LA-UR-14-22923
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Title:	Evaluation and Uncertainty Quantification of the Prompt Fission Neutron Spectrum of 239Pu
Author(s):	Neudecker, Denise
Intended for:	International Workshop on Nuclear Data Covariances, 2014-04-28/2014-05-01 (Santa Fe, New Mexico, United States)
Issued:	2014-04-29 (rev.1)

Evaluation and Uncertainty Quantification of the Prompt Fission Neutron Spectrum of ^{239}Pu

CW2014 April 30, 2014

D. Neudecker, T-2, LANL

In collaboration with:
T-2, LANL: P. Talou, T. Kawano
LANSCE-NS, LANL: T. Taddeucci, R.C. Haight, H.Y. Lee
ANL: D.L. Smith
IAEA: R. Capote
X-Division: M.E. Rising, M. White

Goal: Improve existing ^{239}Pu PFNS evaluation and provide reasonable uncertainties

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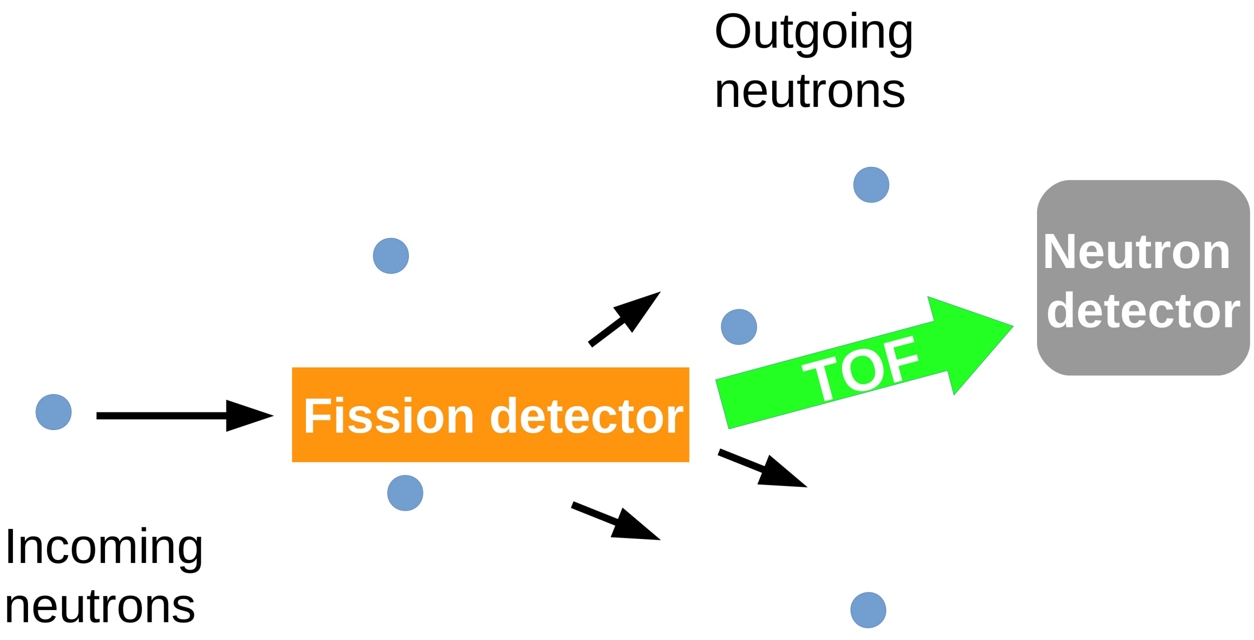
We want to improve the existing ^{239}Pu PFNS evaluation by:

- **Extending** PFNS **model**.
- Including **additional parameter uncertainties**.
- **Careful analysis of experimental** data and associated **uncertainties**.
- New benchmark results.

PFNS: Energy distribution of neutrons emitted within 10^{-14}sec after the fission event



Start signal by counting fission events

Stop signal by counting neutron events

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^{239}Pu PFNS for incident neutron energies up to 30 MeV is a subject of interest for:

- Nuclear data libraries: ENDF/B-VII.1, CIELO (needed for $E_{inc} \leq 30$ MeV)
- Also part of an IAEA CRP on PFNS of major actinides (chair R. Capote).
- Applications: Reactor Physics, development of new reactor types, Dosimetry, Criticality, Stockpile Stewardship, etc. (see e.g., I. Kodeli, NIM A 610, 540 (2009))

Previous works in this group already provided ^{239}Pu PFNS and covariances.

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- *P. Talou et al., NSE 166, 254* ***(2010)****:* First uncertainty quantification for $n_{0.5MeV}+^{239}$Pu in this group, **resulting covariances are in ENDF/B-VII.1**

- *M.E. Rising et al., NSE 175, 81* ***(2013)****:* Extended the analysis to several Pu and U isotopes using systematics of Tudora. Added **an anisotropy in the outgoing neutron emission.**

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- *M.E. Rising et al., NSE 175, 81 **(2013)**:* Extended the analysis to several Pu and U isotopes using systematics of Tudora. Added an anisotropy in the outgoing neutron emission.

- Open issues: **detailed uncertainty analysis for experimental data**,**extending model** with realistic temperature distribution, improve OMP, more model parameter unc., etc.

The open issues need to be also tackled because of low evaluated unc. obtained.

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- <u>Open issues:</u> detailed unc. analysis for exp. data, extending model, additional model par. unc.

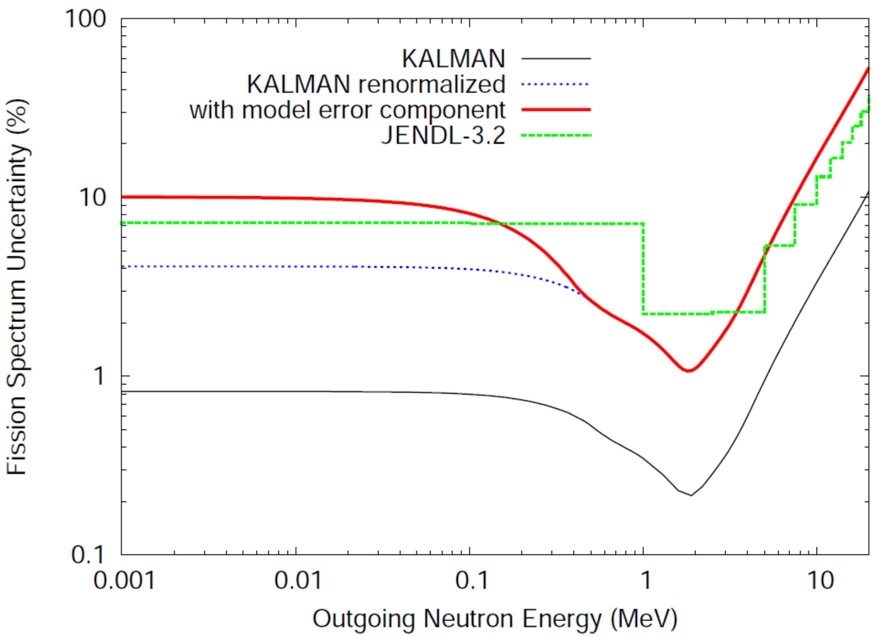
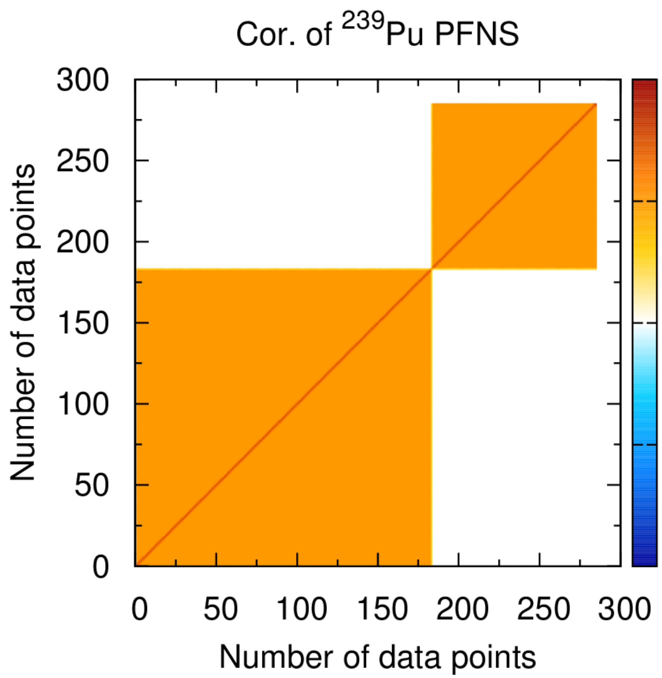


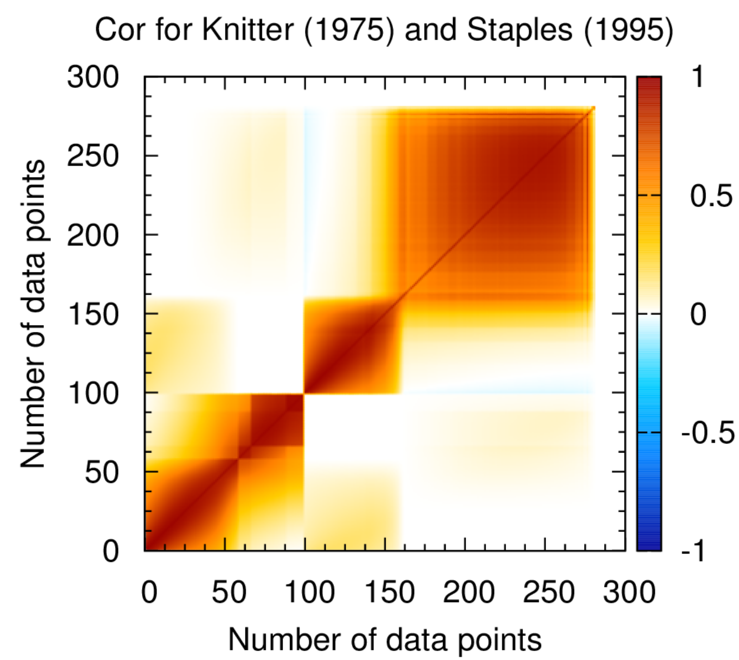
FIGURE 4. Calculated standard deviations for the evaluated PFNS of n(0.5 MeV)+^{239}Pu. See text for details.

Figure from Talou (2010).

Low unc. are due to **strong model cor.** and normalization condition on the PFNS. (D. N., R. Capote, D.L. Smith, T. Burr, P. Talou, LA-UR-13-29431, submitted to NSE.)

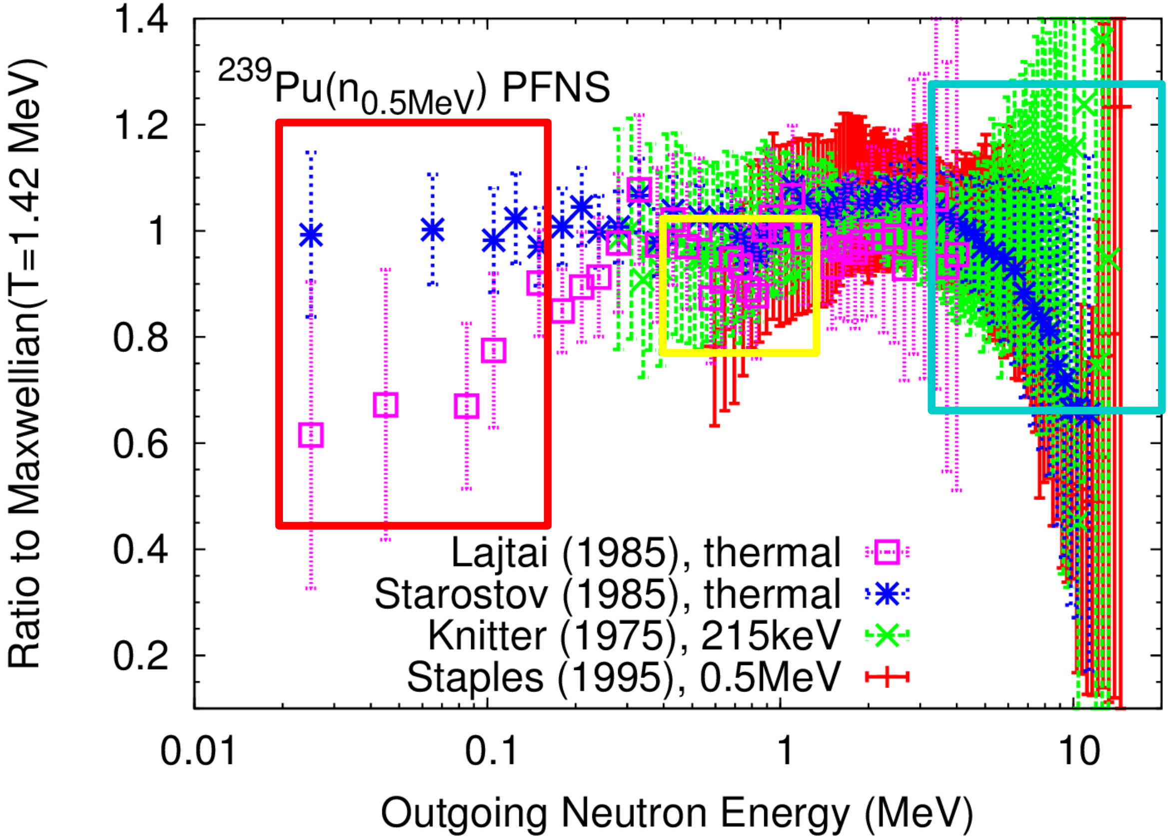
Experimental uncertainties were estimated in close collaboration with Chi-Nu team.





Talou (2010) → This work

Not only to get more realistic unc. .... also to understand discrepancies!



We estimate covariances by partitioning unc. according to their sources.

The uncertainties are partitioned according to their sources (e.g.: reference reaction, specific sample)

→ **Simplifies estimating missing uncertainties** as well as **correlations** of the single uncertainty contributions.

→ **Simplifies estimating correlations between** unc. of **different experiments** because of common uncertainty contributions.

<u>*Typical unc.:*</u> statistical, background, multiple scattering, deconvolution, TOF length, time resolution, Det. Eff., ...

Knitter, (1975): significant increase of unc. for E_{out} < 2MeV due to multiple scattering!

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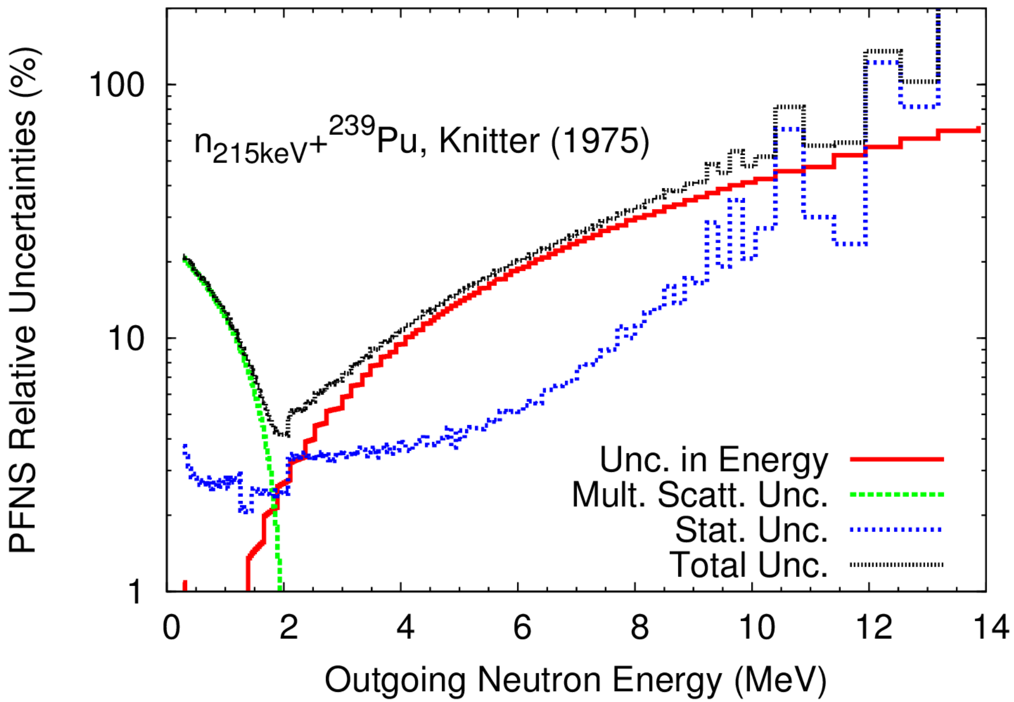
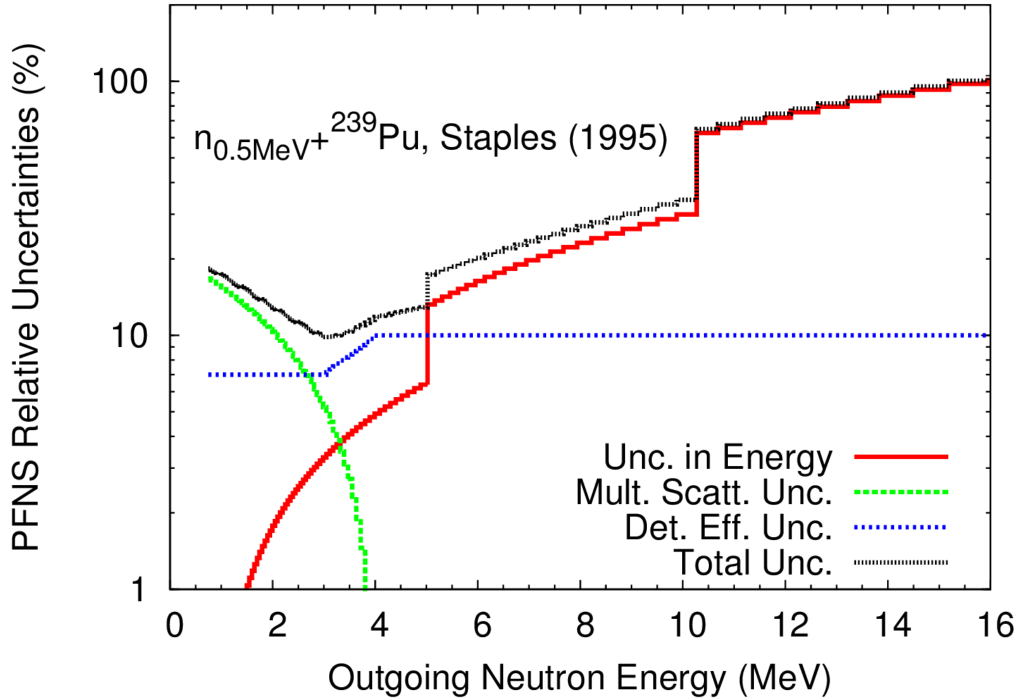
H.-H. Knitter, ATKE 26, 76 (1975): Multiple scattering unc. added due to Monte Carlo study of T. Taddeucci



Staples, (1995): also increase of unc. for E_{out} < 2MeV due to multiple scattering!

P. Staples et al., Nucl. Phys. A 591, 41 (1995): Multiple scattering unc. added due to Monte Carlo study of T. Taddeucci; increased detector efficiency unc.



Starostov and Lajtai were measured using $^{252}Cf(sf)$ PFNS → introduces correlations

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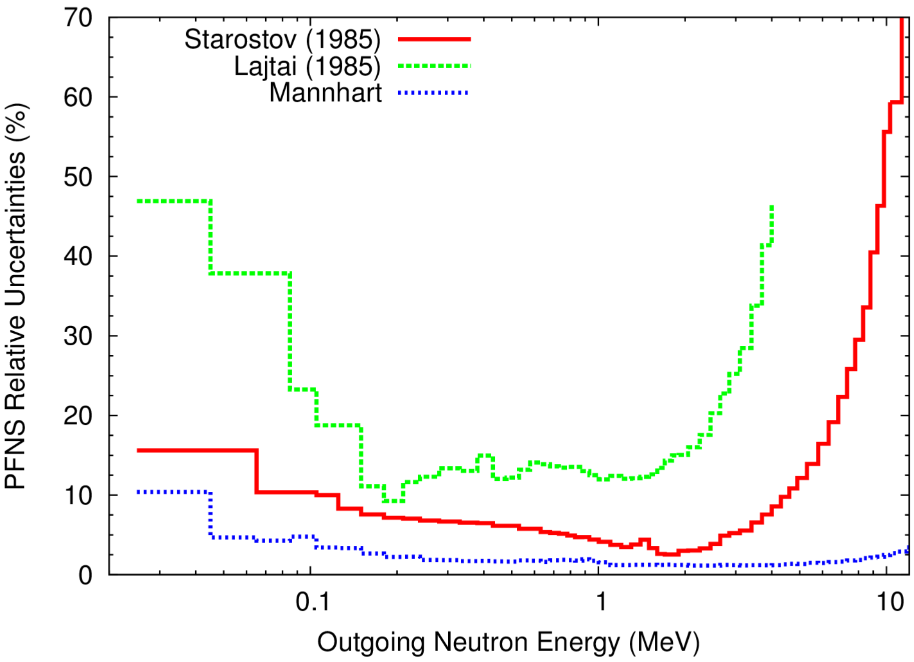
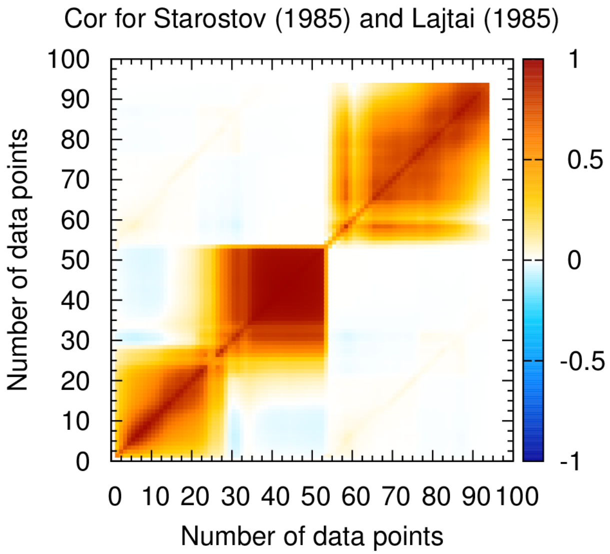
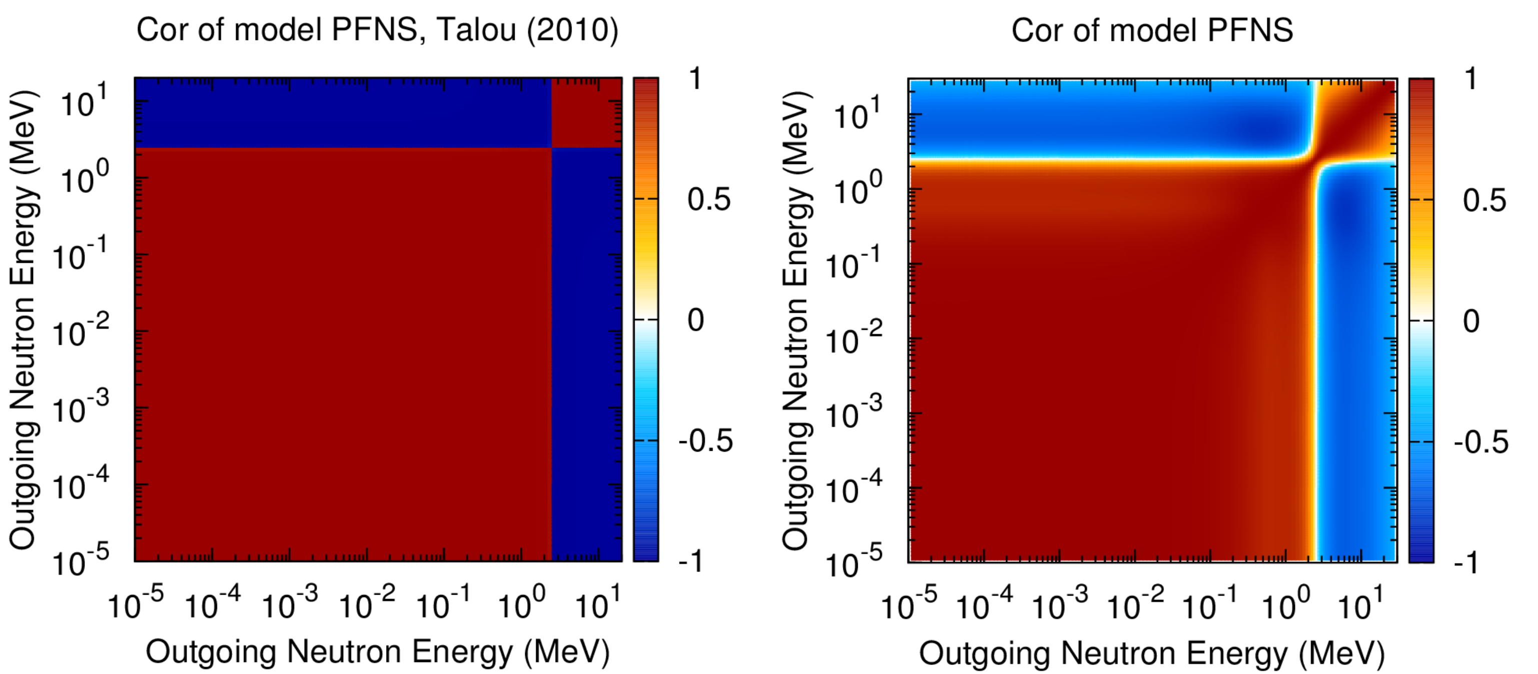




The model was extended and unc. of additional parameters were considered.



Talou (2010)

This work

The Los Alamos model was used and extended.

We use the **phenomenological Los Alamos model** of D.G. Madland and J.R. Nix, NSE 81, p. 231 (1982). This model was also used in Talou (2010) and Rising (2013). The Los Alamos model was implemented in the CoH code (T. Kawano).

The ***total model PFNS*** N^M is an ***average of one light and heavy fission fragment PFNS***, N_l and N_H (x={L,H}).

$$N^M(E) = (\overline{\nu}_L N_L(E) + \overline{\nu}_H N_H(E)) \,/\, (\overline{\nu}_L + \overline{\nu}_H)$$

<u>Light Fragment:</u> ^{100}Zr

<u>Heavy Fragment:</u> ^{140}Xe

The Los Alamos model was used and extended.

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The light and heavy fission fragment PFNS, N_L and N_H ($x=\{L,H\}$) are given by:

$$N_x(E) = \frac{1}{2\sqrt{E_f}T_{m,x}^2 (1+b/3)} \int_{(\sqrt{E}-\sqrt{E_f})^2}^{(\sqrt{E}+\sqrt{E_f})^2} \sigma_{c,x}(\epsilon)\sqrt{\epsilon}\left(1 + b\frac{(E-\epsilon-E_f)^2}{4\epsilon E_f}\right) I(\epsilon)\mathrm{d}\epsilon$$

With a maximum temperature of a fission fragment:

$$T_m = \sqrt{\langle E*\rangle / \langle a \rangle} \quad \langle E*\rangle = \langle E_r \rangle + E_n + B_n - \langle TKE \rangle$$

The **anisotropy of the neutron emission was included in Rising (2013).**

In this work we used an improved OMP and temperature distribution.

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$$N^M(E) = (\overline{\nu}_L N_L(E) + \overline{\nu}_H N_H(E)) \,/\, (\overline{\nu}_L + \overline{\nu}_H)$$

$$N_x(E) = \frac{1}{2\sqrt{E_f}\, T_{m,x}^2 (1+b/3)} \int_{(\sqrt{E}-\sqrt{E_f})^2}^{(\sqrt{E}+\sqrt{E_f})^2} \sigma_{c,x}(\epsilon)\sqrt{\epsilon}\left(1 + b\frac{(E-\epsilon-E_f)^2}{4\epsilon E_f}\right) I(\epsilon)\, \mathrm{d}\epsilon$$

<u>Changes in this work:</u>

- Using a ***modified Koning-Delaroche OMP*** for σ_c.
- Using a more ***realistic temperature distribution I(ε)*** of Hambsch et al., ANE 32, 1032 (2005).
- Weighting of fragment PFNS according to multiplicity.
- Using different maximal temperatures T_m for light and heavy fragment.

Uncertainties of additional parameters were included.

Parameter	Initial Val.	Rel.Unc.(%)	Parameter	Initial Val.	Rel.Unc.(%)
$\langle E_r \rangle$	197 MeV	6	**m_{rV}**	**1.0**	**4**
<TKE>	178 MeV	3	**m_{aV}**	**1.0**	**4**
$\langle E_\gamma \rangle$	6.77 MeV	10	**m_V**	**1.0**	**4**
S_n	5.22 MeV	2	**m_{rW}**	**1.0**	**5**
s	**1.1**	**10**	**m_{aW}**	**1.0**	**6**
R_T	**1.14**	**20**	**m_W**	**1.0**	**10**
b	**0.1**	**50**	a_L	9.09091	10
			a_H	12.72727	10

Green: Added in Rising (2013) with systematics for Pu&U

Red: Added in this work

The resulting model correlations are not as stiff as in Talou (2010).

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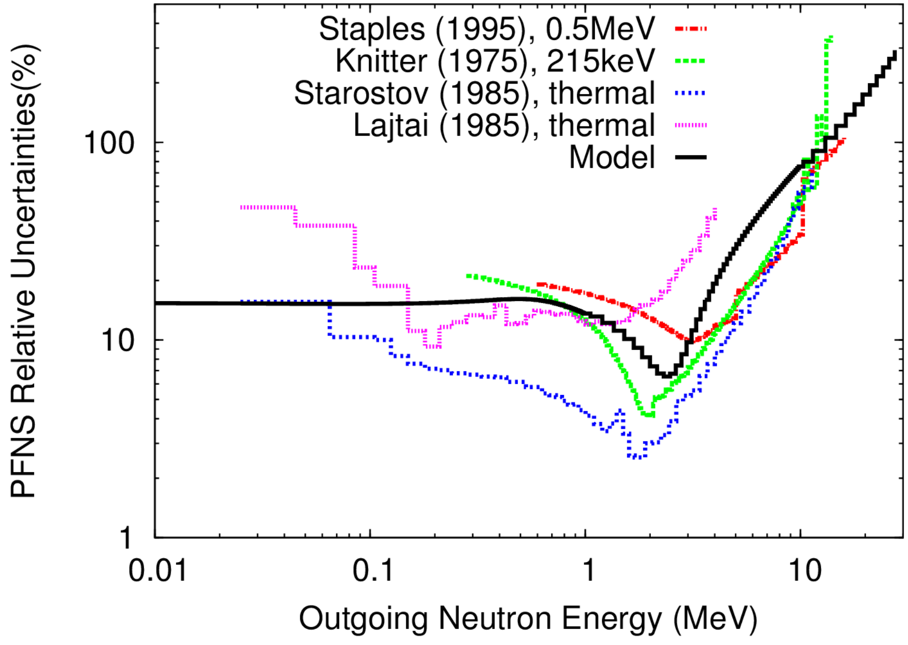
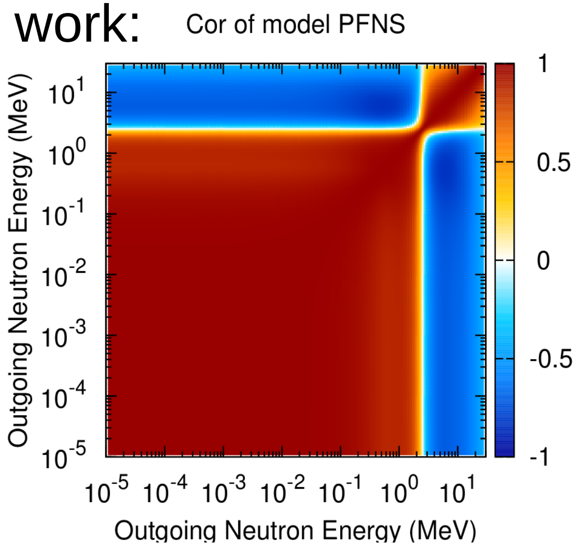
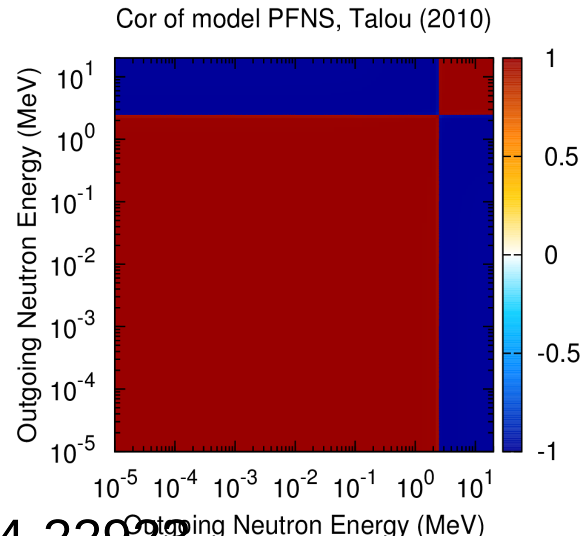


This work:





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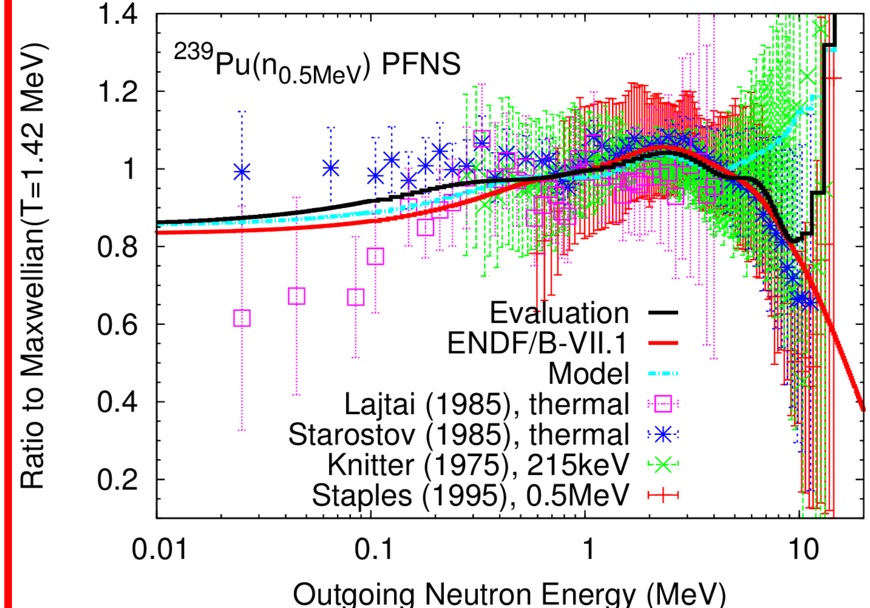
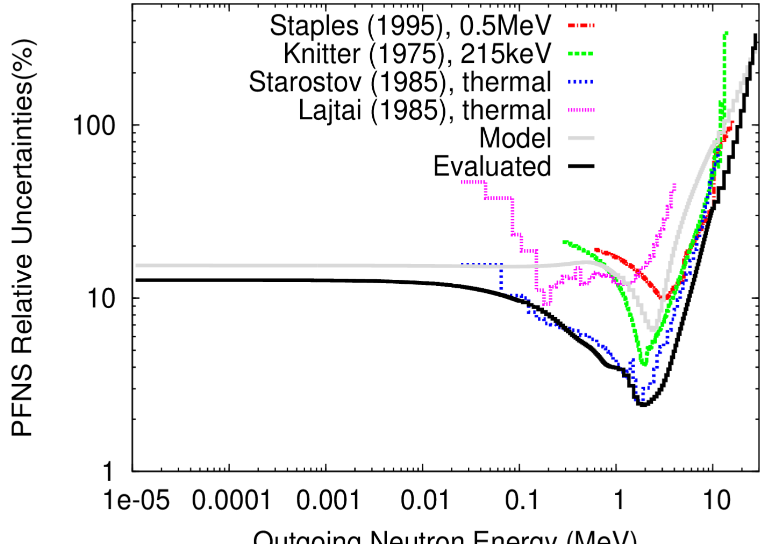
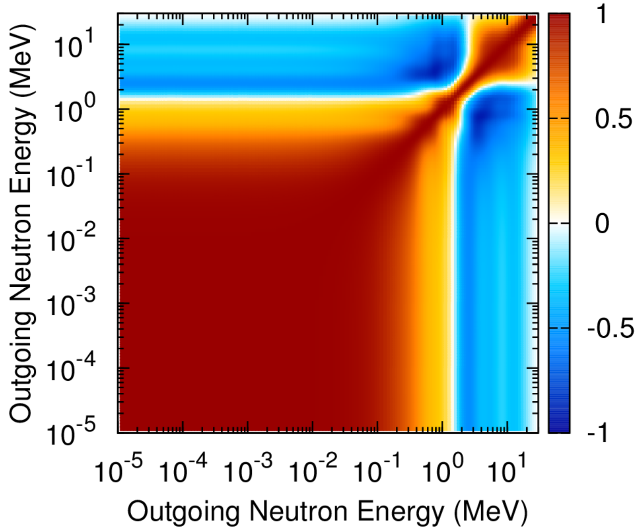
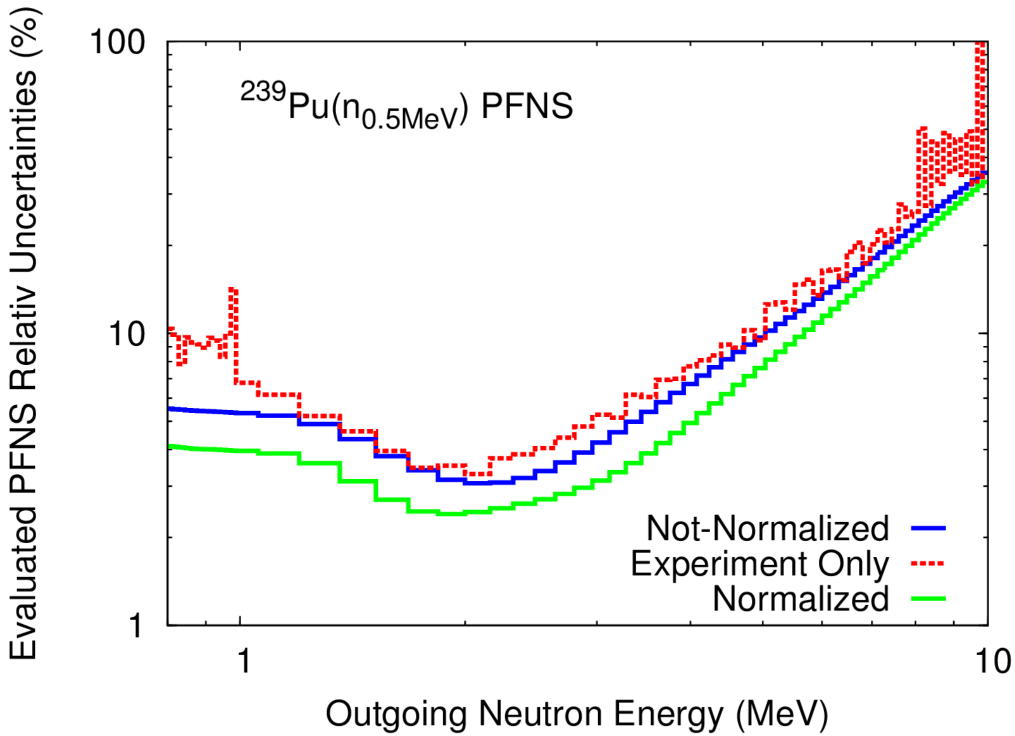
Evaluated results are obtained by GLS with model and experimental data and cov.







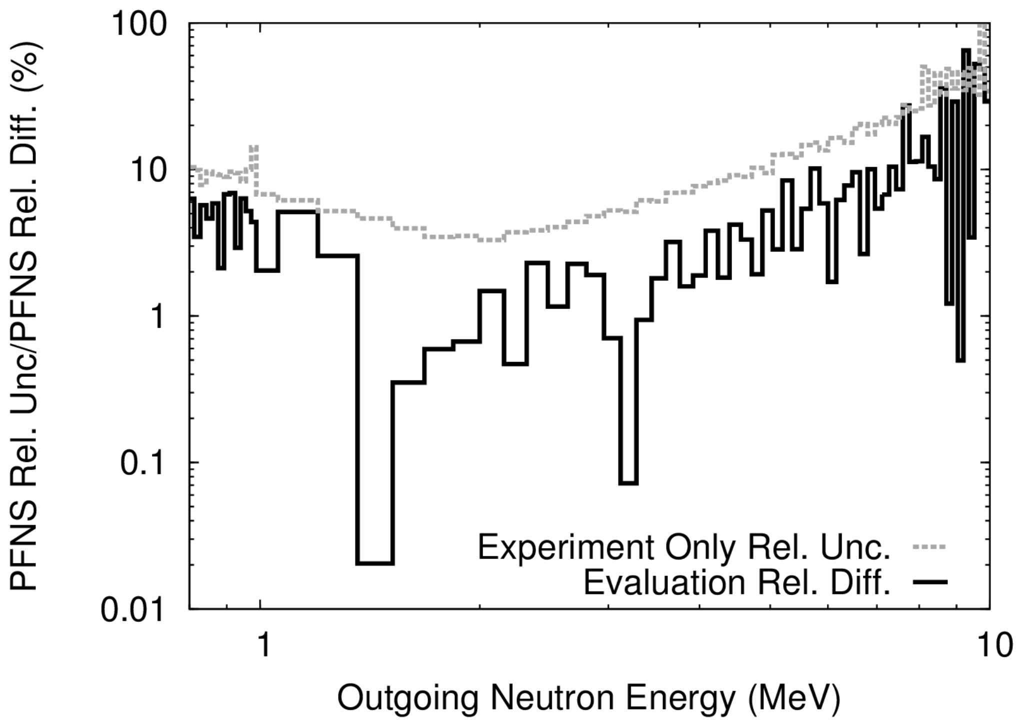
Evaluated unc. agree with unc. of a statistical analysis using mainly exp. information.



Unc. are rescaled by $\sqrt{\chi^2}$ of the input data.

The evaluated unc. are compared before normalizing the PFNS and the covariances (see D. N., R. Capote, D.L. Smith, T. Burr, P. Talou, LA-UR-13-29431, submitted.)

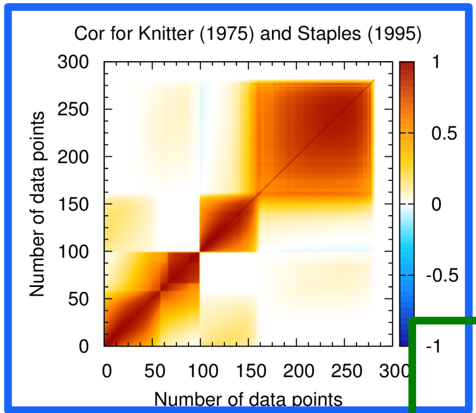
Including model data does not change the result within combined exp. unc.

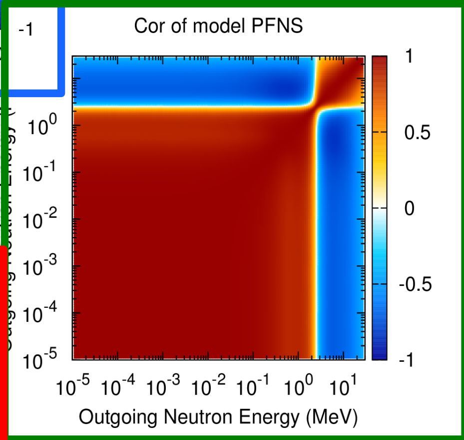


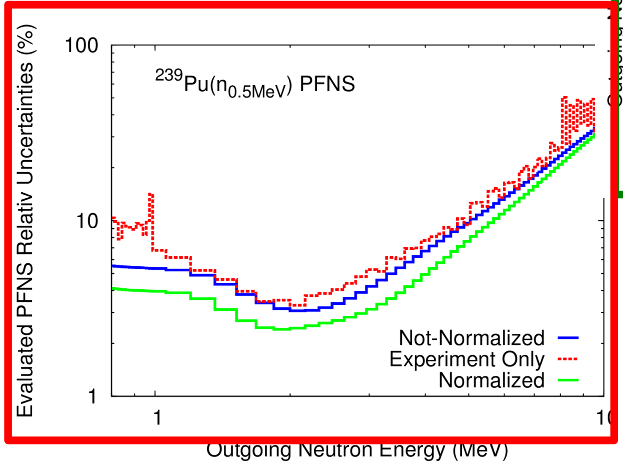
The relative difference between an evaluation with mainly exp. information and with exp. & model info. is smaller than statistically combined exp. unc.

Summary on the work on a new $n_{0.5MeV}+^{239}Pu$ PFNS evaluation and unc. quantification

- Detailed experimental uncertainty analysis.
- Extended model, included unc. of more model parameters.
- Evaluated results correspond to experimental input.







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NNSA

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- Test the data set via benchmark calculations of the criticality k_{eff} of critical assemblies.
- Evaluation for $E_{inc} \leq 30$ MeV (already in development).
- Implement future experimental data of ChiNu.
- Use a more sophisticated model, e.g., Monte Carlo Hauser Feshbach (B. Becker et al., PRC 87, 014617 (2013)).
- Apply to additional isotopes.

Thank you for your attention!

Backup: PFNS for different OMP

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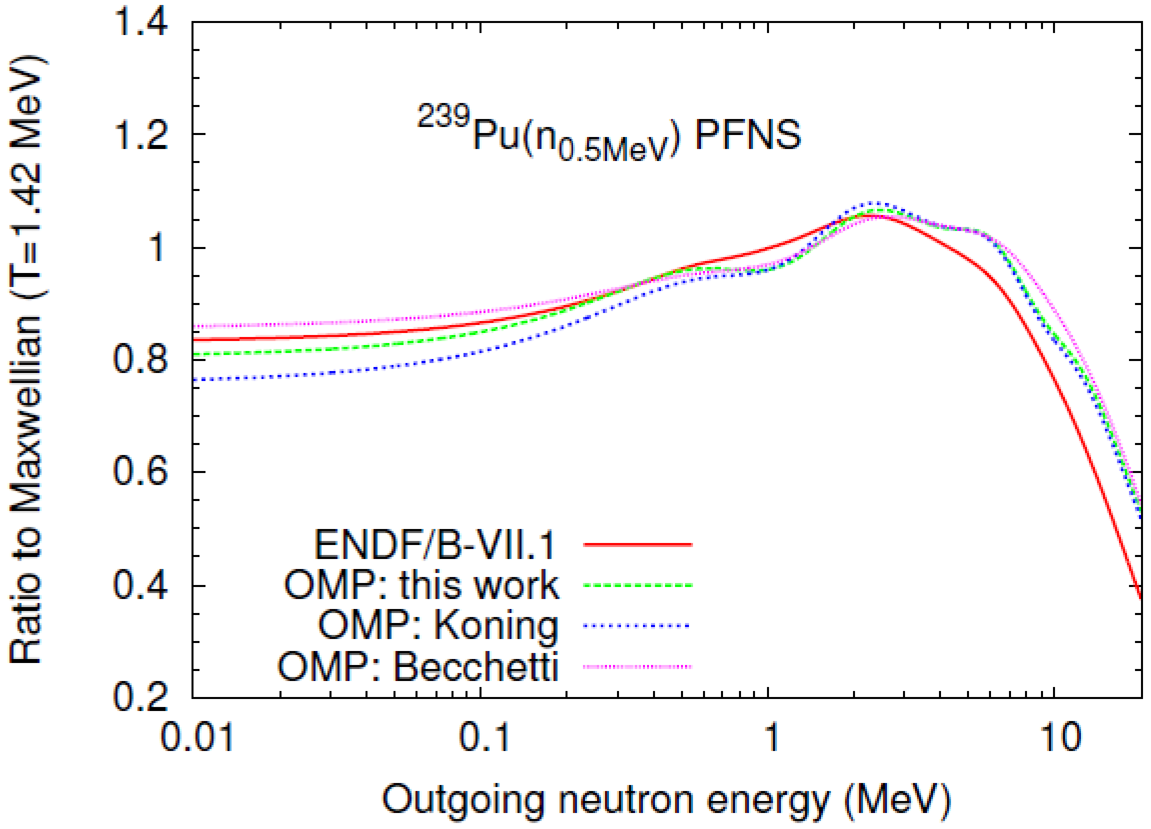

Backup: Impact of different temperature distribution.

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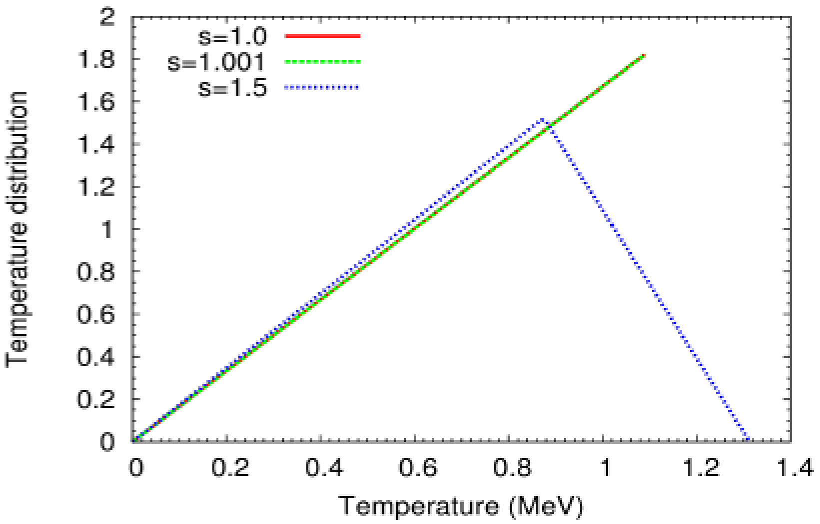
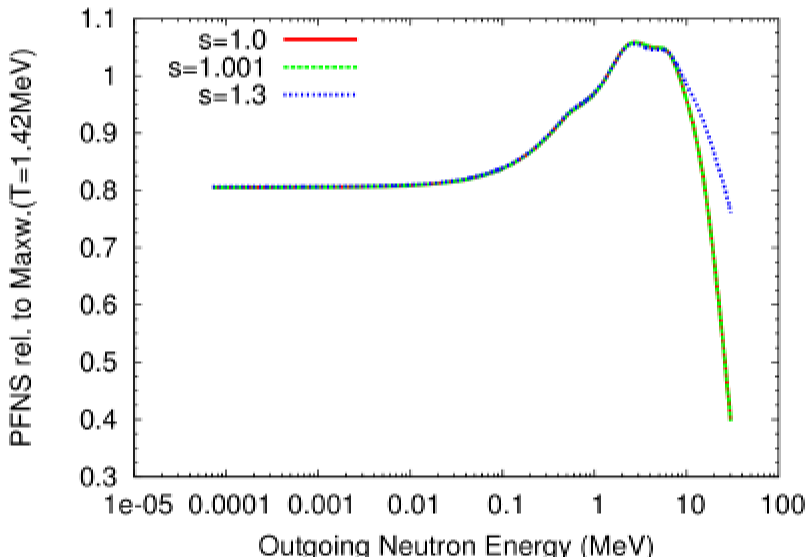
We use the more realistic temperature distribution of Hambsch et al., ANE 32, 1032 (2005).

For s=1, one obtains the original triangular distribution used by Madland and Nix.



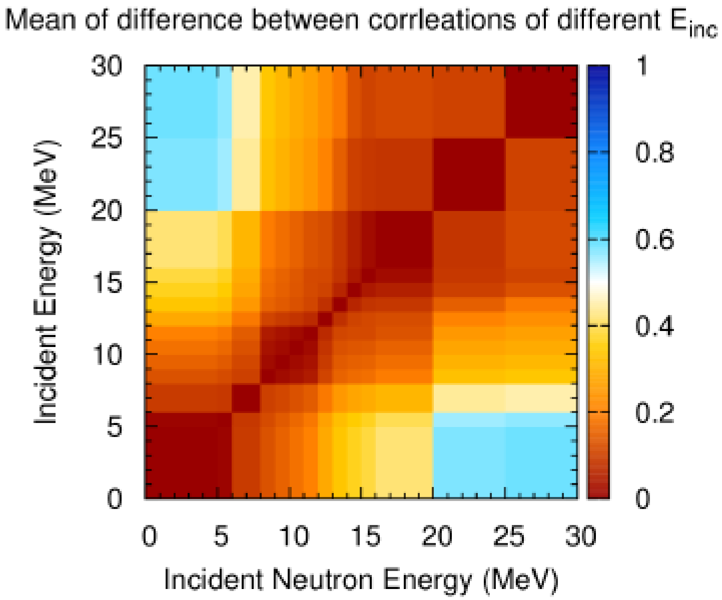


Backup: Towards an evaluation for incident energies up to 30 MeV.

Through parametrization of the Los Alamos model input parameters for incident energies, **correlations between model data of different incident energies** arise.

<u>Parametrization of:</u> J. Lestone et al., LA-UR-13-21567 and D.G. Madland, Nucl. Phys. A 772 (2006).

$$\frac{1}{M^2}\sum_{j,j'=1}^{M}\left|Cor^{i}_{j,j'} - Cor^{i'}_{j,j'}\right|$$



Backup: The pre-equilibrium component of the PFNS is included.