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Title: Open Questions concerning the Evaluation of the 239Pu Prompt Fission Neutron Spectra up to 30 MeV Incident Neutron Energy

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Open Questions concerning the ***Evaluation of the ^{239}Pu Prompt Fission Neutron Spectra*** up to 30 MeV Incident Neutron Energy

Denise Neudecker

FIESTA workshop, 9/11/14

In collaboration with/ thanks to:

+) T-2, LANL: P. Talou, T. Kawano

+) LANSCE-NS, LANL: T.N. Taddeucci, R.C. Haight, H.-Y. Lee

+) X, LANL: M. Rising, M.C. White, J. Lestone

+) ANL: D.L. Smith

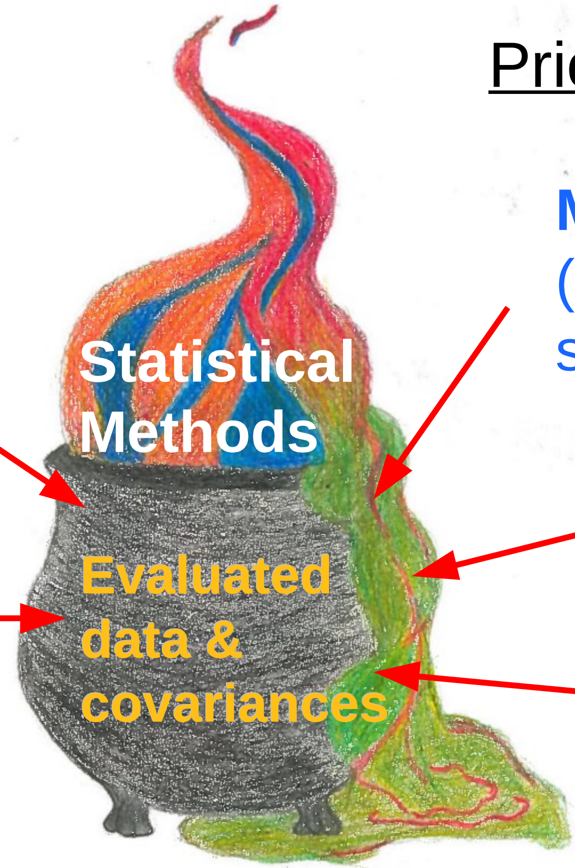
+) IAEA Vienna: R. Capote

Nuclear data evaluations combine model predictions and experimental information.

<u>Experimental Input</u>

Experimental data
(PFNS, <TKE>, cross sections, etc.)

Experimental covariances



<u>Prior (Theoretical) Input</u>

Model predicted data
(PFNS, <TKE>, cross sections, etc.)

Parameter Uncertainties

Model Defects

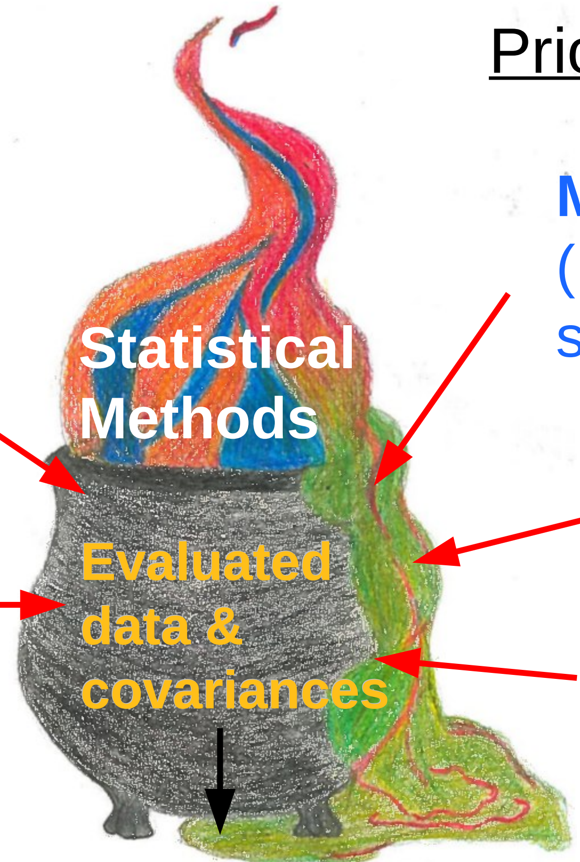
Evaluated nuclear data are assembled in libraries essential for nuclear applications.

<u>Experimental Input</u>

<u>Prior (Theoretical) Input</u>

Experimental data
(PFNS, <TKE>, cross sections, etc.)

Model predicted data
(PFNS, <TKE>, cross sections, etc.)



Experimental covariances

Parameter Uncertainties

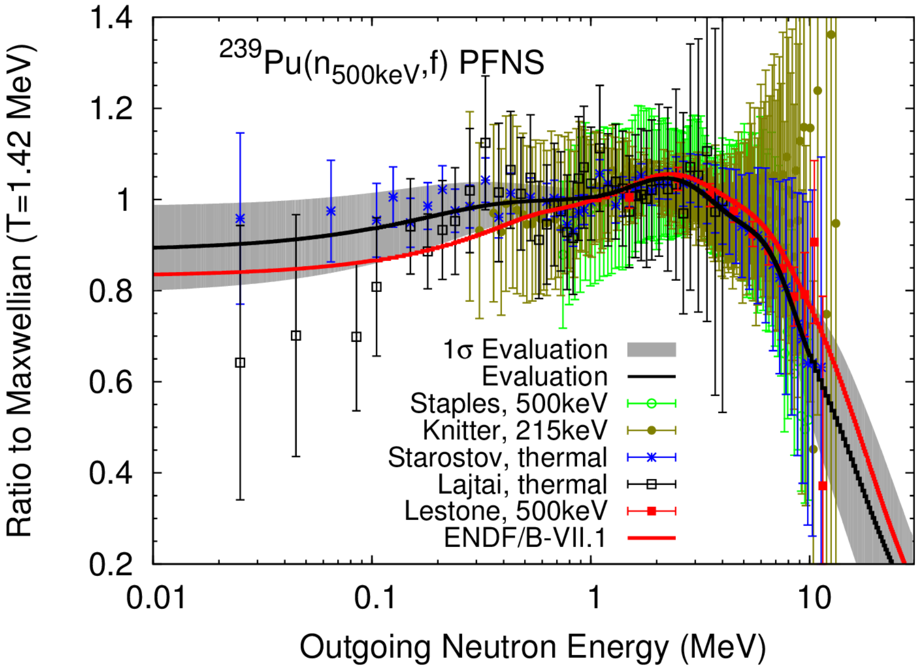
Model Defects

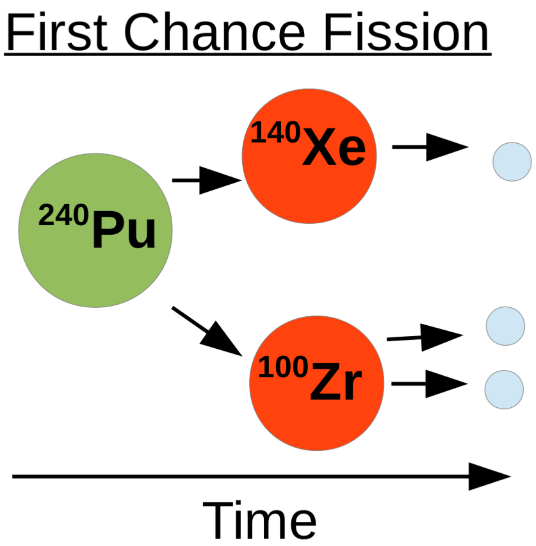
Benchmarking

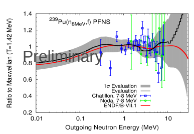
Libraries (CIELO, ENDF/B-VII.1)

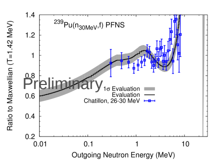
Applications

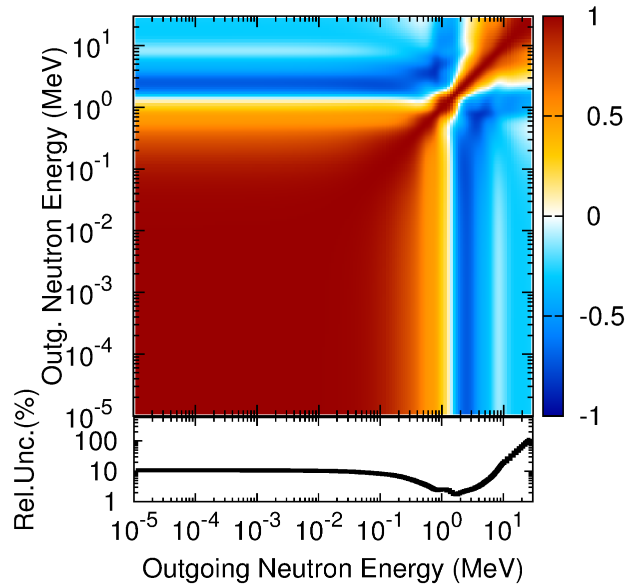
Preliminary evaluated results take into account physics processes.











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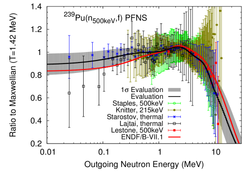

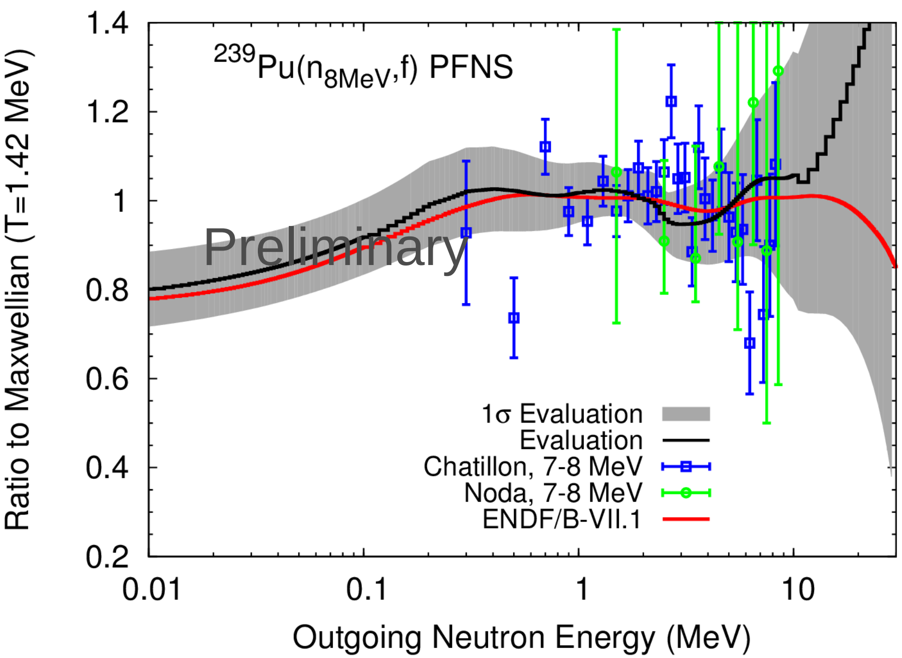

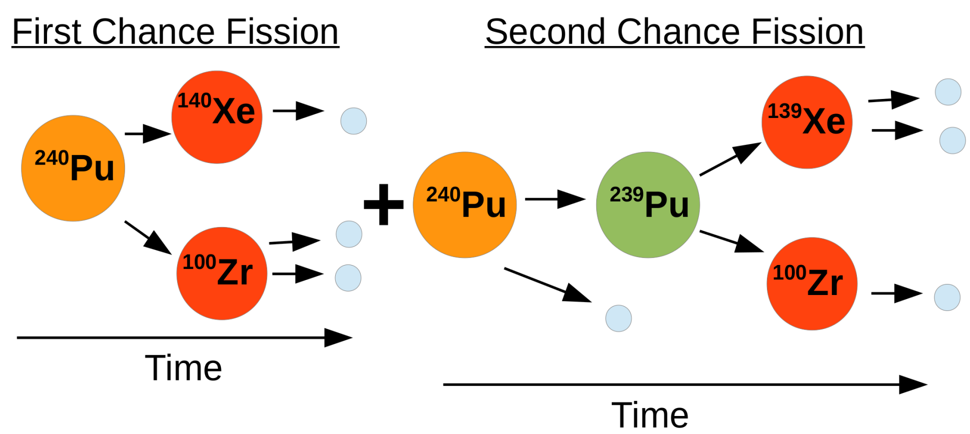

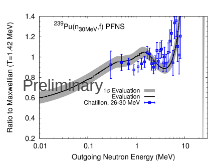

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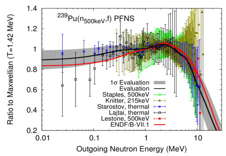
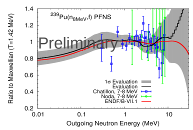
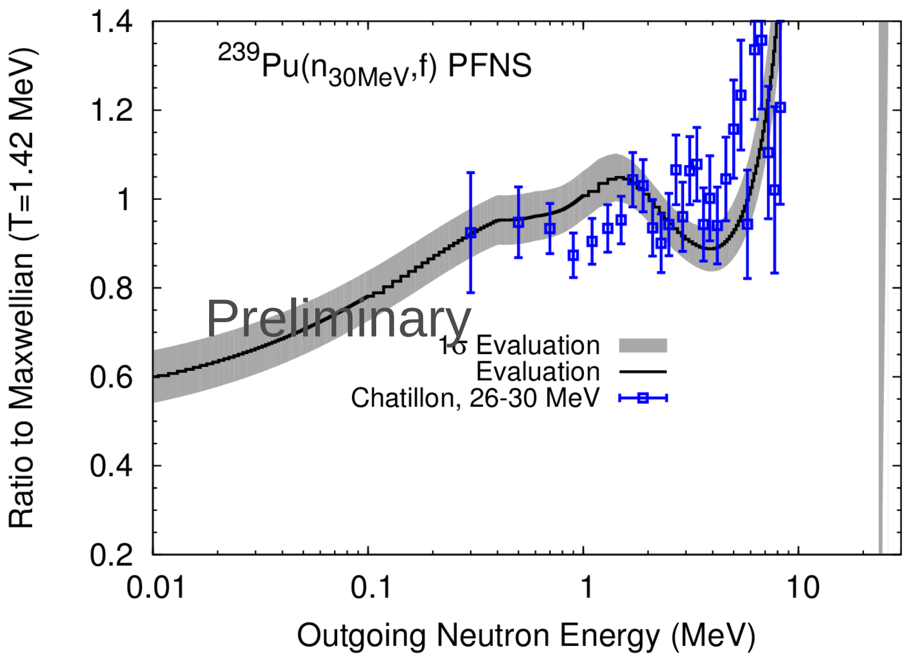
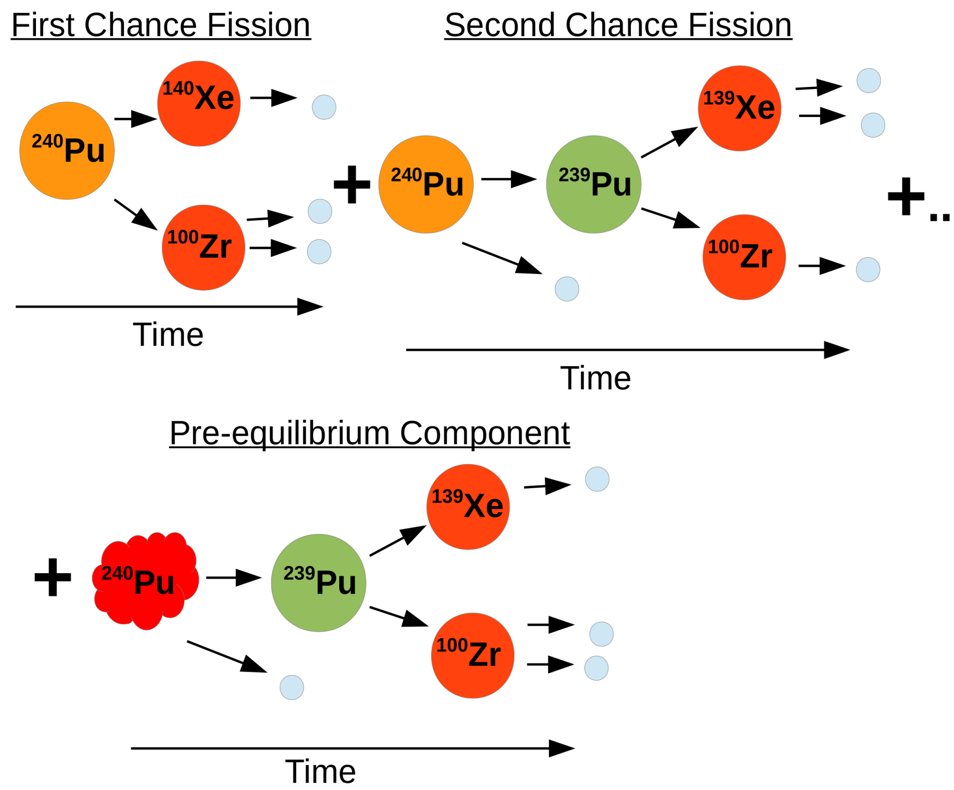
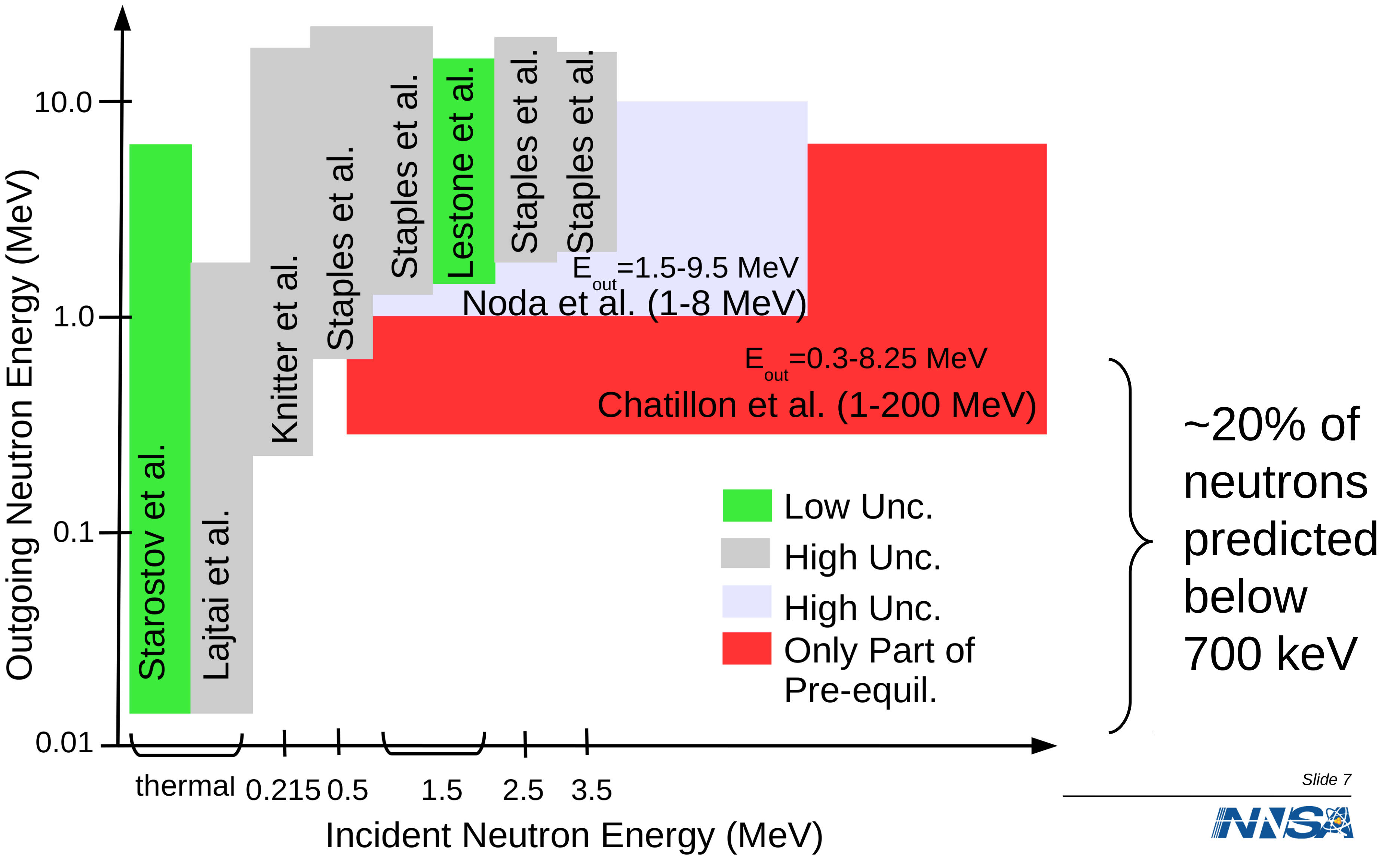






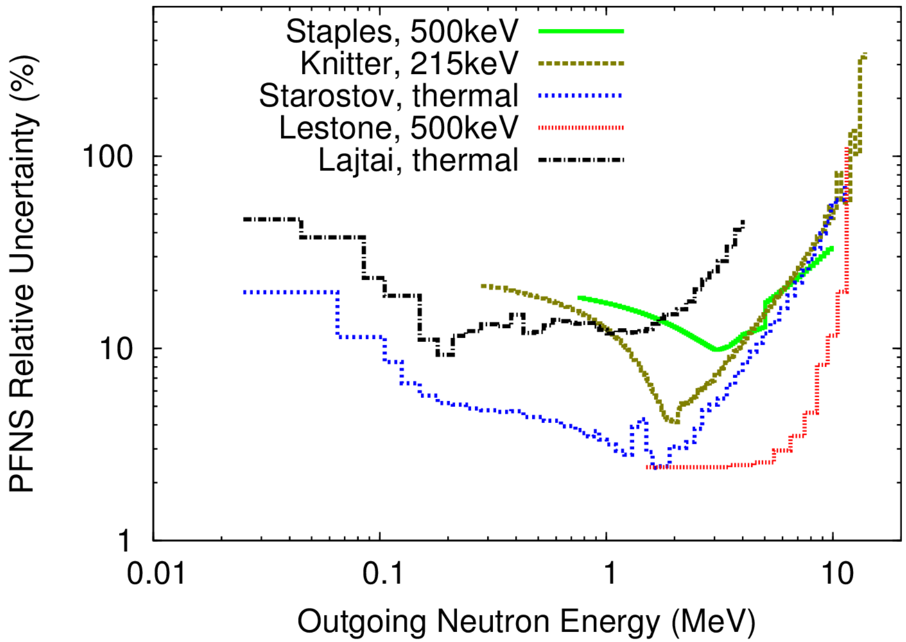


The suitable experimental data base (sufficient unc. and set-up info.):



New measurements of the ^{239}Pu PFNS would be needed at low E_{out} and high E_{inc}.

✗ <u>E_{inc} < 0.5MeV</u>: Measurement of ***comparable energy range (20 keV-6 MeV) and uncertainty of Starostov*** et al. (1989) would be needed for verification. ***<u>Uncertainties and experiment need to be well-documented!!</u>***



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✗ E_{inc} < 0.5MeV: Measurement of ***comparable energy range (20 keV-6 MeV) and uncertainty of Starostov*** et al. (1989) would be needed for verification.

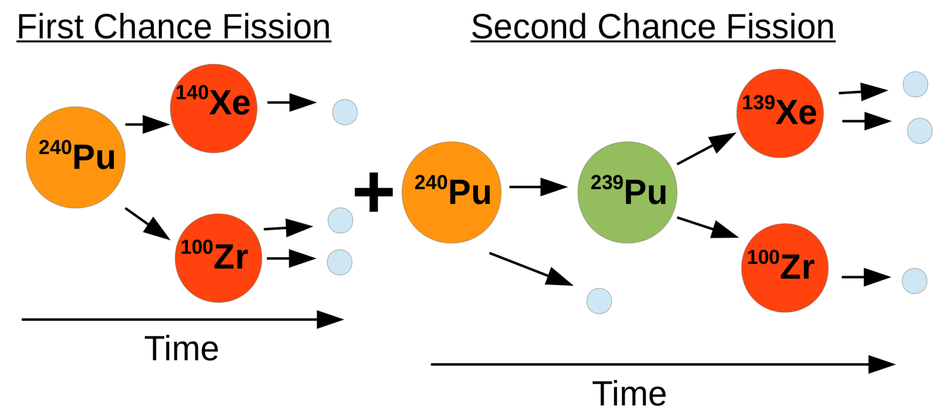
✗ E_{inc} >5 MeV: An ***additional measurement to verify Chatillon et al. (2014) would be needed*** with ***low uncertainties*** and ***including the pre-equilibrium component***.

✗ ***Uncertainties and experiment need to be well-documented!!***

→ the Chi-Nu project at LANSCE (LANL, LLNL) will address some of these needs. (talk of H.-Y. Lee)

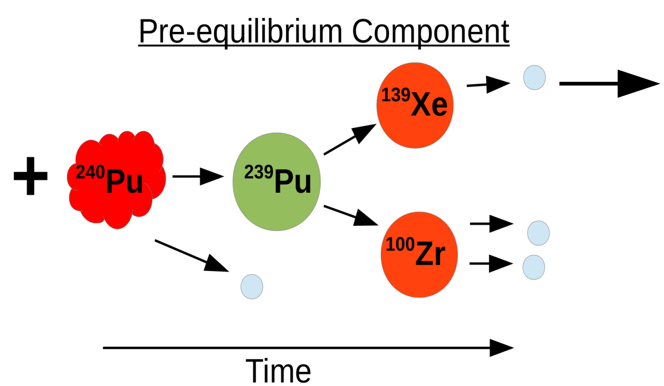
Model predictions allow to extrapolate to energy ranges with scarce exp. info.

The **Los Alamos model** (Madland et al., 1982) as included in the **CoH code** is used for the PFNS.



$$\chi(E) \propto p_f^{(1)}\,\overline{\nu}_1\,\chi_1(E) + p_f^{(2)}\left[\phi_1(E) + \overline{\nu}_2\,\chi_2(E)\right]$$

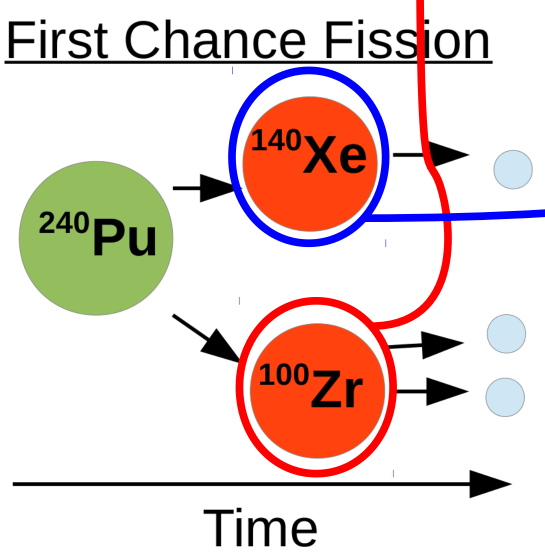
$$+\,p_f^{(3)}\left[\phi_1(E) + \phi_2(E) + \overline{\nu}_3\,\chi_3(E)\right] + \ldots$$



The **exciton model** is used for the **pre-equilibrium component.**

The LAM PFNS are a weighted sum of average light and heavy fission fragment PFNS.

$$\chi_1(E)=\frac{\overline{\nu_{1L}}\,\chi_{1L}(E,T_{mL},a_L,b,s,\ldots)+\overline{\nu_{1H}}\,\chi_{1H}(E,T_{mH},a_H,b,s,..)}{\overline{\nu_{1L}}+\overline{\nu_{1H}}}$$



One average light and heavy fragment pair evaporate prompt neutrons at maximal temperature T_m.

We extended the original LAM:

$$\chi_1(E)=\frac{\boxed{\overline{\nu}_{1\mathrm{L}}}\chi_{1\mathrm{L}}(E,\boxed{T_{mL}},a_L,b,s,\ldots)+\boxed{\overline{\nu}_{1\mathrm{H}}}\chi_{1\mathrm{H}}(E,\boxed{T_{mH}},a_H,b,s,\ldots)}{\overline{\nu}_{1\mathrm{L}}+\overline{\nu}_{1\mathrm{H}}}$$

- With ***b***, an anisotropy in the neutron emission in the cms frame is considered effectively (Terrell, 1959)
- $\boxed{\overline{\nu}_{1\mathrm{L}}\neq\overline{\nu}_{1\mathrm{H}} \quad \text{and} \quad T_{mL}\neq T_{mH}}$ (e.g., Ohsawa et al., 2000)
- Instead of a triangular temperature distribution, one by Hambsch, et al., 2005 is considered (with parameter ***s***).
- The pre-equilibrium component is considered.

In addition, an E_{inc}-dependence of some model parameters is considered.

$$\chi_1(E)=\frac{\overline{\nu_{1L}}\,\chi_{1L}\left(E,T_{mL},\langle TKE\rangle(E_{inc}),\ldots\right)+\overline{\nu_{1H}}\,\chi_{1H}\left(E,T_{mH},\langle TKE\rangle(E_{inc}),\ldots\right)}{\overline{\nu_{1L}}+\overline{\nu_{1H}}}$$

The **incident energy-dependent average total kinetic energy** of the fission fragments is related to the maximum temperature through the excitation energy:

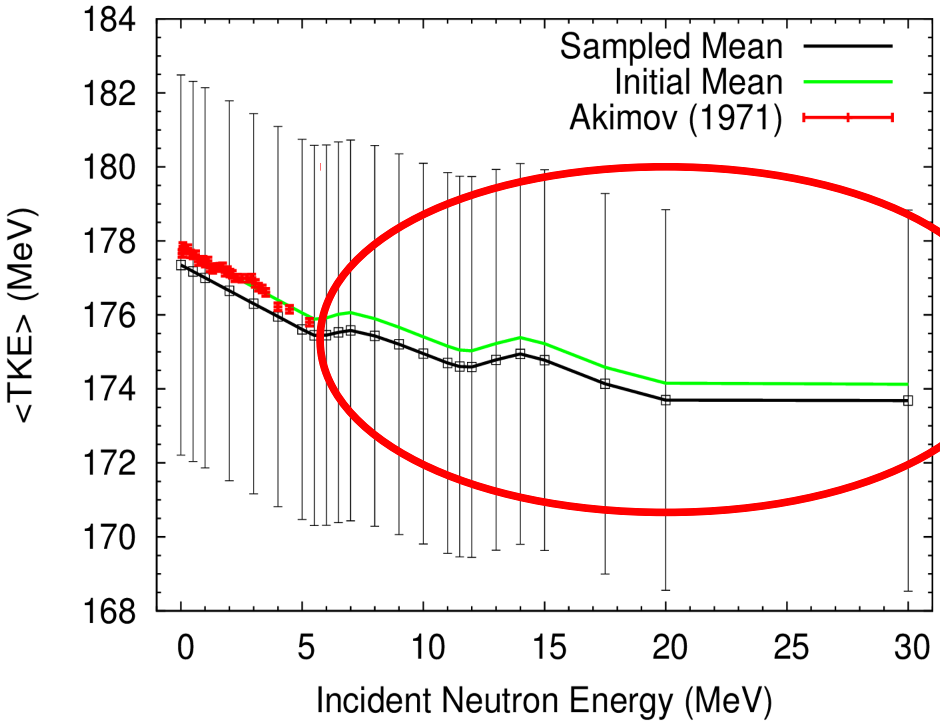
$$T_{mL}=\sqrt{\langle E^{exc}(E_{inc})\rangle / a_L}$$

$$\langle E^{exc}(E_{inc})\rangle=\langle E_r(E_{inc})\rangle+B_n+E_{inc}-\langle TKE(E_{inc})\rangle$$

For <TKE>, we use an E_{inc} dependence of Lestone et al., (2014) but scarce exp. info ...

$$\langle TKE(E_{inc})\rangle = \sum_{i=1}^{n=4} p_f^{(i)}(E_{inc})\langle TKE^{(i)}(E_{inc})\rangle$$

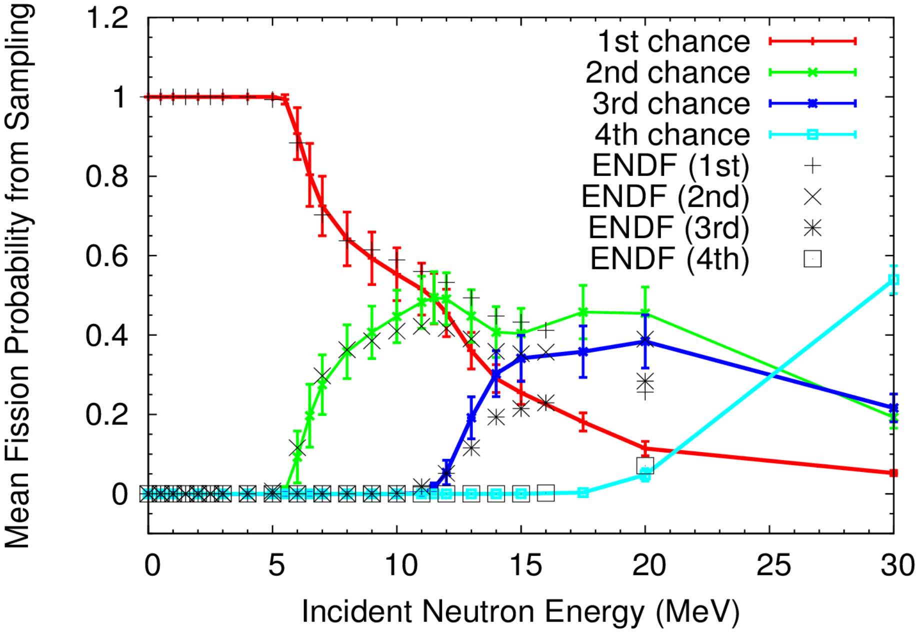
$$\langle TKE^{(i)}(E_{inc})\rangle = \begin{cases} \langle TKE^{therm}\rangle & E_{inc} < E^i_{start} \\ \langle TKE^{therm}\rangle - \delta\langle TKE\rangle^{(1)}(E_{inc} - E^i_{start}) & E_{inc} \geq E^i_{start} \end{cases}$$

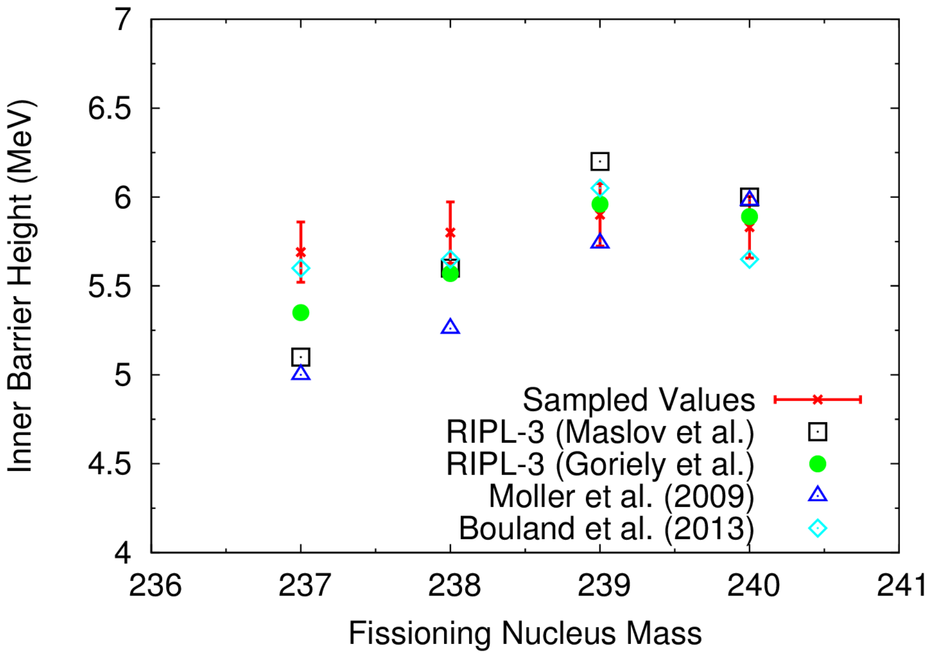


Experimental data are needed!

A measurement is right now underway at LANSCE (see talk of D. Duke.) and see also talk of Loveland.

The fission barrier parameters are obtained by fitting to ENDF/B-VII.0 fission probabilities





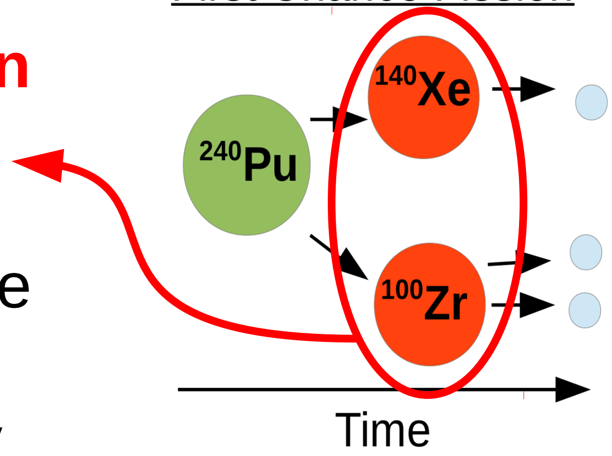
But, there are certain limitations in the Los Alamos model ...

- **Only one average fission fragment pair** considered.

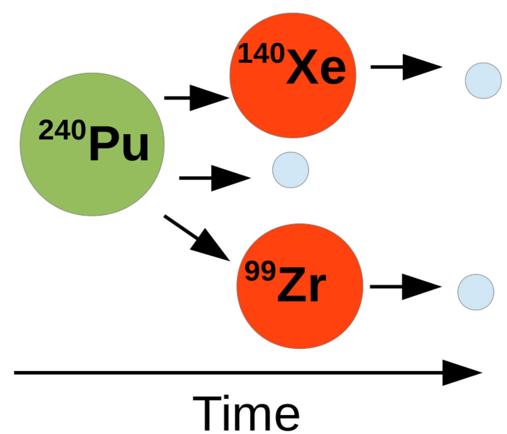
- No **scission neutrons** are considered. (possibly, 10-15% of the neutrons, Petrov et al., 2008)

- **Neutrons** are assumed to be **emitted from fully accelerated fragments.**

First Chance Fission

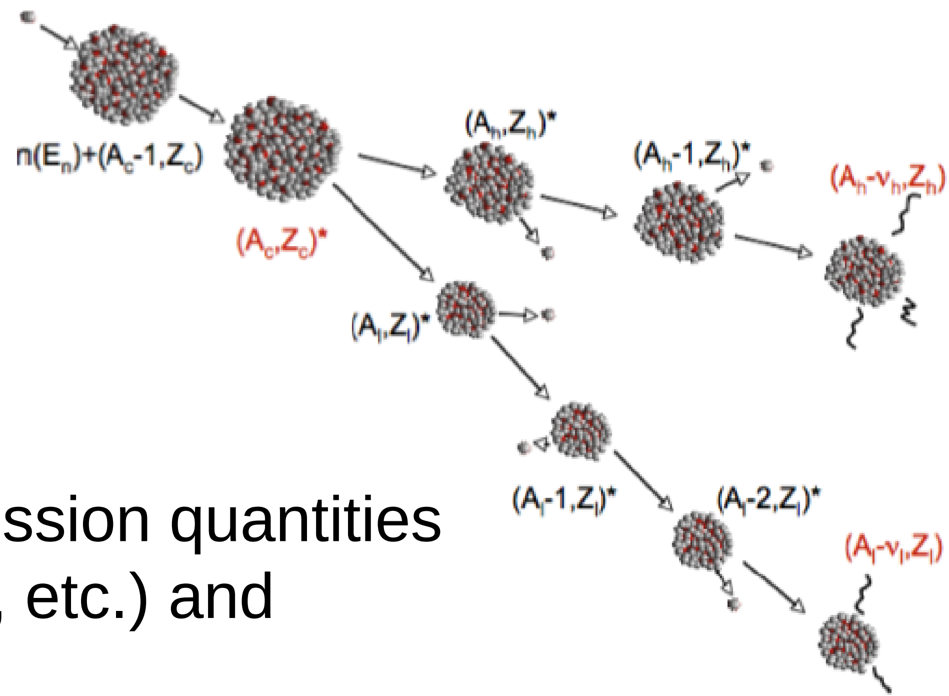


Scission Neutrons?



Into the future: Using recently developed models for PFNS eval. and other quantities

Using models which follow each decay step using sampled emission probabilities and Monte Carlo sampling. (MCHF, FREYA, FIFRELIN, e.g., talks of Stetcu, Vogt).



Thanks to P. Talou for this figure.

Provide predictions of several fission quantities (PFNS, multiplicity, γ-spectrum, etc.) and several isotopes

→ **BUT MORE (measurable) INPUT QUANTITIES NEEDED.**

Stetcu et al., (2014); Vogt et al., (2009), Litaize et al., (2010).

Summary:We employ experimental and model information for an E_{inc}-dependent evaluation.

✔ The **Los Alamos model was extended** (anisotropy, temperature distribution, etc.) and the **pre-equilibrium component** was included in the calculations.

✔ The **E_{inc}-dependence** of some **model parameters** was obtained using exp., evaluated and theoretical information.

✔ The experimental data and associated uncertainties were analyzed in detail.

✔ We have **final evaluated results for E_{inc} = 500 keV** and **preliminary ones up to 30 MeV**.

A wish-list of a PFNS evaluator:

- **New PFNS ^{239}Pu exp.**: E_{inc} < 0.5 MeV: comparable unc. and energy range to Starostov et al.; E_{inc} > 5 MeV: additional measurements with pre-equilibrium component. **Good documentation of unc. and measurement is needed.**

- **Measurement of <TKE>** up to E_{inc} = 30 MeV.

- **Using models for the evaluation which follow the fission process more closely** (MCHF, FREYA, FIFRELIN, etc.) and provide suitable predictions of the PFNS. → further experimental information needed.

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Thank you for your attention!

Literature:

^{239}Pu PFNS Experiments:

[1] H.-H. Knitter, Atomkernenergie 26, 76 (1975), EXFOR-No. 20576.001.

[2] P. Staples et al., Nucl. Phys. A 591 41 (1995), EXFOR-No. 13982.001.

[3] A. Lajtai et al., in Proc. of the Conf. on Nuclear Data for Basic and Applied Sciences, Santa Fe, USA, 1985, (1), 613 (1985), EXFOR-No. 30704.001.

[4] B.I. Starostov et al., INDC(CCP)-293/L, INDC Report, p. 19 (1989), EXFOR-No. 40930.001.

[5] J.P. Lestone et al., LA-UR-14-24087, Los Alamos National Laboratory (2014).

[6] A. Chatillon et al., Phys. Rev. C 89, 014611 (2014).

[7] S. Noda et al., Phys. Rev. C 83, 034604 (2011), EXFOR-No. 14290.001.

[8] T.N. Taddeucci et al., Nuclear Data Sheets (special issue for CW2014 workshop), submitted.

Literature:

Los Alamos model and extensions:

[1] D.G. Madland et al., Nucl. Sci. Eng. 81, 213 (1982).

[2] F.-J. Hambsch et al., Ann. Nucl. Eng. 32, 1032 (2005).

[3] T. Ohsawa et al., Nucl. Phys. A 665, 3 (2000).

[4] J. Terrell, Phys. Rev. 113, 527 (1959).

[5] T. Kawano et al., Phys. Rev. C 63, 034601 (2001).

E_{inc}-dependence of parameters:

[1] D.G. Madland, Nucl. Phys. A 772, 113 (2006).

[2] J. Lestone et al., Nucl. Data Sheets 118, 208 (2014).

[3] A. Tudora, Ann. Nuc. Eng. 36, 72 (2009) and references therein.

[4] O. Bouland et al., Phys. Rev. C 88, 054612 (2013).

Literature:

Additional models for PFNS:

[1] R. Vogt et al., Phys. Rev. C 80, 044611 (2009).

[2] I. Stetcu et al., Phys. Rev. C 90, 024617 (2014).

[3] O. Litaize et al., Phys. Rev. C 82, 054616 (2010).

^{239}Pu PFNS evaluations at LANL:

[1] P. Talou et al., Nucl. Sci. Eng. 166, 254 (2010).

[2] M.E. Rising et al., Nucl. Sci. Eng. 175, 81 (2013).

[3] D. Neudecker et al., Nucl. Sci. Eng., accepted.

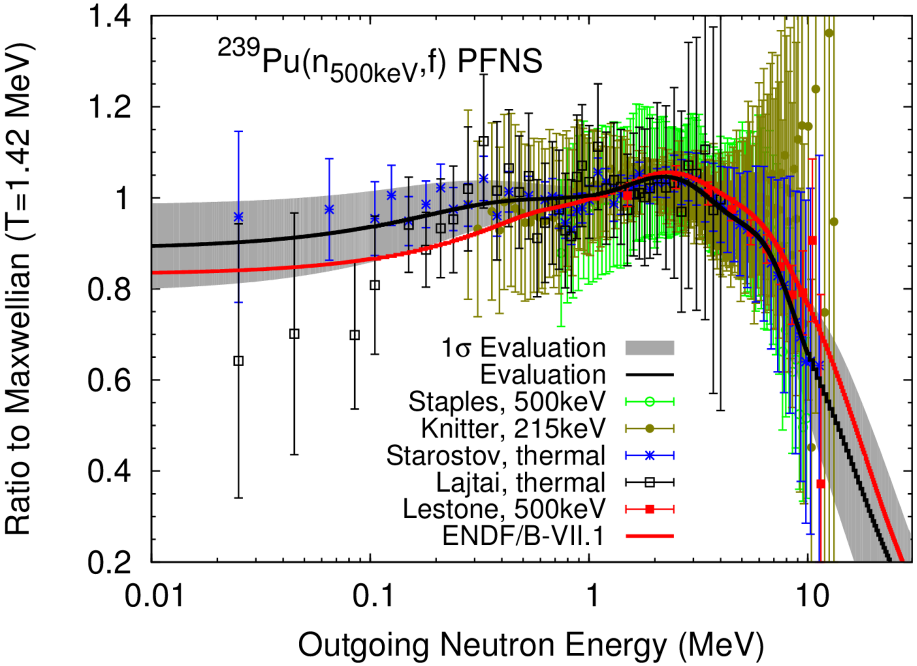
[4] D. Neudecker et al., LA-UR-14-28817, (in preparation, 2014).

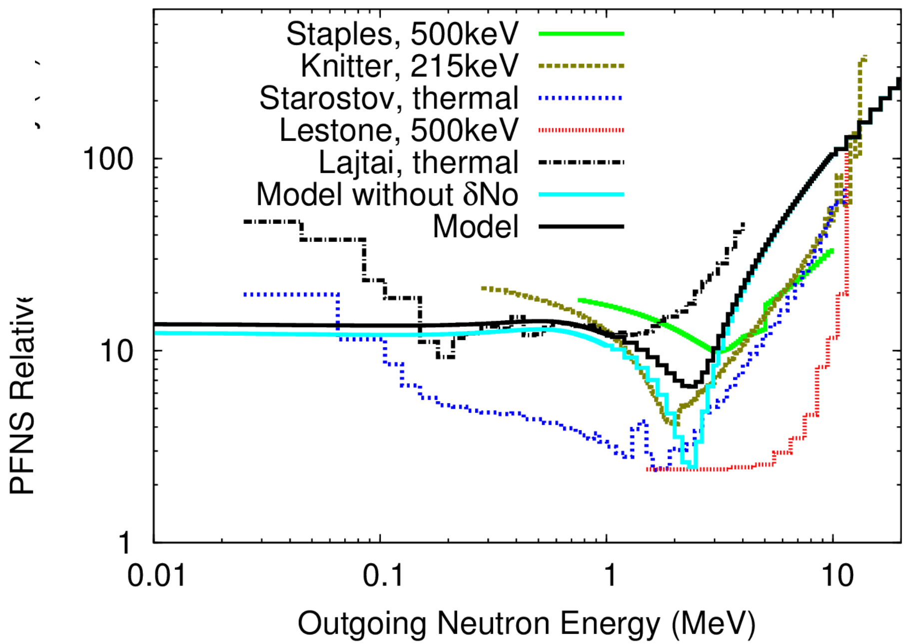
Scission Neutrons:

[1] G.A. Petrov et al., Phys. At. Nucl. 71, 1137 (2008).

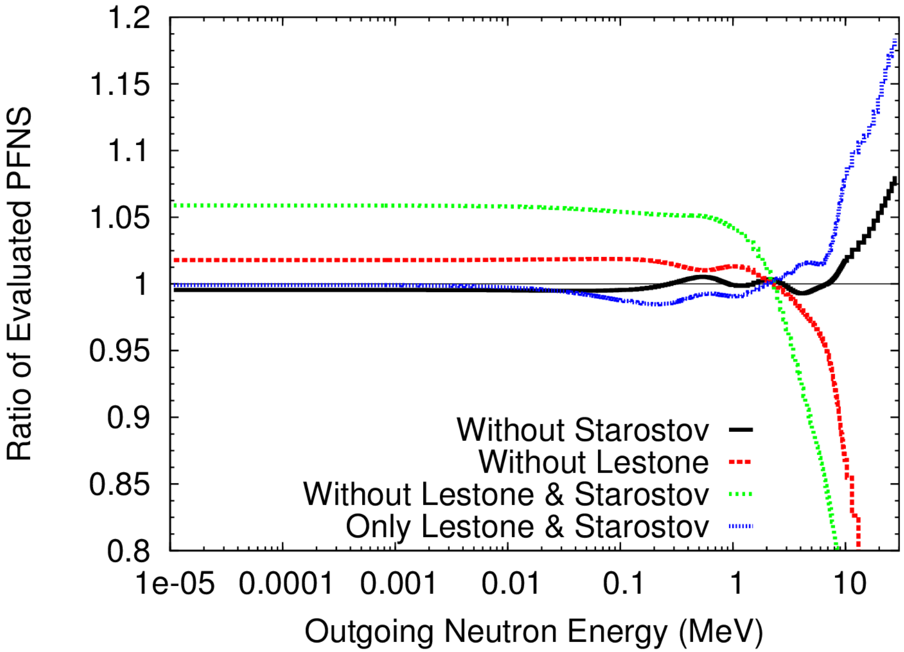
[2] N.V. Kornilov et al., Phys. At. Nucl. 64, 1371 (2001).

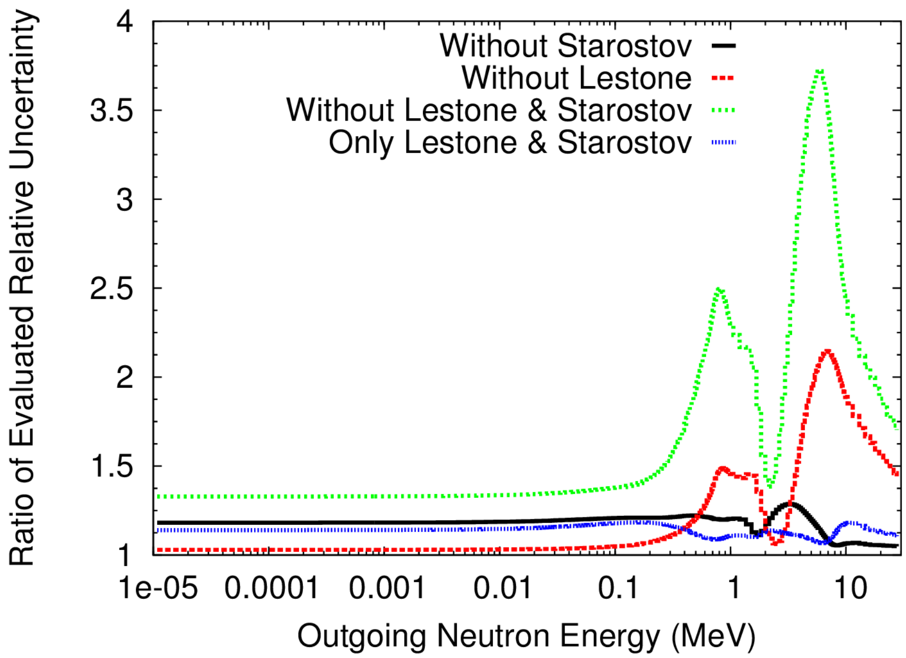
Backup: Starostov and Lestone data have the lowest experimental uncertainties ...





Backup: … and define to a large extent the evaluation at E_{inc} = 500 keV.

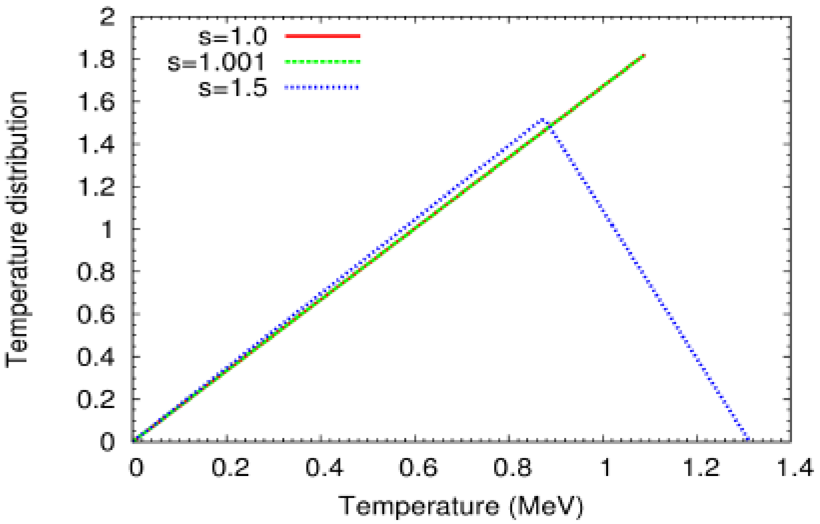


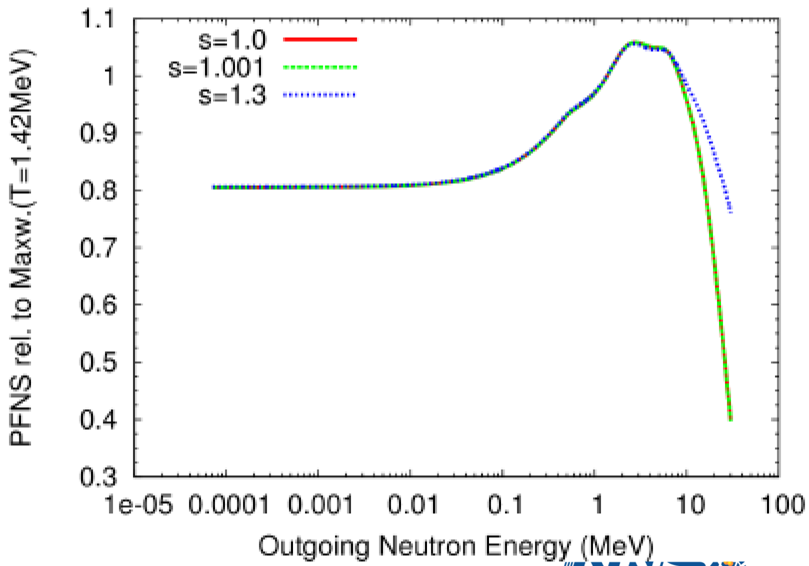


Backup: Impact of different temperature distribution.

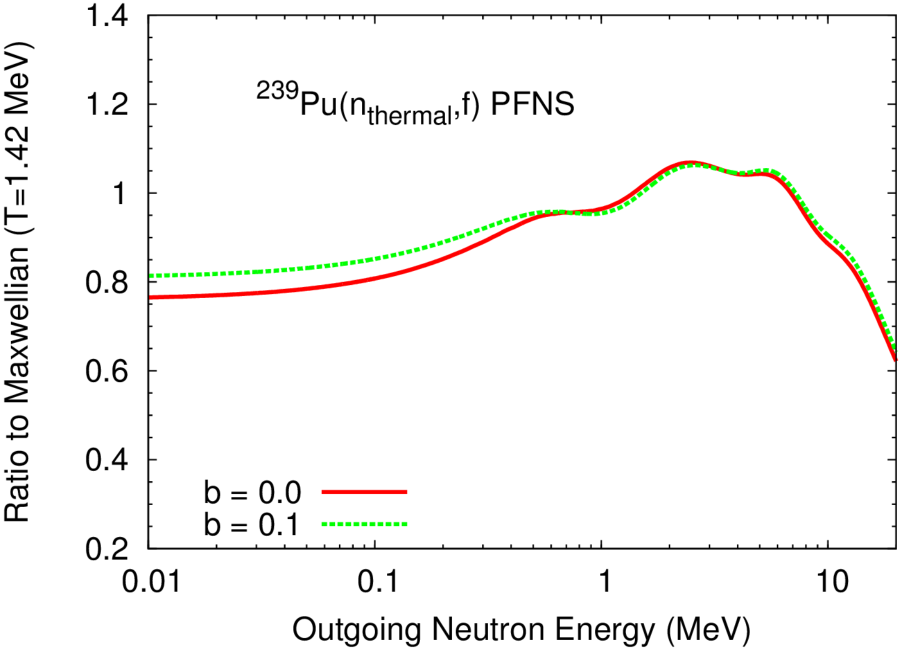
We use the more realistic temperature distribution of Hambsch et al., ANE 32, 1032 (2005).

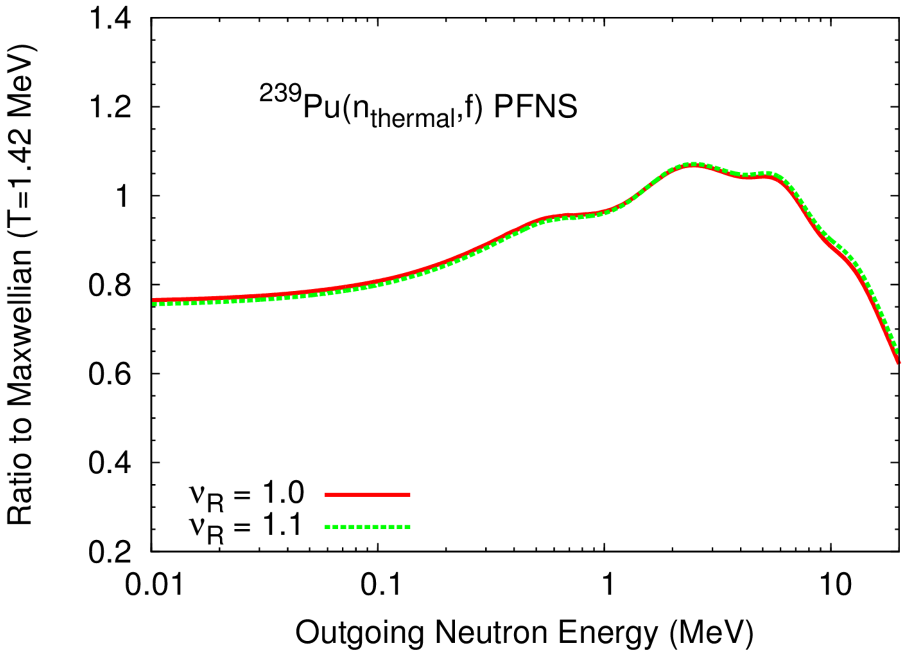
For s=1, one obtains the original triangular distribution used by Madland and Nix.





Backup: Impact of b and $\overline{\nu_{1L}} \neq \overline{\nu_{1H}}$





Backup: Impact of using different OMP

In the LAM, the cross section of the inverse process of compound nucleus formation is used. A new OMP is used for its description.