Microscopic modeling of direct and pre-equilibrium emission mechanisms for nucleon induced reactions

NT Program INT-17-1a
Toward Predictive Theories of Nuclear Reactions Across the Isotopic Chart

20 March, 2017

E. Bauge, G. Blanchon, M. Dupuis, G. Haouat, S. Hilaire, B. Morillon, A. Nasri, S. Péru, P. Romain
T. Kawano
M. Kerveno, P. Dessagne, G. Henning
R. Capote

CEA, DAM, DIF, France.
LANL, New Mexico, USA.
IPHC, Strasbourg, France.
IAEA, Vienna, Austria.
Outline

- Introduction: microscopic models for applications.
- Folding model: direct inelastic scattering and pre-equilibrium emission.
- Applications:
  - Nucleon induced reaction - rearrangement corrections.
  - Pre-equilibrium contribution to $(n,xn)$ reactions.
  - Spin-parity distributions and $^{238}\text{U} (n,n\gamma)$ cross-sections.
  - Inferring $^{239}\text{Pu} (n,2n)$ cross-sections form $(n,2n\gamma)$ measurements: impact of a microscopic description of pre-equilibrium.
- Conclusions, a few questions, future works and perspectives.
**Context**

**Basic science questions:** better understanding of nuclear structure and reaction, cross sections for astrophysical models

**Applications** for security, nuclear energy, waste management, medical applications etc.

⇓

Nuclear reactions observables for a **wide range** of nuclear masses and incident energies.

⇓

All needed nuclear reaction observables cannot be measured.

Fine precision required: \((n,n')\) or \((n,2n)\) for actinides.

First principles ➞ reaction observables for light and a few medium mass nuclei at low incident energy.

Select the relevant parts of the dynamical many-body problem.

Use available experimental knowledge.

⇓

**Modeling**

Phenomenological ➔ Microscopic
Context

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Select the relevant parts of the dynamical many-body problem.
Use available experimental knowledge.

\[\downarrow\]

**Modeling**

Phenomenological \(\rightarrow\) Microscopic

**Our goal**: improve modeling of nucleon induced reactions up to actinides
Modeling reaction mechanisms - example of inclusive \((n,xn)\) cross section

**Reaction mechanisms**
- **Direct** reactions: elastic, inelastic to discrete states and to giant resonances;
- Large energy transfer: **pre-equilibrium** emission;
- **Compound nucleus** formation then evaporation;

**Phenomenological approach**
- Optical potential, level densities;
- \(\beta_l\) for discrete states, response functions for G.R. (inferred from electron, hadron scatterings exp.);
- Pre-equilibrium: exciton model (coupling constants from global fit);

\[
\frac{d^2\sigma}{d\Omega dE} (\text{mb/sr/MeV})
\]

\(E_f (\text{MeV})\)

\(E_i=14.1 \text{ MeV}\)
\(\theta_{\text{c.m.}} = 30^\circ\)

**\(208\)Pb \((n,xn)\)**

Talys 1.8 (default)

Two-components exciton model


**Direct models models well constrained**: \(\beta_l\), %EWSR well known.
Modeling reaction mechanisms - example of inclusive \((n,xn)\) cross section

**Reaction mechanisms**

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- Large energy transfer: **pre-equilibrium** emission;
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**Phenomenological approach**

- Optical potential, level densities;
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- Pre-equilibrium: exciton model (coupling constants from global fit);

\[
\frac{d^2\sigma}{d\Omega dE} \text{(mb/sr/MeV)}
\]

\(E_f\) (MeV)

\(\theta_{\text{c.m.}} = 60.0\)

\(^{238}_\text{U} (n,xn)\)

Emission from fission fragments. 
Talys 1.4 (adjusted)
Direct reaction models not well constrained:
Evaluations for actinides: 
+ **pseudo-states** (see ENDFBVII and others).

M. Dupuis (CEA,DAM,DIF)
Connections between mechanisms

Direct + pre-equilibrium:
- Particles emission.
- Residual nucleus: $E_x, J, \Pi$. 

Diagram:
- Direct + pre-equilibrium emission
- Thermalization
- Evaporation
- (n,2n)
- (n,\gamma)
- (n,2\gamma)
Connections between mechanisms

Direct + pre-equilibrium:
- Particles emission.
- Residual nucleus: $E_x, J, \Pi$.

Pre-equilibrium models:
- Account for known doubly-differential cross-sections.
- Junction with direct process arbitrary (continuum).
- $J, \Pi$ distributions of the residual nucleus: ad-hoc prescriptions for exciton models.

$\Rightarrow J, \Pi$ distributions:
- $(n,n'\gamma)$ cross sections (indirect determination of the total $(n,n')$ cross sections).
- Surrogate applications.

M. Dupuis (CEA,DAM,DIF)
Microscopic approach to direct and pre-equilibrium reactions

**Direct elastic:** \((K + U^{\text{opt}} - E_i) \chi_{k_i}^+ = 0,\)
\[U^{\text{opt}} = \langle GS|V|GS \rangle.\]

**Direct inelastic scattering to discrete excitations:**
\[
\frac{d\sigma(k_i, k_f)}{d\Omega} \sim \left| \langle \chi_{k_f}^-, E_x J^\pi | T | \chi_{k_i}^+, GS \rangle \right|^2
\]
\[T = V + VGV + ...\]

DWBA: \(T \simeq V.\)
Microscopic approach to direct and pre-equilibrium reactions

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DWBA: \( T \simeq V. \)

Pre-equilibrium emission: quantum models

\[
\frac{d\sigma(k_i, k_f)}{d\Omega dE_f} \sim \frac{1}{2\delta} \int_{E_f-\delta}^{E_f+\delta} dE \sum_{E_xJ^\pi} \delta(E_i - E_x - E) |\langle \chi_{k}^-, E_xJ^\pi | T | \chi_{k_i}^+, GS \rangle|^2
\]
Target final states: \( |E_xJ^\pi\rangle = \sum_{n,ph} c_{ph}^n(E_x) |npnh\rangle \)

One-step (DWBA) + 2-body interaction:
\[
T \simeq V \quad \Rightarrow \quad |GS\rangle \rightarrow c_{ph}^1(E_x) |ph\rangle
\]
Microscopic description of target states

Target masses up to actinides, ground state and transition properties

⇒ **Mean-field and beyond** nuclear structure models, with phenomenological effective interactions (Skyrme, *Gogny* etc.).
Microscopic description of target states

Target masses up to actinides, ground state and transition properties
⇒ **Mean-field and beyond** nuclear structure models, with phenomenological effective interactions (Skyrme, Gogny etc.).

Direct inelastic scattering to **particle-hole** excitations, collective **vibrations/rotations** for many $J^\Pi$.

Weak perturbation ⇒ small amplitude collective motion ⇒ **linear response theory**.
Microscopic description of target states

Target masses up to actinides, ground state and transition properties

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⇓

(Quasi-particle) Random phase Approximation

⇒ Nucleus excitation are phonons

$$|E_x, J^\pi \rangle = \Theta^\dagger |\tilde{0} \rangle$$

**RPA**

$$\Theta^\dagger = \sum_{ph} X^{J\pi}_{ph} a_p^\dagger a_h + Y^{J\pi}_{ph} a_h^\dagger a_p$$

**QRPA**

$$\Theta^\dagger = \sum_{\alpha, \alpha'} X^{J\pi}_{\alpha\alpha'} \eta_{\alpha}^\dagger \eta_{\alpha'}^\dagger + Y^{J\pi}_{\alpha\alpha'} \eta_{\alpha} \eta_{\alpha'}$$

**p-h and h-p components**

2-qp creation and annihilation
Folding model for direct elastic and inelastic scattering

Direct inelastic scattering: optical potentials and DWBA matrix elements

\[
U^{opt} = \langle GS | V | GS \rangle \langle \chi^{-}_{k_f}, E_{x} J^\pi | V | \chi^{+}_{k_i}, GS \rangle
\]

**JLM folding model:** Brueckner-Hartree-Fock calculation


- Effective interaction \( V \) complex, \( E, \rho \)-dependent + normalizations.
- Local optical and transition potentials, no \( S = 1 \) transitions.
Folding model for direct elastic and inelastic scattering

Direct inelastic scattering: optical potentials and DWBA matrix elements

\[ U^{opt} = \langle GS| V |GS\rangle \quad \langle \chi_{k_f}^{-}, E_xJ^\pi | V | \chi_{k_i}^{+}, GS \rangle \]

**JLM folding model:** Brueckner-Hartree-Fock calculation


- Effective interaction \( V \) complex, \( E, \rho \)-dependent + normalizations.
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**Large range of applications:**

Unique structure model: HF(B)/(Q)RPA (Gogny D1S interaction).

JLM: parametrization unchanged for all calculations.

⇒ Direct elastic, inelastic, pre-equilibrium mechanisms, spherical and deformed targets.
Inelastic scattering to discrete excitations

\[ E_x \text{ (MeV)} \]
<table>
<thead>
<tr>
<th>Exp.</th>
<th>QRPA</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.65</td>
<td>3.73</td>
</tr>
</tbody>
</table>

\[ B(E3, \uparrow) \exp(10^6 e^2 f m^6) \]
<table>
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<tr>
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<th>QRPA</th>
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<tr>
<td>0.611(15)</td>
<td>0.635</td>
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QRPA with Gogny force, consistent implementation, spherical and axial def.


Consistent description of structure and reactions observables.
Inelastic scattering to discrete excitations: $^{206}Pb\ 2^+_1$

<table>
<thead>
<tr>
<th>$E_x$ (MeV)</th>
<th>$B(E2,↑)_{\text{exp}}(10^4 e^2 fm^4)$</th>
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<tbody>
<tr>
<td>Exp. QRPA</td>
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<tr>
<td>0.803</td>
<td>0.1000(20) 0.099</td>
</tr>
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YRAST $2^+_1\ \rho_{tr}(r)$

Isoscalar surface vibration $\rho_{tr}(r)$

M. Dupuis (CEA,DAM,DIF)
Inelastic scattering to discrete excitations: $^{206}Pb\ 2^+_1$

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YRAST $2^+_1\ \rho_{tr}(r)$

Isoscalar surface vibration $\rho_{tr}(r)$

$(p,p')$  

$206Pb\ (p,p')\ 2^+_1\ Ex=0.803\ MeV$

$(n,n')$  

$206Pb\ (n,n'),\ 2^+_1\ 0.8\ MeV$
Transition potential: rearrangement

Inelastic process: $\rho_{GS} \to \rho_{GS} + \delta \rho$:

$\Rightarrow$ Dynamical corrections to $V(\rho_{GS})$

Transition potential:

$$\langle E_x, J^\pi | V | GS \rangle \equiv \rho_{tr}^{gs \leftarrow E_x} \left\{ V(\rho_{GS}) + \rho_{GS} \frac{\delta V(\rho)}{\delta(\rho)} \right\}$$


$$U^{(0)} \equiv V(\rho_{GS})\rho_{tr}$$

$$U^{(R)} \equiv \rho_{GS} \frac{\delta V(\rho)}{\delta(\rho)}\rho_{tr}$$

Re($U^{(0)} + U^{(R)}$)  
Im($U^{(0)} + U^{(R)}$)  
Re($U^{(0)}$)  
Im($U^{(0)}$)

M. Dupuis (CEA,DAM,DIF)
Inelastic process: $\rho_{GS} \rightarrow \rho_{GS} + \delta \rho$:

$\Rightarrow$ Dynamical corrections to $V(\rho_{GS})$

Transition potential:

$$\langle E_x, J^\pi | V | GS \rangle \equiv \rho_{tr}^{gs \leftarrow E_x} \left\{ V(\rho_{GS}) + \rho_{GS} \frac{\delta V(\rho)}{\delta (\rho)} \right\}$$


$$U^{(0)} \equiv V(\rho_{GS}) \rho_{tr}$$

$$U^{(R)} \equiv \rho_{GS} \frac{\delta V(\rho)}{\delta (\rho)} \rho_{tr}$$

Re(U(0)+U(R))

Im(U(0)+U(R))

Re(U(0))

Im(U(0))

Re(U(0)+U(R))

Im(U(0)+U(R))

Re(U(0))

Im(U(0))

135 MeV $^{208}$Pb(p,p') $2^+_1$

Ratio $\sigma^{(0)}/\sigma^{(0+R)}$:
Microscopic approach to direct and pre-equilibrium reactions

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

$$\frac{d\sigma(k_i, k_f)}{d\Omega dE_f} \sim \frac{1}{2\delta} \int_{E_f-\delta}^{E_f+\delta} dE \sum_{E_x, J^\pi} \delta(E_i - E_x - E) \left| \langle \chi_k^- , E_x J^\pi | V | \chi_{k_i}^+ , GS \rangle \right|^2$$
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Target final states: mix of n-phonons states ($n = 1 2 ...$)

$$|F = E_xJ^\pi\rangle = \sum_{n,{\{k\}}} c^F_{n,{\{k\}}}(E_x) \prod_i \Theta^\dagger_{\{k\}} |\tilde{0}\rangle = c^F_{1,N} \Theta^\dagger_N |\tilde{0}\rangle + c^F_{2,{\{N,N'\}}} \Theta^\dagger_N \Theta^\dagger_{N'} |\tilde{0}\rangle +$$

One-step + 2-body interaction + Quasi-boson:  

$$|\tilde{0}\rangle \rightarrow c^F_N(E_x) \Theta^\dagger_N |\tilde{0}\rangle$$
Microscopic approach to direct and pre-equilibrium reactions

**Pre-equilibrium emission** \( E_{in} < 20 \text{ MeV}: \) one-step direct

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\frac{d\sigma(k_i, k_f)}{d\Omega dE_f} \sim \frac{1}{2\delta} \int_{E_f-\delta}^{E_f+\delta} dE \sum_{E_x J^\pi} \delta(E_i - E_x - E) \left| \langle \chi^-_k, E_x J^\pi | V | \chi^+_k, GS \rangle \right|^2
\]

Target final states: mix of \( n \)-phonons states \((n = 1 2 \ldots)\)

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\]

One-step + 2-body interaction + Quasi-boson:

\[
|\tilde{0}\rangle \to c^F_N(E_x) \Theta^\dagger_N |\tilde{0}\rangle
\]

**Statistical hypothesis:**

\[
\langle c^F_N(E_x) c^F_{N'}(E_x) \rangle_E = \delta_{N,N'} \left| C^F_N(E_x) \right|^2
\]

\[
\left| c^F_N(E_x) \right|^2 = \frac{\Gamma_N}{2} \frac{1}{(E_x - E_N)^2 + \frac{\Gamma_N^2}{4}}
\]

\( \Gamma_N = \) damping widths: phenomenological prescription.
Microscopic approach to direct and pre-equilibrium reactions

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

$$
\frac{d\sigma(k_i,k_f)}{d\Omega dE_f} \sim \frac{1}{2\delta} \int_{E_f-\delta}^{E_f+\delta} dE \sum_N \frac{\Gamma_N}{2} \frac{1}{(E_i-E-E_N)^2 + \frac{\Gamma_N^2}{4}} \left| \langle \chi^-_{k_i}, N^{RPA} | V | \chi^+_{k_f}, \tilde{0} \rangle \right|^2
$$

Target final states: mix of n-phonons states ($n = 1\ 2\ ...$)

$$
|F = E_x J^\pi \rangle = \sum_{n,\{k\}} c_{n,\{k\}}^F(E_x) \prod_i \Theta^\dagger_{\{k\}} \tilde{0} \rangle = c_{1,N}^F \Theta^\dagger_N \tilde{0} \rangle + c_{2,\{N,N'\}}^F \Theta^\dagger_N \Theta^\dagger_{N'} \tilde{0} \rangle + ...
$$

One-step + 2-body interaction + Quasi-boson: $|\tilde{0} \rangle \rightarrow c_{N}^F(E_x) \Theta^\dagger_N |\tilde{0} \rangle$

Statistical hypothesis:

$$
\langle c_{N}^F(E_x) c_{N'}^F(E_x) \rangle_E = \delta_{N,N'} \left| C_{N}^F(E_x) \right|^2
$$

$$
\left| c_{N}^F(E_x) \right|^2 = \frac{\Gamma_{N}}{2} \frac{1}{(E_x-E_N)^2 + \frac{\Gamma_{N}^2}{4}}
$$

$\Gamma_{N}$ = damping widths: phenomenological prescription.
One-step direct \((n,n') - ^{208}\text{Pb}(n,xn)\)

JLM with RPA excitations (natural parities)
JLM: no spin flip possible.

\[ V_{JLM} \Rightarrow V_{CDM3Y} \] non-natural parity transitions \((0^+ \rightarrow J^\pi \text{ with } \pi = -(\pi)^J)\)

CDM3Y: real, \(\rho\)-dependent, include two-body spin-orbit and tensor interactions.
One-step direct \((n,n') - ^{208}\text{Pb}(n,xn)\)

Comparison to calculations from Talys 1.8 (default settings).
One-step direct \((n,n')\) - \(^{208}\text{Pb}(n,xn)\)

\[
\begin{align*}
\sigma_2/\Omega dE &= 10^{-2} \\
\sigma_1/\Omega dE &= 10^{-1} \\
\sigma_0/\Omega dE &= 10^0 \\
\sigma_1/\Omega dE &= 10^1 \\
\sigma_2/\Omega dE &= 10^2 \\
\sigma_3/\Omega dE &= 10^3
\end{align*}
\]

\(E_f\) (MeV)

\(E_i = 14.1\) MeV

\(\theta_{\text{c.m.}} = 60^\circ\)

Takahashi (1987)
Elfruth (1986)
Talys
Total

\(E_f\) (MeV)

\(E_i = 14.1\) MeV

\(\theta_{\text{c.m.}} = 120^\circ\)

Takahashi (1987)
Elfruth (1986)
Talys
Total

\((n,n')\) from RPA states: **spin-parity distributions** / impact of **rearrangement**.

\[
\begin{align*}
\text{Normalized spin distributions (no units)} \\
J (h\omega\text{ units})
\end{align*}
\]

\(E_i = 14.1\) MeV

\(E_x = 4\) MeV

\(E_x = 10\) MeV

M. Dupuis (CEA,DAM,DIF)
Nuclear structure
GS and excitations

HF(B)+(Q)RPA, Gogny force

- Densities, radii, deformations
- Radial transition densities, $B(E_L)$
- Response functions, EWSR

In-medium: n-n two-body interaction

JLM, from nuclear matter
semi-microscopic normalizations fixed
+ two-body S.O. and tensor for unnatural parity transitions.

Nucleon induced direct reactions for spherical nuclei:

- Elastic scattering
- Inelastic scattering to discrete states
- First step of pre-equilibrium emission

⇒ Application to n + actinides → axial deformation.
Neutron induced reactions on actinides

JLM model + HFB axial densities: \( L = 0, 2, 4 \ldots \) multipoles.

\[ \text{Ground state in the intrinsic frame} \]

\[ \text{States in the laboratory frame: Ground state rotational band} \]

Neutron scattering data:
Sum of 0\(^{+}\), 2\(^{+}\), 4\(^{+}\) cross sections

\[ \text{238U(n,n)} \]

\[ \text{JLM 0\(^{+}\), 2\(^{+}\), 4\(^{+}\)} \]

\[ \text{Ma Gonggui (1988)} \]
\[ \text{Shen Guanran (1984)} \]
\[ \text{Voignier (1968)} \]
\[ \text{Hansen (1986)} \]
\[ \text{Bucher (1975)} \]
\[ \text{Qi Huiquan (1991)} \]
\[ \text{Qi Bujia (1992)} \]
\[ \text{Schreder (1988)} \]

M. Dupuis (CEA,DAM,DIF)
Excitation spectrum of a nucleus with a static axial deformation

QRPA with axial deformation, good quantum numbers:
- Projection $K$, of the total angular momentum $\vec{J}$ on the symmetry axis $Oz$,
- Parity $\pi$.

Target excitations in the intrinsic frame: $|\alpha K\Pi\rangle = \Theta_{\alpha K\Pi}^+ |\tilde{0}\rangle$. 
Excitation spectrum of a nucleus with a static axial deformation

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$$|\alpha K \Pi \rangle = \Theta_{\alpha K \Pi}^{+} |\tilde{0} I \rangle.$$ 

Target states in the laboratory frame:
projection on total angular momentum $\Rightarrow$ rotational bands, on for each intrinsic excitation, $J \geq K$
Excitation spectrum of a nucleus with a static axial deformation

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Target states in the laboratory frame: projection on total angular momentum $\Rightarrow$ rotational bands, on for each intrinsic excitation, $J \geq K$.

E3 transition probabilities
Excitation spectrum of a nucleus with a static axial deformation

QRPA with axial deformation, good quantum numbers:

- Projection $K$, of the total angular momentum $\tilde{J}$ on the symmetry axis $Oz$,
- Parity $\pi$.

Target excitations in the intrinsic frame: $|\alpha K\Pi\rangle = \Theta_{\alpha K\Pi}^+ |\tilde{0}\rangle$.

Target states in the laboratory frame: projection on total angular momentum $\Rightarrow$ rotational bands, on for each intrinsic excitation, $J \geq K$

E2 transition probabilities

E2 transitions from GS to $2^+$ states for $K^\pi=0^+,1^+,2^+$


M. Dupuis (CEA,DAM,DIF)
Excitation spectrum of a nucleus with a static axial deformation

QRPA with axial deformation, good quantum numbers:

- Projection $K$, of the total angular momentum $\vec{J}$ on the symmetry axis $Oz$,
- Parity $\pi$.

Target excitations in the intrinsic frame: $|\alpha K\Pi\rangle = \Theta^+_{\alpha K\Pi} |\tilde{0}_I\rangle$.

Target states in the laboratory frame: projection on total angular momentum $\Rightarrow$ rotational bands, on for each intrinsic excitation, $J \geq K$

E2-E5 response functions
11-18 MeV (n,xn) $^{238}$U spectra

Direct emission component:

$$\frac{d\sigma(k_i, k_f)}{d\Omega dE_f} = \frac{1}{2\delta} \int_{E_f-\delta}^{E_f+\delta} dE \sum_{N=K^\pi, J\geq K} \frac{\Gamma_N}{2} \frac{1}{(E_i - E - E_N)^2 + \frac{\Gamma_N^2}{4}} \frac{d\sigma_N}{d\Omega}$$
11-18 MeV \((n,\gamma n)\) \(^{238}\text{U}\) spectra

Direct emission component:

\[
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\]

\(\theta = 30^\circ\)

\(\theta = 60^\circ\)

\(\theta = 120^\circ\)
Comparison to previous more phenomenological calculations

Excitons + collective model + pseudo states

⇒ need n.n.p states and 2-step process for $E_{in} \approx 10$ MeV
Modeling $^{238}\text{U} (n,n'\gamma)$ reactions

Direct process

Decay from CN

$\gamma$ cascade
Modeling $^{238}$U (n,n'$\gamma$) reactions

- Direct process
- Decay from CN
Modeling $^{238}\text{U} (n,n'\gamma)$ reactions

Direct process

Decay from CN

M. Dupuis (CEA,DAM,DIF)
Modeling $^{238}\text{U} \ (n,n'\gamma)$ reactions

Direct process

$\gamma$ cascade

Residual nucleus: $E_x, J^\pi$

Normalized spin distributions (%)

$J (h\omega \text{ units})$

$E_{in} = 6 \text{ MeV}$

$E_{in} = 18 \text{ MeV}$

M. Dupuis (CEA,DAM,DIF)
Modeling $^{238}\text{U} (n,n'\gamma)$ reactions

Direct process

Residual nucleus: $E_x, J^{\pi}$

M. Kerveno et al., IPHC, Strasbourg, France.

M. Dupuis (CEA,DAM,DIF)
Modeling $^{238}$U $(n,n'\gamma)$ reactions

Direct process

$\gamma$ cascade

TALYS default model
TALYS + QRPA

Fiotades (2004)
IPHC (2015)
Hutcheson (2009)

E$_{\gamma}$ = 103.5 keV

E$_{\gamma}$ = 158.8 keV

E$_{\gamma}$ = 210.9 keV

E$_{\gamma}$ = 257.8 keV

M. Dupuis (CEA,DAM,DIF)
Inter-band transitions

Direct + Preequilibrium from JLM+QRPA

Odd actinides - early developments

Direct excitation process in $^{239}$Pu:

Transitions: $|\frac{1}{2}^+\rangle \rightarrow |j^\pi\rangle$
Odd actinides - early developments

Direct excitation process in $^{239}\text{Pu}$:

Transitions: $|\frac{1}{2}^{+}\rangle \rightarrow |j^{\pi}\rangle$

$a_{\frac{1}{2}^{+}}|0^{+}\rangle \rightarrow a_{\frac{1}{2}^{+}}|N\rangle$.

$|N\rangle \Rightarrow$ phonons calculated in $^{240}\text{Pu} \Rightarrow \text{weak-coupling}$ approximation.

Main features of collective responses in $A$ and $A \pm 1$ are expected to be similar.
Odd actinides - early developments

Direct excitation process in $^{239}\text{Pu}$:

Transitions: $|\frac{1}{2}^{+}\rangle \rightarrow |j\pi\rangle$

$a_{\frac{1}{2}^{+}}|0^{+}\rangle \rightarrow a_{\frac{1}{2}^{+}}|N\rangle$.

$|N\rangle \Rightarrow$ phonons calculated in $^{240}\text{Pu} \Rightarrow$ weak-coupling approximation.

Main features of collective responses in $A$ and $A \pm 1$ are expected to be similar.

14. MeV $^{239}\text{Pu}(n,\alpha n)$

Missing neutron contributions: fission fragments.

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$^{239}\text{Pu (n,2n) : reaction mechanisms}$

- Emission n
  (CN / Direct / Pre-eq.)
- Fission
  1ère chance

$^{239}\text{Pu} \rightarrow ^{240}\text{Pu}$

Emission gamma
Voie $^{239}\text{Pu}(n,\gamma)^{240}\text{Pu}$

$^{239}\text{Pu}(n,n')^{239}\text{Pu}$
Emission gamma
Voie $^{239}\text{Pu}(n,n'\gamma)^{239}\text{Pu}$

BRC (P. Romain, B. Morillon, H. Duarte).

M. Dupuis (CEA,DAM,DIF)
$^{239}\text{Pu (n,2n)}$ : reaction mechanisms

- Emission n ($\text{(CN / Direct / Pre-eq.)}$)
- Fission
  - 1ère chance
  - 2ème chance
- Emission gamma

$^{239}\text{Pu} \rightarrow ^{240}\text{Pu}$
- Voie $^{239}\text{Pu}(n,y)^{240}\text{Pu}$
- Fission

$^{239}\text{Pu} \rightarrow ^{238}\text{Pu}$
- Voie $^{239}\text{Pu}(n,n')^{239}\text{Pu}$
- Emission gamma

$^{239}\text{Pu}(n,2n)^{238}\text{Pu}$
- Emission gamma
- Voie $^{239}\text{Pu}(n,2ny)^{238}\text{Pu}$

BRC (P. Romain, B. Morillon, H. Duarte).

M. Dupuis (CEA,DAM,DIF)
$^{239}\text{Pu} (n,2n)$: reaction mechanisms

$^{239}\text{Pu}$

$^{238}\text{Pu}$

Emission $n$

(CN / Direct / Pre-eq.)

$^{239}\text{Pu}(n,n')^{239}\text{Pu}$

Emission gamma

Voie $^{239}\text{Pu}(n,y)^{240}\text{Pu}$

$^{239}\text{Pu}(n,2n)^{238}\text{Pu}$

$^{239}\text{Pu}(n,2n)^{238}\text{Pu}$

Emission gamma

Voie $^{239}\text{Pu}(n,2ny)^{238}\text{Pu}$

Fission

1ère chance

$^{239}\text{Pu}$

$^{240}\text{Pu}$

Emission gamma

Voie $^{239}\text{Pu}(n,y)^{240}\text{Pu}$

Fission

2ème chance

Emission $n$

(essentiellement CN)

$^{238}\text{Pu}$

Fission

3ème chance

Etc.

BRC (P. Romain, B. Morillon, H. Duarte).

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Measurements and evaluations $^{239}\text{Pu} \ (n,2n) \ ^{238}\text{Pu}$

GEANIE/GNASH (Bernstein 2002) : (n,2n) extrapolated (using GNASH code) from partial (n,2nγ) measured cross sections (GEANIE : Germanium array).

Lougheed (2002)
Frehaut (1986)
Mather (1972)
Measurements and evaluations $^{239}\text{Pu} (n,2n) ^{238}\text{Pu}$

Large discrepancies between various evaluations:
for $E_{in}$ in the 6.5 - 8 MeV range
for $E_{in} > 11$ MeV.
GEANIE measurements
LANL 1999
height measured transitions
(seven cross sections) \((n,2n\gamma)\)

**Difficulties**

- \(E < 6.5 < MeV\) \((n,2n)\) without \(\gamma\) emission.
- Internal conversion : \(2^+_1 \rightarrow 1^+_1\) \(\gamma\)-ray conversion : 735.
- \(\gamma\) from fission fragments, sample activity.
- Exemple: the \(4^+_1 \rightarrow 2^+_1\) \(\gamma\)-ray yields was overwhelmed by a fission-product \(\gamma\)-ray.

\[
\Sigma_i (n,2n\gamma_i) / i = J^{\pi} \rightarrow 0^+ \\
\Sigma_i (n,2n\gamma_i) / i = J^{\pi} \rightarrow 2^+ \\
\Sigma_i (n,2n\gamma_i) / i = J^{\pi} \rightarrow 4^+
\]
Pre-equilibrium models - $^{239}$Pu (n,xn) spectrum

**JLM / one-phonon QRPA**

![JLM / one-phonon QRPA graph](image1)

**Excitons (two-components, TALYS impl.)**

![Excitons graph](image2)

**JLM : No unnatural parity excitations.**

$^{208}$Pb(n,xn)

![JLM graph](image3)

**QRPA + $\frac{1}{2}$ Excitons**

![QRPA + Excitons graph](image4)

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Discussion

$\sigma$ (mb)

Neutron incident energy (MeV)

$^{239}$Pu(n,2n)

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Discussion: $^{241}$Am(n,2n)

$^{239}$Pu(n,2n)

$^{241}$Am(n,2n)

Cross Sections (barn)

Neutron Energy (MeV)

Preeq: excitons. (BRC original)
Preeq: QRPA + 0.5 excitons
Preeq: 2 QRPA + 0.5 excitons
GEANIE
ENDF-BVII.1

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Conclusions and questions

- Direct inelastic and pre-equilibrium (first-step): QRPA one phonon excitations.
- $\rho$-dependent effective interaction $\rightarrow$ large rearrangement corrections.
- Improve high energy neutron spectra in (n,xn) and (n,n'γ) cross-sections for $^{238}$U.

- Future of folding models for low energies? Which interactions?
- Folding models / inelastic processes / rearrangement: full-folding models (Melbourne), link with beyond low density expansions NM theories (H. Arellano, University of Chile).
Future works

Work in progress

- Analysis of \((n,xn)\) and \((n,xn\gamma)\): \(^{239}\text{Pu}\) and \(^{241}\text{Am}\), \(^{232}\text{Th}\) and Tungsten (IPHC, GELINA).
- \(^{239}\text{Pu}\) \((n,2n)\) cross section extracted from \((n,2n\gamma)\) data: new analysis with microscopic direct reaction modeling.

Plans for model improvements

Better interaction, **two-step process with 2-phonon states, qp-blocking+QRPA for odd-nuclei, QRPA charge exchange**, consistent description of structure and reaction

**Actinides**: microscopic derivation of coupling **non-local potentials**, solving coupled channels for a large coupling scheme (PhD of A. Nasri, CEA, DAM, DIF, Bruyères-le-Châtel)

Thank you