

DE LA RECHERCHE À L'INDUSTRIE



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# Study of the (n, $\gamma$ f) process on $^{239}\text{Pu}$

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Esther LEAL CIDONCHA, Gilles NOGUERE,  
Olivier BOULAND and Olivier SEROT

CEA/DEN/CAD/DER/SPRC/LEPh

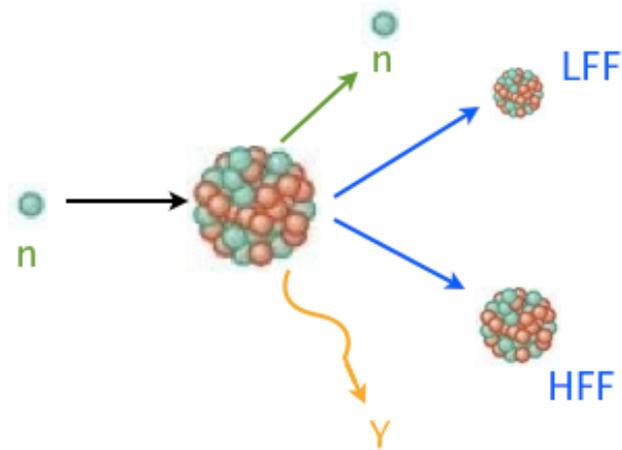
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*CEA/Cadarache (France)*

WONDER-2018  
8-12 October 2018

## Slow neutron-induced reactions

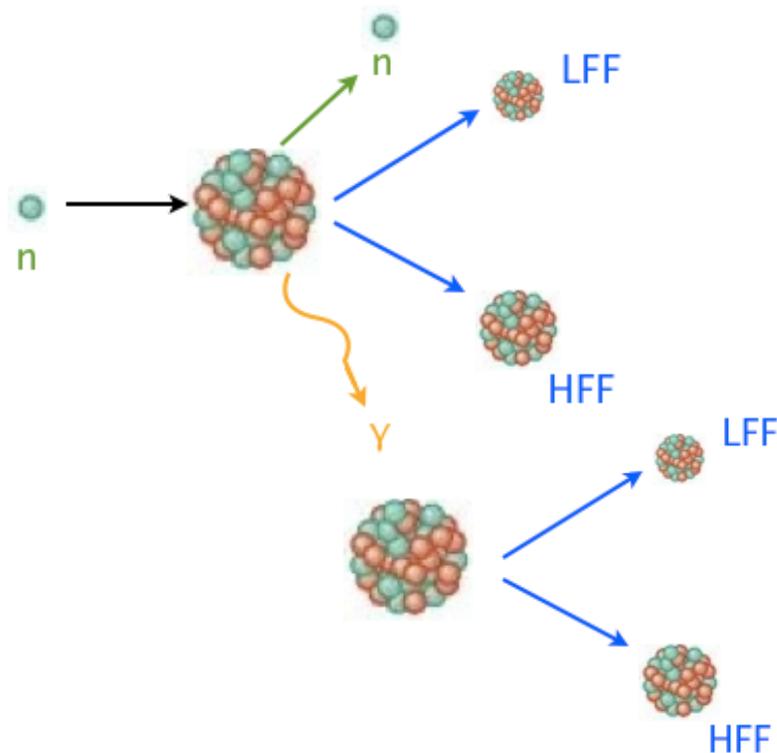
- The compound nucleus may decay by:



<u>Reaction</u>	<u>Channel</u>
• Neutron emission	(n,n')
• $\gamma$ -ray emission	(n, $\gamma$ )
• Fission	(n,f)

## Slow neutron-induced reactions

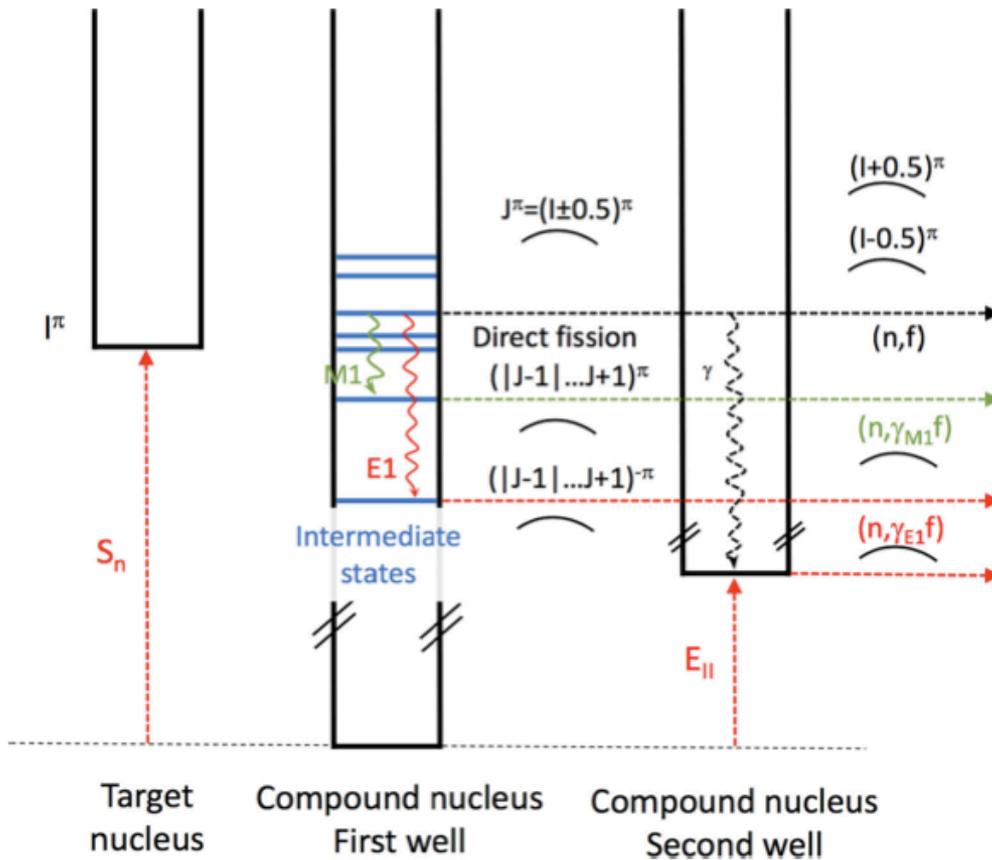
- The compound nucleus may decay by:



<u>Reaction</u>	<u>Channel</u>	
• Neutron emission	(n,n')	$\rightarrow \sigma_n$
• $\gamma$ -ray emission	(n, $\gamma$ )	$\rightarrow \sigma_\gamma$
• Fission	(n,f)	$\rightarrow \sigma_f$
• $\gamma$ -ray emission + Fission	(n, $\gamma$ f)	

## Slow neutron-induced reactions

- Double-humped fission barrier:



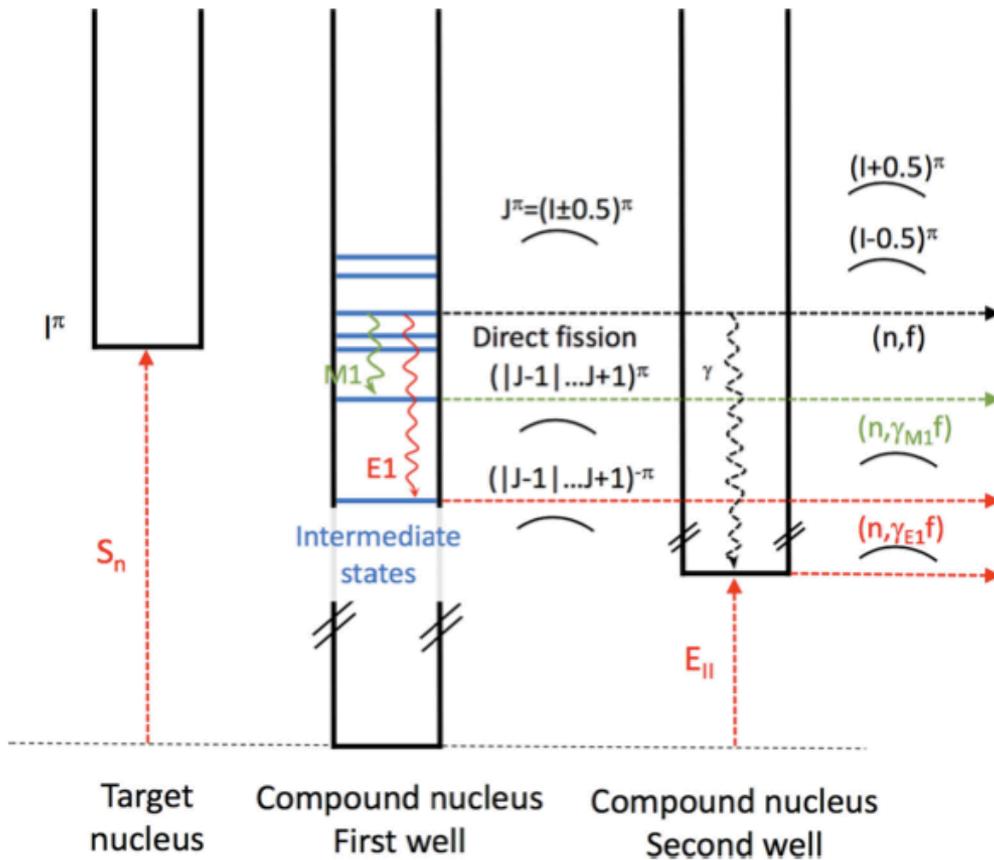
- If a  $\gamma$  is emitted before fission then the available excitation energy to the FF is lower and less prompt neutrons are emitted => **anticorrelation** between **prompt neutron emission** and  **$\gamma$  multiplicities**.

J.E. Lynn, P. Talou and O. Bouland, PRC 97, 064601 (2018)

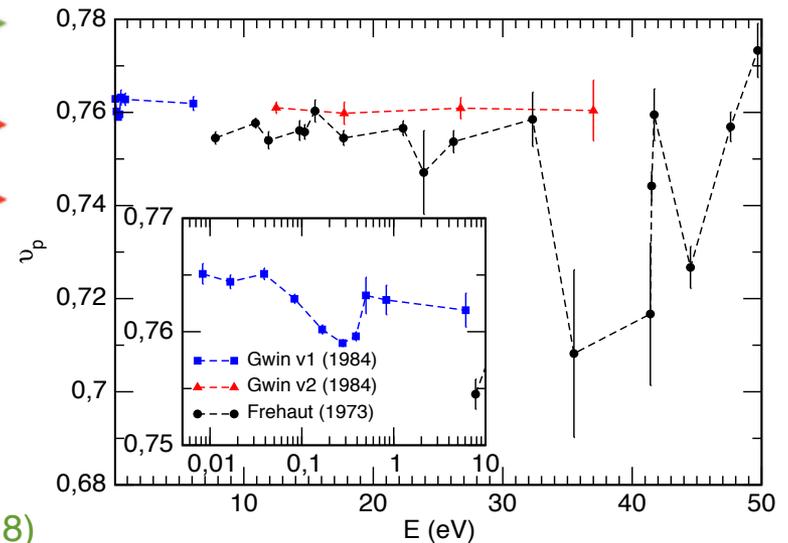
Esther Leal Cidoncha, WONDER-2018, 8-12 October, 2018.

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- The  $^{239}\text{Pu}(n,f)$  cross section can be described by:

$$\sigma_f(E_n) = \sigma(E_n)_{(n,f)} + \sigma(E_n)_{(n,\gamma f)} \quad ?$$

$$\sigma_\gamma(E_n) \cdot \frac{\Gamma_{\gamma f}}{\Gamma_\gamma}$$

- Partial fission width:

$$\Gamma_{\gamma f}(E^*, J^\pi) = \sum_{Xl} \sum_{J_f=|J-l|}^{J+l} \int_0^{E^*} d\varepsilon_\gamma \rho(E^* - \varepsilon_\gamma, J_f^{\pi(-)Xl}) \times \Gamma_{\gamma Xl}(\varepsilon_\gamma) P_f(E^* - \varepsilon_\gamma, J_f^{\pi(-)Xl})$$

$Xl$  → multipolarity (E1, M1)  
 $\rho$  → nuclear level density  
 $E^* = E_{\text{inc}} + B_n$  → Residual excitation energy  
 $P_f$  → fission probability  
 $\pi$  (M1) /  $-\pi$  (E1)

J.E. Lynn, P. Talou and O. Bouland, PRC 97, 064601 (2018)

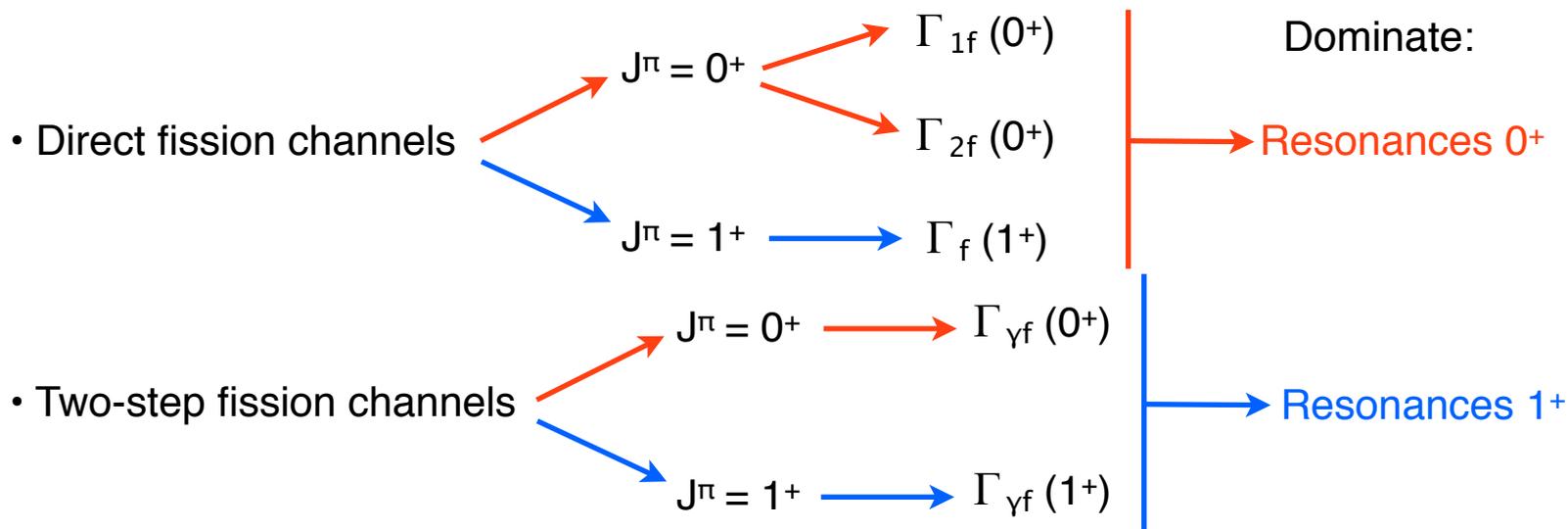
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$$\sigma_\gamma(E_n) \cdot \frac{\Gamma_{\gamma f}}{\Gamma_\gamma}$$

- Partial fission widths in the R-Matrix Theory:



- The **evaluated file** of the fission cross section considers the  $J^\pi=1^+$  resonances as being produced only through direct fission reactions.
- New resonance analysis with the **CONRAD\*** (COde for Nuclear Reaction Analysis and Dated Assimilation) R-Matrix code including:
  - Multiple analysis:
    - Total cross section
    - Fission cross section
    - Prompt neutron multiplicity (Frehaut and Gwin experimental data)
    - Capture cross section
    - Total neutron multiplicity
  - Resonance parameters:
    - Direct reactions contribution from the evaluations  $\Rightarrow \Gamma_\gamma, \Gamma_f$  and  $\Gamma_n$
    - Two-step fission contribution from Trochon [1] vs. Bouland [2]  $\Rightarrow \Gamma_{\gamma f}$
  - Free parameters:
    - $\nu_{n\gamma f}$
    - $\nu_0$  and  $\nu_1$
    - Normalization of experimental data
- Prompt neutron multiplicity ( $\nu_p$ ) reproduced including the two-step fission process.

[1] Trochon, Proc. 3rd Symp. Physics and Chemistry of Fission, Rochester, New York, Aug. 13-17 (1973)

[2] J.E. Lynn, P. Talou and O. Bouland, PRC 97, 064601 (2018)

\* *Developed at CEA/Cadarache*

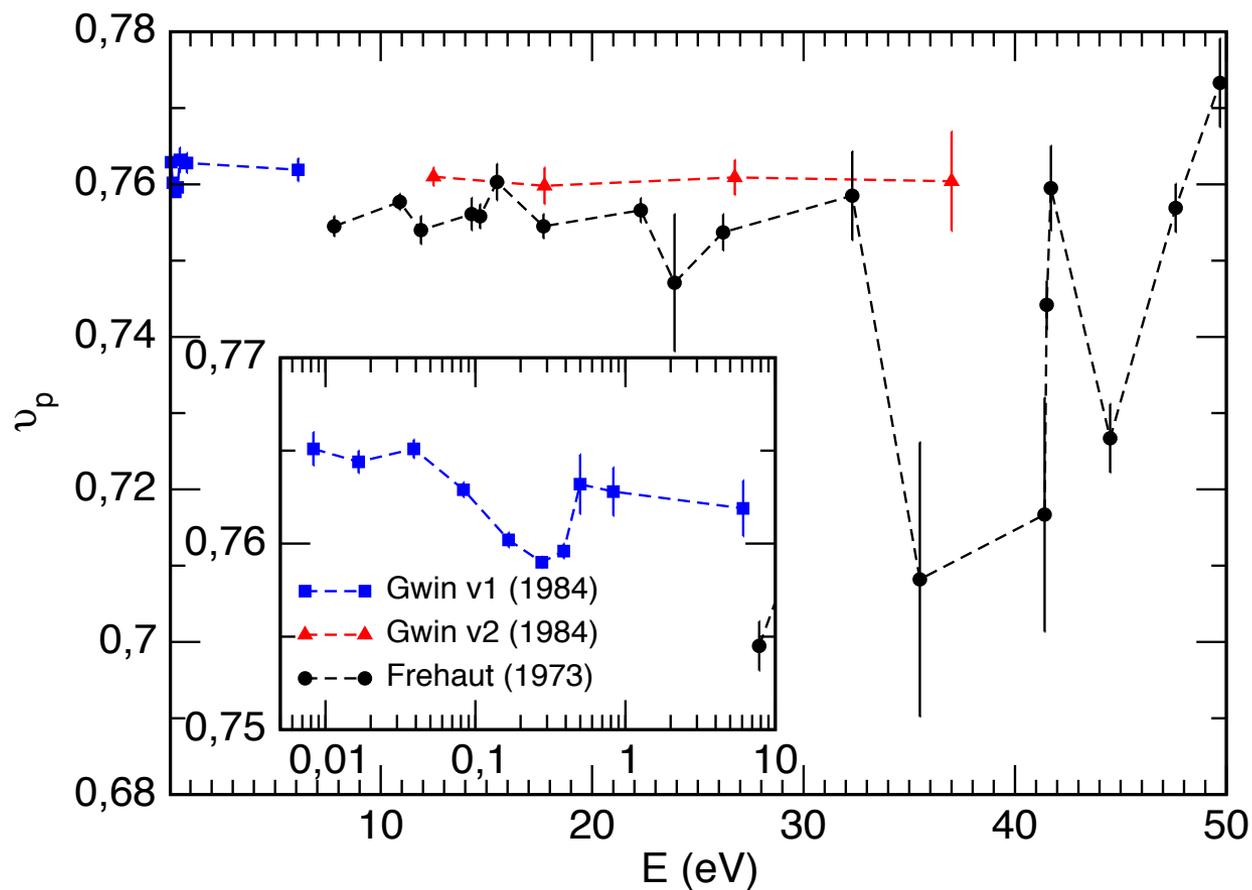
# TWO-STEP FISSION CONTRIBUTION ( $\Gamma_{\gamma f}$ )

- Calculation of  $\Gamma_{\gamma f}$  from Trochon [1]:
  - **Single-humped** fission barrier.
  - Only **E1** transitions are considered.
- Calculation of  $\Gamma_{\gamma f}$  from Bouland [2]:
  - **Double-humped** fission barrier.
  - **E1** transitions are considered.
  - A low-lying **M1** resonance known as the **scissors mode** has been also taken into account.

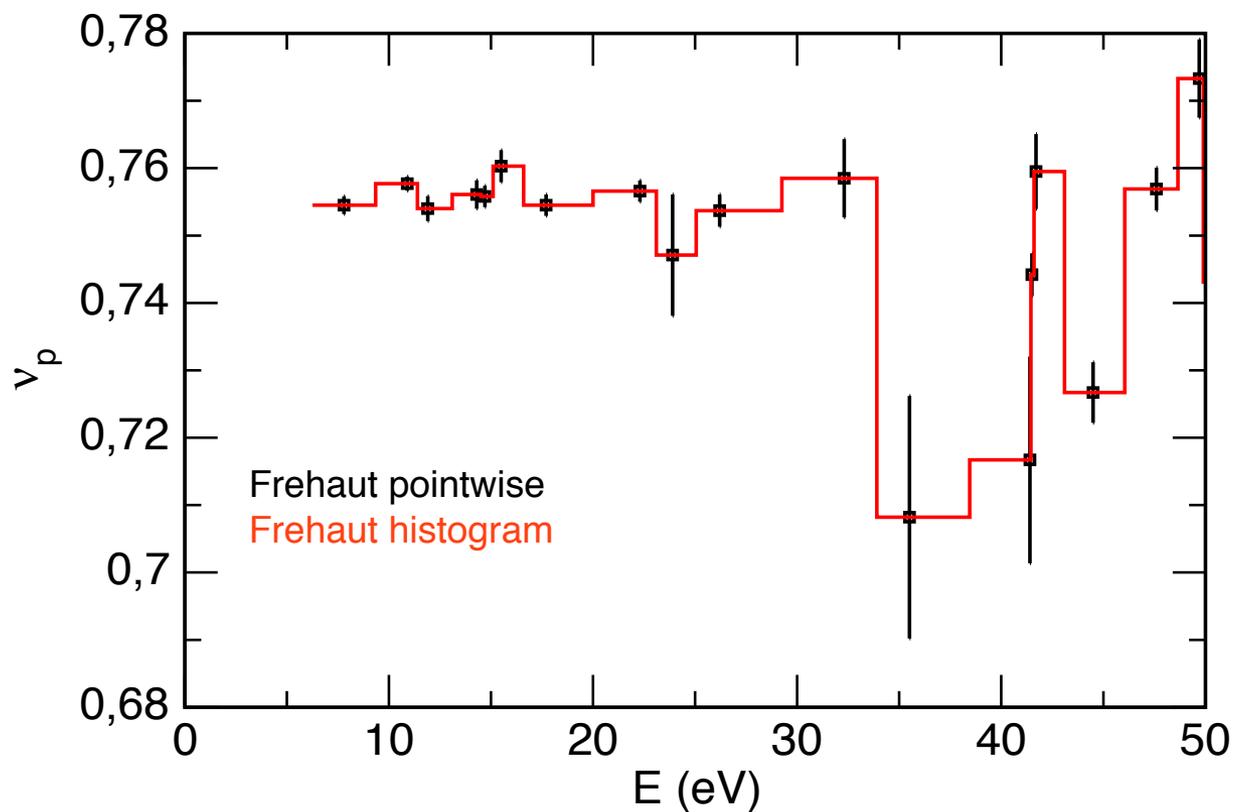
[1] Trochon, Proc. 3rd Symp. Physics and Chemistry of Fission, Rochester, New York, Aug. 13-17 (1973)

[2] J.E. Lynn, P. Talou and O. Bouland, PRC 97, 064601 (2018)

- Frehaut and Gwin experimental data:



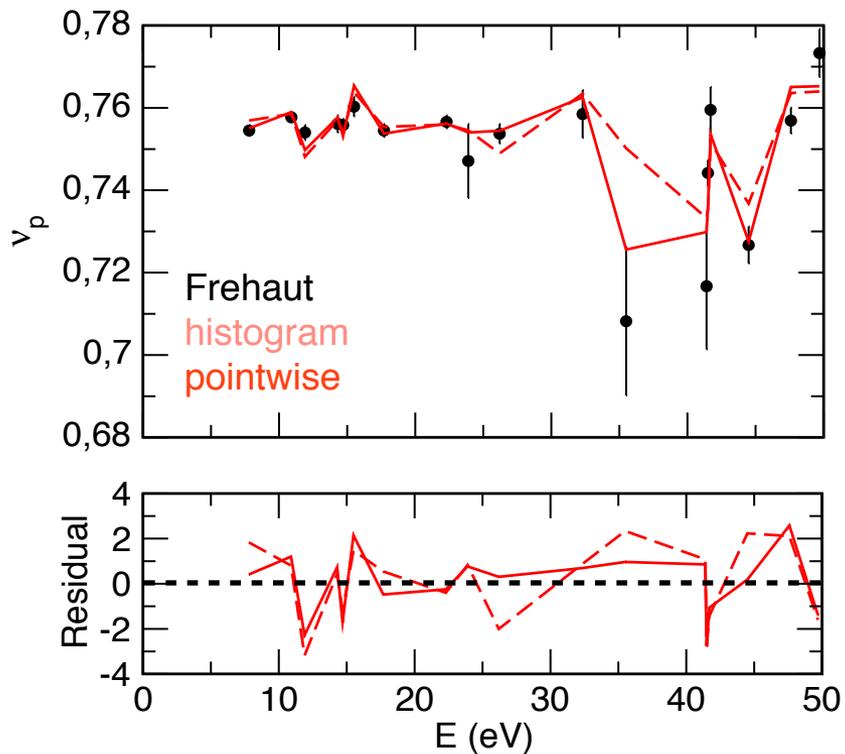
- Problem: how to treat **Frehaut** data (histogram/pointwise) better description with pointwise.



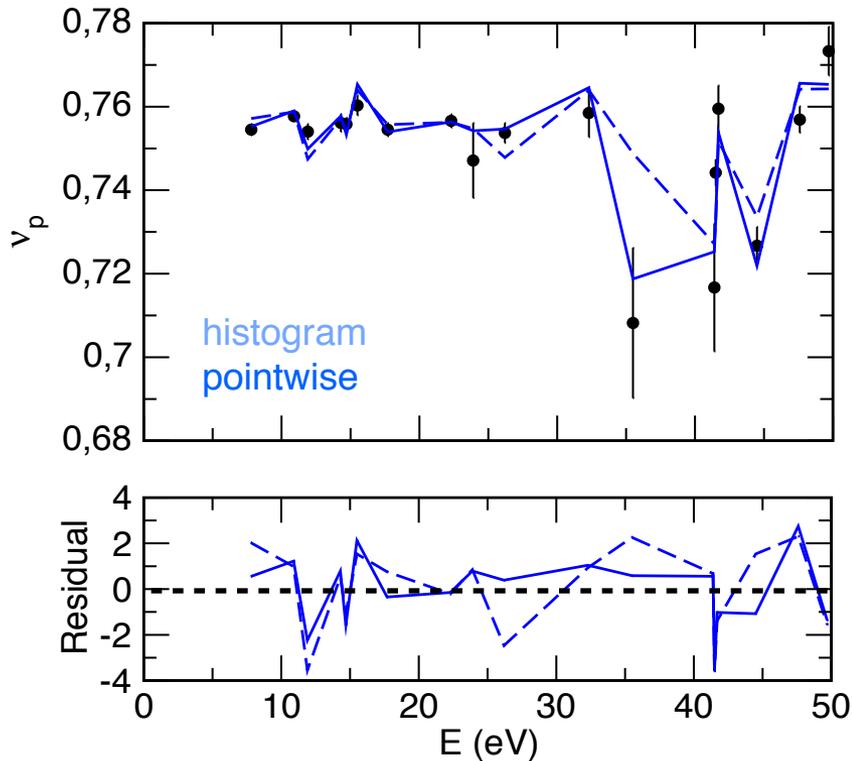
# CONRAD RESULTS OF $V_p$ UP TO 50 eV

- CONRAD results from the fit below 50 eV of **Frehaut** data:
  - Comparison of results obtained treating Frehaut data as histogram/pointwise.

with  $\Gamma_{\gamma f}$  from Trochon

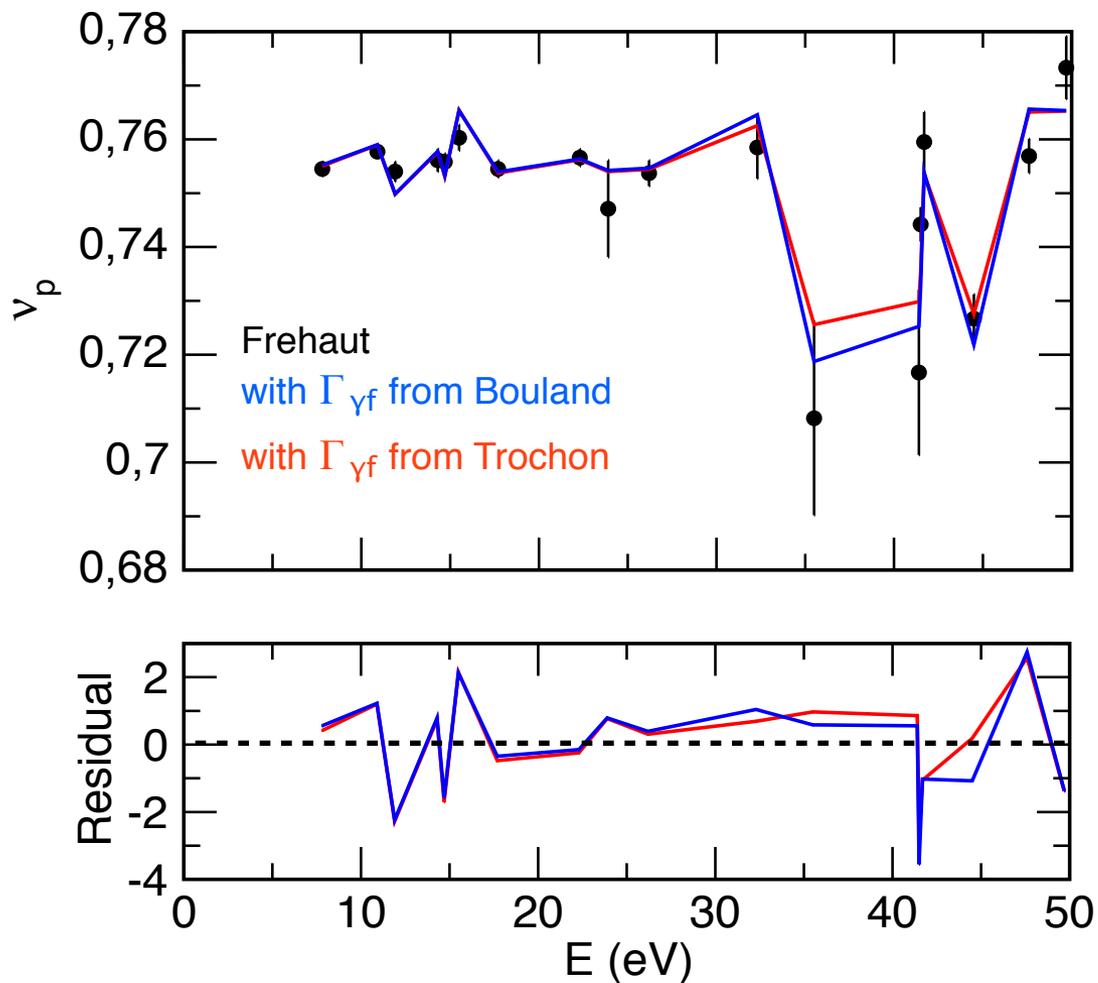


with  $\Gamma_{\gamma f}$  from Bouland



# CONRAD RESULTS OF $v_p$ UP TO 50 eV

- CONRAD results from the fit below 50 eV of **Frehaut** data:



- Output parameters:

$$\langle v_0 \rangle = 2.891 \pm 0.002$$

$$\langle v_1 \rangle = 2.867 \pm 0.002$$

$$\langle v_{nyf} \rangle = 2.61 \pm 0.02$$

$$N_{\text{Frehaut}} = 0.9963 \pm 0.0007$$

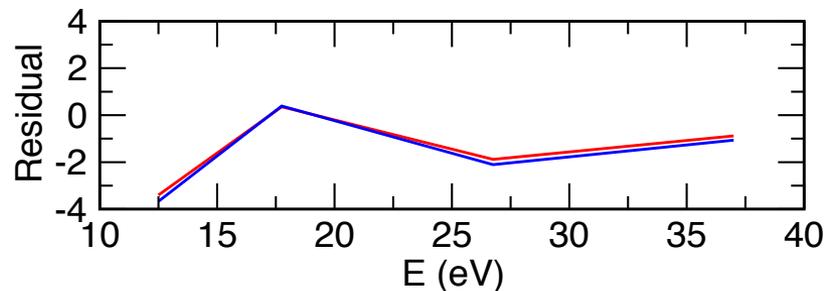
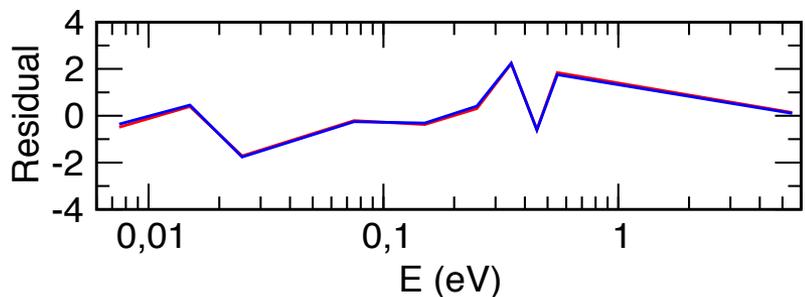
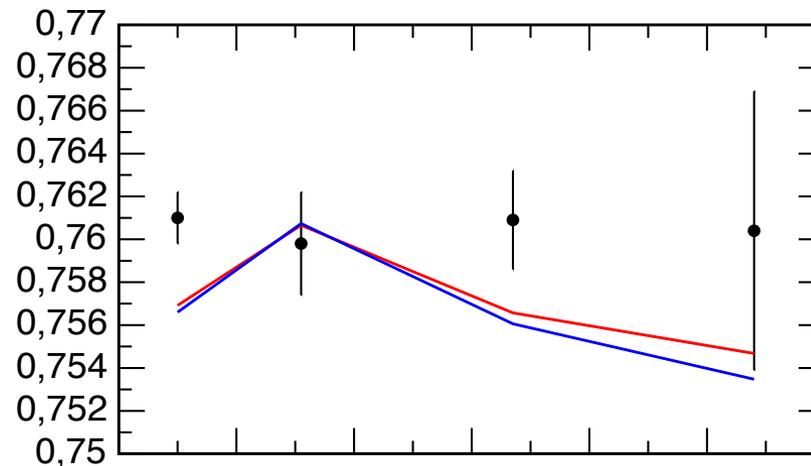
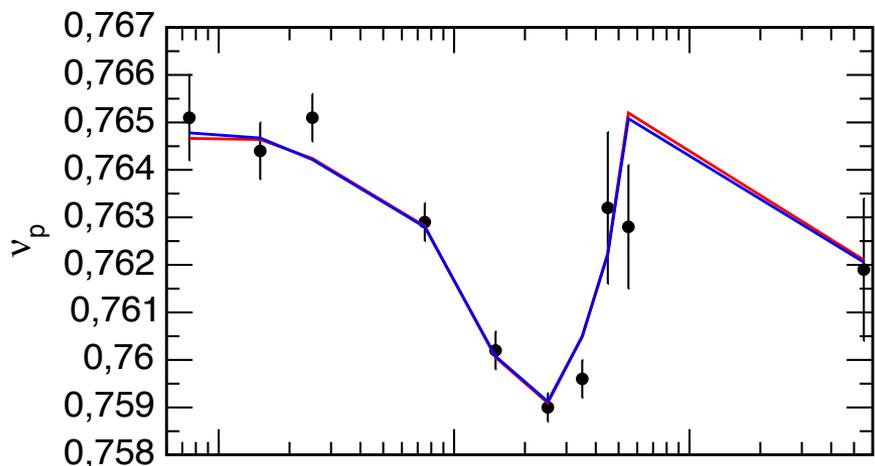
$$\langle v_0 \rangle = 2.888 \pm 0.002$$

$$\langle v_1 \rangle = 2.866 \pm 0.002$$

$$\langle v_{nyf} \rangle = 2.43 \pm 0.03$$

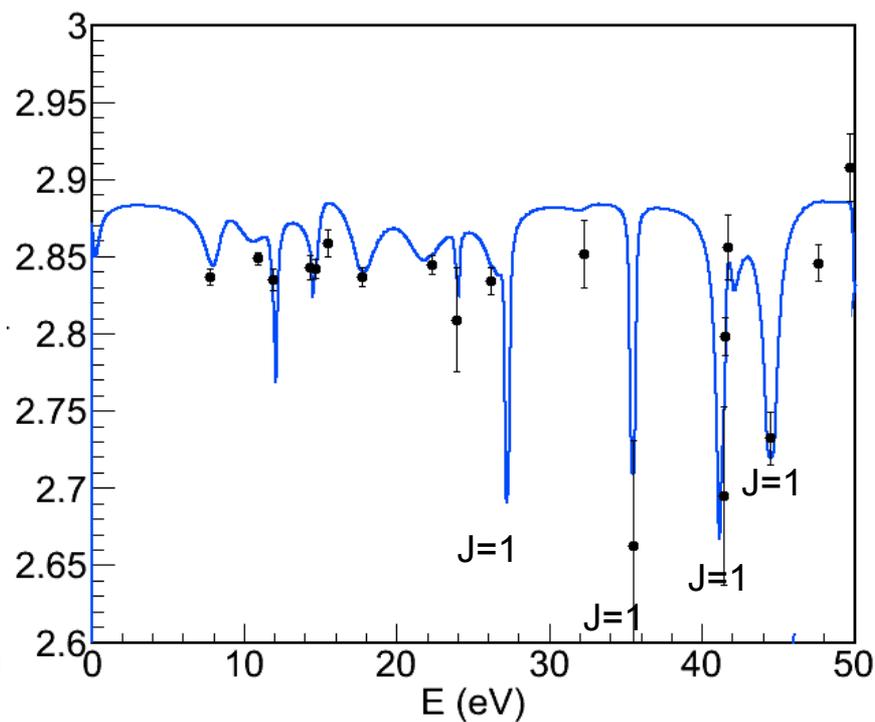
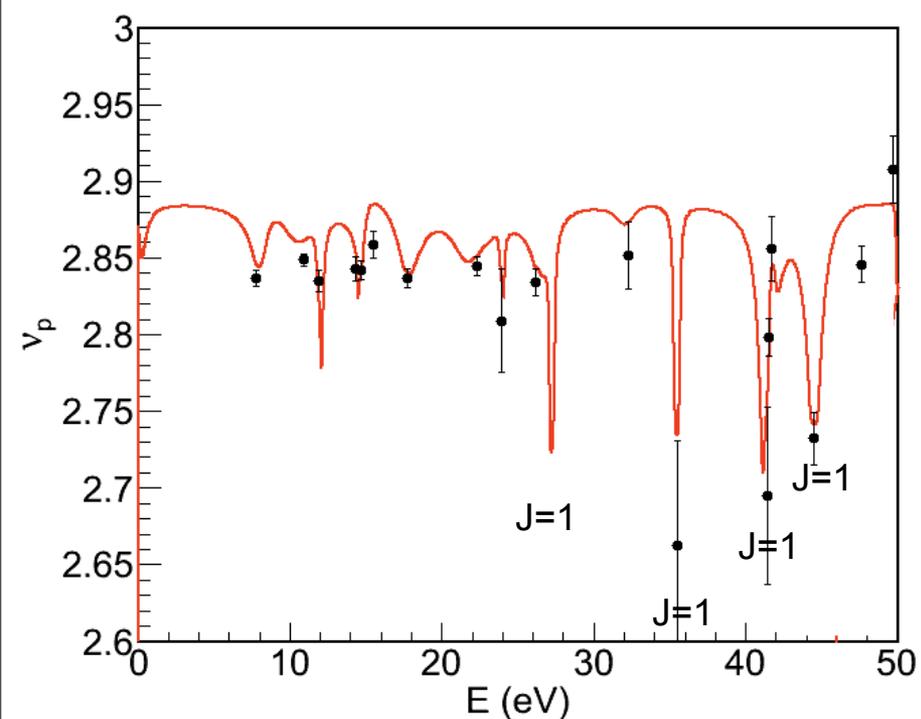
$$N_{\text{Frehaut}} = 0.9965 \pm 0.0007$$

- CONRAD results from the fit below 50 eV of **Gwin** data:



Gwin  
with  $\Gamma_{\gamma f}$  from Bouland  
with  $\Gamma_{\gamma f}$  from Trochon

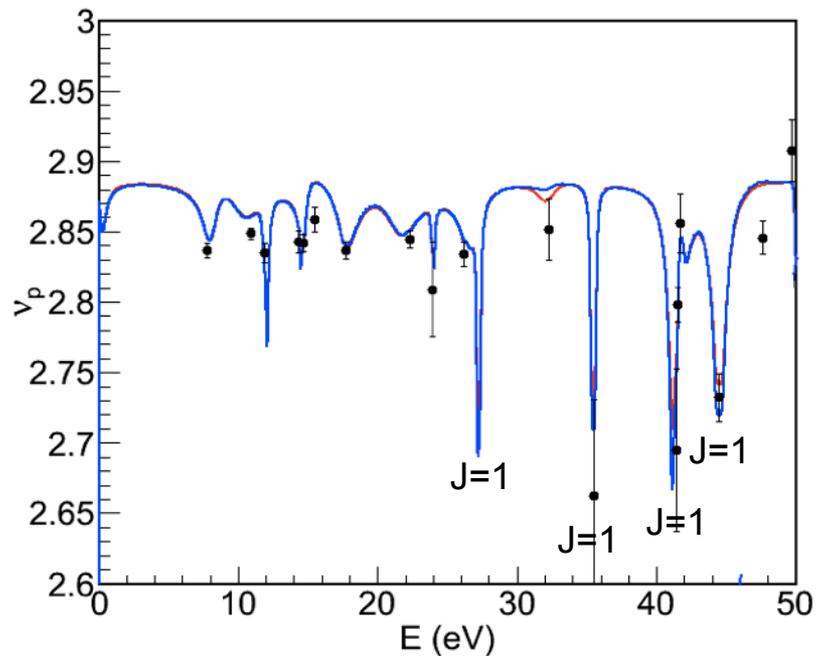
- Final results up to 50 eV:



Frehaut (normalized)  
with  $\Gamma_{\gamma f}$  from Bouland  
with  $\Gamma_{\gamma f}$  from Trochon

# RESULTS OF $\nu_p$ UP TO 50 EV

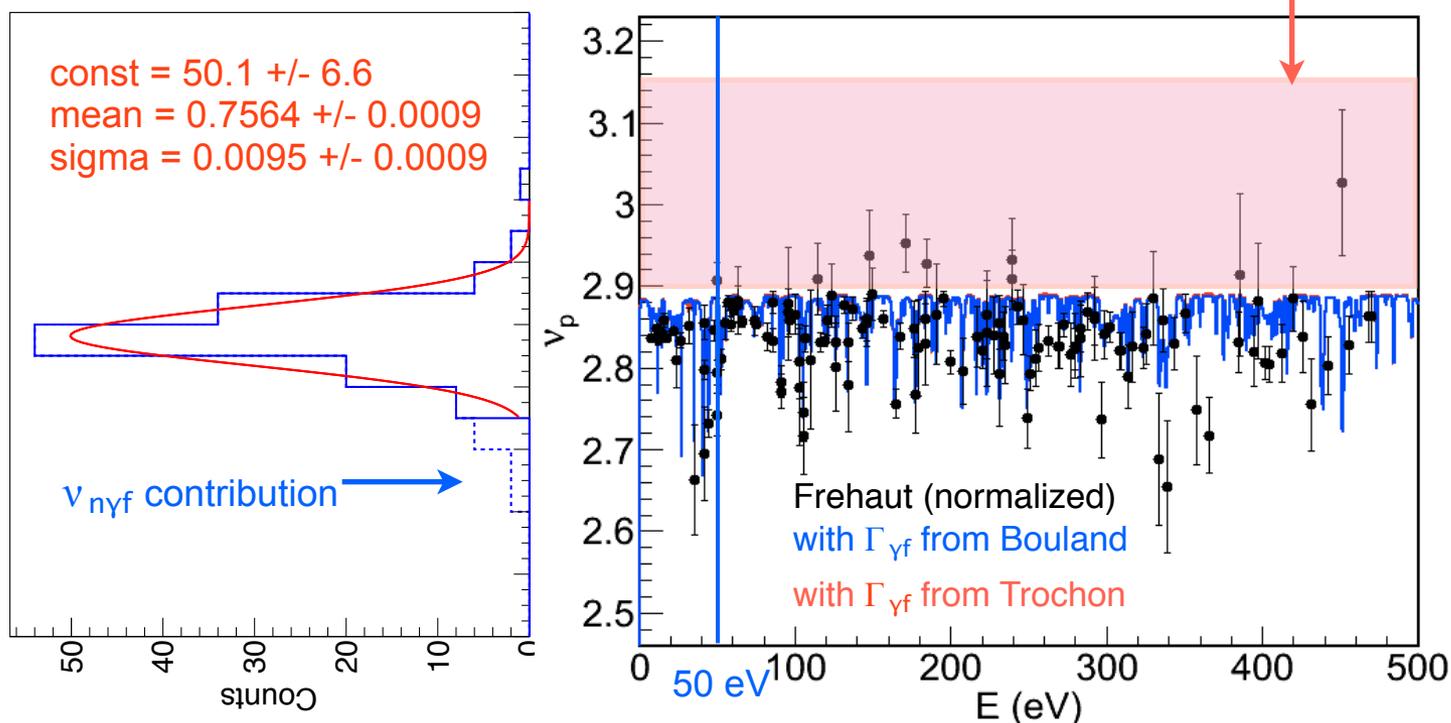
- The spin contribution can reproduce the data at low energies.
- The  $\nu_{nyf}$  contribution reproduces the dips of the  $\nu_p$  up to 50 eV.



Frehaut (normalized)  
with  $\Gamma_{\gamma f}$  from Bouland  
with  $\Gamma_{\gamma f}$  from Trochon

# DISCUSSION ABOVE 50 eV

- Large dispersion in the experimental data from **Frehaut** at  $E > 50\text{eV}$ .
- Frehaut data with high  $v_p$  can not be described by the equations.



- Large error bars from **Gwin** experimental data => not reliable.  
=> New experimental data are required.

## CONCLUSIONS

### • Experimental data:

- Large dispersion (1.2%) in the experimental data from Frehaut at  $E > 50\text{eV}$ .
- Frehaut data with high  $v_p$  can not be described by the equations.
- Large error bars from Gwin experimental data => not reliable.
- Incompatibility in the normalization between Gwin and Frehaut datasets.

=> New experimental data are required.

### • Model:

- Do not reproduce the data in the full energy range (above 50 eV).
- The inclusion of  $\Gamma_{\gamma f}$  from Trochon/Bouland produces similar results.
  - Lower  $\langle v_{n\gamma f} \rangle$  with Bouland data.

## PERSPECTIVES

- To implement this model in CONRAD.