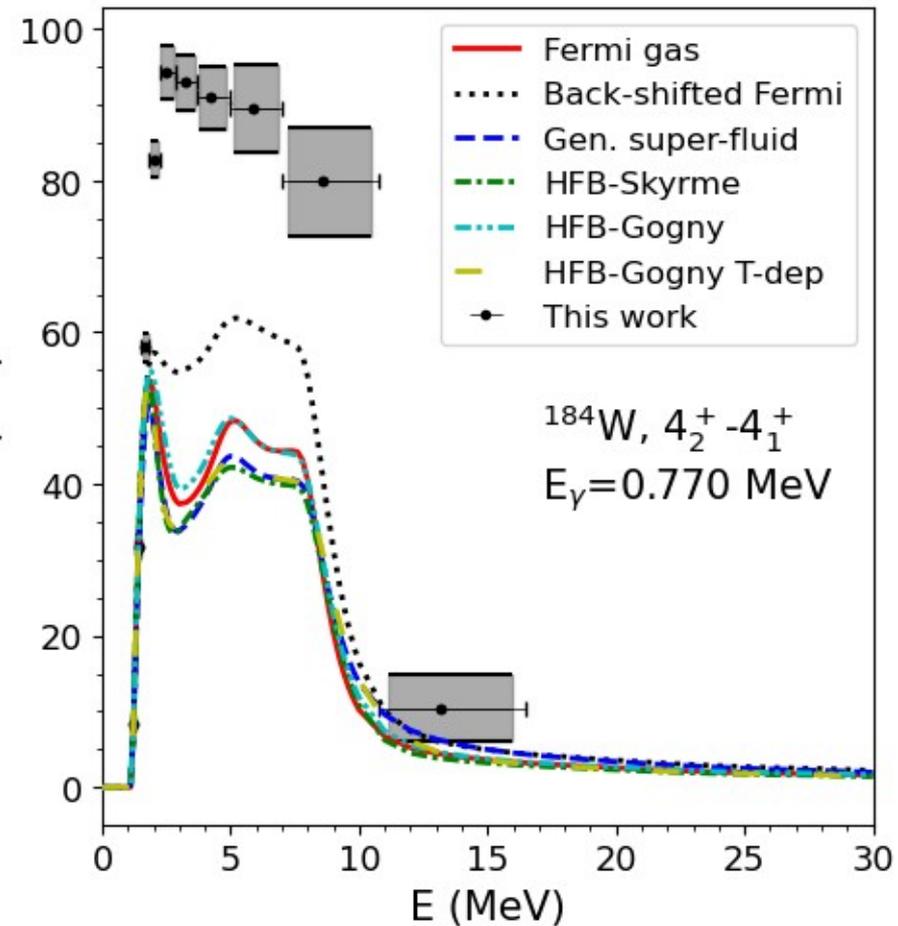
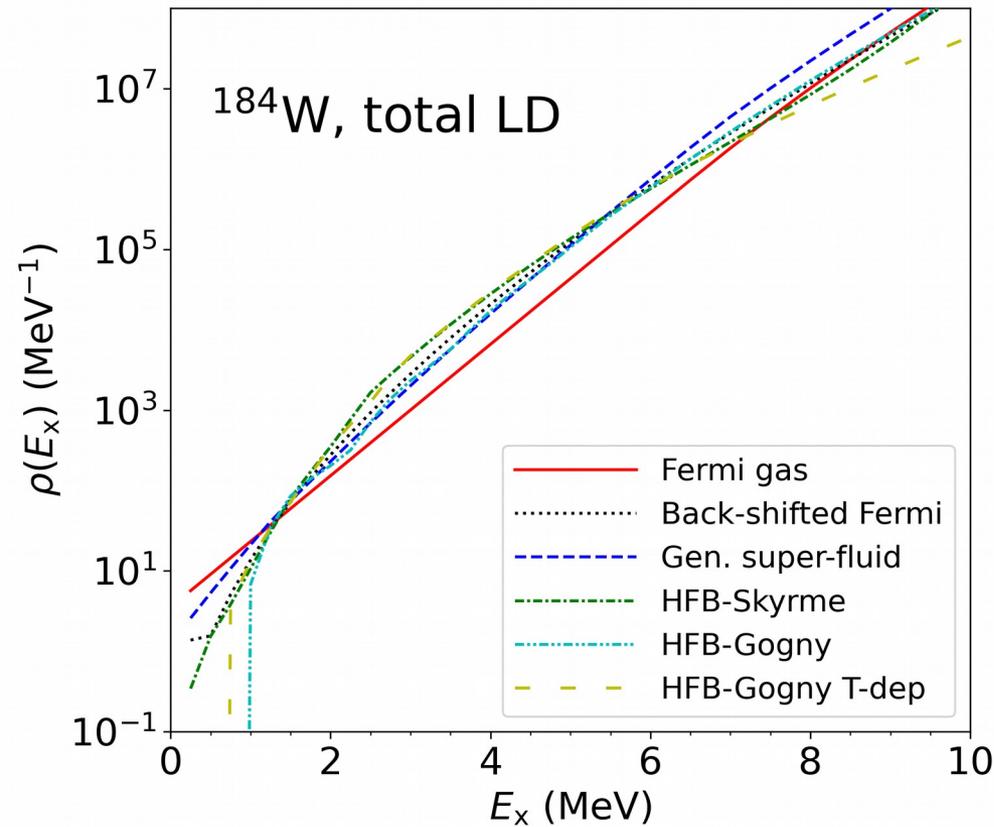
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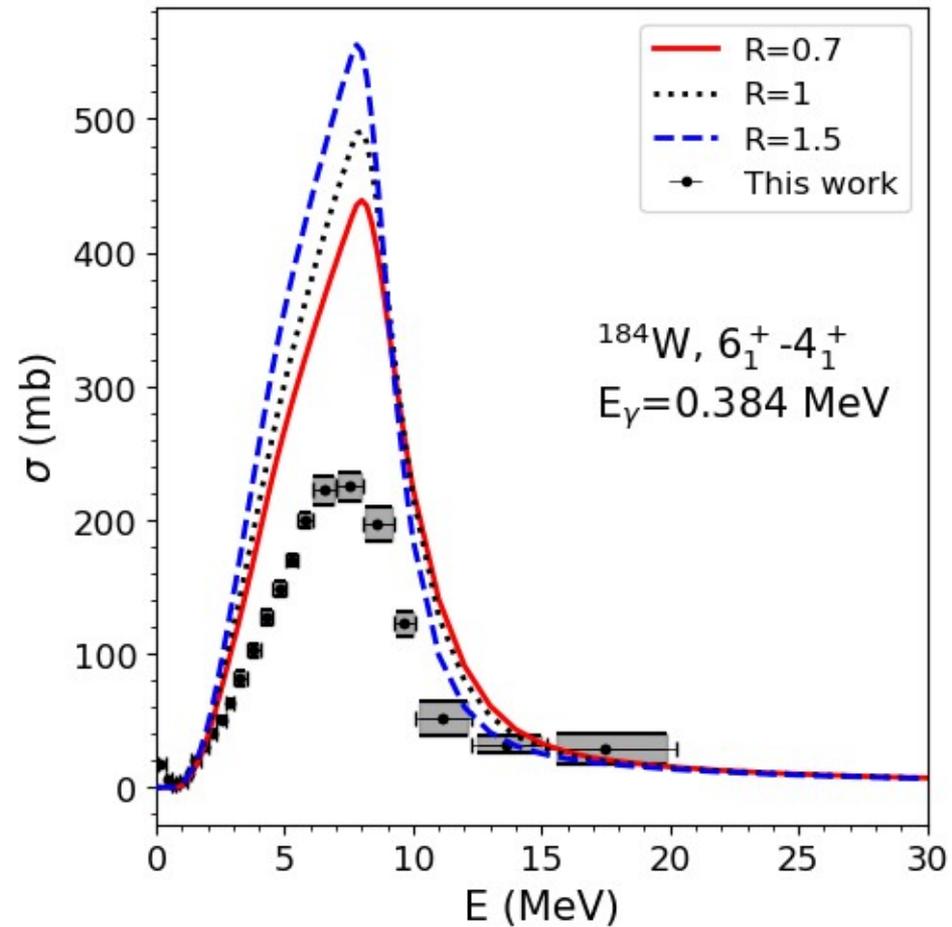
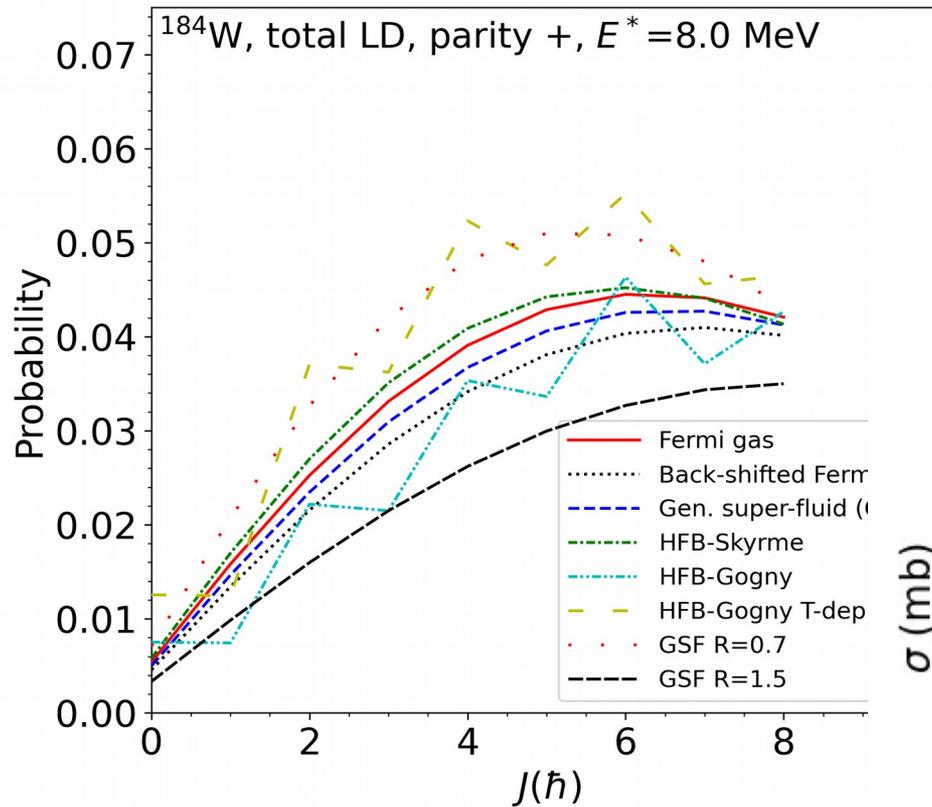
Densités de niveaux



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Fluctuations de largeur de voie

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Masses

Déformations

Niveaux discrets

Densités de niveaux

Densités de matière

Fonctions de force- γ

Paramètres de fission

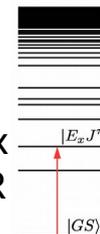
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RÉACTION DIRECTE

Diffusion élastique

Inélastique vers niveaux discrets, GR

Transfert



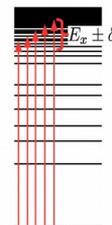
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Sensibilité aux détails de structure (densités de matière)

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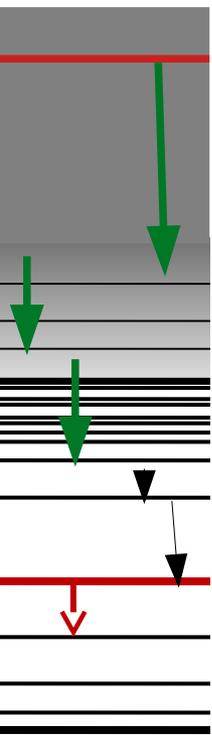
Diffusion élastique vers niveaux du continuum, Émission multiple



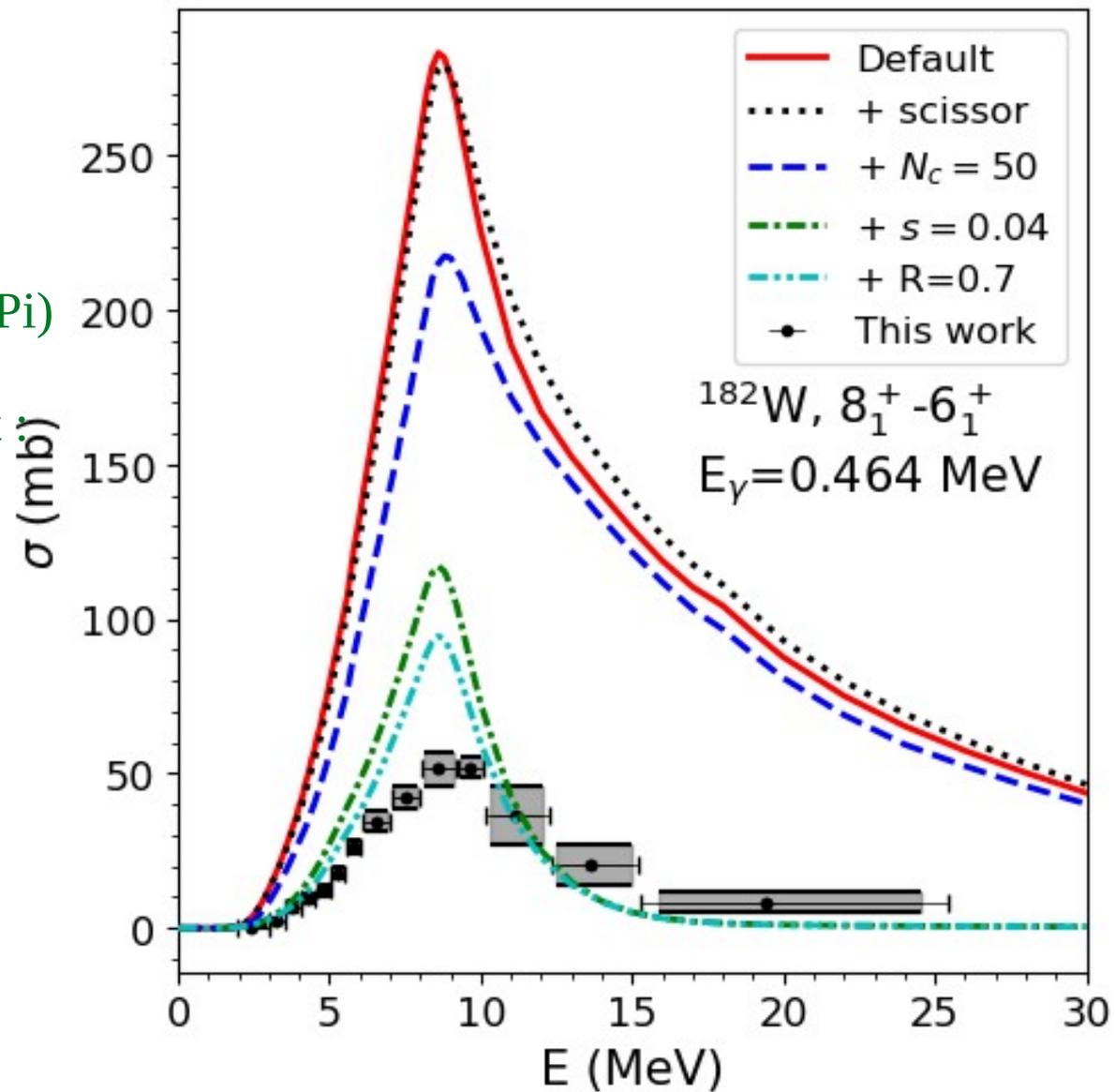
Approches :

- Phénoménologiques : (excitons, hybrides)
- Semi-classiques (cascade intra-nucléaire)
- Quantiques

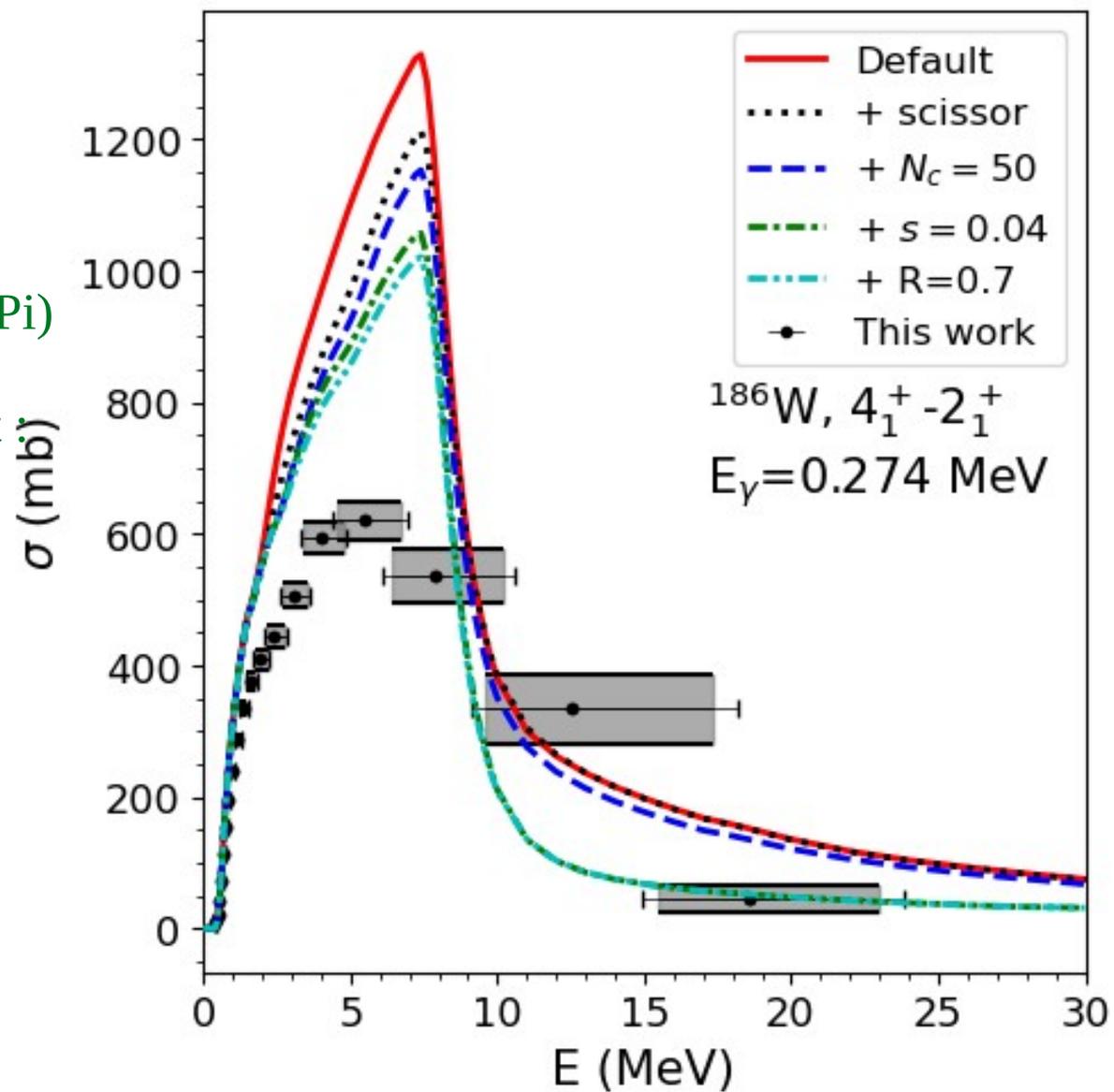
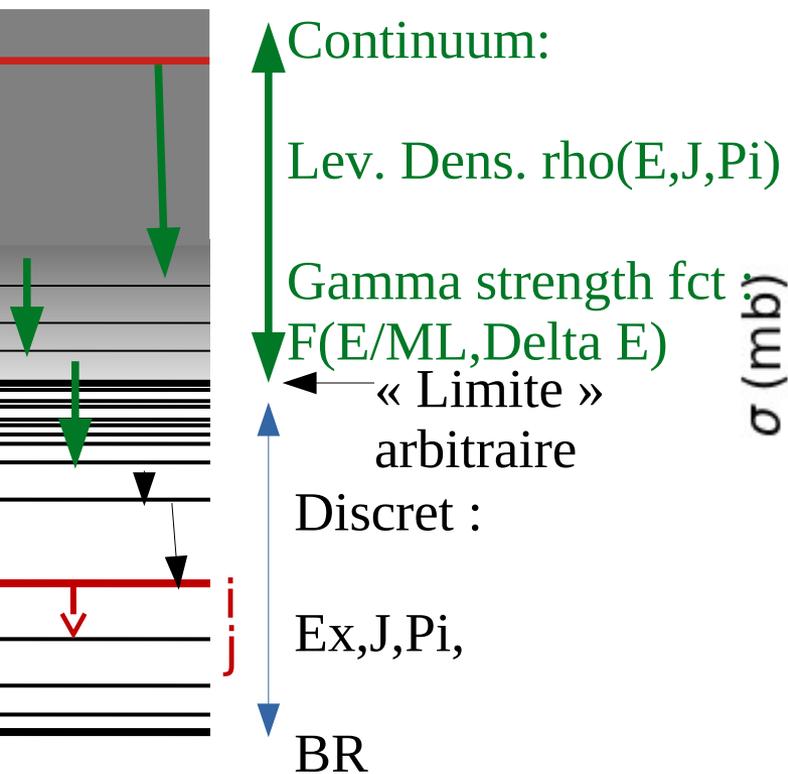
Comment selectionner le meilleur modèle ?



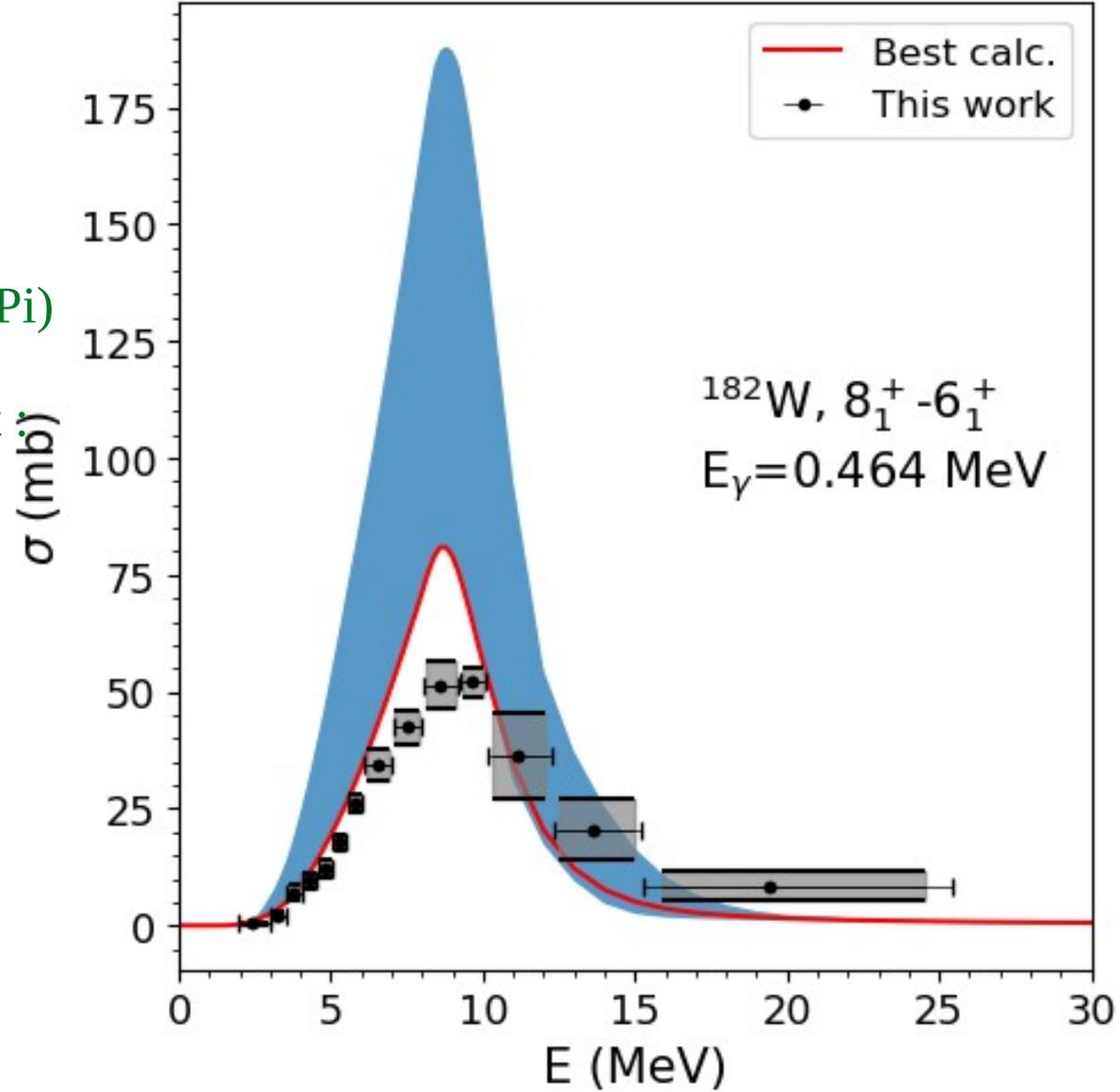
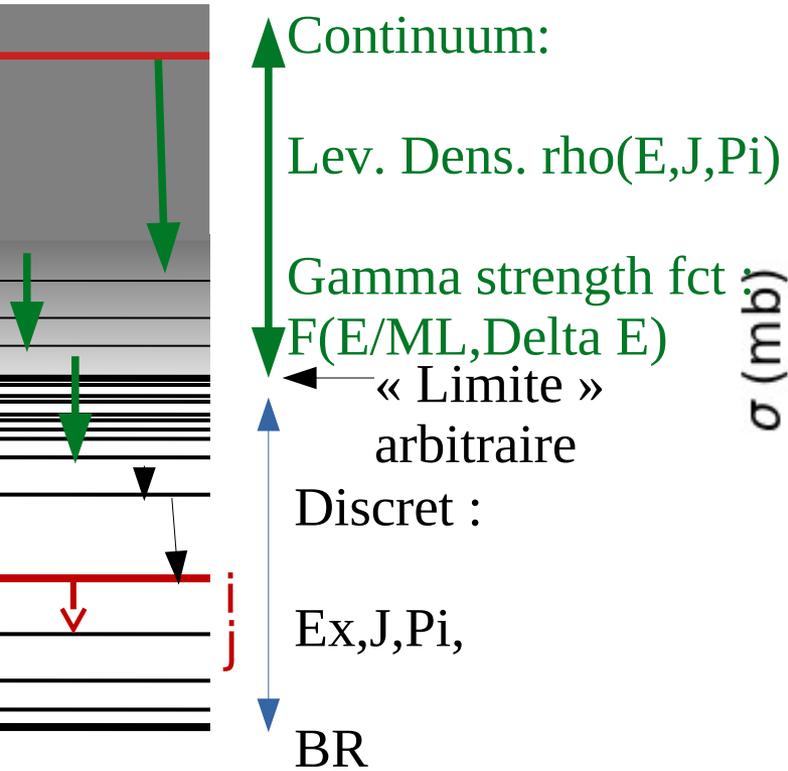
Continuum:
 Lev. Dens. $\rho(E, J, \Pi)$
 Gamma strength fct
 $F(E/ML, \Delta E)$
 « Limite »
 arbitraire
 Discret :
 Ex, J, Pi,
 BR



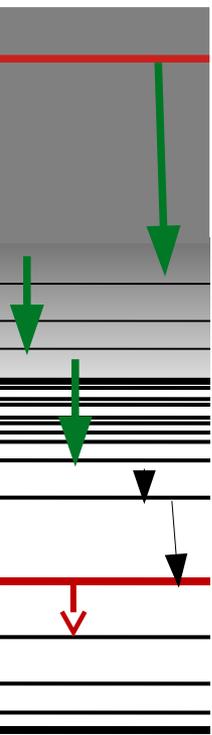
Comment selectionner le meilleur modèle ?



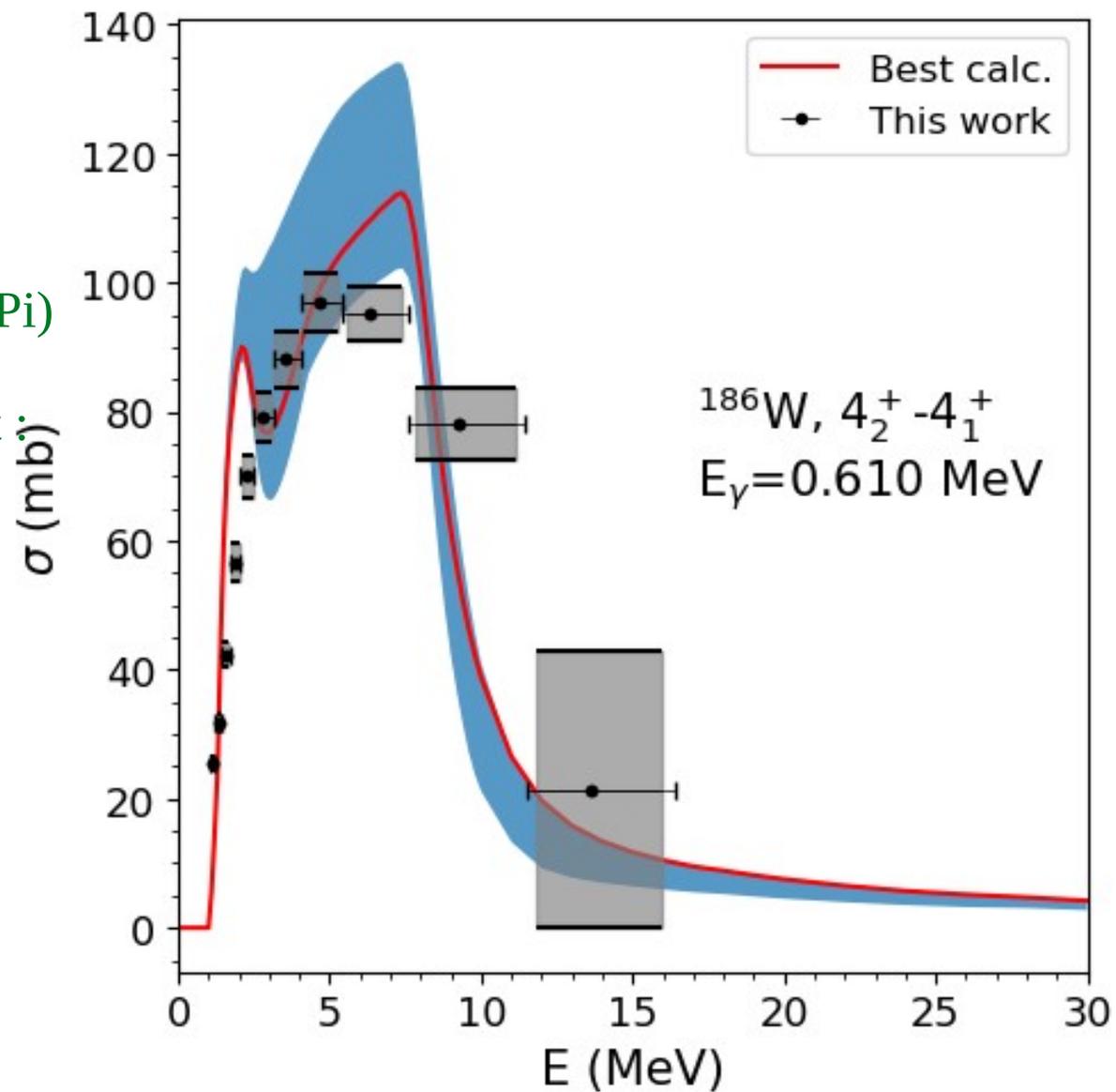
Recherche du meilleur jeu de paramètres / ensemble des transitions pour un noyau

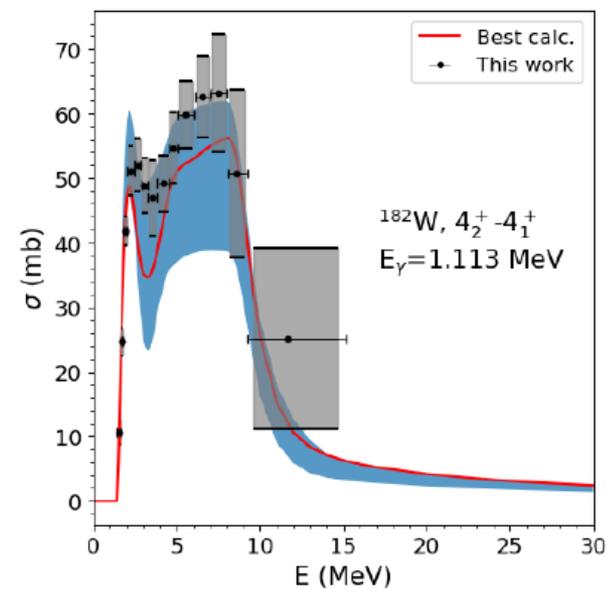
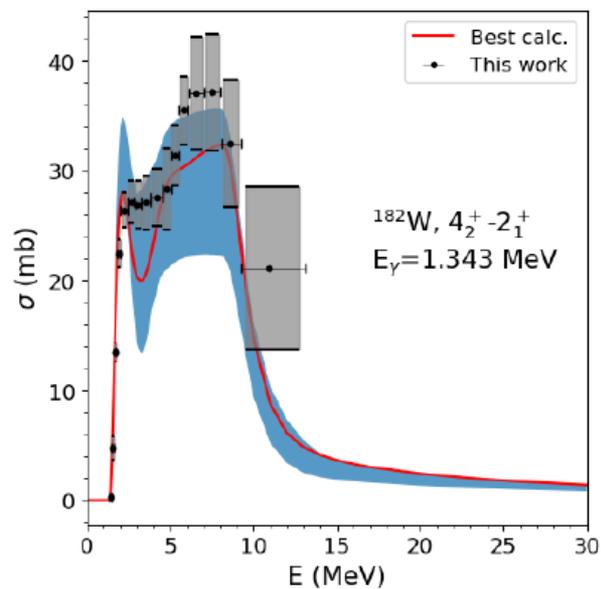
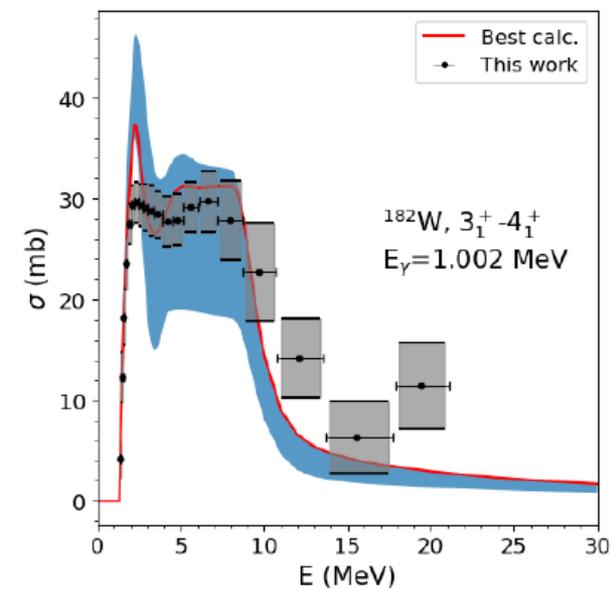
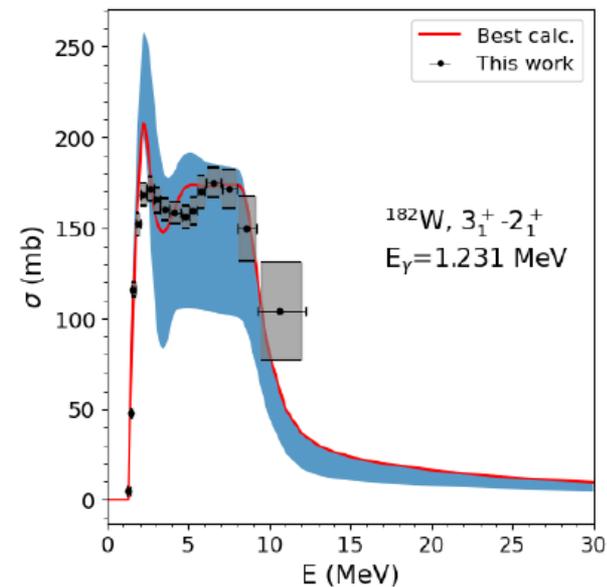
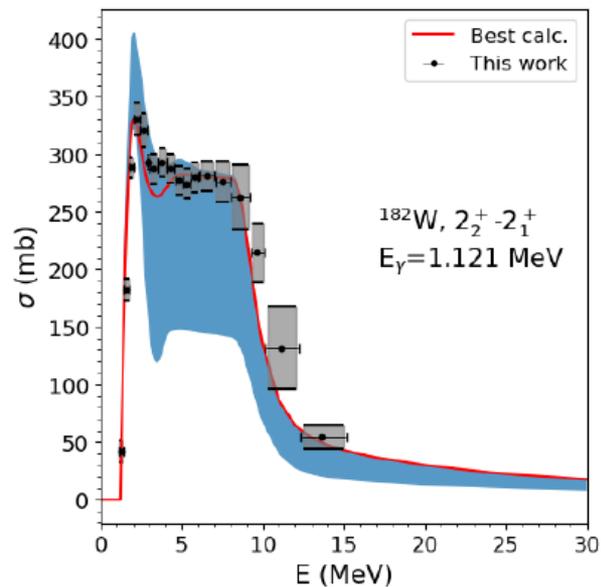
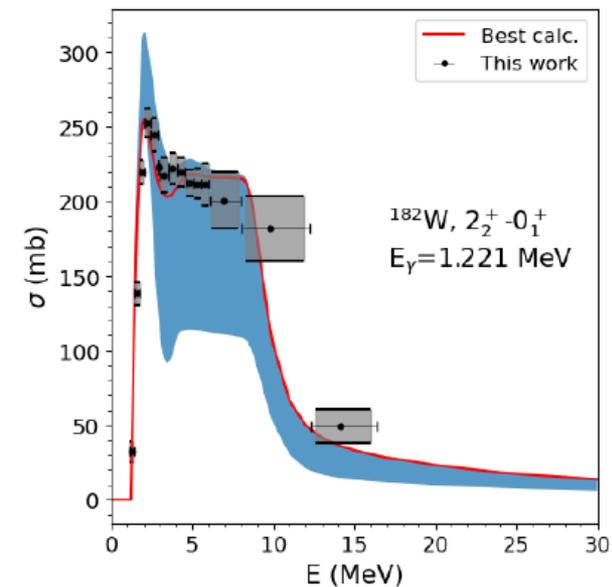


Comment selectionner le meilleur modèle ?

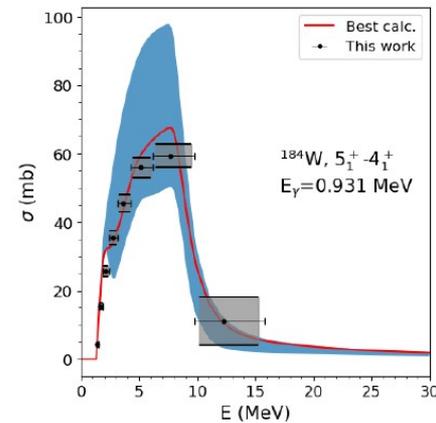
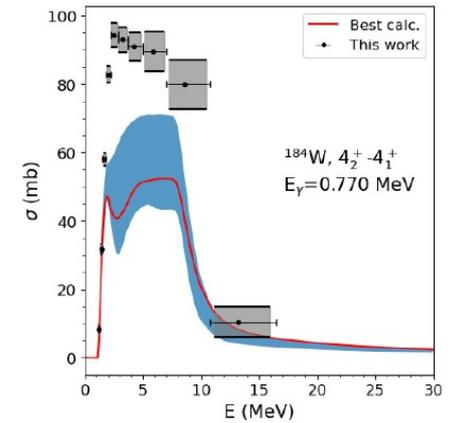
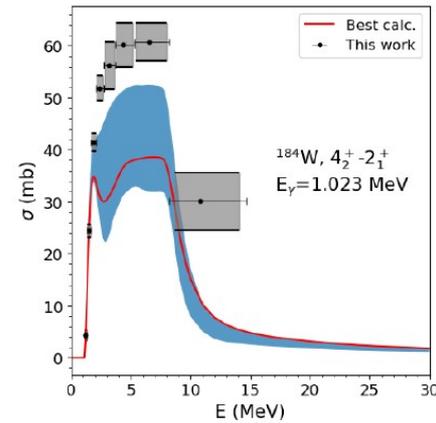
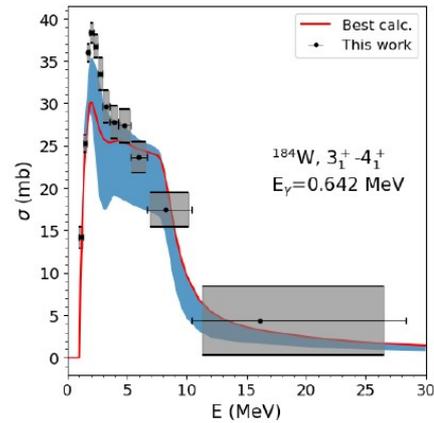
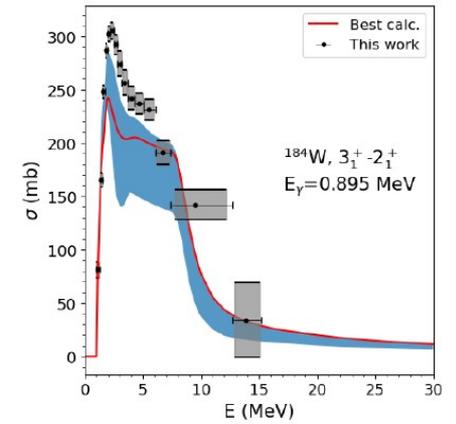
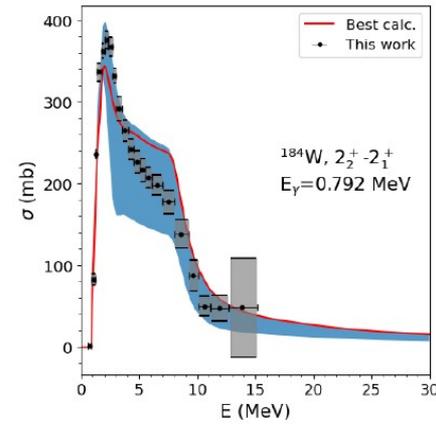
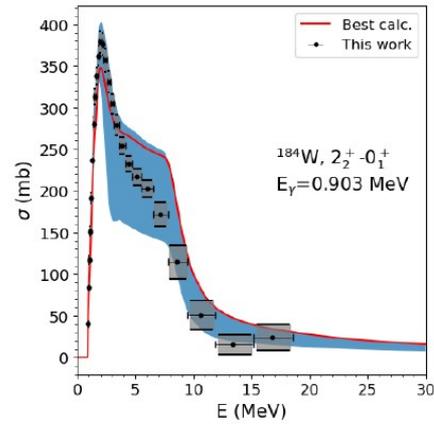


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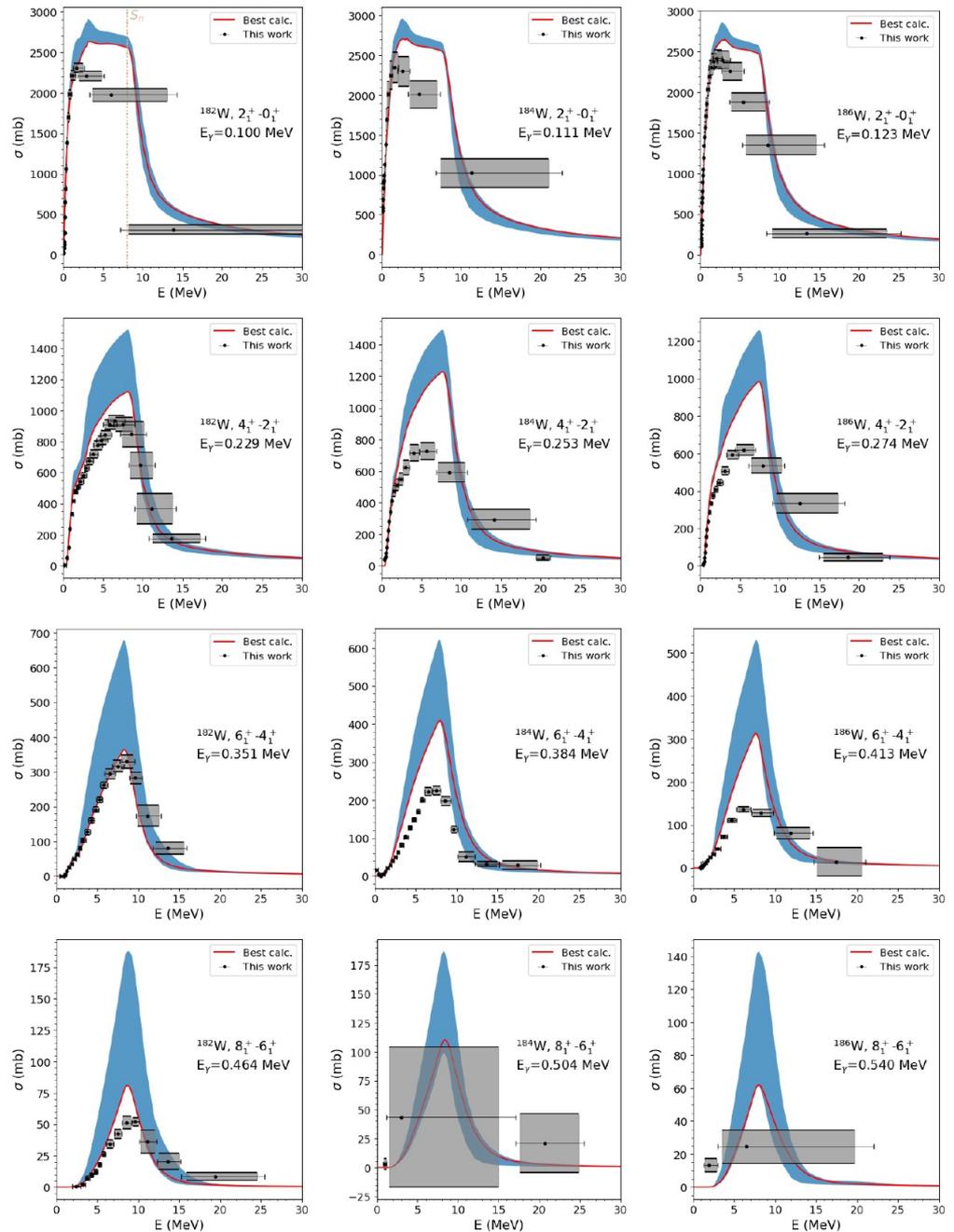


Recherche systématique efficace dans certains cas



Toutes les transitions ne peuvent être reproduites simultanément

Certaines données ne peuvent être reproduites dans l'espace des modèles/paramètres considéré



Conclusions

Approche de pré-équilibre microscopique permet d'améliorer la description des sections efficaces double différentielles (n,xn) et certaines partielles $(n,n'g)$ + impact sur sections exclusives $(n,2n)$, $(n,3n)$, (n,f)

**Divers aspects des modèles peuvent être testés grâce aux nouveaux jeux de données $(n,n'g)$:
Mesures IPHC tungstènes.**

Analyse $(n,n'g)$ mesurées révèle des tendances, et peut confirmer / infirmer des choix physiques

- **besoin de composantes M1 basse énergie**
- **distribution en spin des densités de niveaux**
- **plus de niveaux discrets (trans. discret - continuum)**
 - **pré-équilibre microscopique**

Approche étendue pour tenir compte des captures radiatives + application "cohérente" sur chaîne isotopique