Pre-equilibrium Nuclear Reactions: Reaction Mechanisms and Impact on Observables

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Collaborators

- Microscopic inelastic scattering modeling :
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  B. Menant (CEA, DAM, DIF - PhD)

- Application to surrogate studies :
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- Applications to nuclear data:
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- Applications to nuclear structure studies :
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Outline

- Microscopic inelastic scattering modeling, to discrete levels and continuum, spherical/deformed targets : answer to applicative questions ?
  - Nuclear data production
    - Experimental set-up optimization
      - Experimental interpretation, especially for exotic nuclei.

- Applications for nuclear data : (n,n'γ) ; (n,xn) ; fission ; isomer production ; (n,γ) .

- Nuclear reaction modeling input for surrogate reaction method.

- Applications for nuclear structure : new mean field input.

- Three main directions of improvements : NS input / reaction mechanisms / UQ and propagation.

- Conclusions and perspectives.

What pre-equilibrium means ?

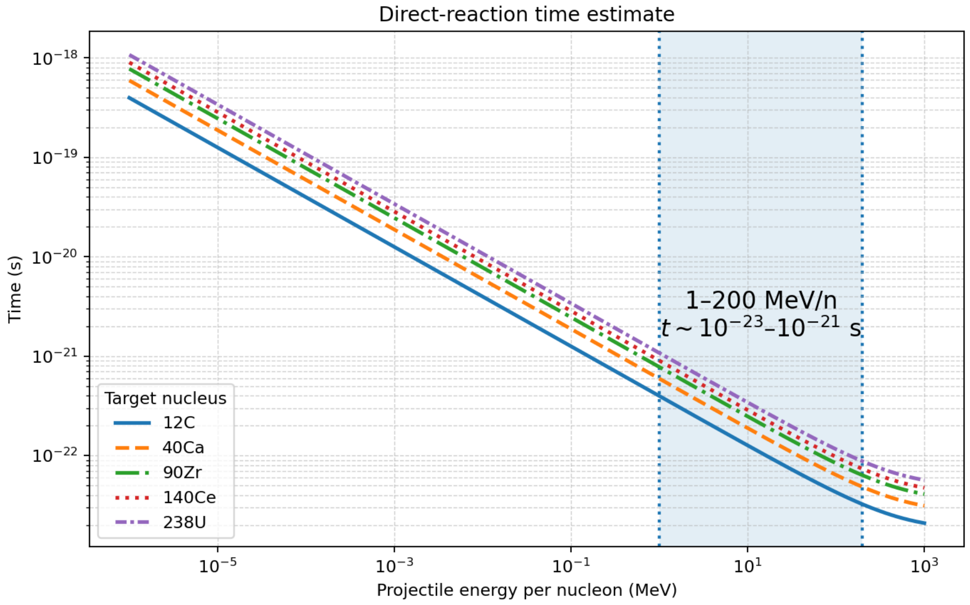
→ Inclusive spectra often require more than “direct + compound”.

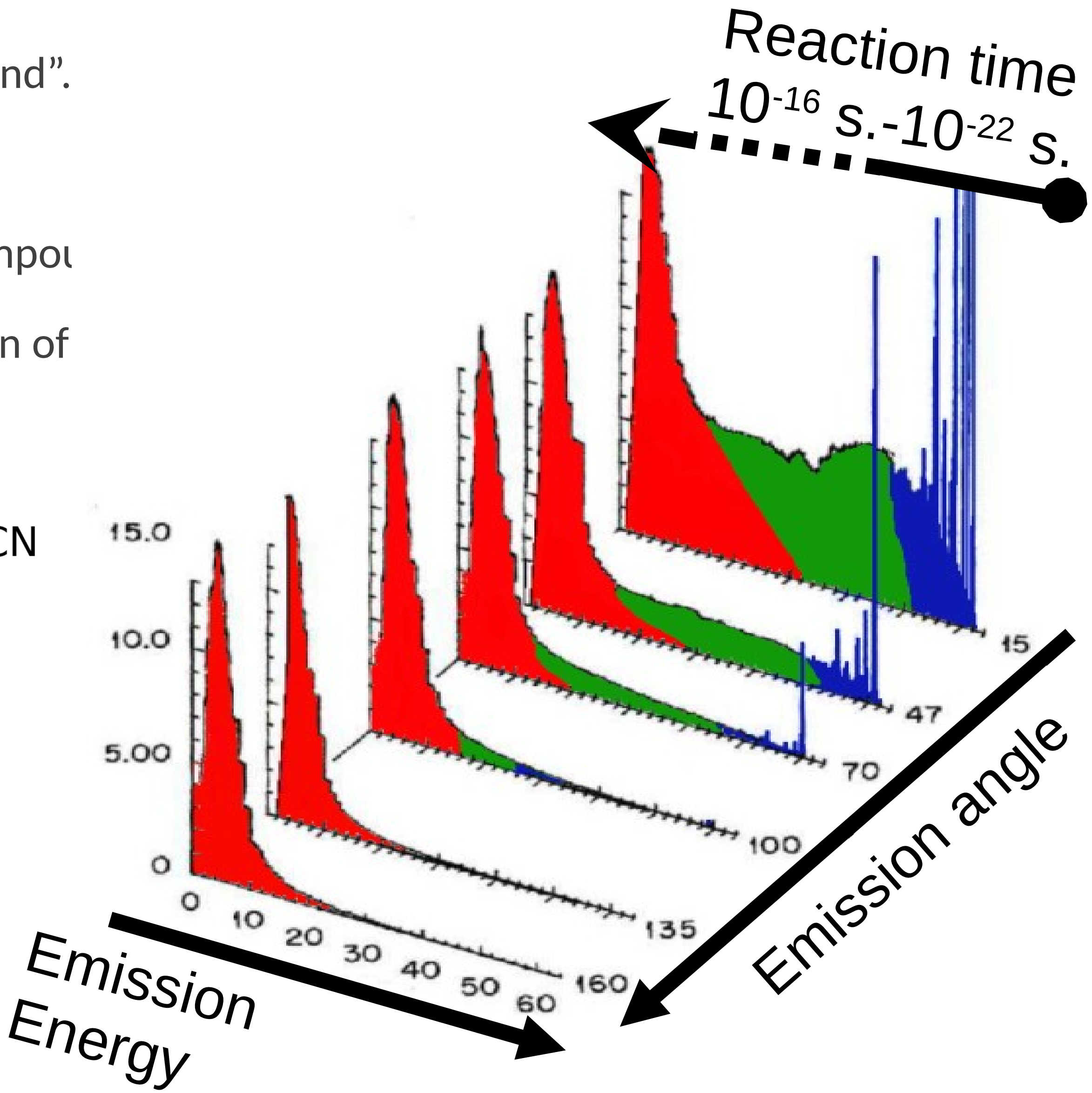
→ Process of thermalisation of the composite system

→ Reaction time : longer than direct but much faster than compou

→ Pre-equilibrium emission = emission before full equilibration of compound nucleus.

$$\frac{d^2\sigma}{dE\,d\Omega} \approx \left(\frac{d^2\sigma}{dE\,d\Omega}\right)_{\text{direct}} + \left(\frac{d^2\sigma}{dE\,d\Omega}\right)_{\text{preeq}} + \left(\frac{d^2\sigma}{dE\,d\Omega}\right)_{\text{CN}}$$





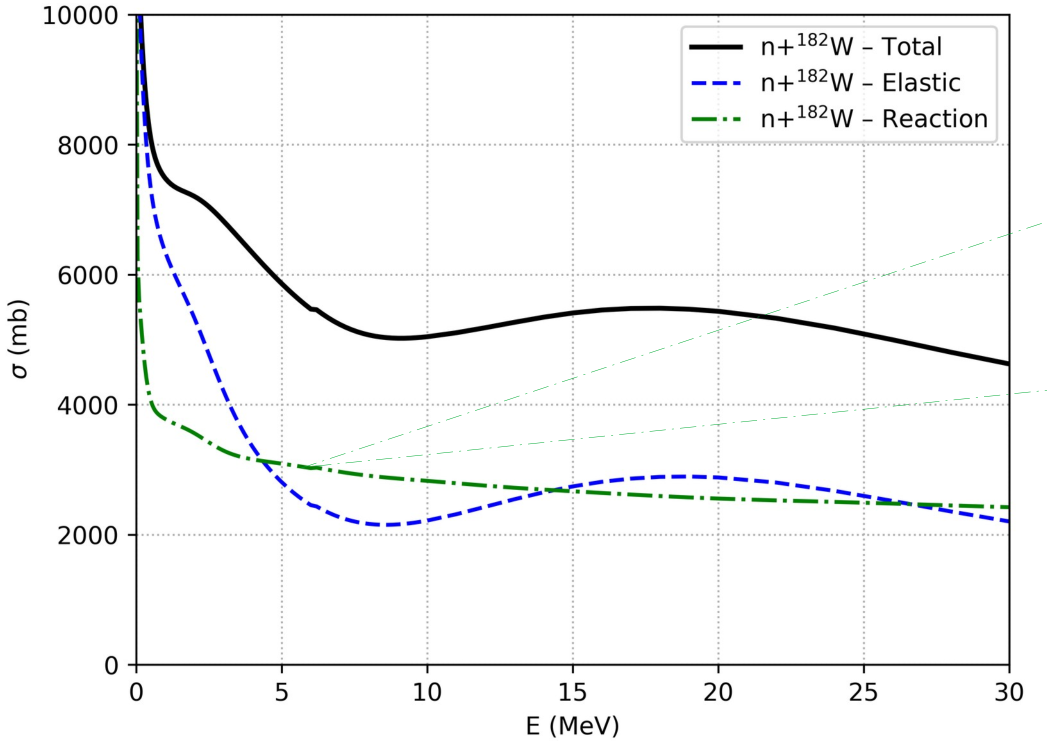
Pre-quilibrium Emission

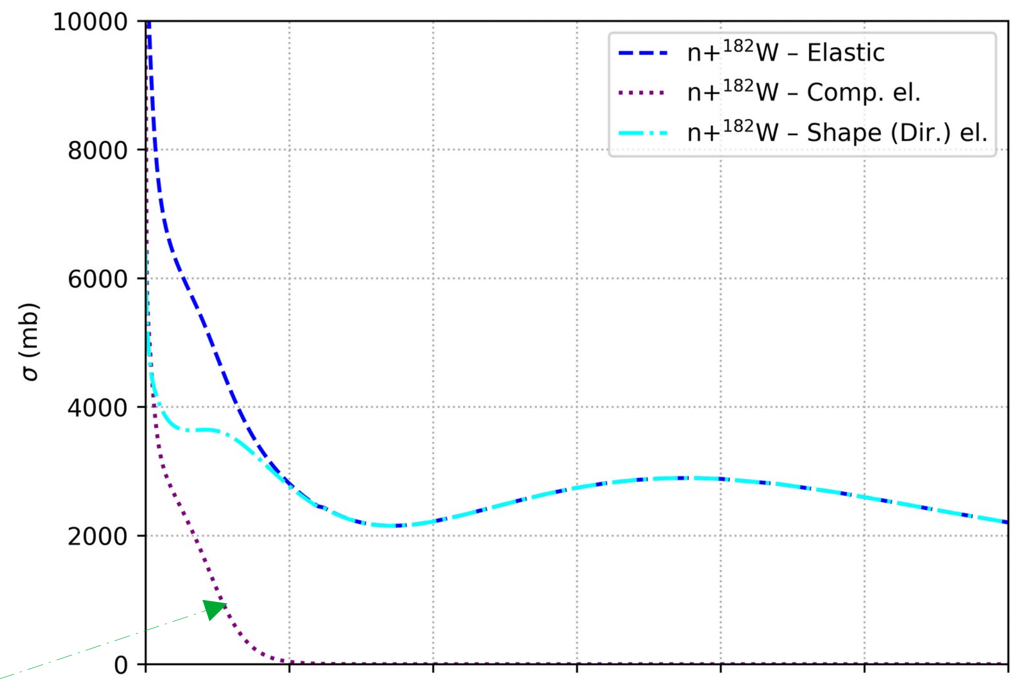
Total = Dir. Elastic + Reaction

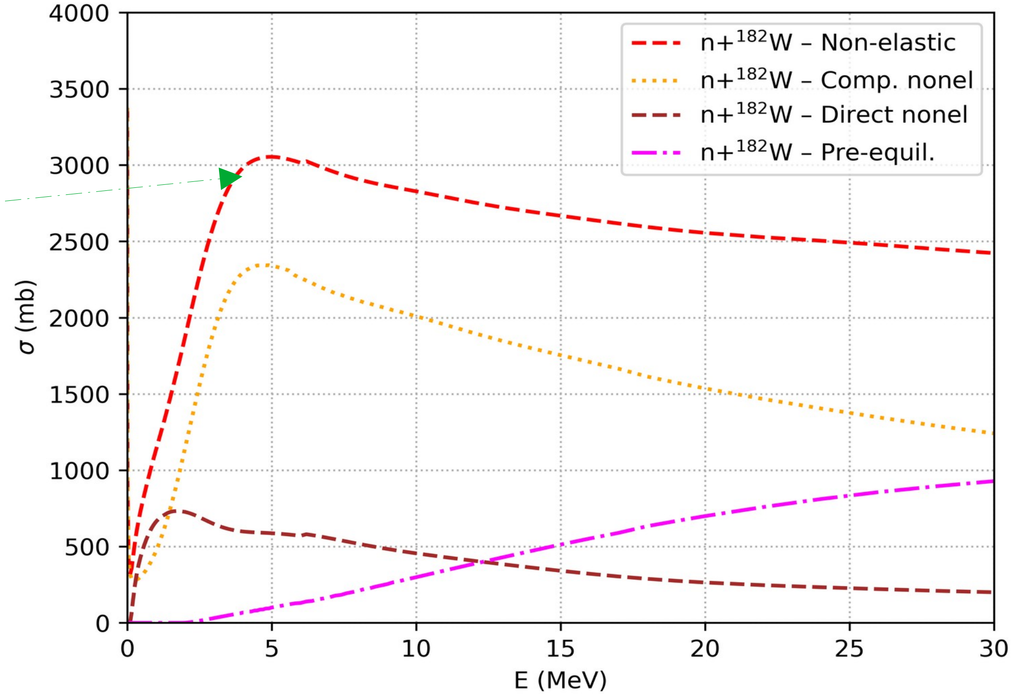
Reaction = Non Elastic + CN elastic

Non Elastic = Dir Non el. + Pre-eq + CN non-eq

(Direct)

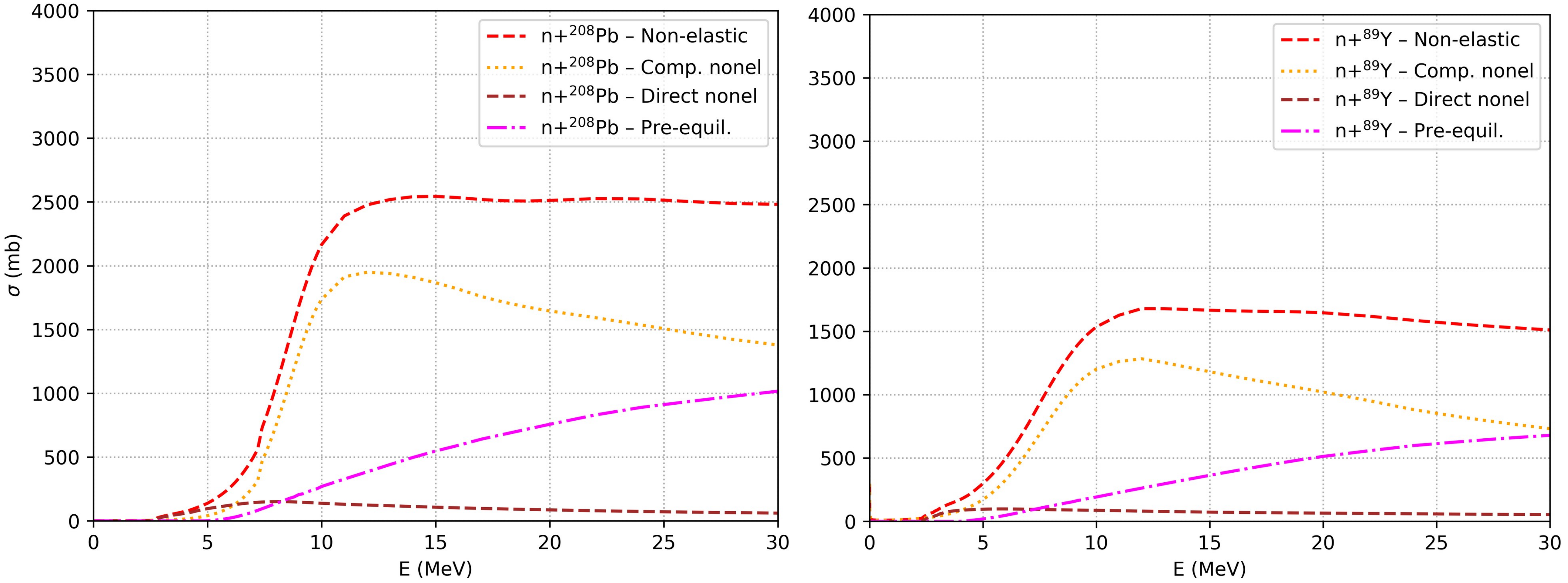






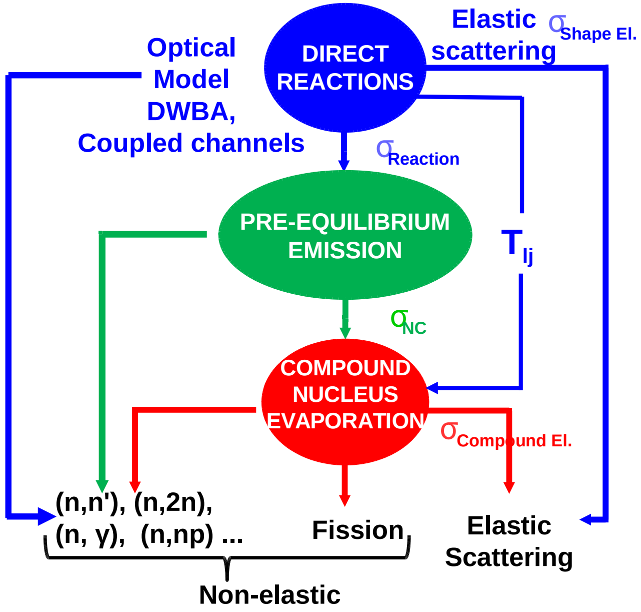
Calculated with code Talys

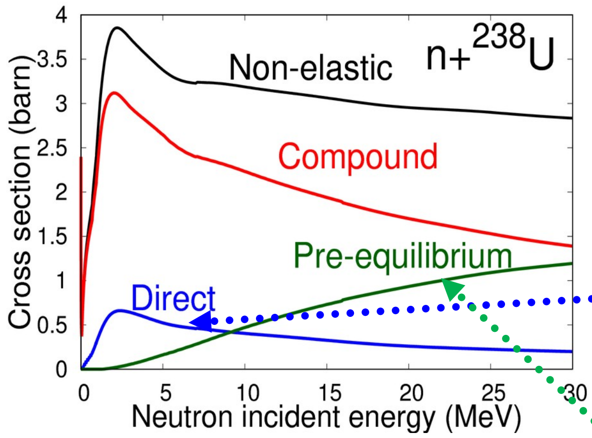
Pre-quilibrium Emission

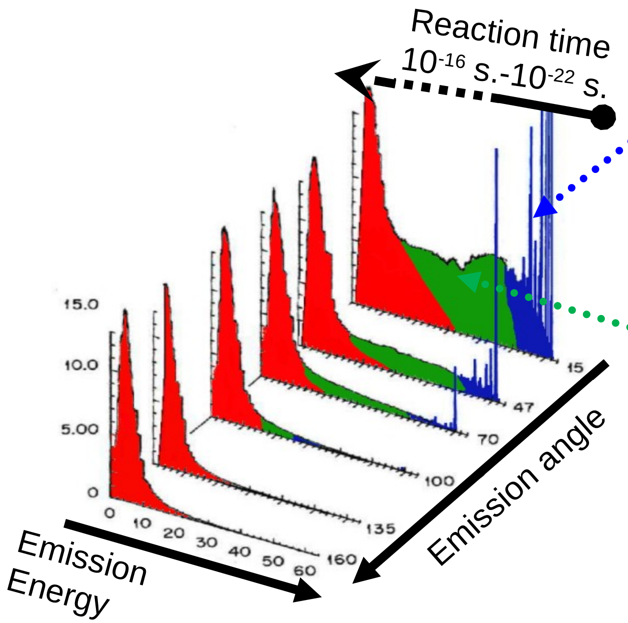


Calculated with code Talys

Reaction mechanisms





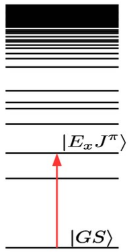


Direct reactions

Shape elastic

Inelastic to discrete levels and GR

Transfer



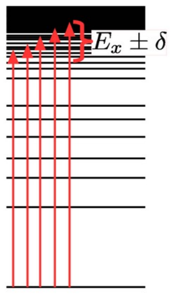
Optical Potential
Coupled Channels,
DWBA

Sensitivity to NS
Details (matter densities)

Pre-equilibrium

Inelastic scattering to continuum

Multiple emission



Phenomenological (exciton)

Hybrid, semi-classical
(intranuclear cascade)

Quantum approaches (FKK, NWY, TUL)

Multistep process

Compound Emission

Compound elastic

Compound inelastic : optical potential, CC, LD

Gamma emission : GSF

Hauser-Feshbach
Width fluctuations
LD, GSF, OMP, NS

Pre-equilibriumModels

- Exciton (statistical master equation) : **E = few MeV - 200 MeV**

- Quantum multistep direct and compound (MSD vs MSC) : **E = threshold - 200 MeV,** perturbative, statistical approximation (energy/ensemble averaging, sudden/adiabatic approximation ...)

- Hybrids (non-equilibrium nuclear dynamics, smooth connection to CN regime, excited configuration with time evolution) → solve effective transport equation in exciton space. **E = 20-200 MeV**

- Intra-nuclear cascade (INC, classical trajectory, event by event dynamic, quantum correction) : **E > 100 MeV, but good results for E> 14 MeV**,

- Eikonal/Glauber : **E > 100 MeV**

Exciton model for pre-equilibrium emission

→ Time evolution of excitons number which caracterise the system state

→ Incident nucleon, n particle – n hole excitation : N = 2n + 1 excitons (projectile count as 1)

→ N=2n+1 → p=n+1 ;

→ transition rate :

$$\lambda^{\pm}(n,E) \sim |M|^2\, \omega^{\pm}(n,E)$$

→ Master equation for occupation probability :

$$\begin{aligned} \frac{dP(n,t)}{dt} &= P(n-2,t).\lambda^{+}(n-2,E) + P(n+2,t)\lambda^{-}(n+2,E) \\ &- P(n,t)\left[\lambda^{+}(n+2,E) + \lambda^{-}(n-2,E) + L(n,E)\right] \end{aligned}$$

→ Ingredients : **M** → matrix element is an adjustable parameter.

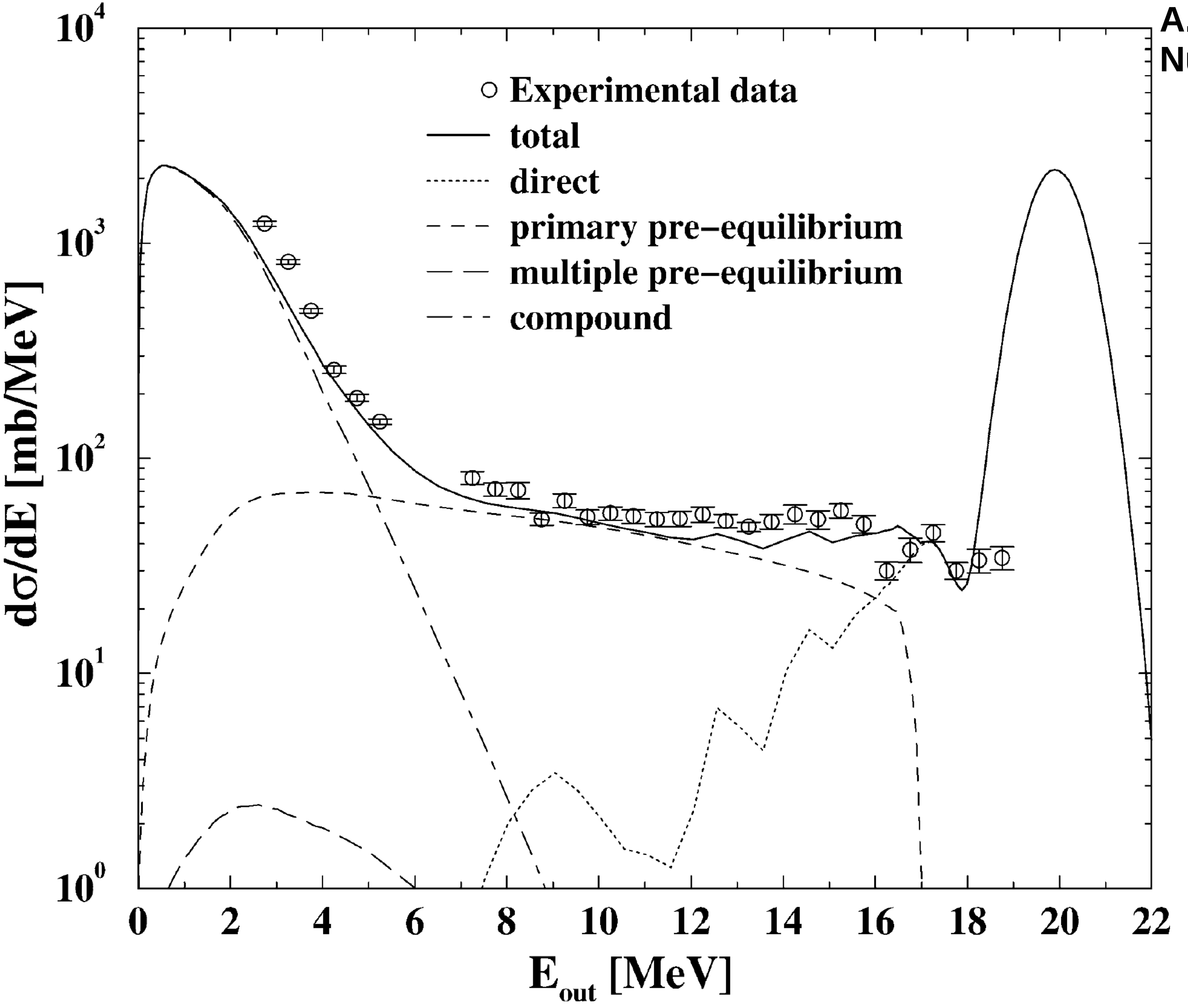
$\rho_{n'}$ → model level density for n' particle- n' hole.

→ Angular distribution : not modeled, use Kalbach systematics (emperical shape).

→ **Pros** : fast calculations – good fit of energy distribution of emitted particles

→ **cons** : do not predict angular distribution nor spin transfer,
do not include collective effects – transition direct – pre-equilibrium

A.J. Koning, M.C. Duijvestijn, Nuclear Physics A 744 (2004) 15–76



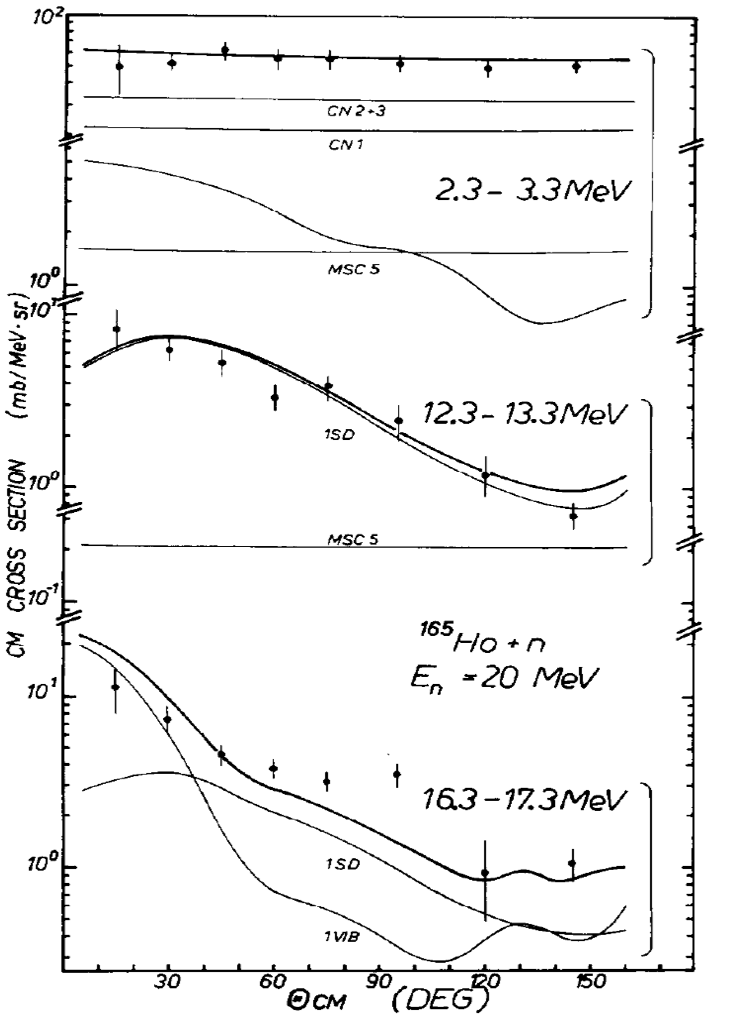
^{209}Bi(n, xn) spectrum at 20 MeV.

Transition Direct – Pre-eq : ad-hoc → subjective

Double-counting

Why quantum model ?

$$T_{f\leftarrow i} = \langle f|V \sum_{n=0}^{\infty} \left(\frac{1}{H - E + i\eta} V \right)^n |i\rangle$$



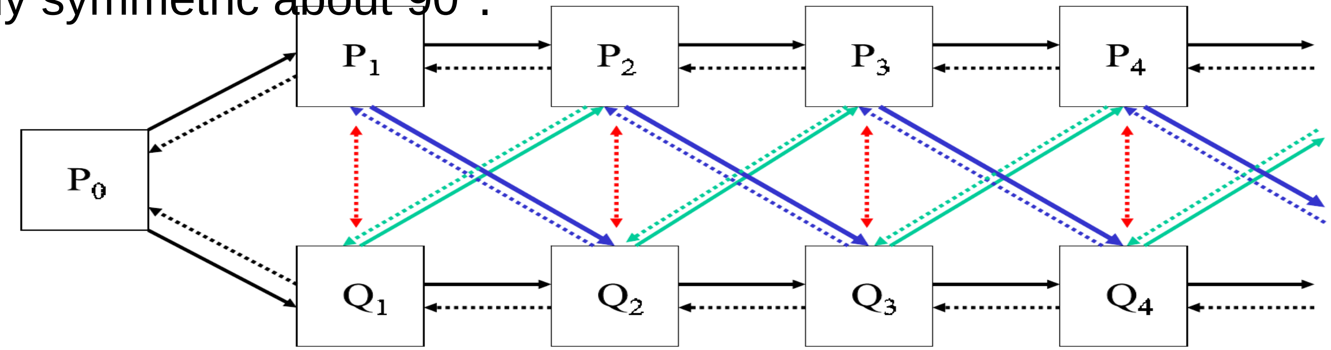
Nuclear Physics A561 (1993) 387–415

→ Semi-classical models (such as the exciton model) capture part of the reaction evolution but remain limited in their treatment of nuclear structure.

→ **Coherent effects (collectivity: vibrations/rotations, interference effects)** are intrinsically quantum-mechanical.

→ A quantum framework allows a unified treatment of both incoherent excitations (1p1h, 2p2h, ..) and collective modes.

→ Quantum models separate the spectrum into continuum (P) and bound-state (Q) components, which lead to very different angular distributions: the continuum may be forward-peaked, whereas the bound-state contribution is necessarily symmetric about 90°.



MSD: Multistep Direct

MSC : Multistep Compound

Multi-step Direct Theories

$$T_{f\leftarrow i} = \langle \chi^{(-)}(\mathbf{k}_f), F | V + VG^{(+)}V + VG^{(+)}VG^{(+)}V + \dots \, | \chi^{(+)}(\mathbf{k}_i), 0 \rangle$$

→ FKK: Feshbach, Kerman, Koonin (1980) On-Shell Approximation for Green's Function + Non-normal matrix elements.

→ TUL: Tamura, Udagawa, Lenske (1982) : Adiabatic Approximation for the Second Step

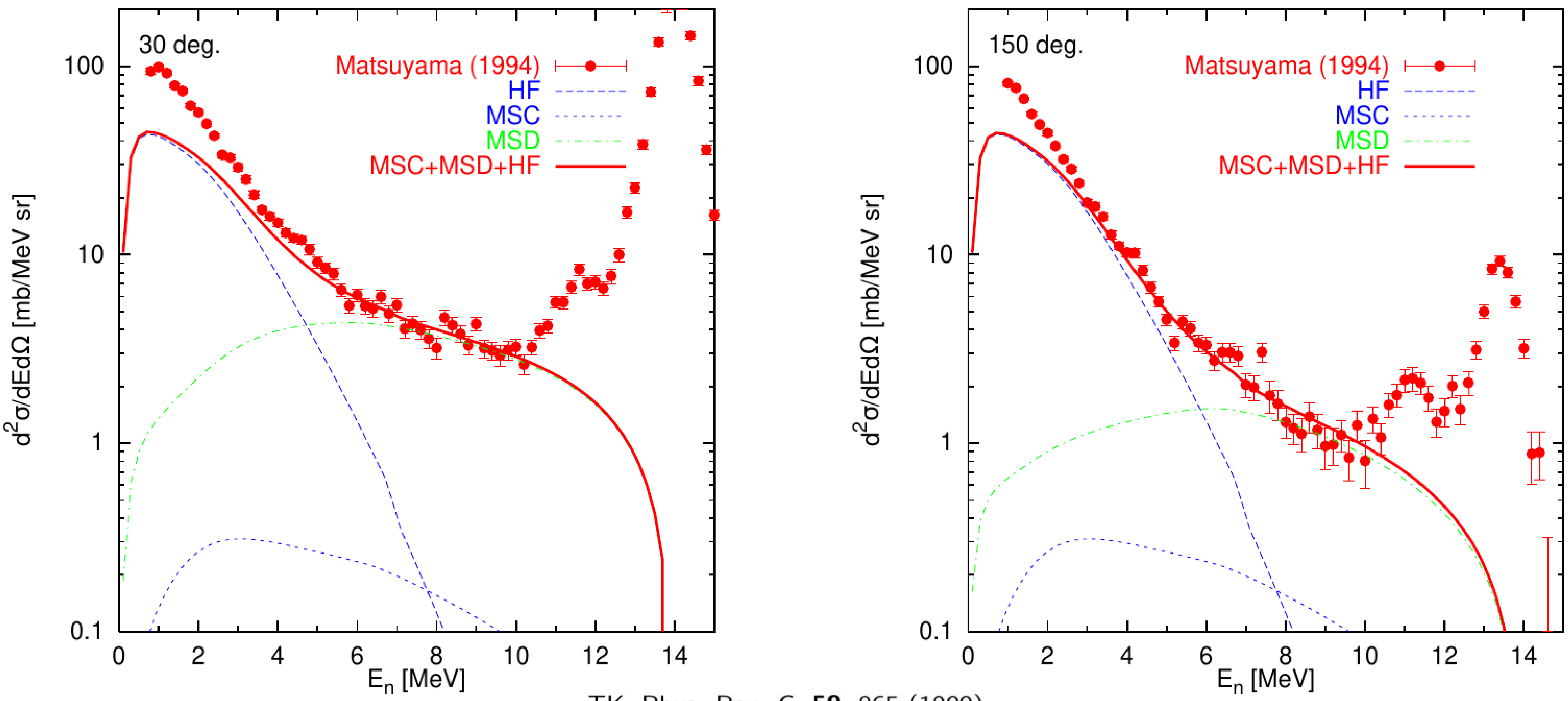
→ NWY: Nishioka, Weidenmüller, Yoshida (1988) : GOE for residual interaction, Sudden Approximation for the Second Step

H. Feshbach, A. Kerman, S. Koonin, Ann. Phys. (N.Y.) **125** (1980) 429.
H. Nishioka, H.A. Weidenmüller, S. Yoshida, Ann. Phys. (N.Y.) **183** (1988) 166.
T. Tamura, T. Udagawa, H. Lenske, Phys. Rev. C **26** (1982) 379.

→ One-step process is believed to be dominant below 10-20 MeV

→ The First step expression of FKK, TUL, and NWY is the same ; various implementation : **choice of nuclear structure**

Multistep Direct and Multistep Compound Contribution



TK, Phys. Rev. C, **59**, 865 (1999).

MSD : focus on first step

→ Description of direct inelastic scattering and one-step process within the same formalism :

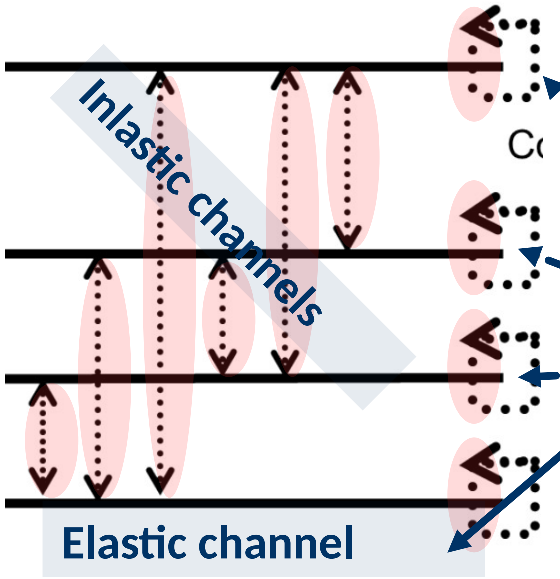
→ Effective interaction for projectile – target interactions

→ Accurate description of target excitations within a large range of excitation energy.

→ Pros:
- No ad-hoc transition direct – pre-eq, no double-counting
- predicts angular distribution
- predicts spin transfer,
- includes collective effects

One microscopic approach to direct inelastic scatering

Folding potentials derived from nuclear-matter interaction : **very successfull for medium mass to heavy nuclei, nucleon and ion scattering.**



Target states

Effective interaction

$$\left(E - \hat{T} - \langle\psi_0|\hat{V}_{\text{Eff.}}|\psi_0\rangle\right)|w_0\rangle = \sum_{i\neq 0}\langle\psi_0|\hat{V}_{\text{Eff.}}|\psi_i\rangle|w_i\rangle$$

$$\left(E' - \hat{T} - \langle\psi_N|\hat{V}_{\text{Eff.}}|\psi_N\rangle\right)|w_N\rangle = \sum_{i\neq N}\langle\psi_N|\hat{V}_{\text{Eff.}}|\psi_i\rangle|w_i\rangle$$

Inelastic scattering to discrete levels

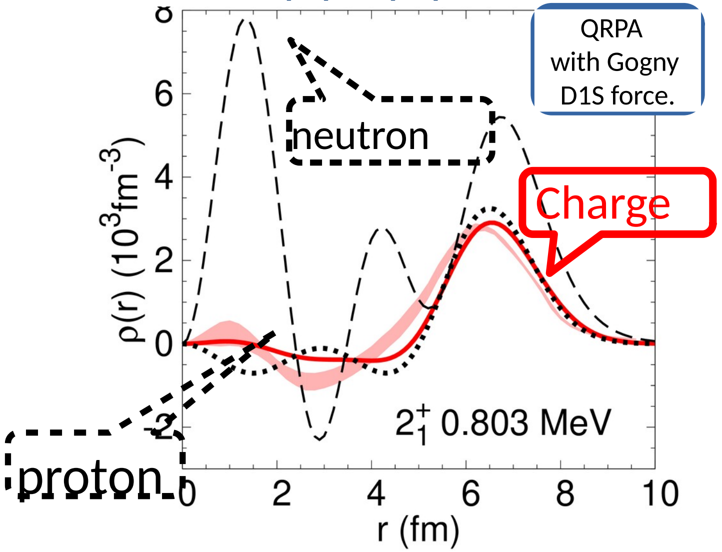
$$U_T(r,E,t_i,t_r) = (t\sqrt{\pi})^{-3}\int\Big[Re[V_T(\rho_p(r_t),\rho_n(r_t),E,V_c(r_t))]e^{-|\vec{r}-\vec{r}_t|^2/t_r^2} + Im[V_T(\rho_p(r_t),\rho_n(r_t),E,V_c(r_t))]e^{-|\vec{r}-\vec{r}_t|^2/t_i^2}\Big]\rho_T d^3\vec{r}_t$$

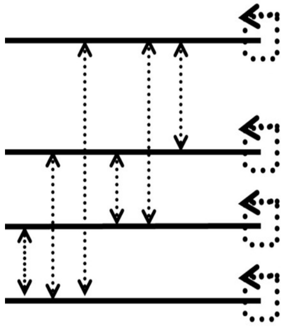
Nuclear optical/transition potentials

+ Rearrangement

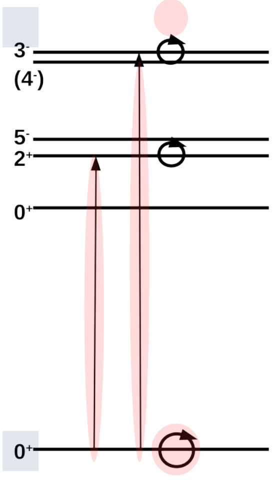
$$\rho_{T=0/1} = \rho_n \pm \rho_p$$

HF(B) / (Q)RPA densities

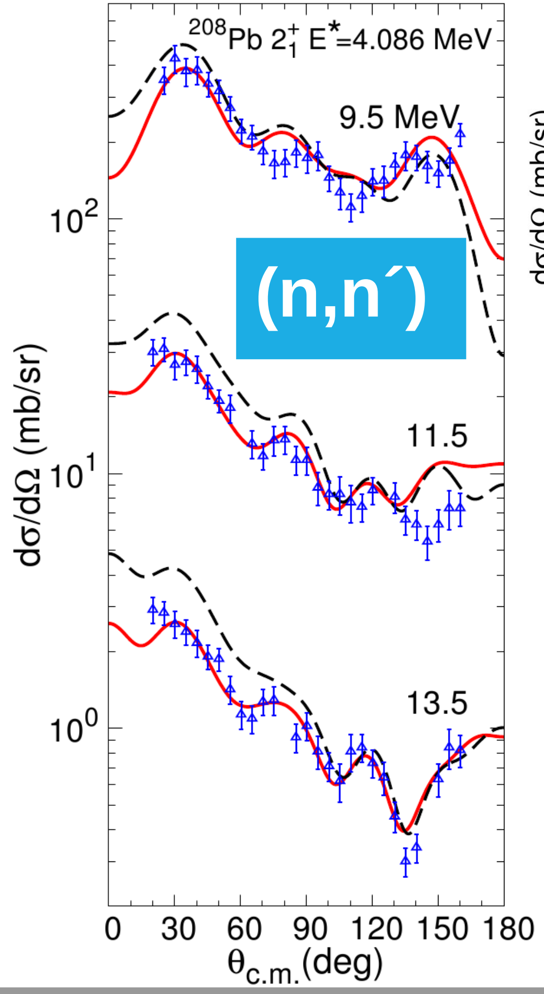


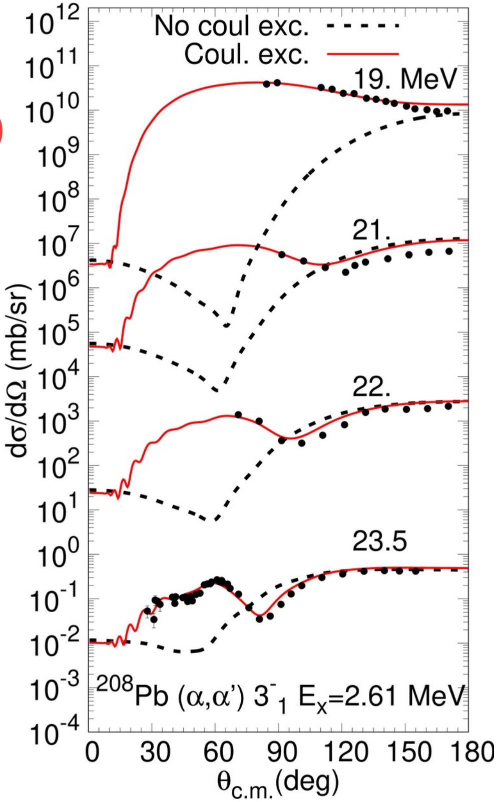


DWBA:
spherical,
vibrational nucleus



JLM + (Q)RPA-Gogny-D1S





(α,α´)
Double
folding

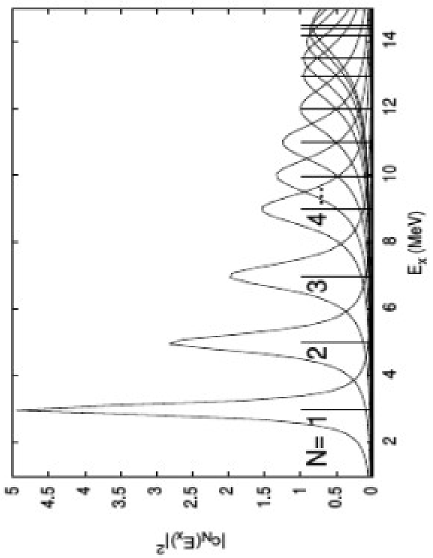
M. Dupuis, G. Haouat, J.-P. Delaroche *et al.*, Phys. Rev. C 100 (2019) : (n,n') ; (p,p')

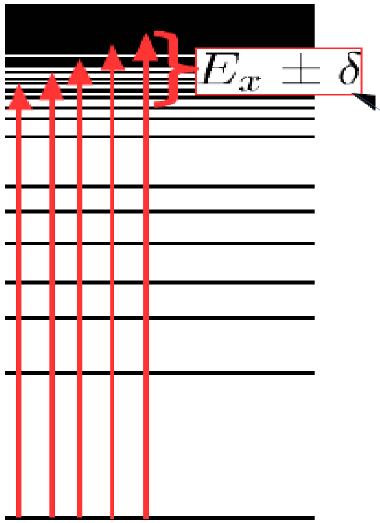
Inelastic to the continuum

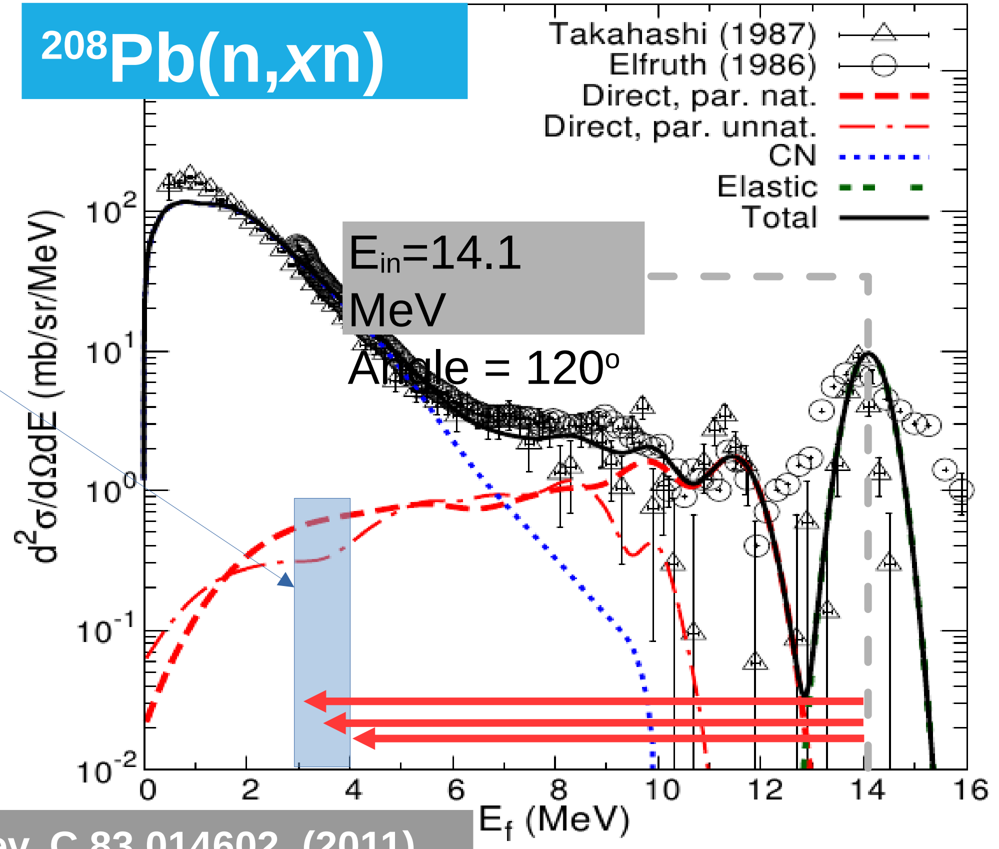
Pre-equilibrium emission $E_{in} < 20$ MeV: one-step direct

$$\frac{d\sigma(\mathbf{k}_i,\mathbf{k}_f)}{d\Omega dE_f} \sim \frac{1}{2\delta} \int_{E_f-\delta}^{E_f+\delta} dE \sum_N \frac{\Gamma_N}{2} \frac{1}{(E_i - E - E_N)^2 + \frac{\Gamma_N^2}{4}} \left| \langle \chi_{\mathbf{k}}^- , N^{RPA} \mid V \mid \chi_{\mathbf{k}_i}^+ , \tilde{0} \rangle \right|^2$$

Target excited states : RPA one-phonon + damping widths

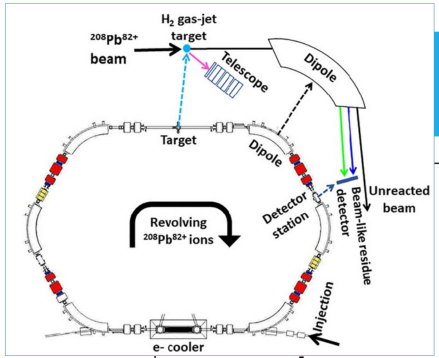


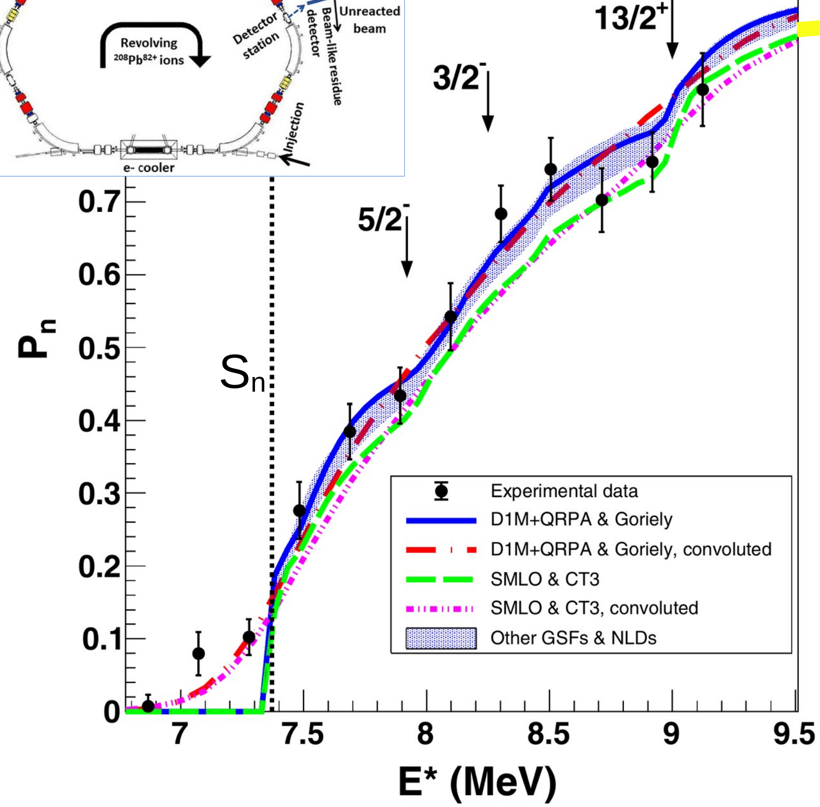




M. Dupuis, T. Kawano, E. Bauge and J.-P. Delaroche, Phys. Rev. C 83 014602 (2011)

Surrogate sutdies: ^{208}Pb(p,p') ← → ^{207}Pb(n,γ)

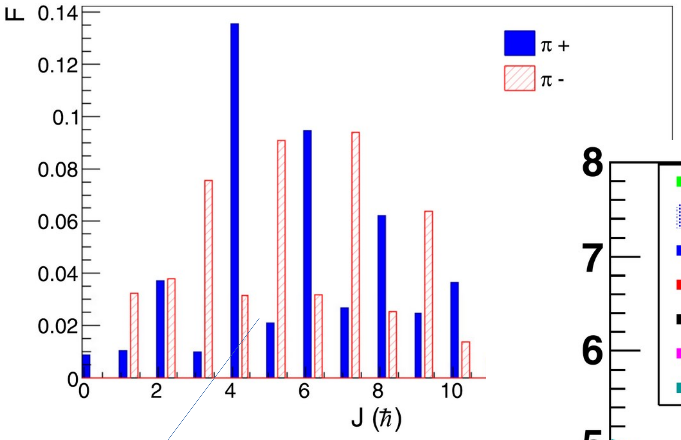




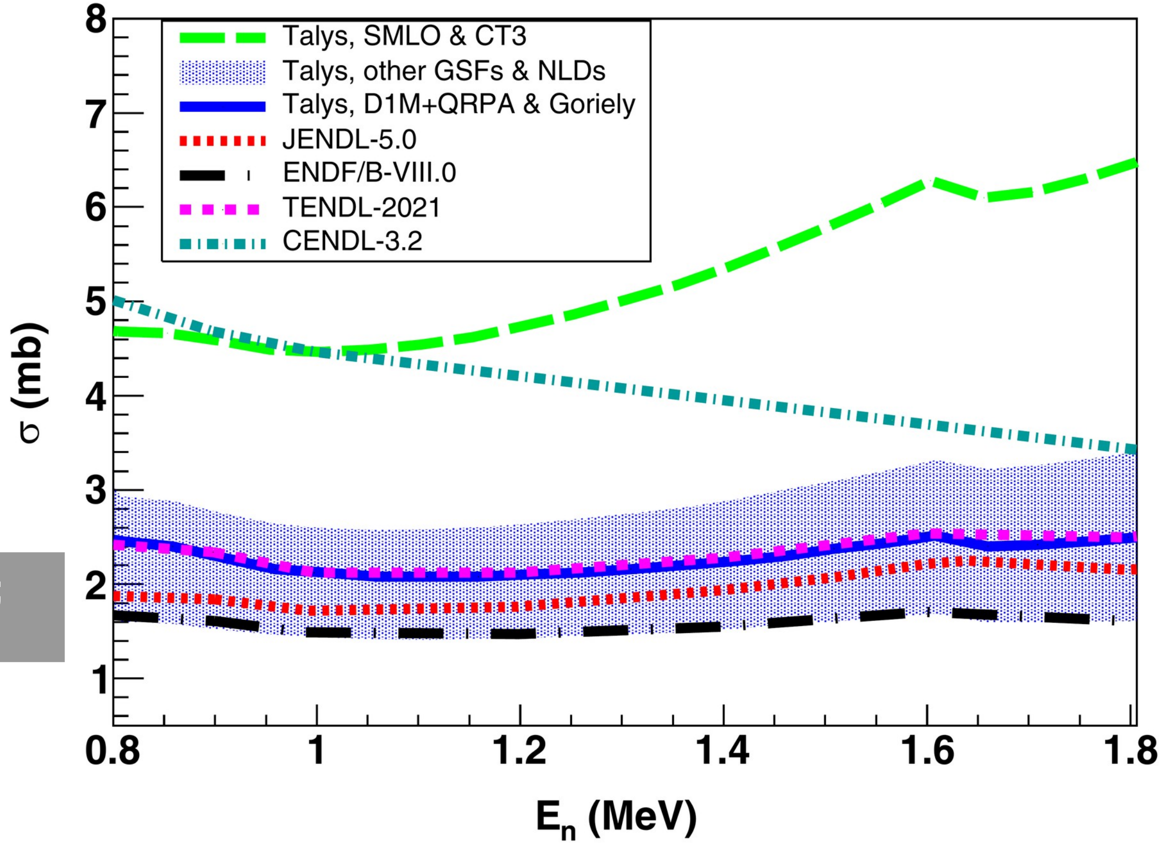
$$P_\chi(E^*) = \sum_{J^\pi} F(E^*,J^\pi)\cdot G_\chi(E^*,J^\pi)$$ TALYS

Spin distribution in ^{208}Pb*
JLMB / RPA-D1S (Nat. Par.)
Melbourne/KD (Unnat. Par.)

$$\sigma^A_{n,\chi}(E^*) = \sigma^{A+1}_{CN}(E^*)\sum_{J^\pi} S(E^*,J^\pi)\cdot G_\chi(E^*,J^\pi)$$

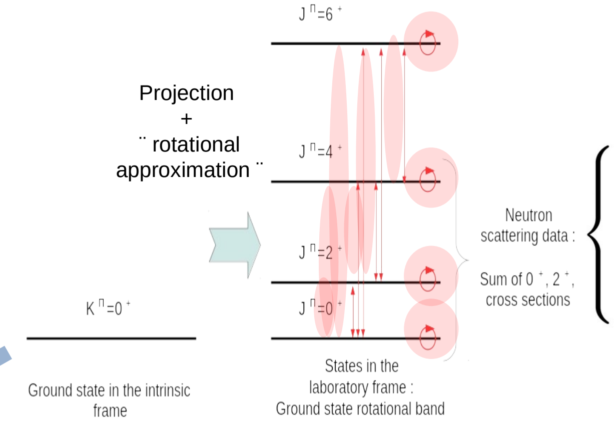


Details later on



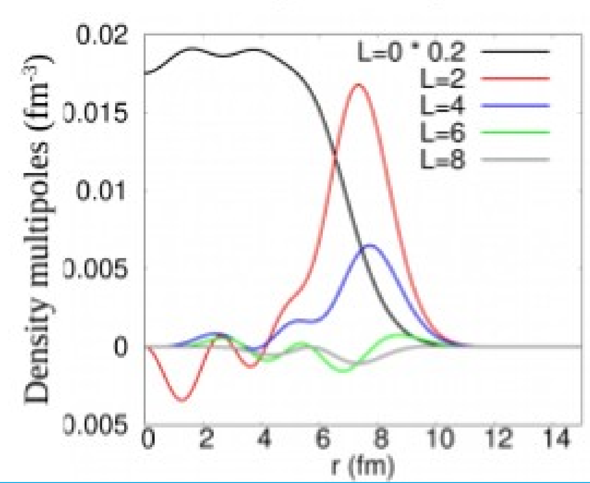
S. Sguazzin, B. Jurado et al., Phys. Rev. Lett. 134, 072501 (2025) ; Phys. Rev. C 111 024614 (2025)

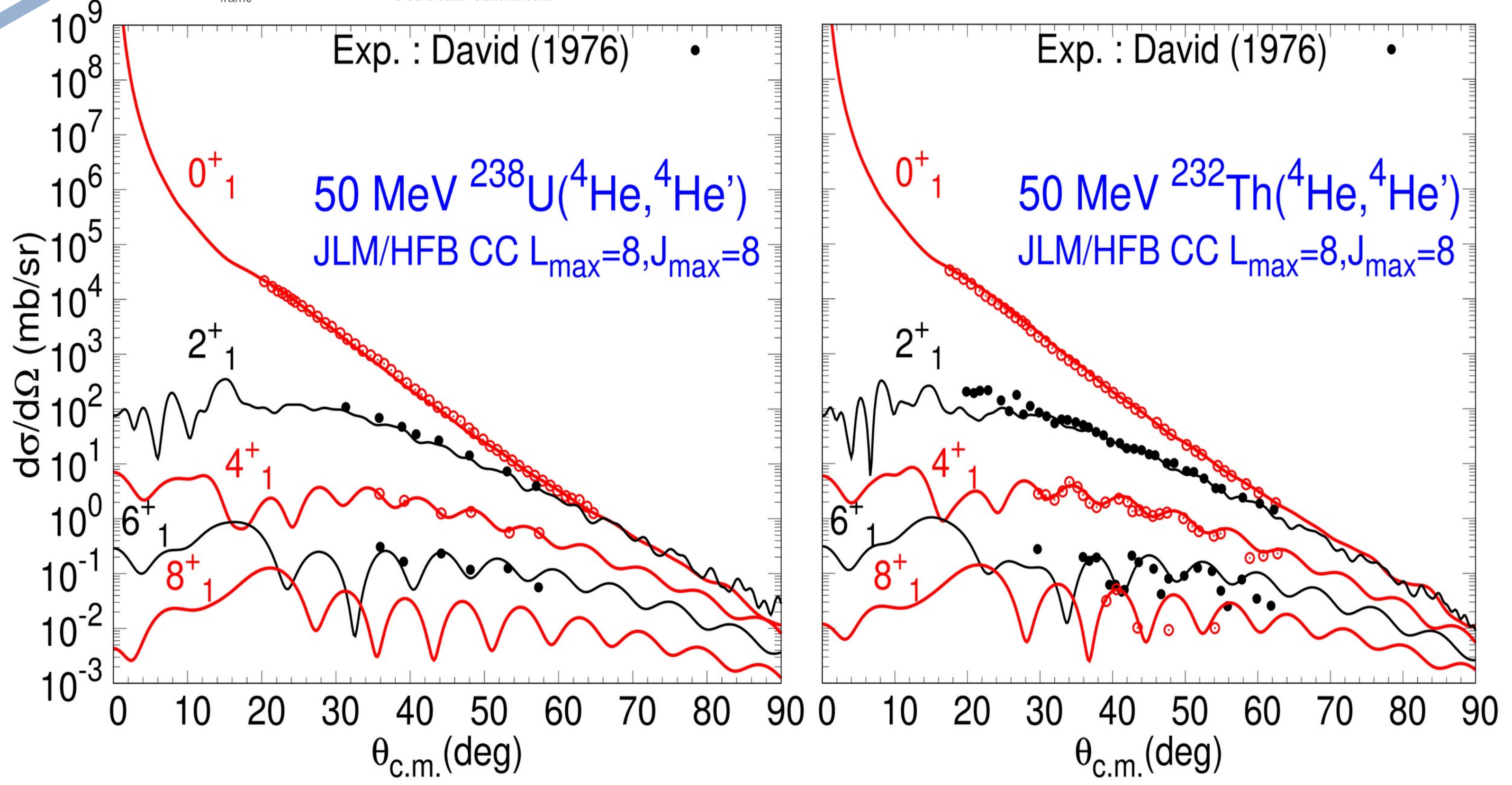
Deformed targets



$$
\begin{cases}
\left(E - \hat{T} - \langle \psi_0 | \hat{V}_{\text{Eff.}} | \psi_0 \rangle\right) |w_0\rangle = \sum_{i \neq 0} \langle \psi_0 | \hat{V}_{\text{Eff.}} | \psi_i \rangle |w_i\rangle \\
\left(E' - \hat{T} - \langle \psi_N | \hat{V}_{\text{Eff.}} | \psi_N \rangle\right) |w_N\rangle = \sum_{i \neq N} \langle \psi_N | \hat{V}_{\text{Eff.}} | \psi_i \rangle |w_i\rangle
\end{cases}
$$

Nuclear structure input :HFB-Gogny D1S deformed axial densities

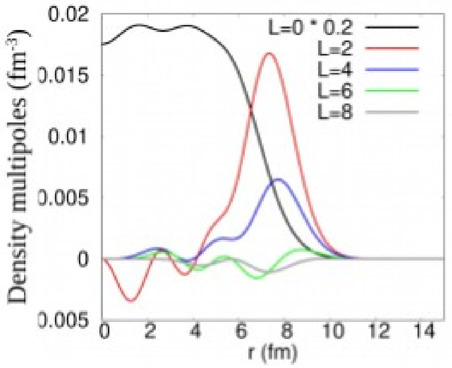




JLM deformed with state of the art NR and NS codes
→ TALYS 1.97
→ HFB3 1.0

HFB solver, N. Dubray,et al.

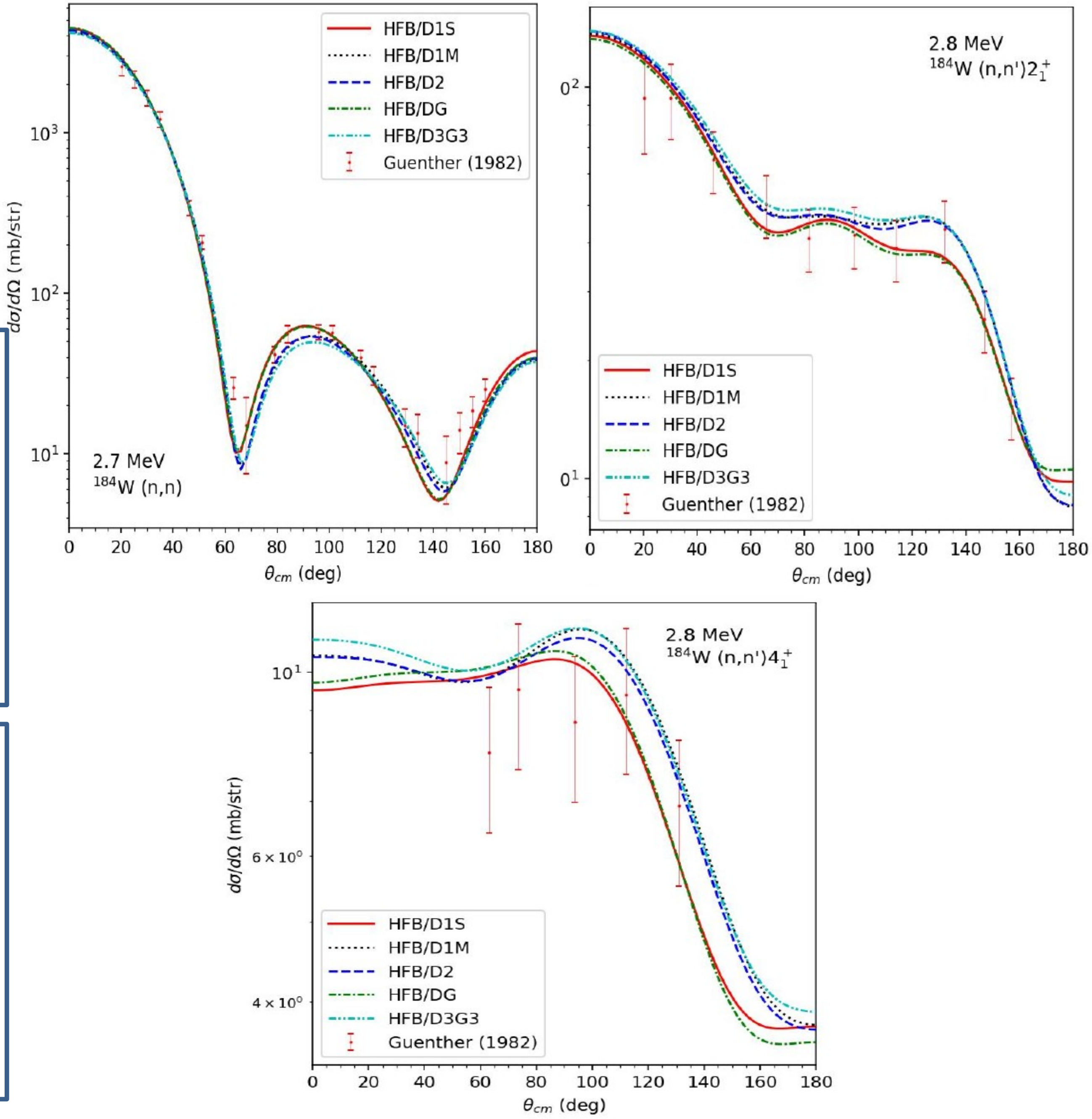
→to built nuclear structure database for various Gogny forces : D1S, D1M, D2, DG ...



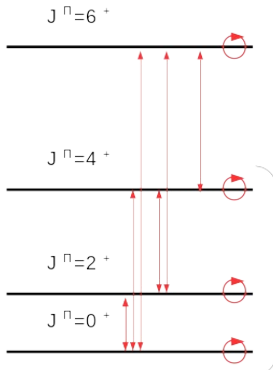
Local CEA Talys-1.97 :

→ include latest developpement (EWT, pre-eq micro ...)

→ Now microscopic deformed JLM model for incident channel and CN decay.

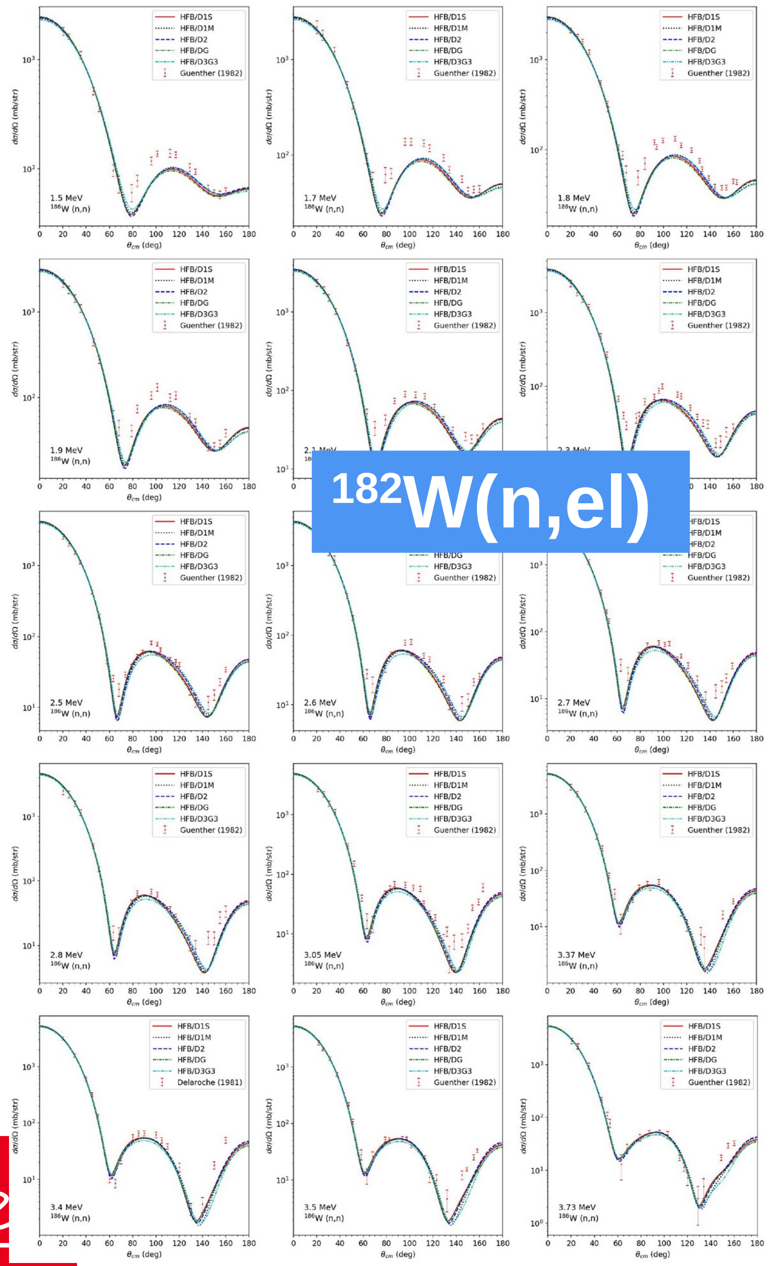


Systematic study of neutron cross sections for GS band levels for deformed nuclei In progress (actinides, rare earth ..,) : ntot, excitation functions, differential cross sections

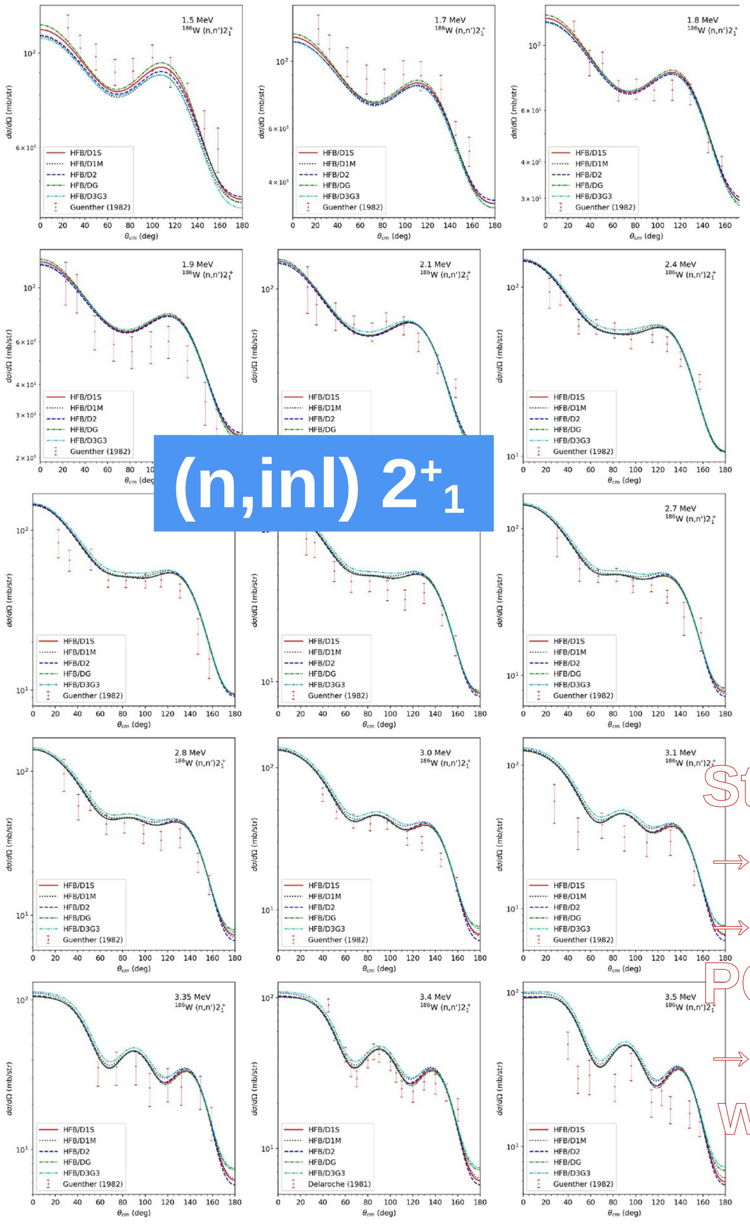


States in the laboratory frame : Ground state rotational band

$^{182}W(n,el)$



(n,inl) 2^+_1



State of the Art NS Models :

→ HFB with new interactions

→ Beyond HFB (QRPA, MPMH, PGCM/5DCH ...)

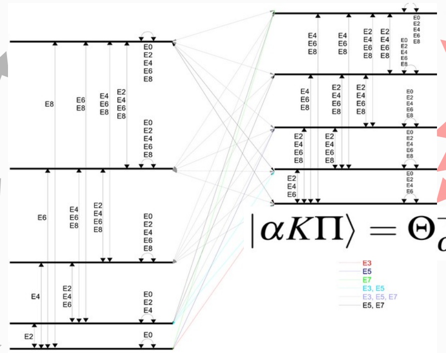
→ Prediction for targets/energies with no data :

* fission fragments
* astrophysis

$$\left(E-\hat{T}-\langle\psi_0|\hat{V}_{\text{Eff.}}|\psi_0\rangle\right)|w_0\rangle=\sum_{i\neq 0}\langle\psi_0|\hat{V}_{\text{Eff.}}|\psi_i\rangle|w_i\rangle$$

$$\left(E'-\hat{T}-\langle\psi_N|\hat{V}_{\text{Eff.}}|\psi_N\rangle\right)|w_N\rangle=\sum_{i\neq N}\langle\psi_N|\hat{V}_{\text{Eff.}}|\psi_i\rangle|w_i\rangle$$

GS rot. band

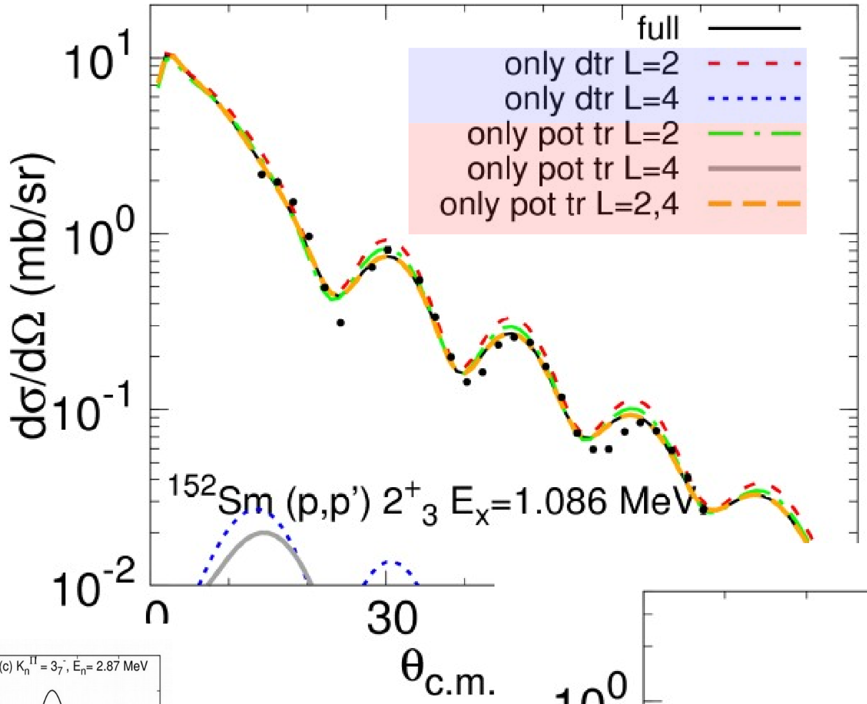


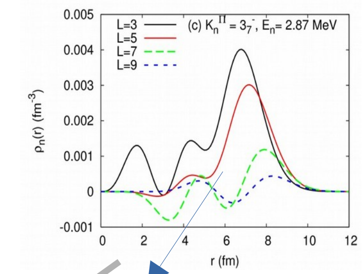
$$|\alpha K\Pi\rangle=\Theta^{+}_{\alpha K\Pi}|\tilde{0}_I\rangle.$$

QRPA one-phonon excitation

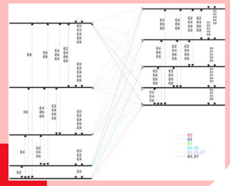
$$|\Psi_i\rangle=|\alpha J_i^{+}M_i\rangle=\sqrt{\frac{2J_i+1}{8\pi^2}}\int d\Omega\,\mathcal{D}^{J_i}_{M_i0}{}^{*}(\Omega)R(\Omega)|0^{+}\rangle_{\mathcal{I}}$$

$$|\Psi_j\rangle=|\alpha JM\Pi\rangle=\sqrt{\frac{2J+1}{16\pi^2}}\int d\Omega\,\mathcal{D}^{J}_{MK}{}^{*}(\Omega)R(\Omega)|\alpha K\Pi\rangle_{\mathcal{I}}+(-)^{J+K}\mathcal{D}^{J}_{M-K}{}^{*}(\Omega)R(\Omega)|\alpha\bar{K}\Pi\rangle_{\mathcal{I}}$$

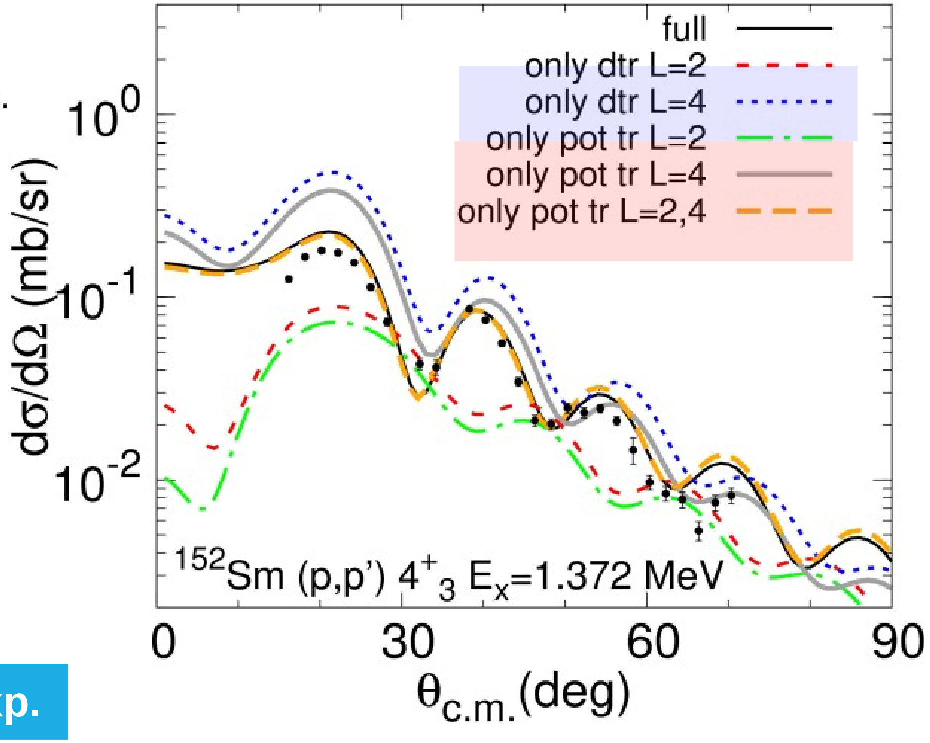




$$U_{L'}^{\tilde{0}\to K^{\Pi}}(r_1)=\int Y_K^{L'}(\Omega_1)\left(\int V(|\mathbf{r}_1-\mathbf{r_2}|,\bar{\rho})\sum_L\rho_L^{\tilde{0}\to K^{\Pi}}(r_2)Y_K^{L}(\Omega_2)d\mathbf{r_2}\right)d\Omega_1$$

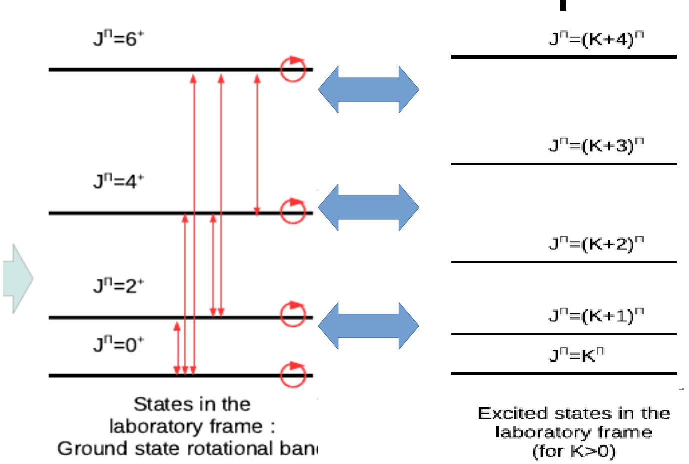


+ Rear.



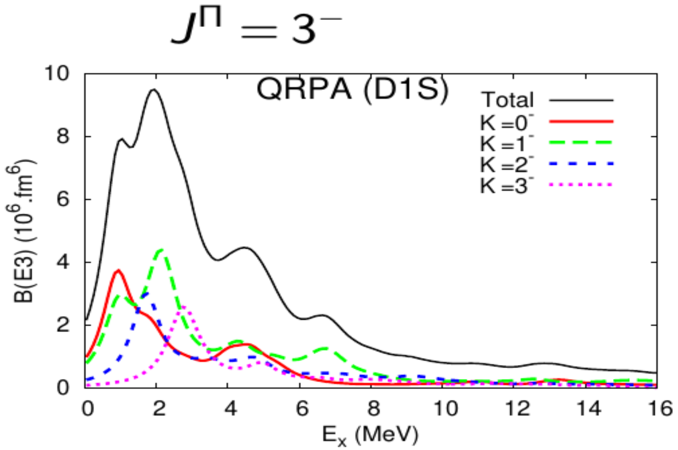
Previous validation of GS multipoles, B(E2), B(E3) HFB/QRPA vs Exp.

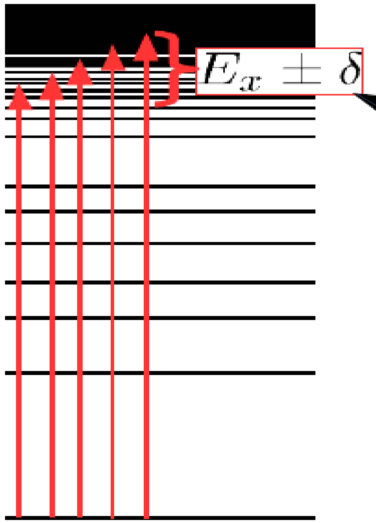
Inelastic to the continuum

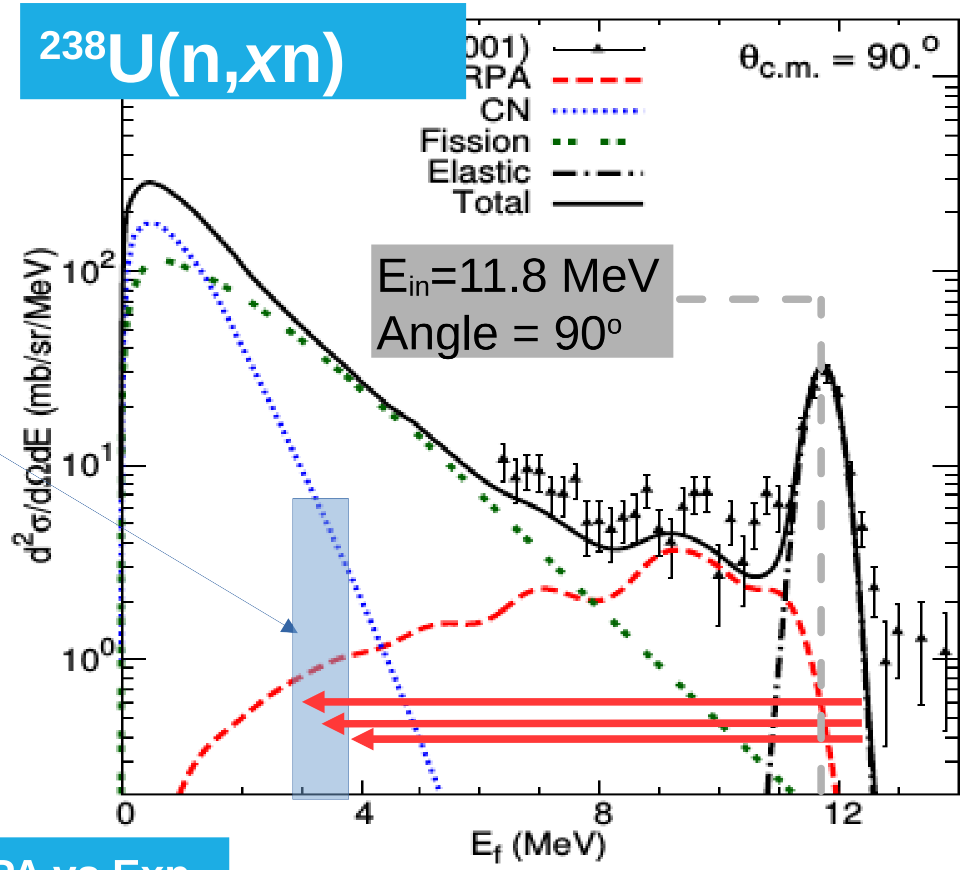


JLM – QRPA potentials
Coupled channels

Target excited states : QRPA one-phonon + damping width

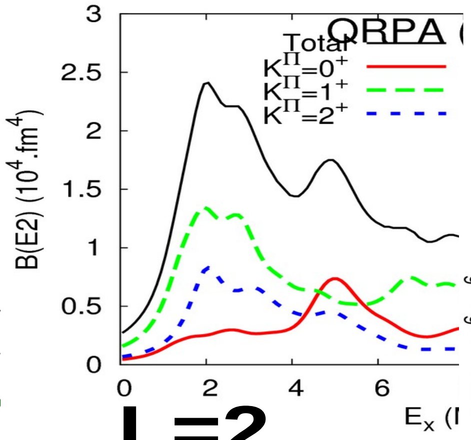




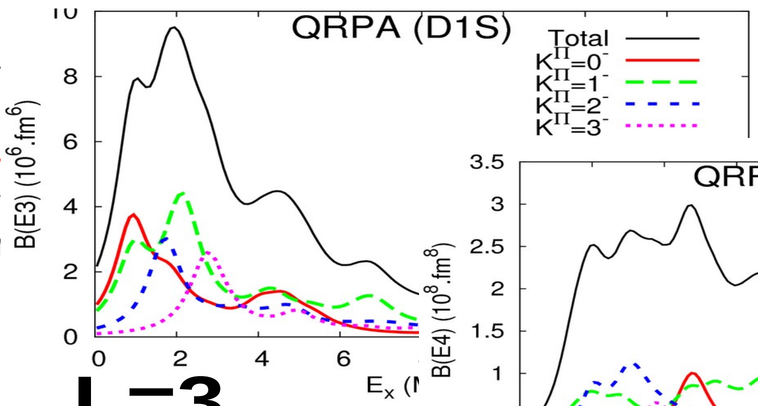


Previous validation of GS multipoles, B(E2), B(E3) HFB/QRPA vs Exp.

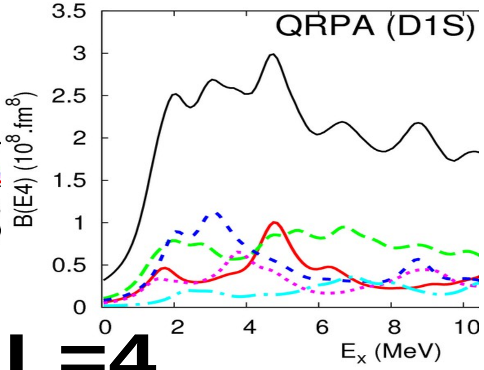
Transitions with angular momentum transfer L=0-8



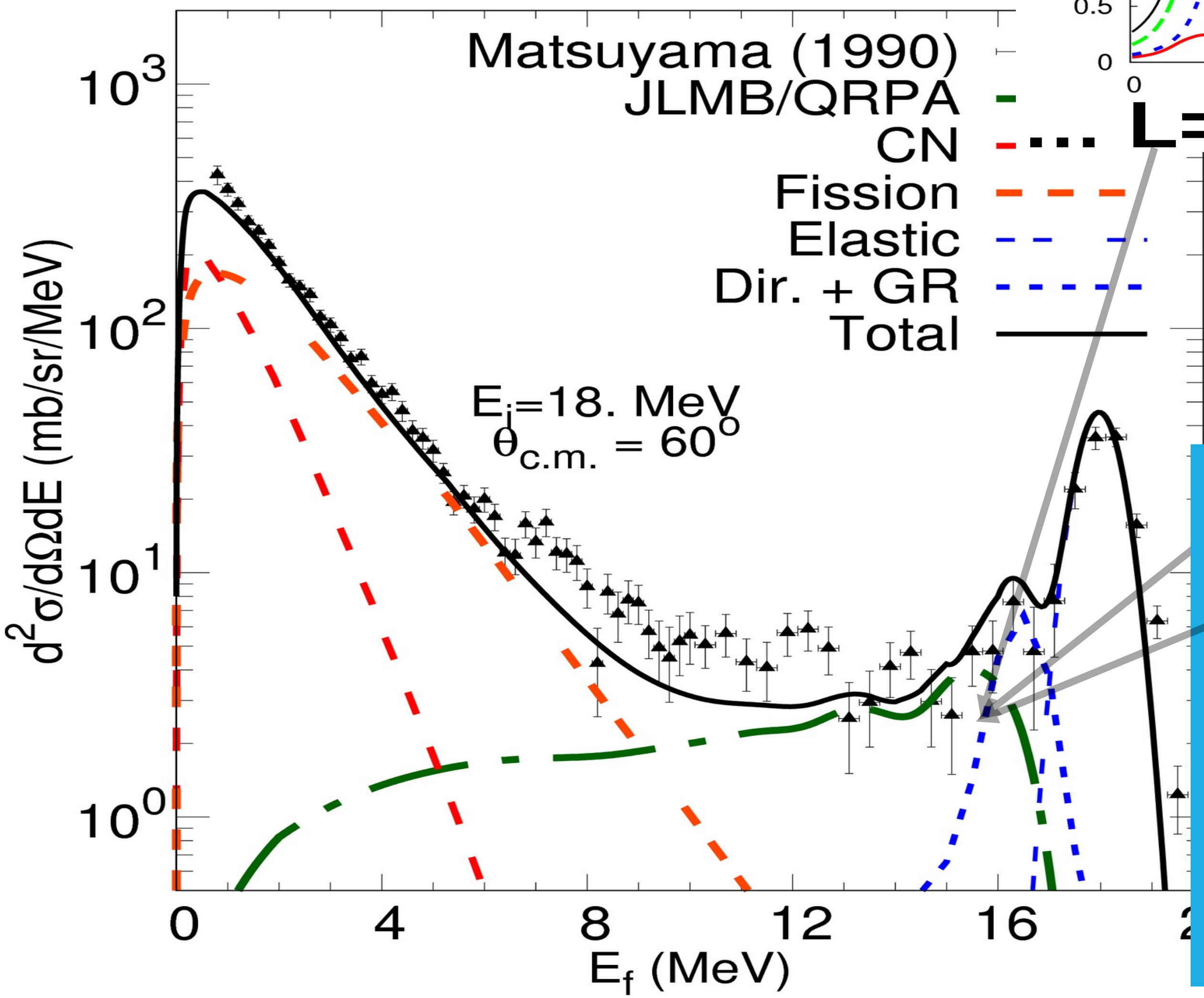
L=2



L=3

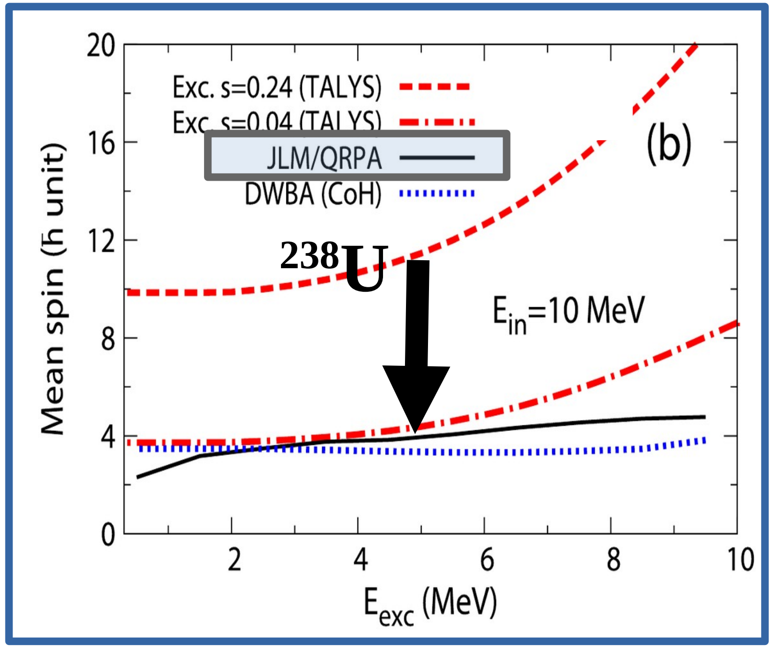


L=4 ...



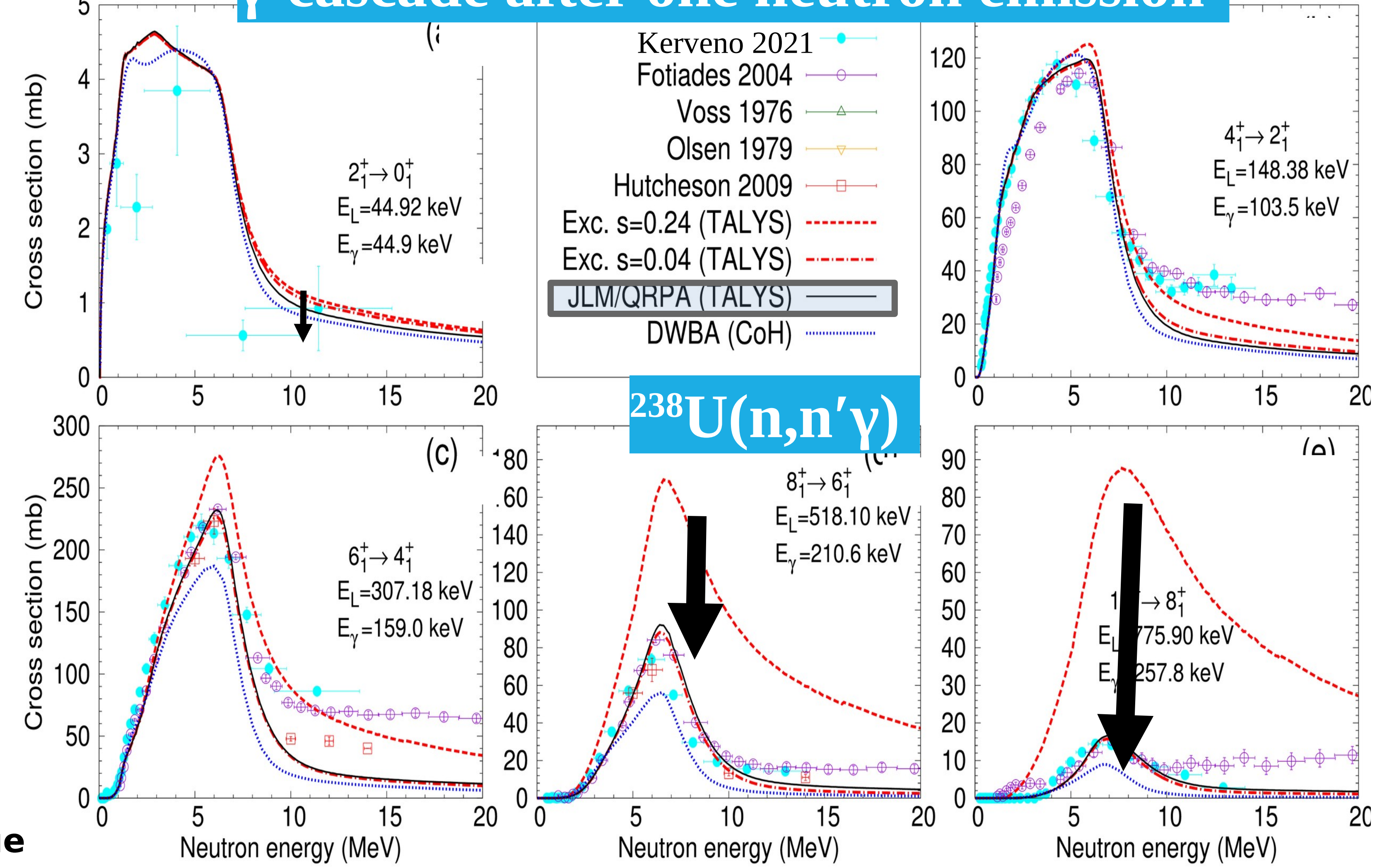
JLMB + QRPA :
collective excitations for Ex=1-6 MeV
→ **do not need pseudo-states (still used to produce latest nuclear data libraries)**
→ **equivalent results for medium mass and heavy targets**

Spin distribution of residual nucleus



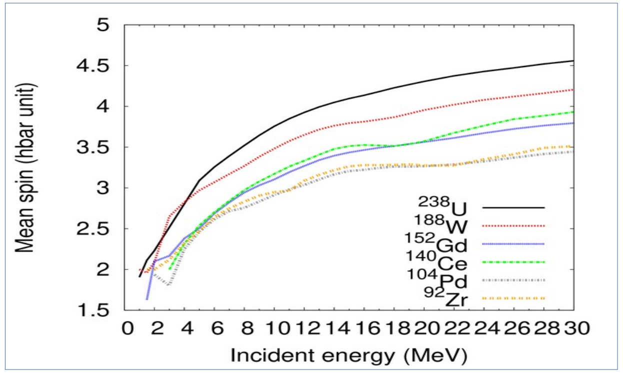
Population of high spin levels very sensitive to the mean value of the spin distribution

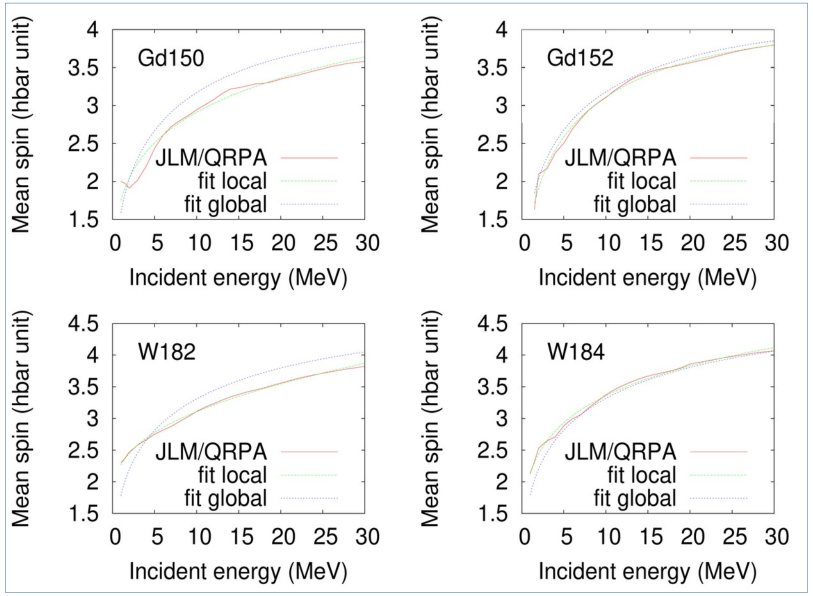
γ-cascade after one neutron emission



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

Spin distribution of residual nucleus





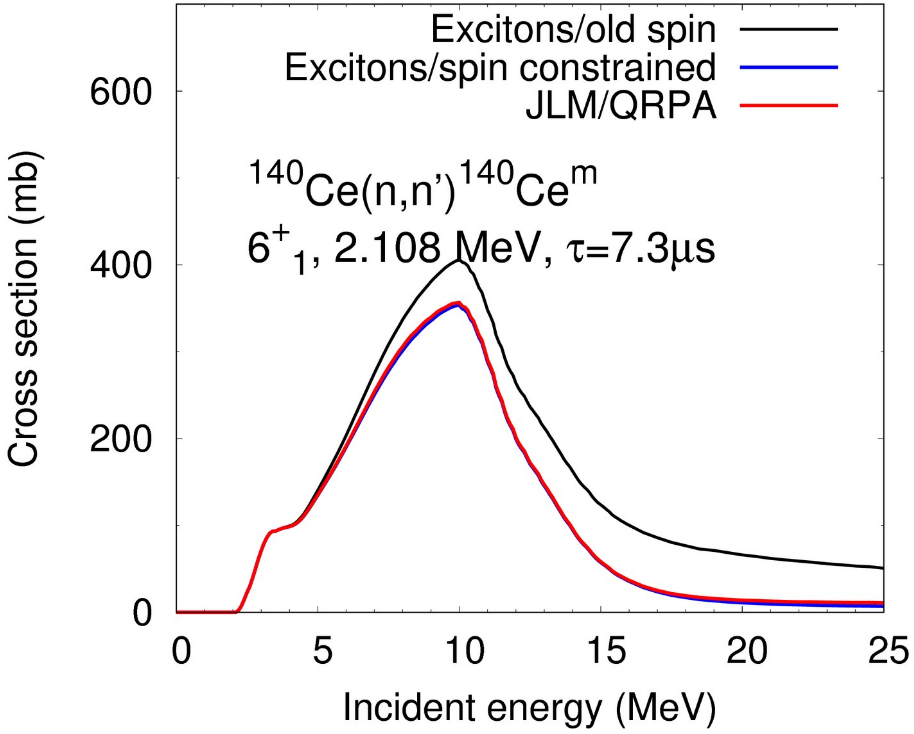
Systematics A=16-240

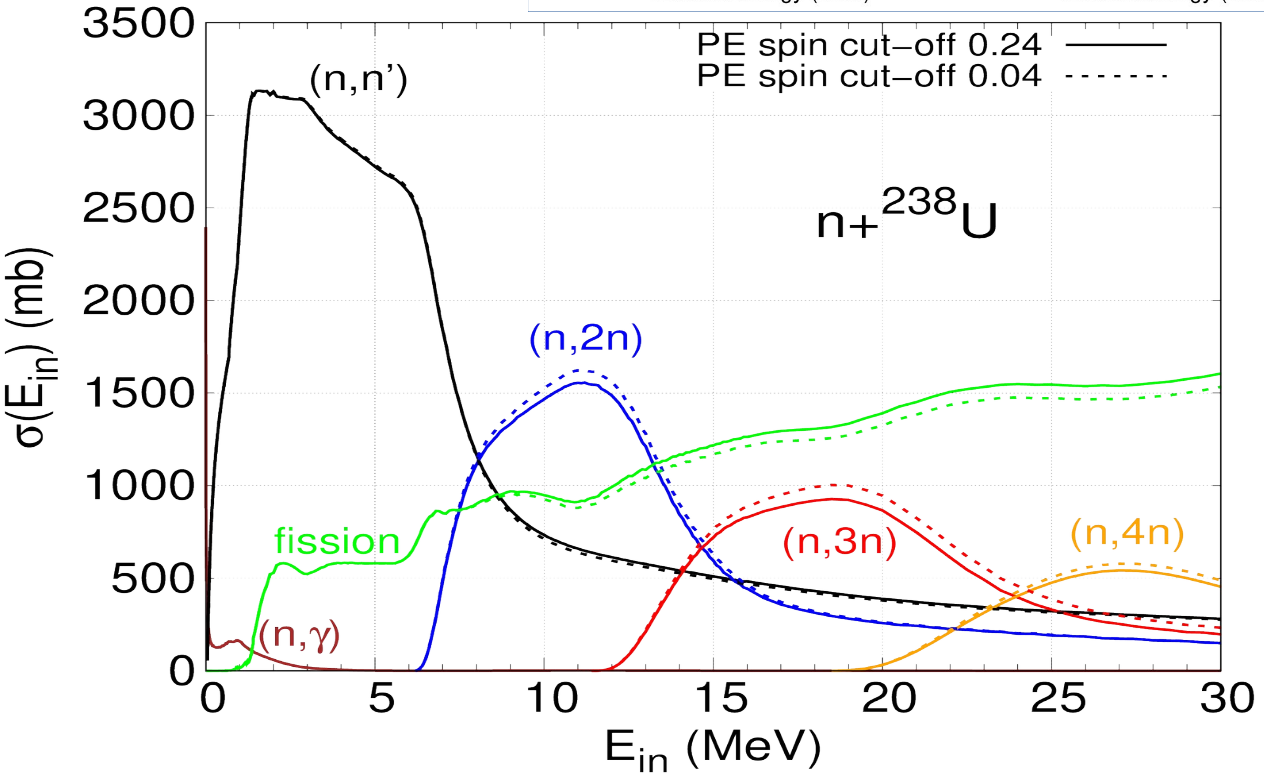
Constraints to spin-distributions for exciton pre-eq. model TALYS ≥ 1.97

$$x(A) = \alpha_x A^{\frac{1}{3}} + \beta_x, \text{ avec } x = a, b, c$$

$$\bar{J} = a(A) E_{in}^{\frac{1}{4}} + b(A) E_{in}^{\frac{3}{4}} + c(A)$$

$$x(A) = \alpha_x A^{\frac{1}{3}} + \beta_x, \text{ avec } x = a, b, c$$





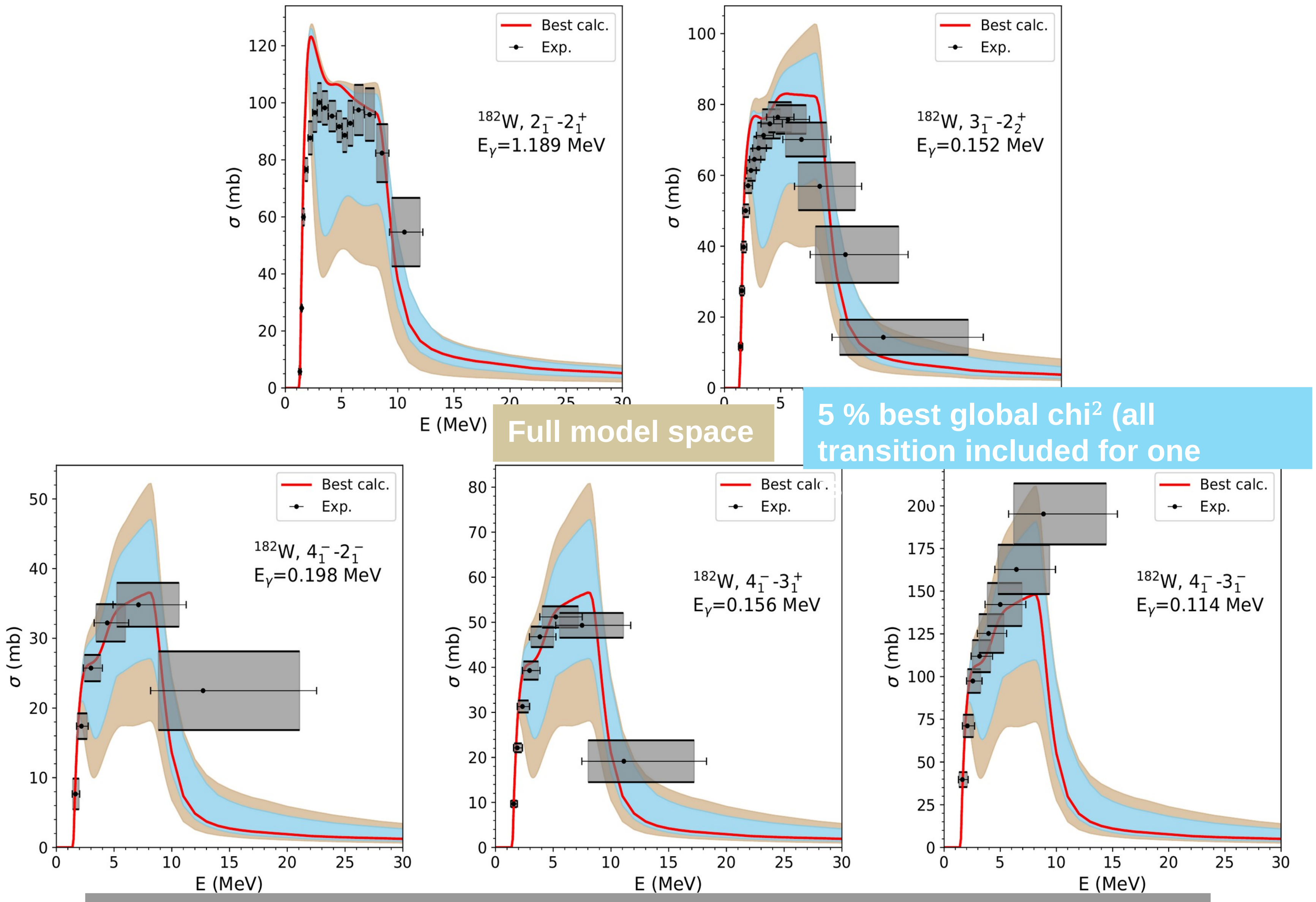
^{182,184,186}W (n,n'γ) : 73 transitions measured
G. Henning et al.

Global Modeling of Inelastic Processes
Recent progress (implemented in TALYS / CoH)

- Microscopic inputs: LD, GSF, pre-equilibrium
- OMP, Engelbrecht–Weidenmüller transformation
- BR, Discrete levels extended into the continuum

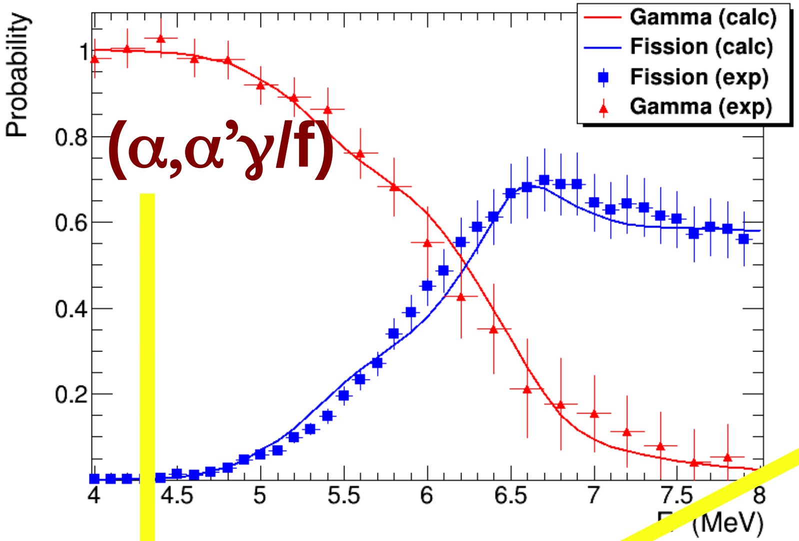
This study confirmed needs

- Inclusion of low-energy M1 upbend + scissors
- Reduced spin distributions (PE residual nucleus & LD)
- Extented discrete-level scheme

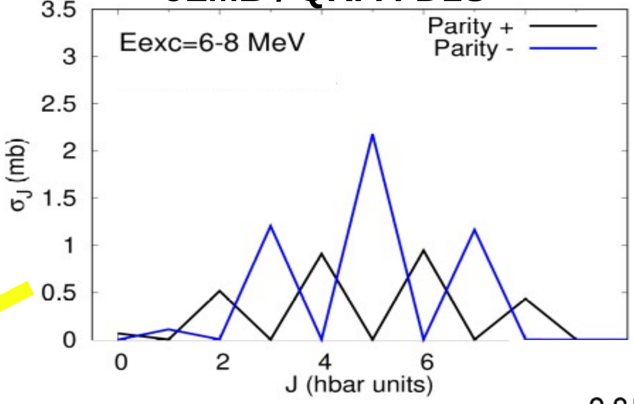


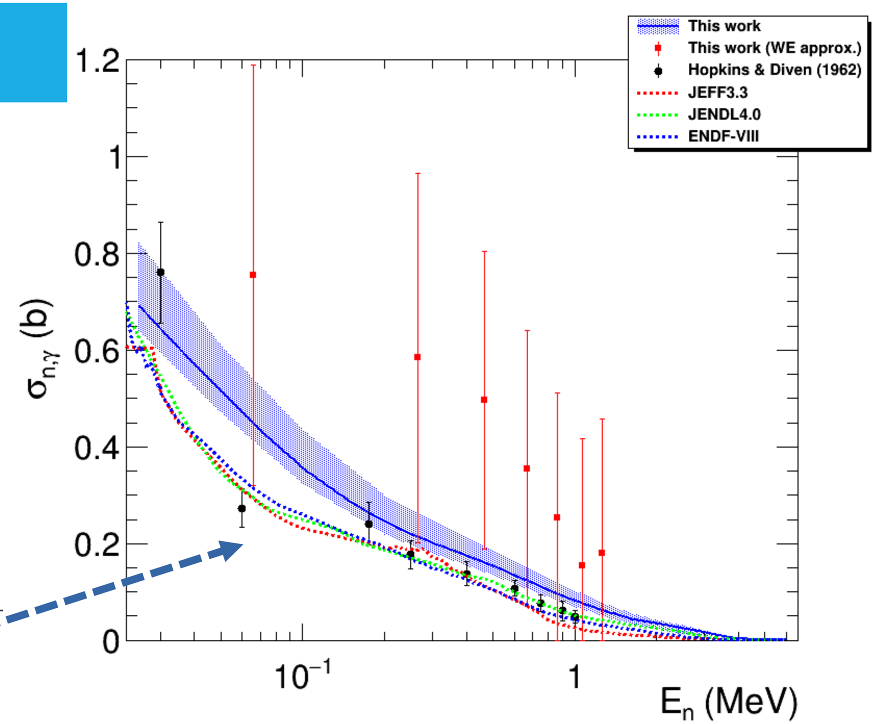
G. Henning *et al.*, to be published in Phys. Rev. C (2026)

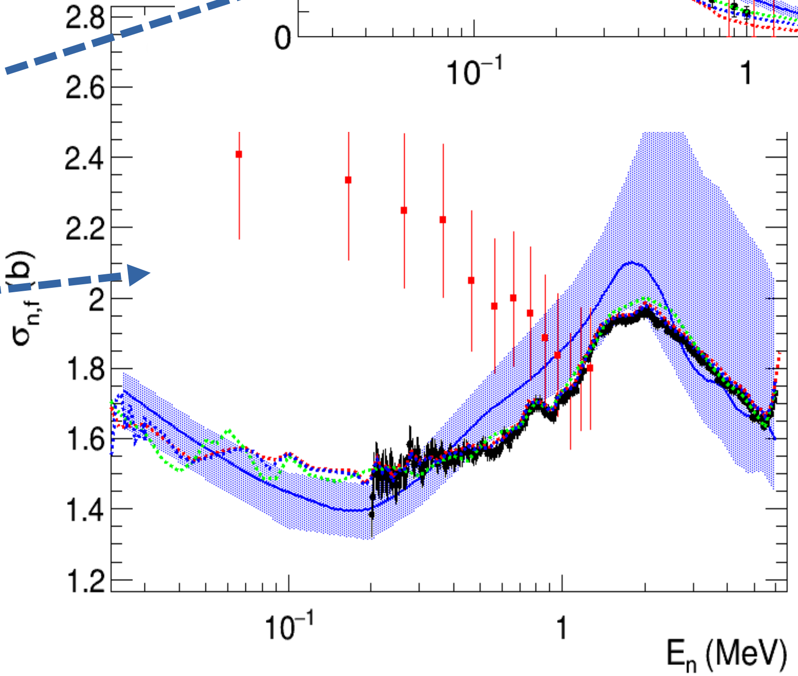
Surrogate sutdies: ^{240}Pu(α,α') ← → ^{239}Pu(n,γ);(n,f)



Spin distribution in 240Pu*
JLMB / QRPA-D1S







$$P_{\chi}(E^*) = \sum_{J^\pi} F(E^*,J^\pi)\cdot G_{\chi}(E^*,J^\pi)$$ TALYS

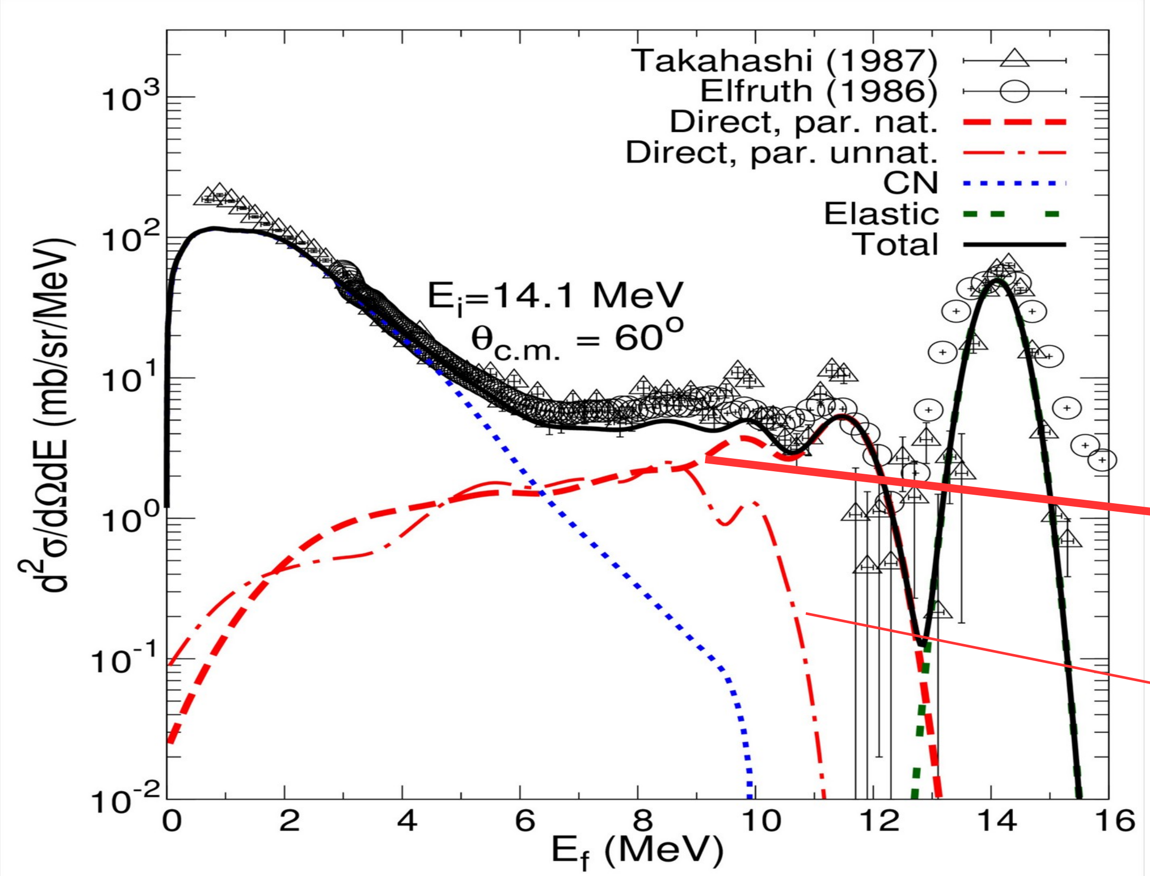
$$\sigma^{A}{}_{n,\chi}(E^*) = \sigma^{A+1}{}_{CN}(E^*)\sum_{J^\pi} S(E^*,J^\pi)\cdot G_{\chi}(E^*,J^\pi)$$

R. Pérez Sànchez et al., Phys. Rev. Lett. 125, 122502 (2020)

Direct/pre-eq (n,n') mechanism for spherical targets

Example:
^{208}Pb(n,*x*n) ddx :
neutron emitted from

- **direct, pre-equilibrium (n,n')**
  - compound nucleus decay.



Structure theory for ^{208}Pb(n,n') :

- RPA one-phonon excitations.

Reaction theory for ^{208}Pb(n,n') :

- **Spherical target**
  → weak coupling → DWBA.
- **One-step** process (one phonon).
- **Non-local** transition potentials (M3Y interaction)
- **Two-body spin-orbit and tensor :**
  generate **unnatural parity transitions.**

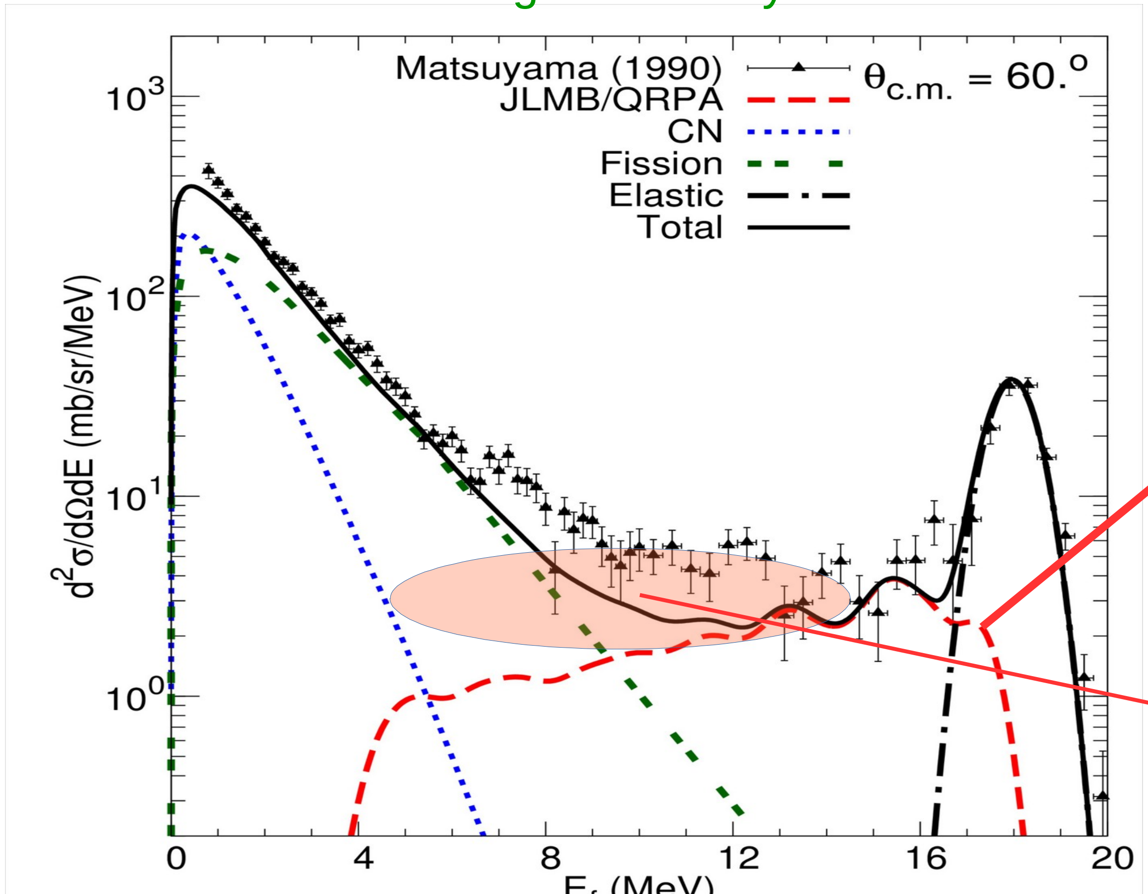
Natural parity : shape vibration (E1, E2, E3 …).

Un-natural parity : vibration in the spin space (ex : scissors M1 mode) : **strong contribution to direct/pre-eq process**.

Direct/pre-eq (n,n') mechanism for deformed targets (actinides)

Example:
^{238} **U(n,*xn*) ddx** :
neutron emitted from

- direct, pre-equilibrium (n,n'),
- compound nucleus decay,
- fission fragment decay.



Structure theory for ^{238} U(n,n')

- **QRPA one-phonon excitations + rotations.**

Reaction theory for ^{238} U(n,n')

- **Strong channels couplings**
  → **Coupled channel (CC) framework.**
- Uses **local** transition potentials (**JLM interaction** and CC code limitations).

Natural parity transitions.

Un-natural parity not included :

No two-body spin-orbit, no tensor in JLM :
→ cannot generate un-natural parity transitions

Missing xsecs :

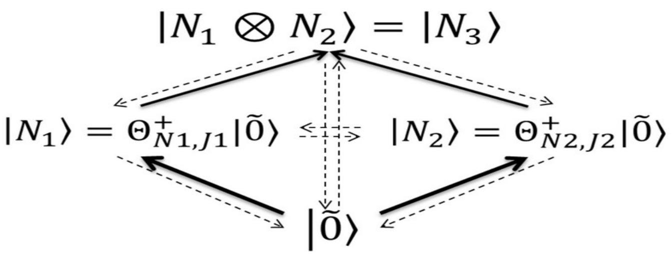
- **un-natural parity ?**
- **Two-step process ?**
  MSC ?

MSD two-step process, with 2-phonon RPA final sates

One and two-step processes, $^{90}Zr(n,n')$

one-step : 1 ph or one-phonon

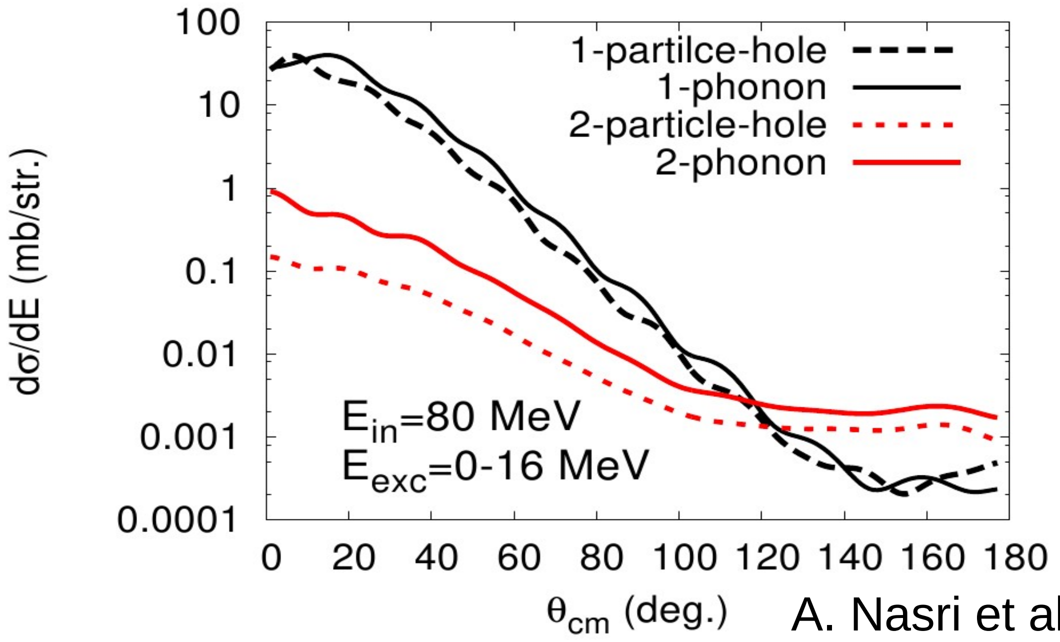
two-step : 2 ph (intermediate 1ph) or two-phonon (intermediate 1 phonon).



Approximations :

- interference between paths not considered,
- on-shell calculation for two-step,
- only central part of Melbourne g-matrix.

(No un-natural parity for now)



A. Nasri et al.

Two step :2-phonon vs 2-particle-hole

- Collective enhancement with two-phonon.
- Quasi-Boson approximation : Pauli principle not respected.

Work in progress :MultiStep Compound

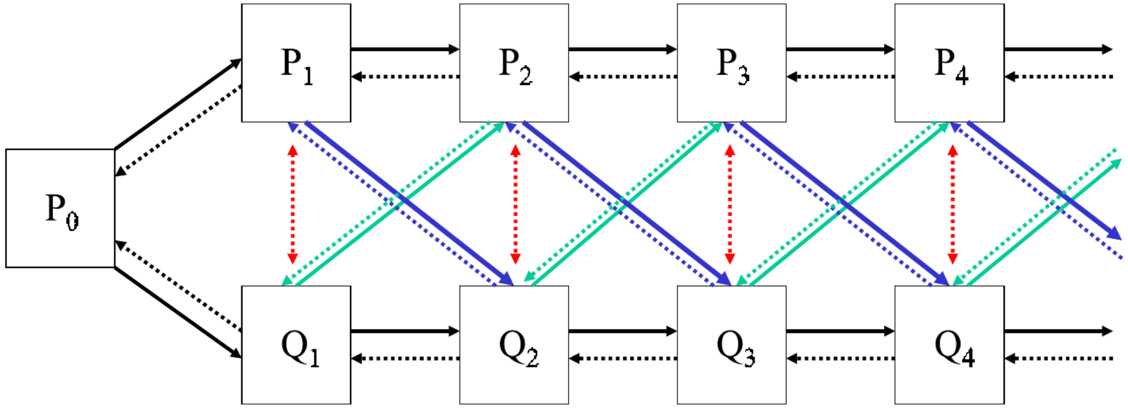
→ The magnitude of the MSC contribution strongly depends on the specific implementation and underlying assumptions.

→Known to be strong for charge exchange

→Inelastic : Magnitude with respect to MSD need to be determined.

→ Impact on spin-distributions of residual system.

→ Implementation with new ingredients (LD...) – computing power to test approximations.



MSD: Multistep Direct

MSC : Multistep Compound

B. Menant, PhD since Jan. 2025.

Principle, choice of unified/hybrid methods

Principle: one interaction/framework should, in spirit, cover natural and unnatural parity; requirement is comparable data quality in both channels.

→ **Broader scope: this questioning also applies to using separate structure and reaction methods, and to competing mechanisms (one-step direct vs various multistep paths), where different ingredients may be required or optimal (structure inputs, effective interactions, continuum coupling).**

Enforce uniformity if it degrades agreement with measurements ?

→ **Consistency is a goal, not a hard constraint; apply it with care and with a clear domain of validity.**

- → **But may reveal missing physics and/or compensating effect.**

When to hybridize methods:

- → **Systematic underperformance after « honest retuning ».**
- → **Physics-based rationale: missing spin–isospin response, tensor or spin–orbit dependance …**

Validation protocol and decision rule:

- → **Metrics (χ2 ...) on a benchmark set : choice of NS method.**
- → **Use various hybrids methods (ex for nat/unnat parity : Melbourne, xx-M3Y)**

State of the art nuclear structure method, Relevant models, Developments

Effective / Chiral interactions : comparison when possible, choice depending on the system.

Small-amplitude vs large-amplitude

QRPA valid for small density-matrix oscillations (linear response, Matrix/QFAM ; S. Péru et al., J.P.Ebran et al.
Large collective motion → GCM → PGCM / 5DCH (J.P. Ebran et al. ; J. Libert et al. CEA/DAM)
QRPA typically excellent for giant resonances for most nuclei.

Rotations

Apply exact projection methods
Rotational approximation for well-deformed nuclei ($|\beta| \gtrsim 0.15$: actinides, rare earth …) : applied with axially-deformed QRPA.

Complex excitations

In 16O, low-lying 0+, 2+ need ~8p–8h → MPMH / configuration mixing (N. Pillet et al.)

Pre-equilibrium

MSD : Two-phonon couplings for 2-step pre-equilibrium (beyond QRPA)
QBA limitations → second-QRPA / SRPA-like extensions (to be developed)
MSC

New interactions (Gogny family)

D1S → D2 (finite-range in density dependence)
DG (D2-like + finite-range spin–orbit & tensor) (N. Pillet et al., CEA, DAM)

Exotic nuclei and coupling to the continuum : weak binding, halo systems, Strong N/Z asymetry

Berggren basis / Gamow Shell Model (bound + resonant + scattering on equal footing).
Continuum HFB/RHB (DFT with explicit scattering channels) ;Continuum QRPA for collective response in weakly bound systems.

Not discussed : cluster, light nuclei.

Uncertainty Quantification and Propagation

Nuclear-structure inputs (work in progress with new Gogny interactions)
Parameterize D1S → D2 → DG variants (density dependence, spin–orbit, tensor, pairing).

Reactions
UQ for optical potentials and two-body effective interactions : JLM, Melbourne g -matrix, M3Y ...

Propagate to all channels: elastic, inelastic (one-step DWBA/CCBA; pre-equilibrium : multistep direct/compound)

Spectrum, angular distributions, total and partial cross sections

End-to-end workflow (structure → reaction) ; obviously not a unique protocole

Likelihood using the experiment's full covariance

Conclusions - Perspectives

- ✓ **Microscopic inelastic scattering model** based on **NM effective interaction** and **HFB+QRPA Gogny-based NS input** provides **good account of various inelastic processes**

  → **Improvement** in (n,n'γ) and(n,xn) reactions modeling, **impact** on (n,xn), fission

- ✓ Analysis of **large set of partial cross sections** : test **various aspects of modeling**

  → move towards **global improvement** of inelastic modeling.

- ✓ **Spin distributions** : input for analyses based on surrogate method.
- ✓ Input for exp. NS studies allows to **calibrate experiment**, and **extract NS informations** from measured cross sections.

Good predictive power, requires validated NS inputs and suitable NR formalism.

- ⇨ **(n,xnγ) data : analyses in progress ^{182,183,184,186}W, ^{238}U … - Application to ND evaluation process.**
- ⇨ **Improve/generalize UQ and propagation.**
- ⇨ **Recent implementation of deformed JLM in TALYS : global analysis EXFOR data.**
- ⇨ **Coupling rotational bands : systematics**
- ⇨ **Elastic/inelastic from MPMH, PGCM : ab-initio / effective forces.**
- ⇨ **Improve P-re-equilibrium model : two-steps and beyond MSD, review of MSC mechanism**

→ **JLM framework : Veff**

+ based Brueckner-Hartree-Fock in Nuclear matter
+ ad-hoc prescriptions :
    * improved LDA (Gaussian form factors)
    * spin-orbit
+ energy dependant parameters (remained close to unity) : fitted on set of el. and charge-exch exp. data for spherical and near-spherical nuclei (Bauge et al., Phys. Rev. C 2001)

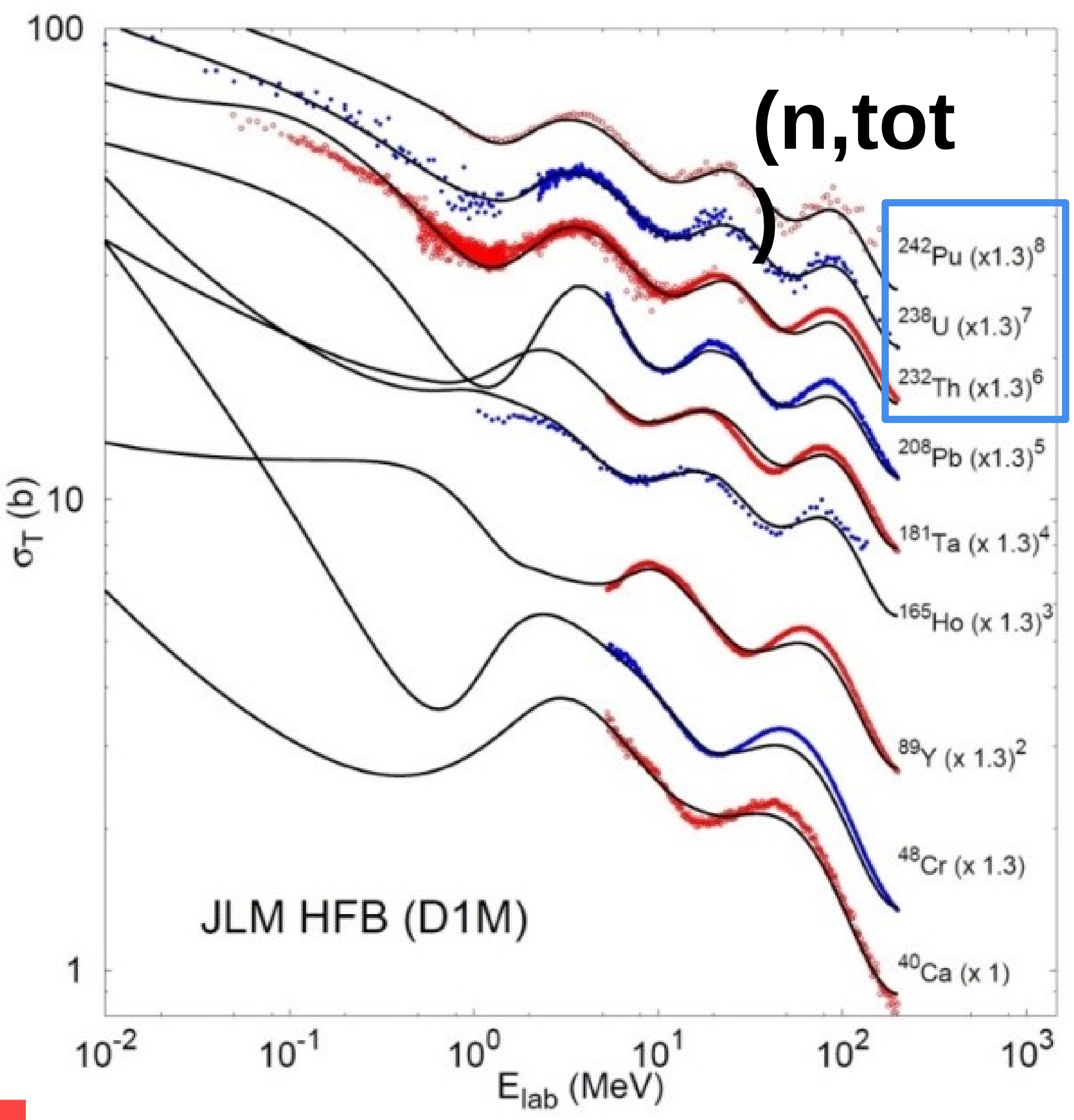
→ **Good description :**

+ total, elastic differential cross sections
    • ~~*spherical*~~/deformed.
    • n,p, (dble folding : ^{4}He, ^{12}C)
+ inelastic cross sections for discrete/continuum excitations

→ **Input : needs accurate NS model :** + mean field HF(B)
+ beyond mean field : (Q)RPA, MPMH, PGCM ...
+ shell model ...

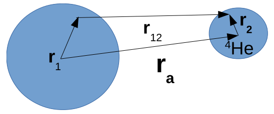
→ **predictive power, "validity domain" : Depends on NS Input, Limit of LDA, use adequate coupled channels framework.**

*** Validation of NS input to reaction models ***



^{240}Pu(α,α’) : validation method for direct model : ii) elastic on spherical

Double folding : $U(\mathbf{r}_\alpha) = \int d\mathbf{r}_1 \int d\mathbf{r}_2 \rho_A(\mathbf{r}_1)\rho_\alpha(\mathbf{r}_2)V(|\mathbf{r}_1 - \mathbf{r}_2|, \rho_1, \rho_2, E)$



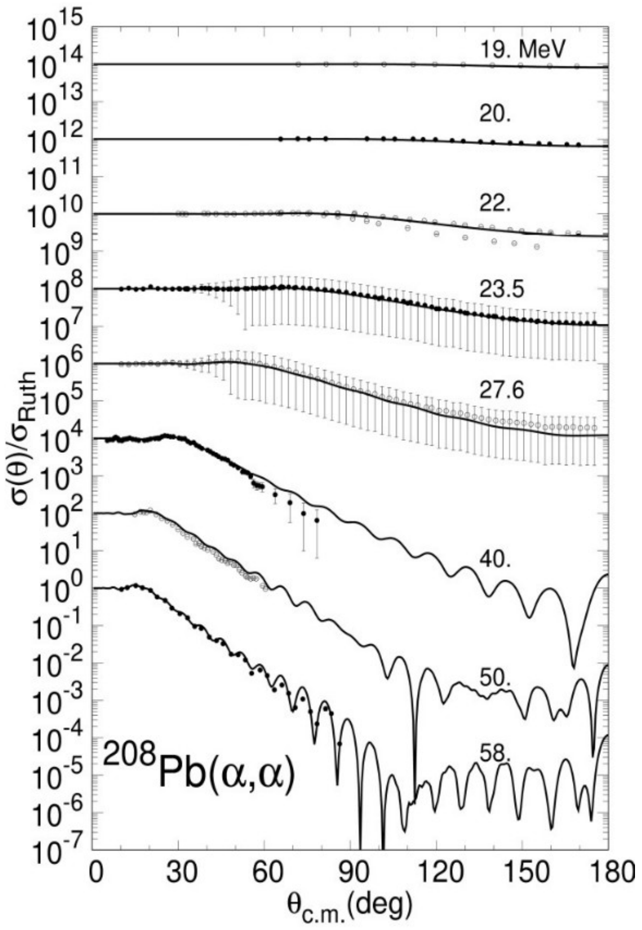
→ Effective N-N interaction: JLM-B.
→ Additional density-dependence
→ Alpha frozen (not too high energy).

Hogenbrik et al., PLB 223, p.282 (1989)

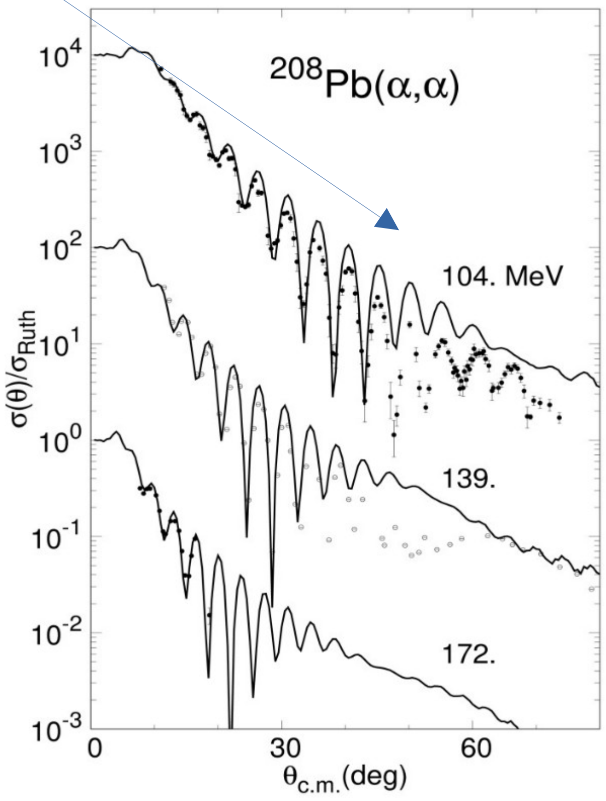
$$V(\rho_1, \rho_2, E) \equiv V_{JLM-B}(\rho_1, E)(1 - \beta\rho_2^{\frac{2}{3}})$$

$$\rho_\alpha(r_2) = 0.4229\ e^{-0.7014\, r_2^2}$$

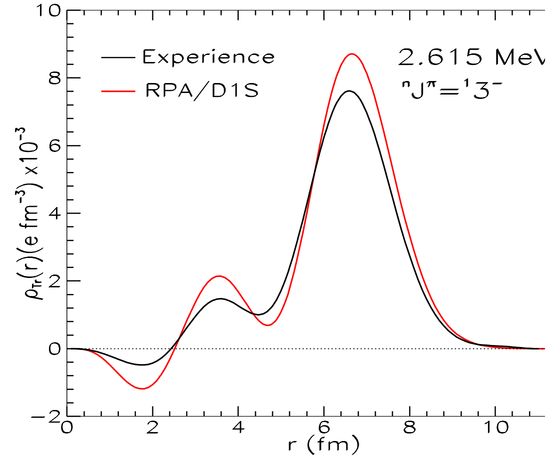
$$\beta_R = 0.4 \quad \beta_I = 0$$

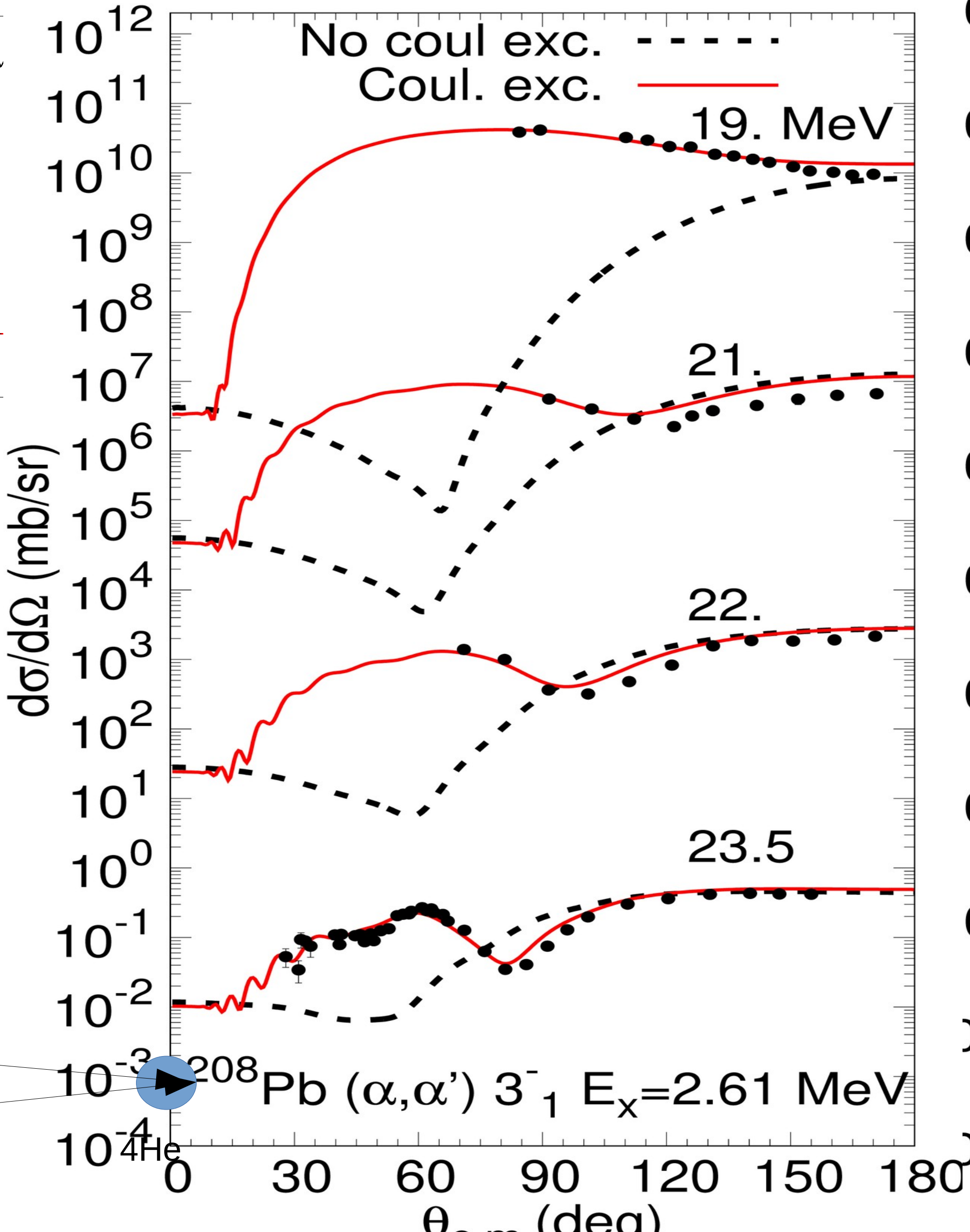


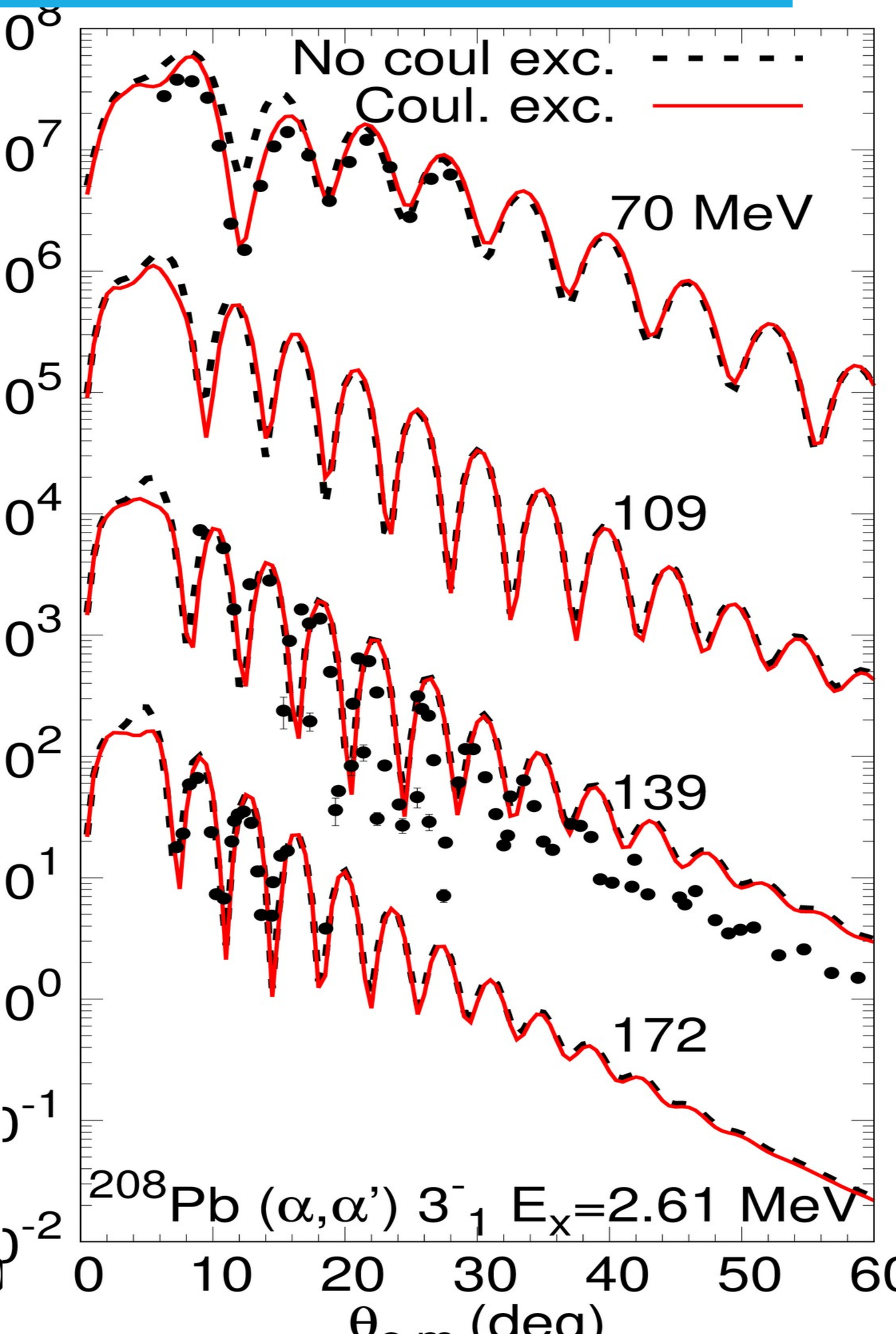
Matter densities RPA

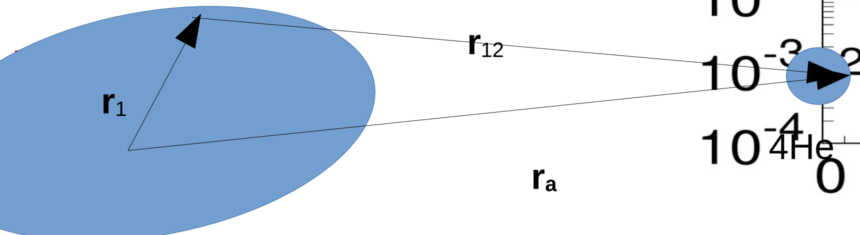


^{240}Pu(α,α') : validation method for direct model : ii) inelastic on spherical

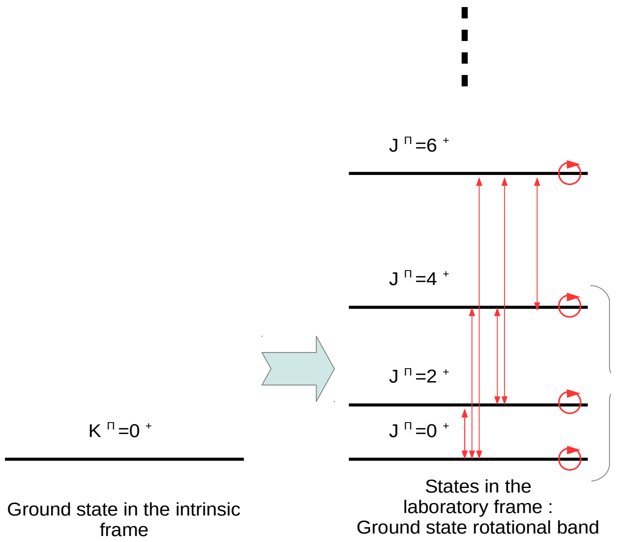








$^{240}Pu(\alpha,\alpha')$: validation method for direct model : iii) elastic + inelastic on deformed



Coupled channels