Study of (n, xn γ) Reactions on Tungsten Isotopes: Retrospective and perspectives

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Context: (n, n' y) cross section measurements

Motivations

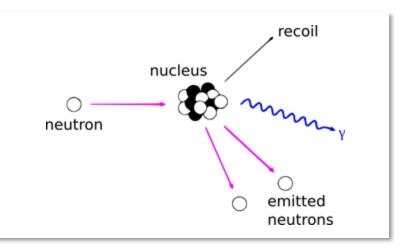
- Nuclear reactor developments rely on evaluated databases for numerical simulations.
- However, these databases still present large uncertainties, preventing calculations from reaching the required precision [1].
- An improvement of evaluated databases requires new measurements and better theoretical descriptions of involved reactions.
- Additionally, with new fuel cycles using fast neutrons and/or different isotopes, current knowledge focused on 235 U($n_{thermal}$, *) reaction is not enough to characterize properly Gen IV designs.
 - Studies must be done on isotopes such as O, F, Na, Pb, 232Th, 233U, 239Pu, ... with a focus on fast neutrons

[1] NEA/WPEC-26, "Uncertainty and Target Accuracy Assessment for Innovative Systems Using Recent Covariance Data Evaluations." (2008)

(n, n' γ) cross section measurements

- Inelastic neutron scattering are of great importance for the operation of a reactor as they modify the neutron spectrum, the neutron population, and produce new elements.
- Constraining reaction models by measuring precisely exclusive (n, xn γ) cross sections [2].

[2] "How to produce accurate inelastic cross sections from an indirect measurement method?" M. Kerveno et al., EPJ Nucl. Sci. Tech. 4, 23 (2018)

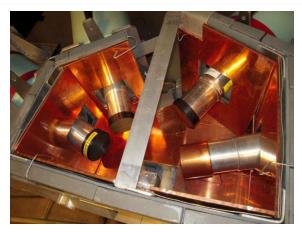


Measuring (n, n') cross section via exclusive (n, n', γ) measurements

Measuring (n, $n'\gamma$) cross sections with GRAPhEME [1]

- Installed at the Gelina facility (JRC-Geel).
- 30 m flight path.
- Fission Chamber to measure incoming neutron flux.
- 6 planar HPGe, high efficiency and resolution at low E_{ν} .
- Digital acquisition.
- Measured: ²³⁵U, ²³²Th, ^{nat,182,183,184,186}W, ²³⁸U, ^{nat}Zr, ²³³U, ⁵⁷Fe, ²³⁹Pu



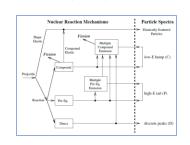


M. Kerveno et al,. EPJ Web of Conferences 239, 01023 (2020)

[1] "GRAPhEME: a setup to measure (n, xn y) reaction cross sections." Greg Henning, et al.. Adv. in Nuc. Instr. Meas. Met. and App., 2015.

Inferring total (n, n') cross section from $(n, n' \gamma)$ ones [2]

Reaction models and codes (input: structure, masses, optical potential, ...)





total (n, n') σ computed by the model after constraining them with measurements

Precise (n, n' γ) experimental cross sections

[2] "How to produce accurate inelastic cross sections from an indirect measurement method?" M. Kerveno et al., EPJ Nuclear Sci. Technol. 4, 23 (2018)

••• Context: Tungsten

Practical interests

- Present in many alloys in reactors (fission and fusion)
- High melting point, strong mechanical resistance, low thermal expansion [1]
- Resistance to oxidation, acid and alkaline attacks

[1] CRC Handbook of Chemistry and Physics, 90th Edition. Taylor & Francis, 2009

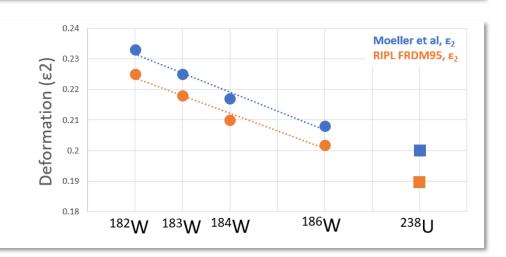
Extra interest

Compared to actinides

- No radioactivity, chemical toxicity
- 3 times less expensive than ^{nat}U (unprocessed raw material)

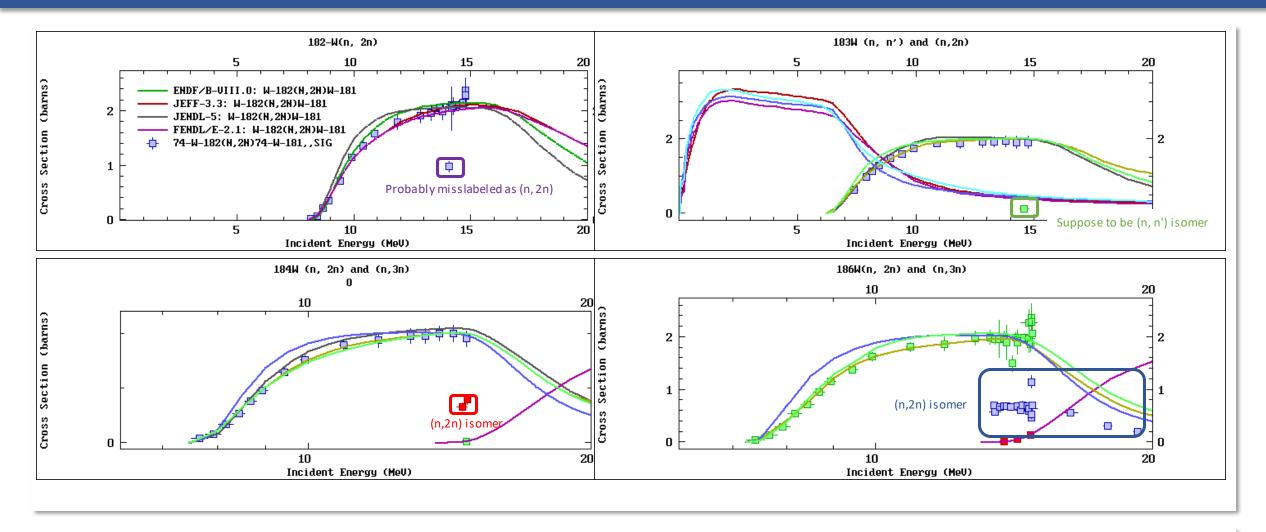
Physics interests

- No fission $(B_f^{LD} \sim 20 \text{ MeV}) \rightarrow \text{simpler description by models}$
- Deformation similar to actinides [2,3].



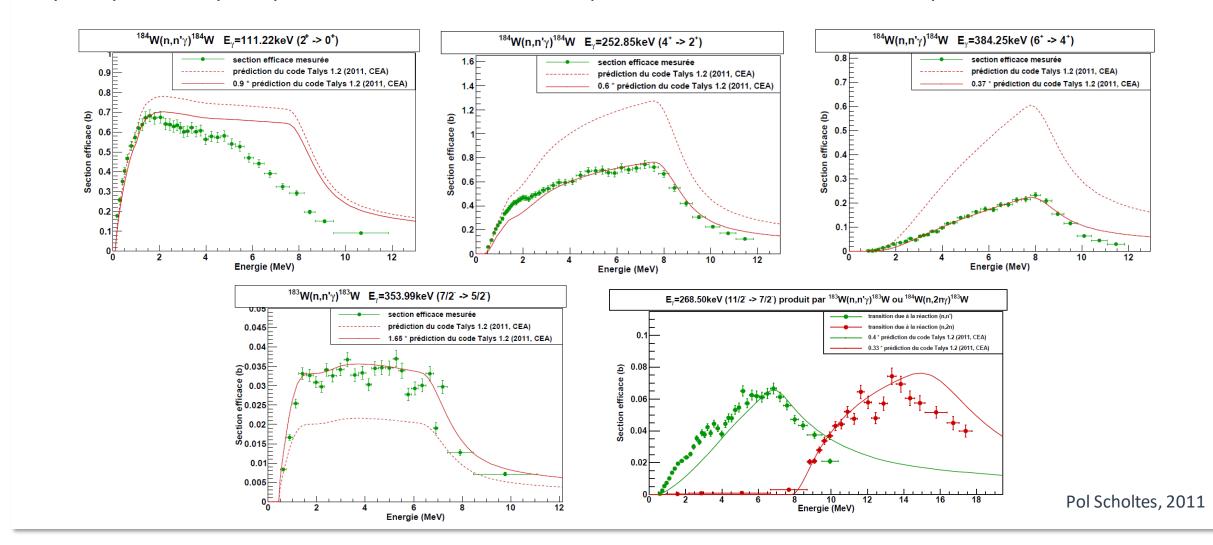
[2] P. Moller, et al., "Nuclear Ground-State Masses and Deformations", Atomic Data and Nuclear Data Tables, 59 (1995) [3] Reference Input Parameter Library (RIPL-3)

••• Tungsten: Current knowledge



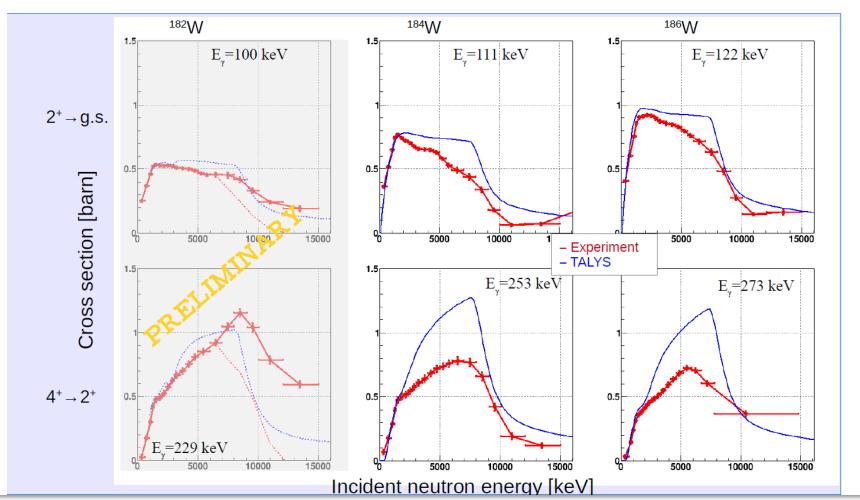
No (n, n') cross section measurements (\exists for some level production), mostly (n, 2n). Getting some inelastic cross sections would be very helpful, and measuring (n, 2n) channel via $(n, 2n\gamma)$ would be nice.

Very first preliminary analysis on ¹⁸⁴W and ¹⁸³W in 2011 as part of a Masters student internship.



2014: Preliminary results from ^{nat}W target presented at WINS for the three even-even isotopes



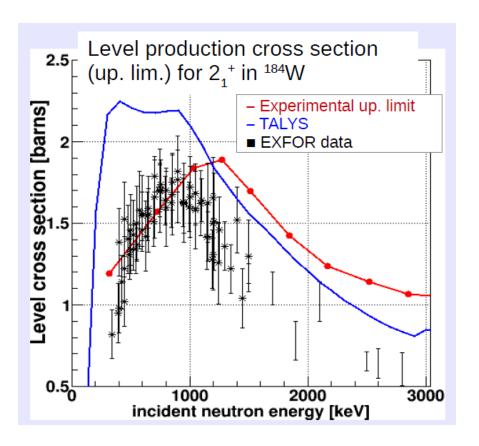


Greg Henning, 2014

PRELIMINARY

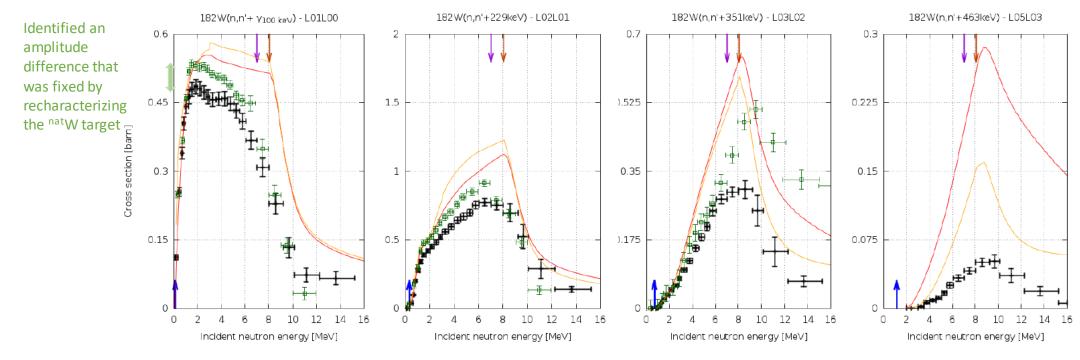
2014: Preliminary results from ^{nat}W target presented at WINS for the three even-even isotopes

+ extraction of a level production cross section (upper limit), compatible with previous data.



2016: Preliminary results from the 182W target at Wins. The analysis now uses a complete Monte Carlo approach

- /!\ Scale different for each transitions.
- + : this work, + results from natW, : TALYS 1.4 default, : TALYS 1.73 [P.Romain],
 - \rightarrow transition threshold, $\rightarrow S_p$, $\rightarrow S_n$

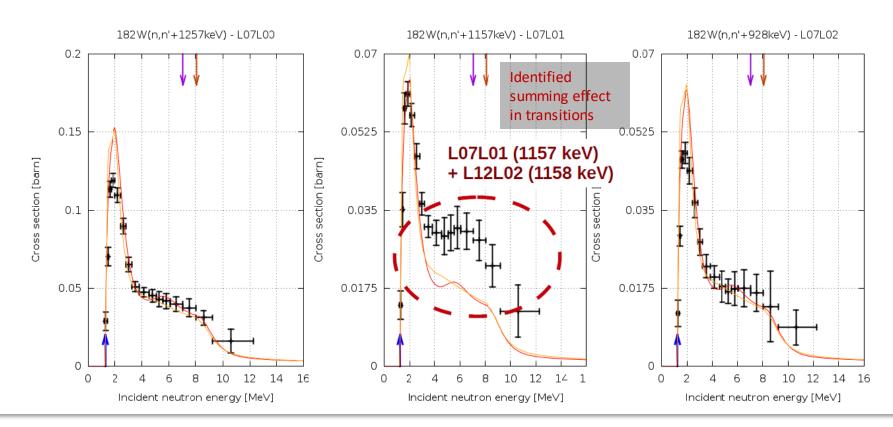


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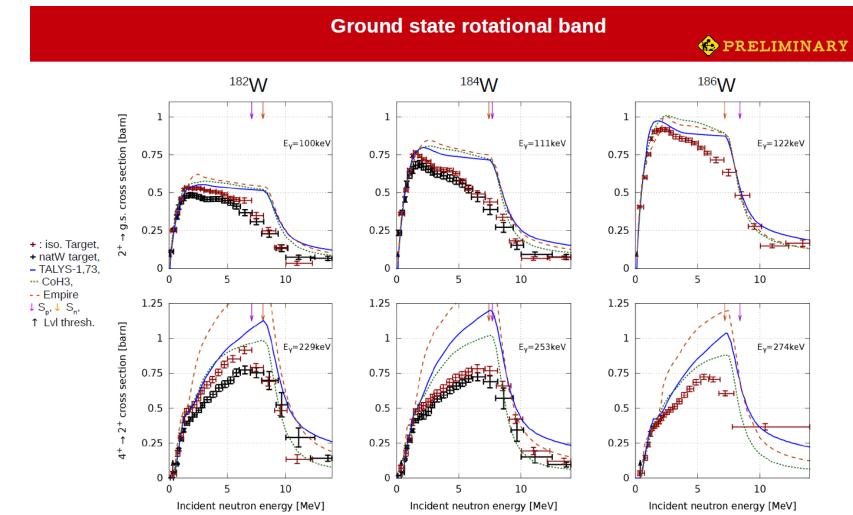
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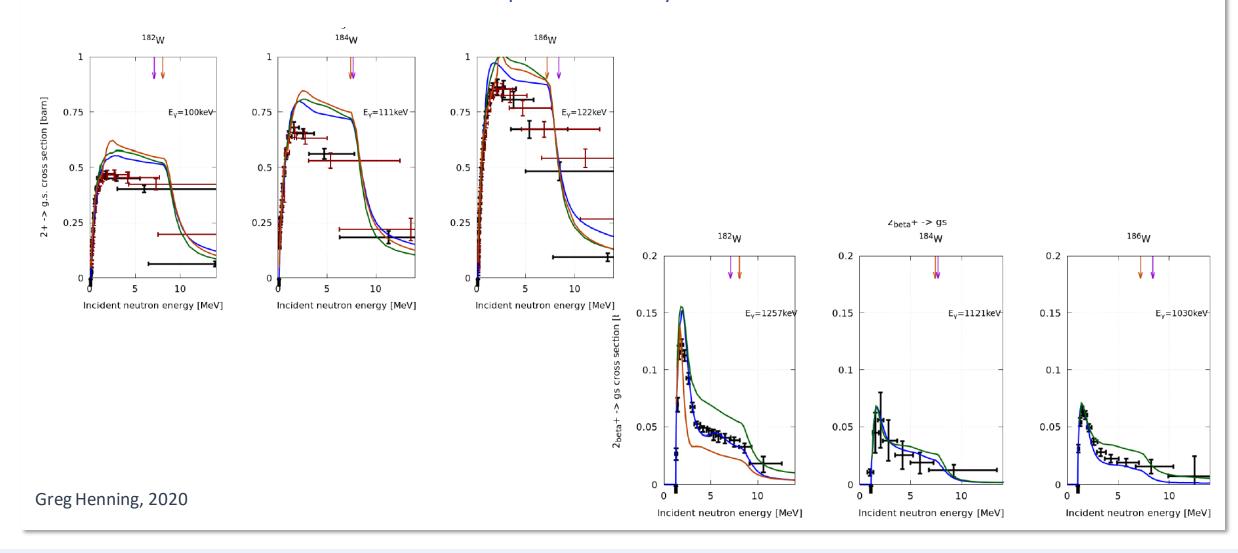
 \rightarrow : transition threshold, \rightarrow : S_p , \rightarrow : S_n



2016: Preliminary results from all enriched targets presented at ND



2020: Results are finalized and should have been presented at Physor and Wins



Today: Finalized results, article in preparation for publication

Improving the accuracy of $^{182,184,186}W$ (n, n' γ) cross sections calculations.

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R. Capote

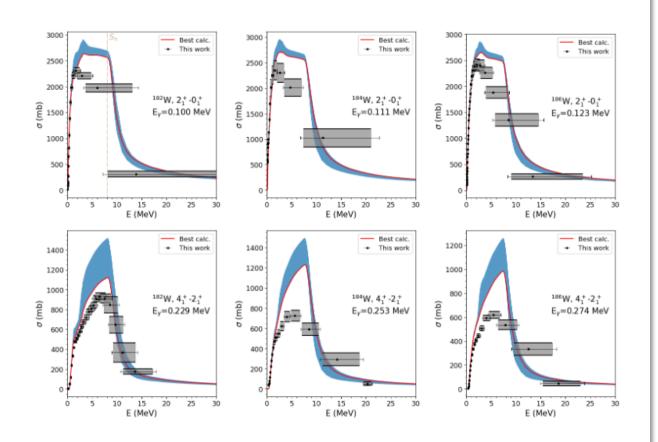
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T. Kawano

Los Alamos National Laboratory, Los Alamos, New Mexico 87545, USA (Dated: September 22, 2023)

Evaluated nuclear databases currently in use for numerical simulations to develop new nuclear reactor designs still present large uncertainties. Their improvement is necessary, in particular through better reaction models and experimental nuclear data. Among the reactions of interest, (n, xn) reactions are of great importance for the operation of a reactor as they modify the neutron spectrum, the neutron population, and produce radioactive species. Providing new data on inelastic scattering reaction can be done via several ways, direct of indirect. Here, we will present experimental data on $(n, xn\gamma)$ reaction that provide strong constraints on inelastic scattering reaction mechanism theories. Tungsten isotopes, being deformed like actinides but free of the fission channel, are of interest to test the models. In this article, we report on 182,184,186 W(n, n' γ) cross-section measurements. 63 γ production cross sections were measured. This large set of new experimental data offer a valuable opportunity to probe modeling of direct, pre-equilibrium and compound nucleus reaction mechanisms. The choice of major reaction ingredients and parameters can be refined thanks to comparison to partial $(n, n'\gamma)$ cross sections which allows to provide recommendation and highlight modeling aspect that may require further work.



••• Tungsten: Major results

$2+ \rightarrow$ g.s. transition is overestimated by models above ~3-5 MeV

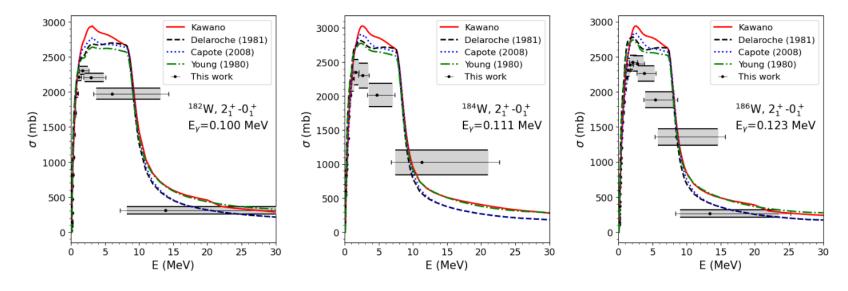
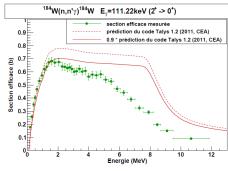


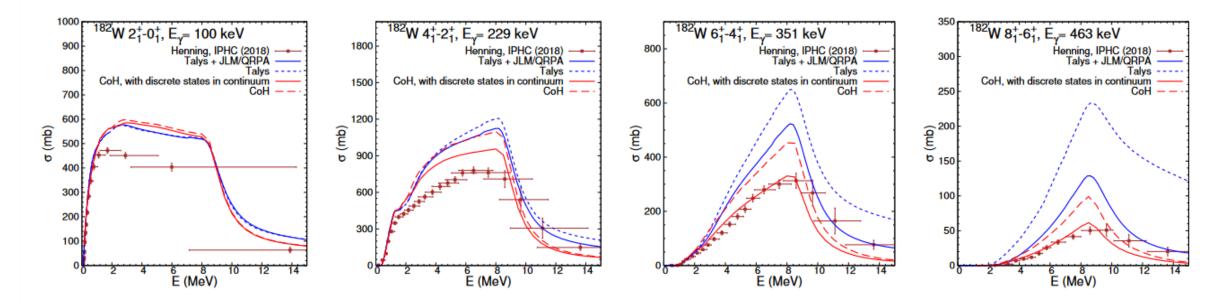
FIG. 17. Gamma productions for the $2_1^+ \to 0_1^+$ transition. The calculations using four different OMP are compared to the present measurements (symbols). Gamma productions are multiplied by the coeficient (1+C) to remove the effect of internal conversion.

- Tried every possible fix from experimental bias, analysis mistake, missing levels and transitions in the level scheme, ...
- It was already there in the 2011 preliminary results



•• Tungsten: Major results

Ground State Band transitions cross sections overestimated by models



As seen in ²³⁸U [1]

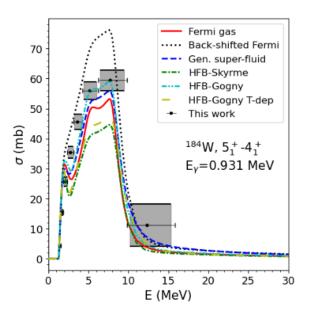
right direction.

- Inclusion of discrete states in the continuum with CoH3 code fixes the discrepancy (in particular at high spin).
- With Talys, QRPA spin distribution in the pre-equilibrium has lower <>> than exciton model and goes in the

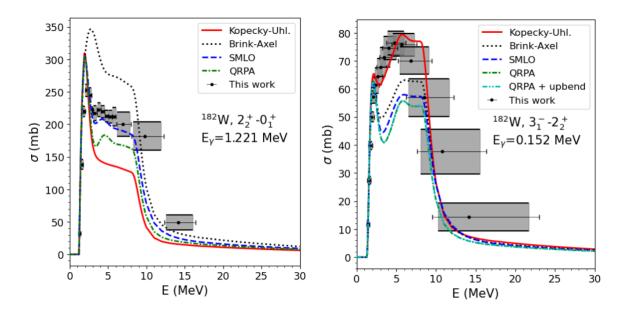
[1] "Measurement of 238U($n,n'\gamma$) cross section data and their impact on reaction models" M. Kerveno, Phys. Rev. C 104, 044605 (2021)

••• Tungsten: Major results

Marc Dupuis studied the impact on many parameters



Level density



Gamma strength function

••• Tungsten: Major results

Marc Dupuis: scanning many parameters to find the best set

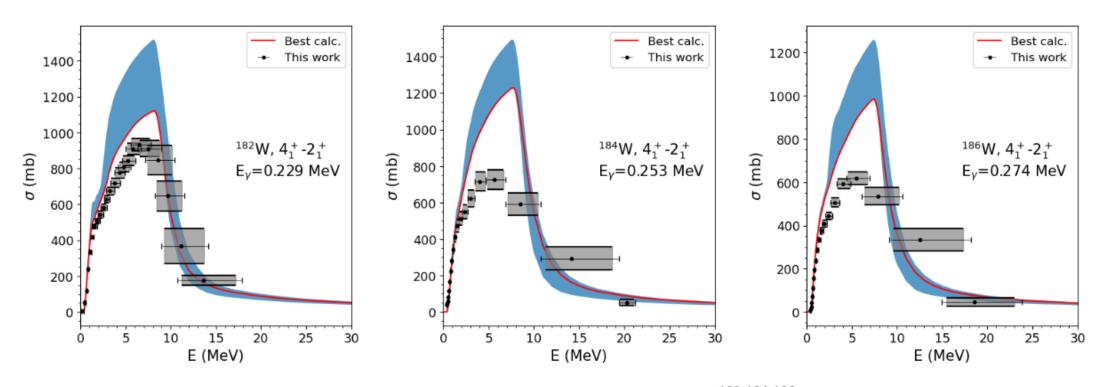


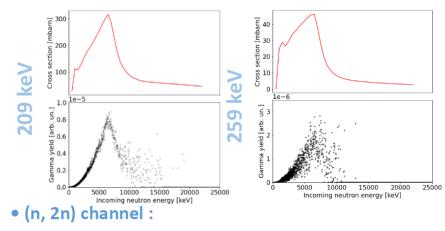
FIG. 4. Gamma productions for transitions between levels of the GS rotationnal band in ^{182,184,186}W. Symbols correspond to the present measurement. Shaded areas span model calculations performed with the Talys code when a spectific set of ingredients are changed. Red curves represent the calculation that displays the best overall agreement with experiment.

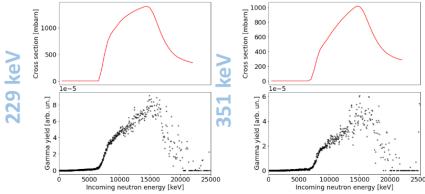
Outlook: 183 W(n, n'y) and (n, 2ny)

Last year: preliminary results at ND2022

γ yields (•) shape compared to default TALYS-1.8 calculations (—).

• (n, n' γ) channel :





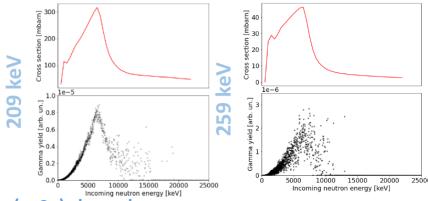
(2) No normalization, hand adjusted background

Outlook: 183 W(n, n' γ) and (n, 2n γ)

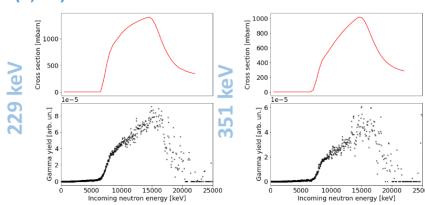
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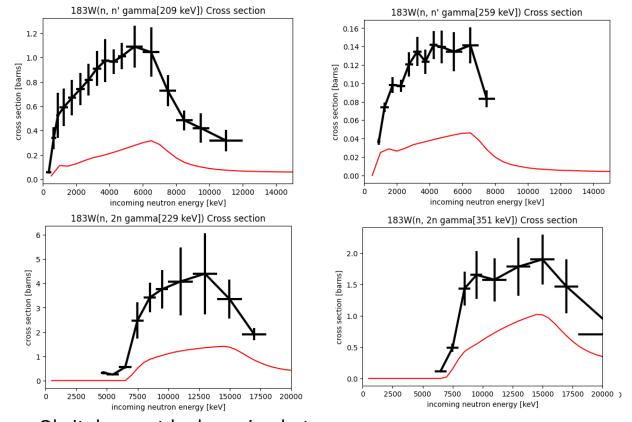


• (n, 2n) channel:



(2) No normalization, hand adjusted background

Oct 2023: Fresh out of the oven



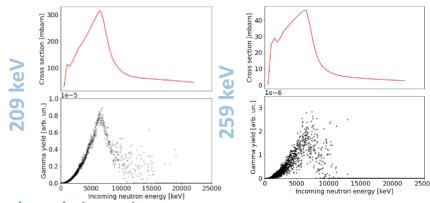
Ok, it does not look as *nice*, but...
Absolute normalization ✓ and **NO** adjustments

Outlook: 183 W(n, n' γ) and (n, 2n γ)

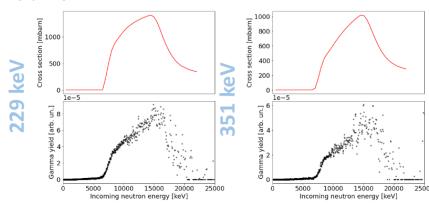
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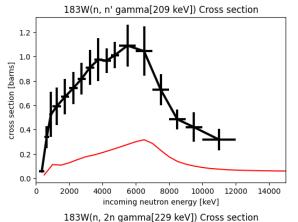


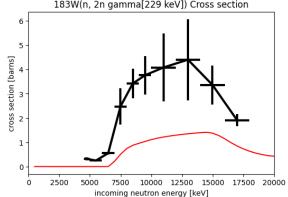
• (n, 2n) channel:

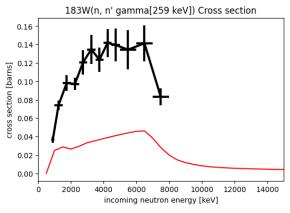


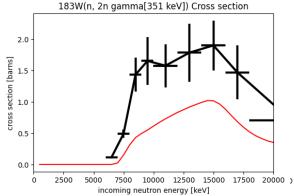
(2) No normalization, hand adjusted background

Oct 2023: Fresh out of the oven









Ok, it does not look as nice, but...

Absolute normalization **√** and **NO** adjustments

I know where to look to improved matching (ε_{ν} , pile up, ...)

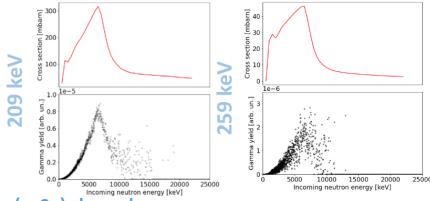
+ Full Monte Carlo analysis pipeline almost ready to be run on 10 γs

Outlook: 183 W(n, n' γ) and (n, 2n γ)

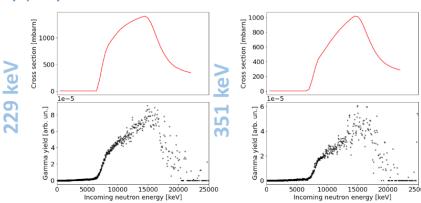
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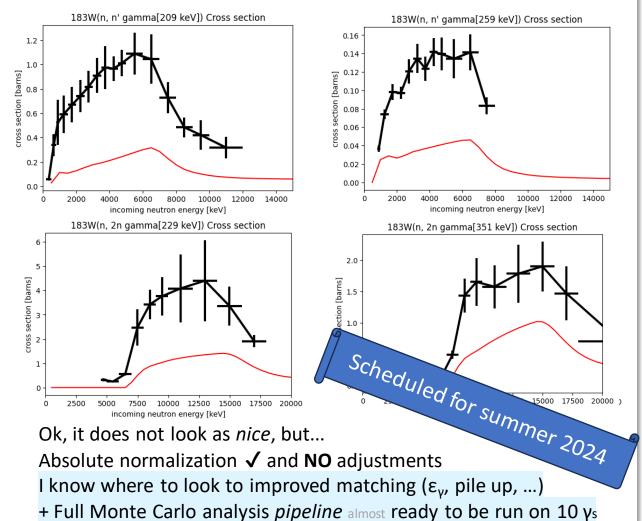


• (n, 2n) channel:

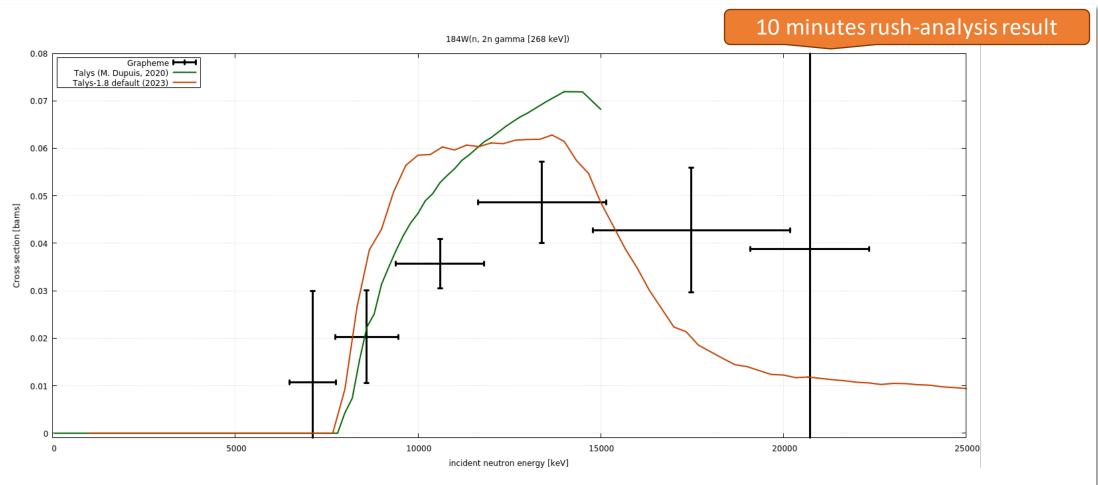


(2) No normalization, hand adjusted background

Oct 2023: Fresh out of the oven

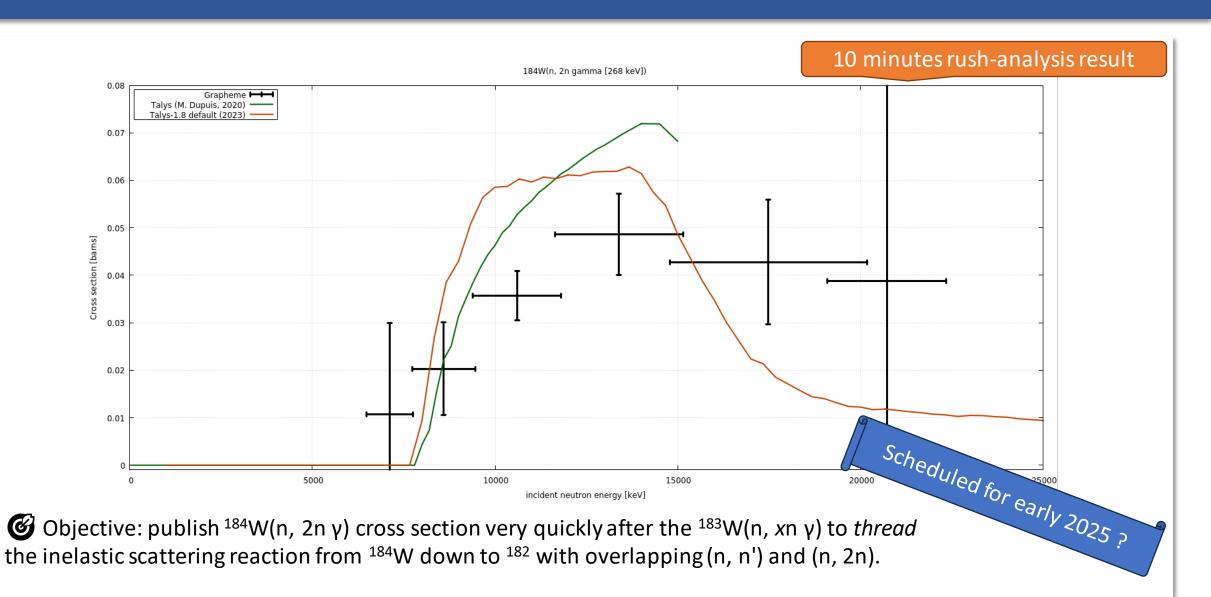


Outlook: ¹⁸⁴W(n, 2n) PRE-PRELIMINARY



With not too much work, $(n, 2n \gamma)$ cross sections can be extracted from the ¹⁸⁴W enriched target data set, using the same analysis code as used for $(n n' \gamma)$.

Outlook: ¹⁸⁴W(n, 2n) PRE-PRELIMINARY



Conclusion and perspectives

Tungsten

- Wide usage in fission and fusion reactors
- Theoretical interest for models

^{182, 184, 186}W (n, n' γ) cross sections measurements

- From natural and enriched targets
- Many transitions studied, compared to model calculations

Results

- Transitions from high spin states in the rotational ground state band are overestimated by calculations
- $2^+ \rightarrow g.s.$ transition overestimated by ~500 mbarns
- Trying to find the best model parameters to match the experimental values over the three isotopes.

Outlook

- Even-even W isotopes $(n,n'\gamma)$ cross section article coming soon.
- ¹⁸³W (n,n' γ) and (n, 2n γ) cross sections in preparation.
- The ¹⁸⁴W(n, 2n γ) ones will be made available quickly after.
- All data will be sent to Exfor, and published on Open Data plateform.