Simultaneous evaluation of ^{232}Th and ^{237}Np fast neutron-induced fission cross sections up to 200 MeV using EXFOR library

Vidya Devi[a] and Naohiko Otuka[b]

[a]Panjab University, Chandigarh, India

[b] IAEA Nuclear Data Section

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Introduction:

- ^{232}Th and ^{237}Np fissions for reactor application
  - ^{232}Th turns into a useful fuel (^{233}U), potential alternative for producing nuclear energy.
  - ^{237}Np in spent nuclear reactor fuel. Challenge for long-term waste management due to long half-life (~2 My).
  - ^{237}Np fission as a dosimetry / reference reaction for MeV neutron (an alternative of ^{238}U fission)
- New measurement at the CERN n_TOF, CSNS Back-n etc. compiled in EXFOR

→ **Reevaluation of ^{232}Th and ^{237}Np fission cross sections for fast neutrons up to 200 MeV.**

Evaluation Method

- **Revisions** of EXFOR entries included adding missing information, removing duplicate datasets from the same measurements, and reformatting.

- **Assignment** of correlation properties for each partial uncertainty by estimating from partial uncertainties and deriving missing values with the quadrature sum rule.

- **Conversion** to SOK input format. The SOX code converts EXFOR data to SOK file.

- **SOK fitting** updates cross sections estimates using experimental data and Schmittroth's roof function.

Selections of Experimental Datasets

- data reported from 1970 to the present

Following datasets were discarded in general:

- Digitized data and compiled data without partial uncertainties.
- data from nuclear explosion

Formalism

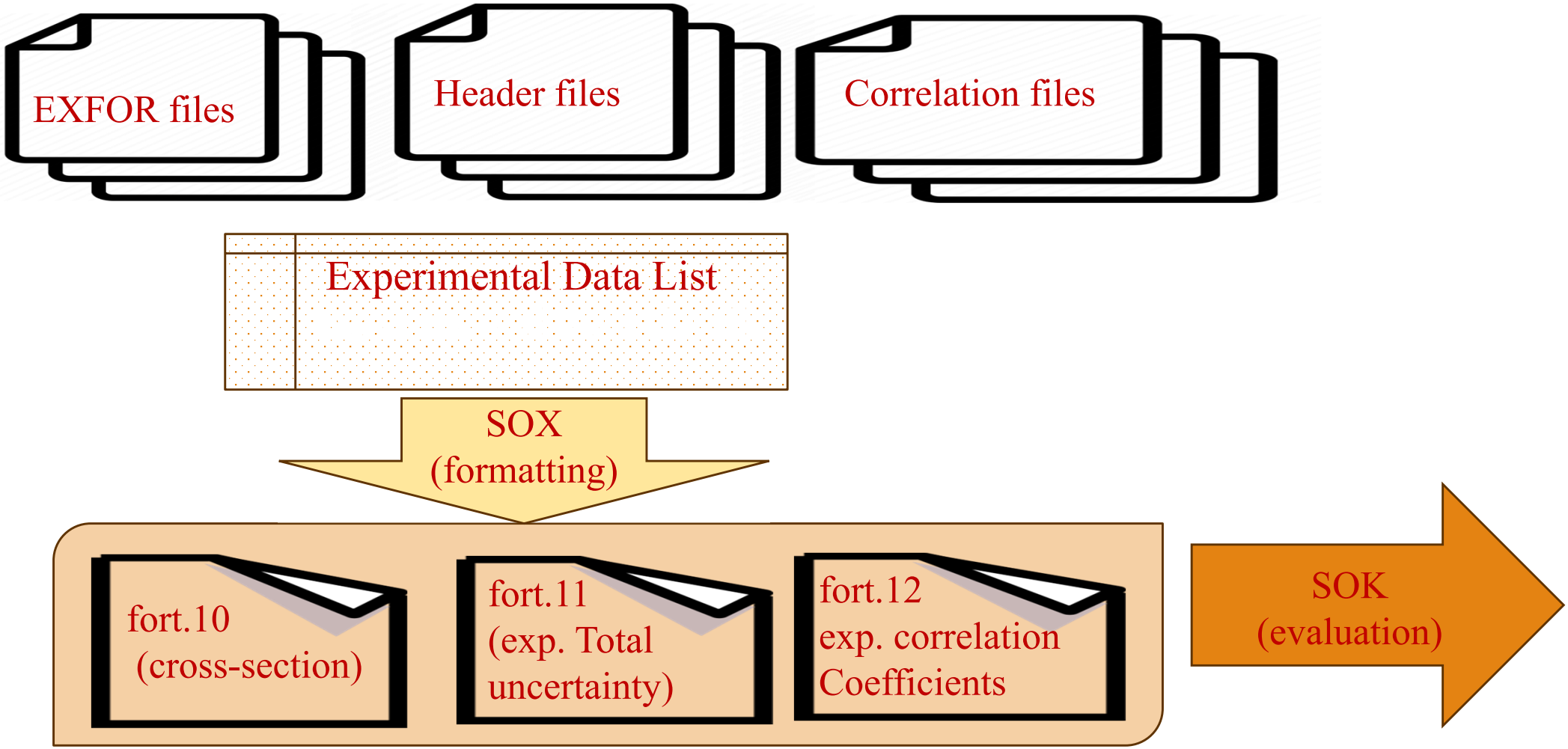
The SOK code models the logarithm of the cross section as a linear combination of Schmittroth's roof functions $\phi_j(E)$ defined by introducing n energy nodes between E_1 and E_n. It is expressed as:

$$\ln \sigma_{exp}(E) = \Sigma_{j=1}^{n} \ln \sigma_{eva,j}\, \phi_j(E) \qquad (1)$$

with $\phi_j(E)$ are the basis functions centered around each energy node E_j, defined by:

$$\phi_j(E) = \begin{cases} \frac{E - E_{j-1}}{E_j - E_{j-1}} & \text{if } \mathrm{E_{j-1}} \leq E \leq E_j\,, \\ \frac{E_{j+1} - E}{E_{j+1} - E_j} & \text{if } \mathrm{E_j} \leq E \leq E_{j+1}\,, \\ 0 & \text{otherwise.} \end{cases} \qquad (2)$$

Data transfer from EXFOR entries to SOK input



EXFOR Input Files

Data list file (list of experimental datasets – subentry# +pointer)

```
%237Np(n,f)/239Pu(n,f):7.0E+04:2.5E+08:0.0:1.2:RT:0.0:1.2:RT
 40507.002    20240617 1.0000E+00 1.0000E+00 4RUSFEI  V.M.Kupriyanov+,1978
 40507.004    20240617 1.0000E+00 1.0000E+00 4RUSFEI  V.M.Kupriyanov+,1978
```

EXFOR (EXF) file

```
SUBENT         40507004    20240617
BIB                   7          17
REACTION    ((93-NP-237(N,F),,SIG)/(94-PU-239(N,F),,SIG))
...
ERR-ANALYS (ERR-T) Root-mean-square sum of all uncertainties from
                 - Energy dependence of the shape ratio
           (ERR-1) Absolute ratios for normalization        (1.5%)
           (ERR-2) Normalization procedure of shape        (0.25%)
...
ENDBIB               17          0
COMMON                2          3
ERR-1       ERR-2
PER-CENT    PER-CENT
 1.5         0.25
ENDCOMMON            3          0
DATA                 4         61
EN          EN-ERR      DATA        ERR-T
MEV         KEV         NO-DIM      PER-CENT
 0.130        21.        0.015        4.8
 0.180        20.        0.022        4.3
 0.230        19.        0.025        4.1
 0.280        18.        0.034        4.0
...
```

Header (HED) file
Correlation property etc.

```
EN
EN
EN-ERR
DATA

ERR-T       U
ERR-1       1.
ERR-2       1.
```

uncertainty treated as uncorrelated

uncertainty treated as fully correlated

EXFOR Input Files: Correlation file

```
#22211.002   T.Iwasaki+,1990                    19
 1.000
 0.410 1.000
 0.340 0.370 1.000
 0.340 0.350 0.280 1.000
 0.340 0.260 0.250 0.260 1.000
 0.410 0.320 0.300 0.310 0.370 1.000
 0.430 0.360 0.320 0.330 0.360 0.430 1.000
 0.430 0.310 0.300 0.320 0.400 0.480 0.470 1.000
 0.500 0.480 0.400 0.400 0.400 0.480 0.500 0.500 1.000
 0.440 0.320 0.310 0.330 0.410 0.480 0.480 0.540 0.520 1.000
 0.450 0.330 0.320 0.330 0.410 0.490 0.480 0.540 0.530 0.550 1.000
 0.410 0.270 0.280 0.300 0.400 0.470 0.460 0.530 0.480 0.540 0.550 1.000
 0.490 0.550 0.420 0.400 0.350 0.430 0.470 0.430 0.590 0.440 0.460 0.400
 1.000
```

A correlation file is created only when correlation coefficients in EXFOR entries are available under COVARIANCE.

SOX output (=Experimental Input of SOK)

fort.10 (experimental cross section: $E_1, \sigma_1, E_2, \sigma_2, \ldots$)

```
40507.004   V.M.Kupriyanov+,1978                61
 1.3000E+05 1.5000E-02 1.8000E+05 2.2000E-02 2.3000E+05 2.5000E-02
 2.8000E+05 3.4000E-02 3.5000E+05 6.8000E-02 4.0000E+05 1.0700E-01
 4.5000E+05 1.7400E-01 5.0000E+05 2.6500E-01 5.5000E+05 3.5600E-01
 6.0000E+05 4.4100E-01 6.5000E+05 5.3900E-01 7.0000E+05 6.1300E-01
```

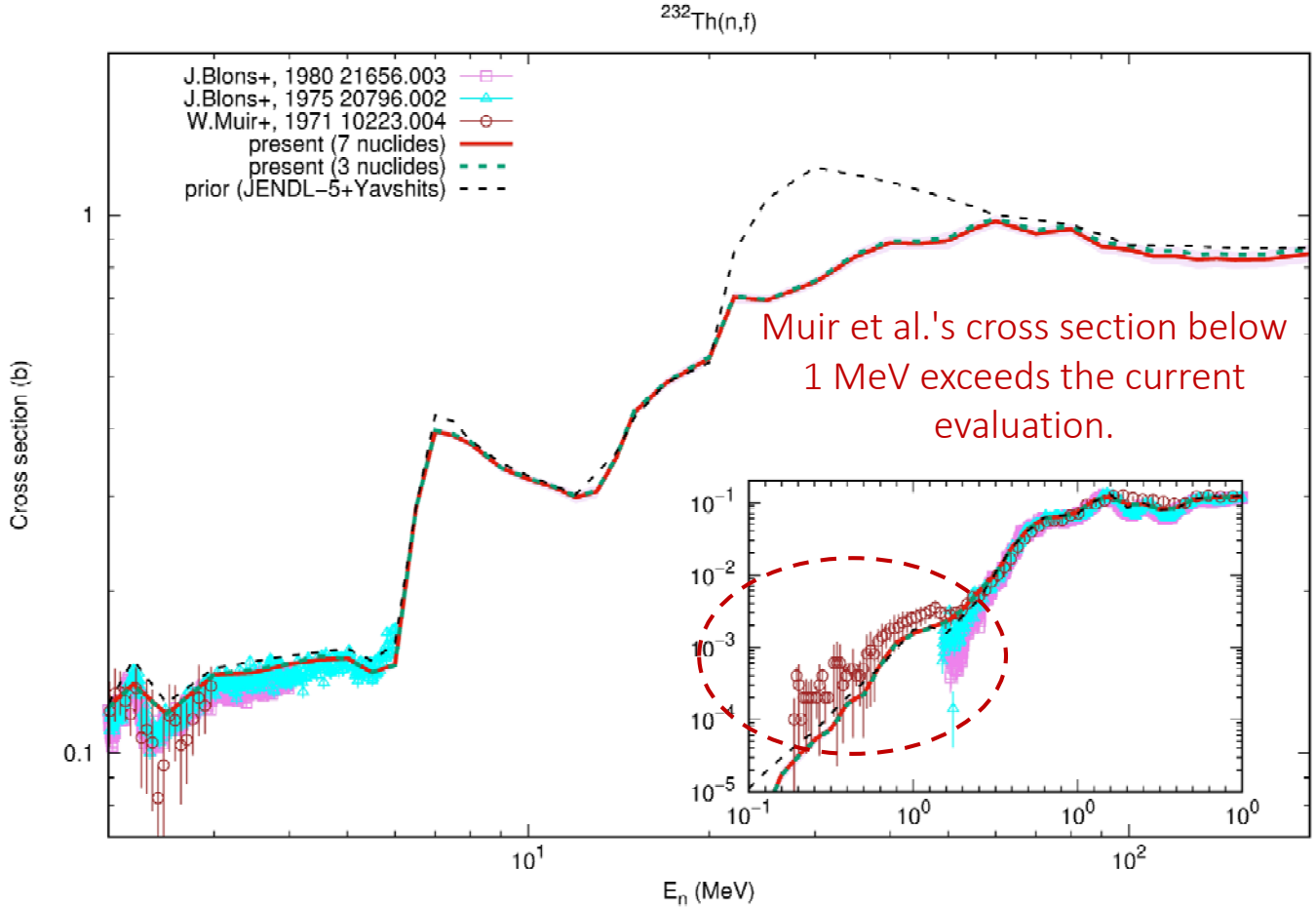
fort.11 (experimental total uncertainty: $E_1, \Delta\sigma 1, E_2, \Delta\sigma 2, \ldots$)

```
40507.004   V.M.Kupriyanov+,1978                61
 1.3000E+05 4.8000E-02 1.8000E+05 4.3000E-02 2.3000E+05 4.1000E-02
 2.8000E+05 4.0000E-02 3.5000E+05 3.5000E-02 4.0000E+05 2.9000E-02
 4.5000E+05 2.7000E-02 5.0000E+05 2.6000E-02 5.5000E+05 2.4000E-02
 6.0000E+05 2.3000E-02 6.5000E+05 2.6000E-02 7.0000E+05 2.3000E-02
```

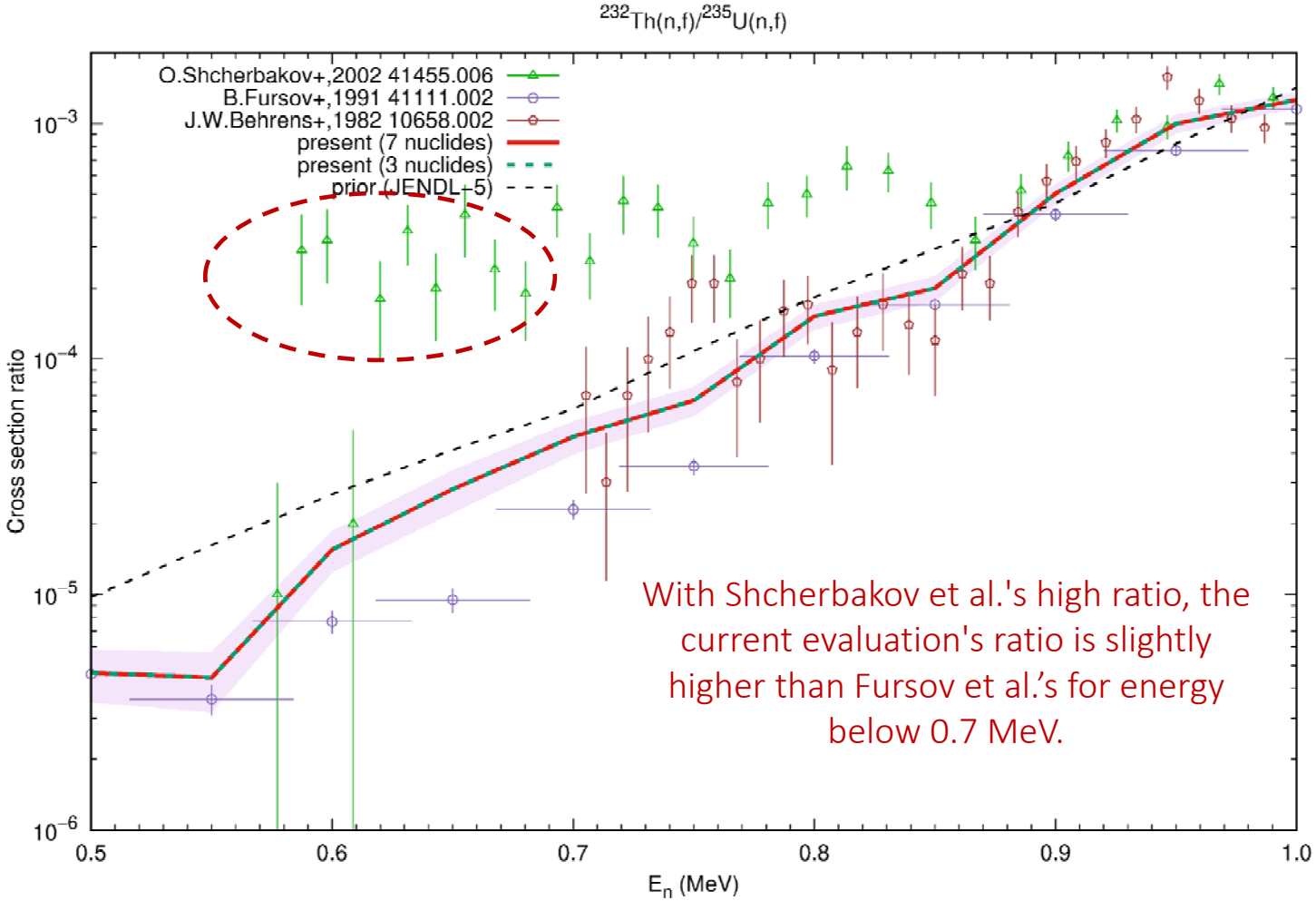
fort.12 (experimental correlation coefficients)

```
40507.004   V.M.Kupriyanov+,1978                61
 1.000
 0.112 1.000
 0.118 0.131 1.000
 0.120 0.134 0.141 1.000
 0.138 0.154 0.161 0.165 1.000
 0.166 0.185 0.194 0.199 0.228 1.000
 0.178 0.199 0.209 0.214 0.245 0.295 1.000
 0.185 0.207 0.217 0.222 0.254 0.307 0.329 1.000
```

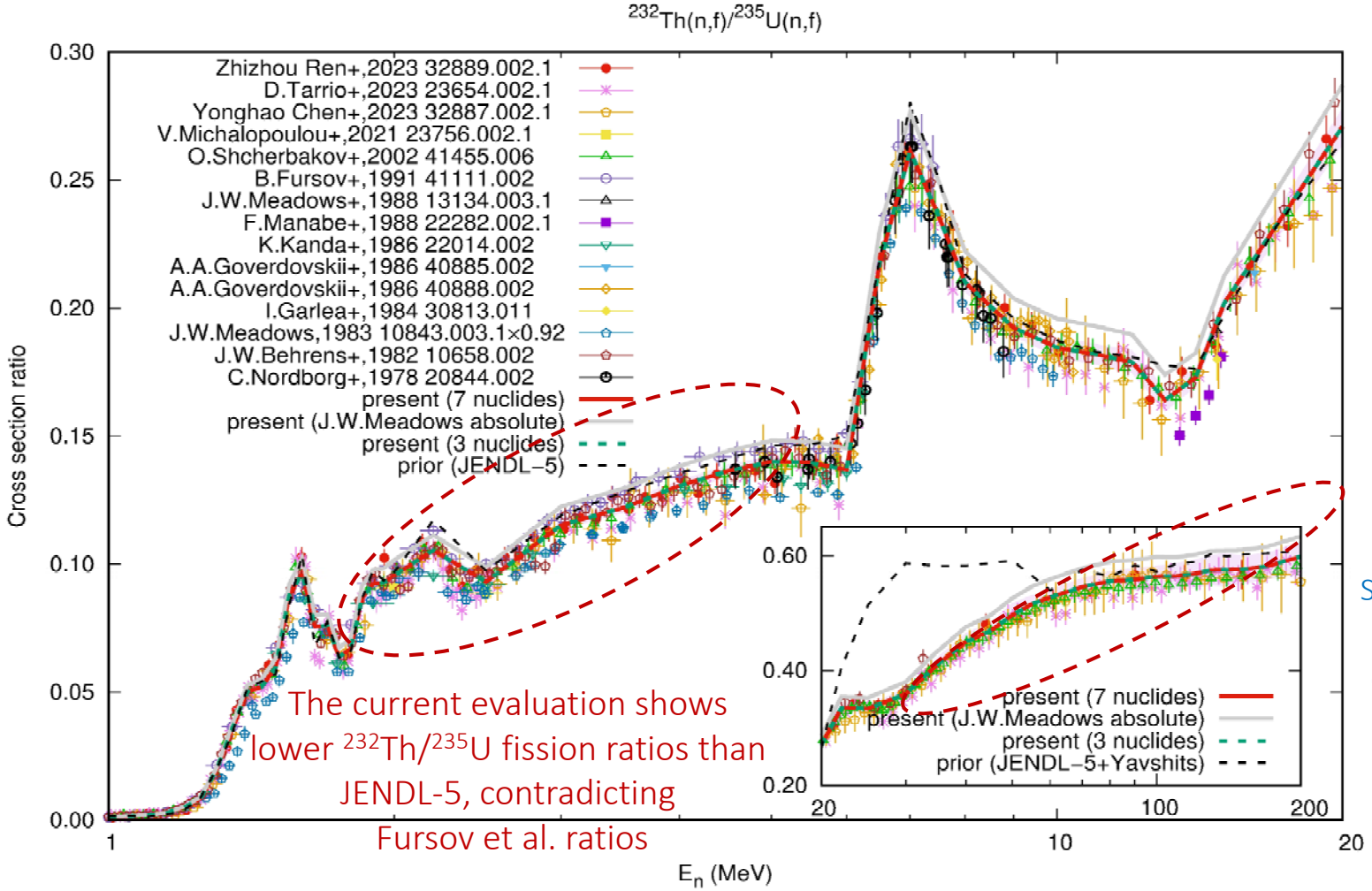
Simultaneous fitting of ^{232}Th with ^{233,235,238}U, $^{239\text{-}241}$Pu fission cross section.



Simultaneous fitting of ^{232}Th/^{235}U with ^{233,235,238}U, $^{239\text{-}241}$Pu fission cross section below 1 MeV.



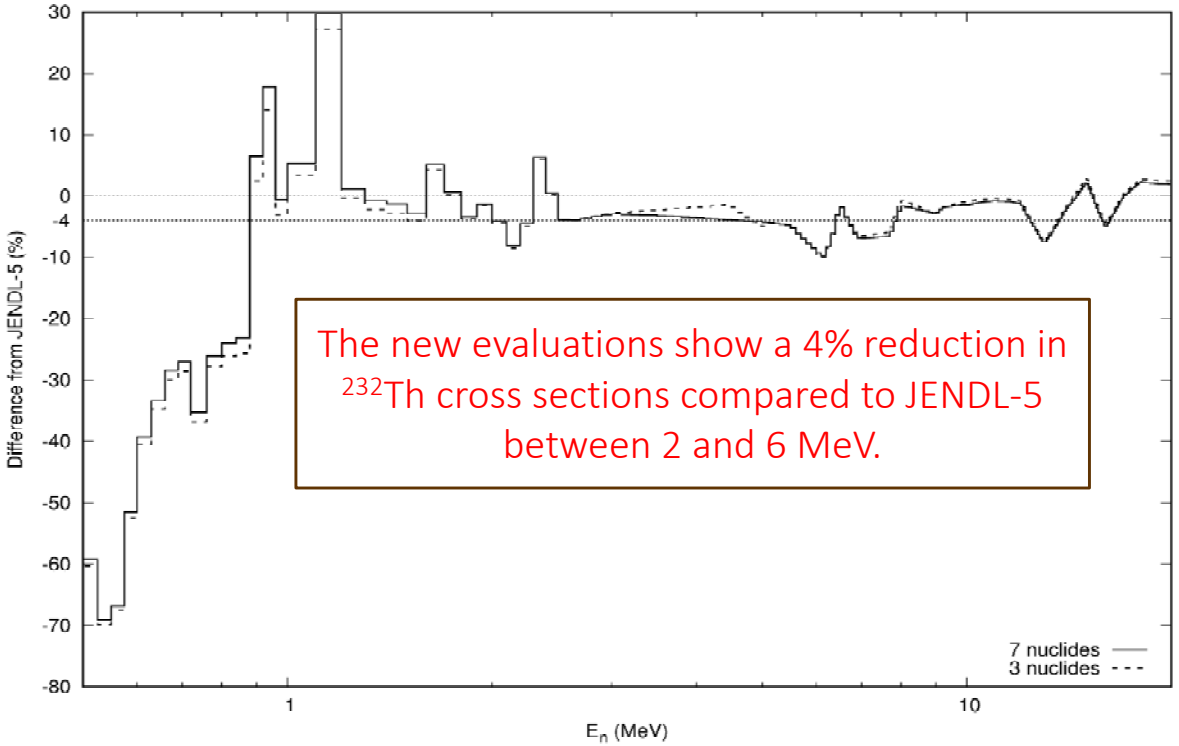
Simultaneous fitting of ^{232}Th/^{235}U with ^{233,235,238}U, $^{239\text{-}241}$Pu fission cross section above 1 MeV.



The current evaluation shows lower ^{232}Th/^{235}U fission ratios than JENDL-5, contradicting Fursov et al. ratios

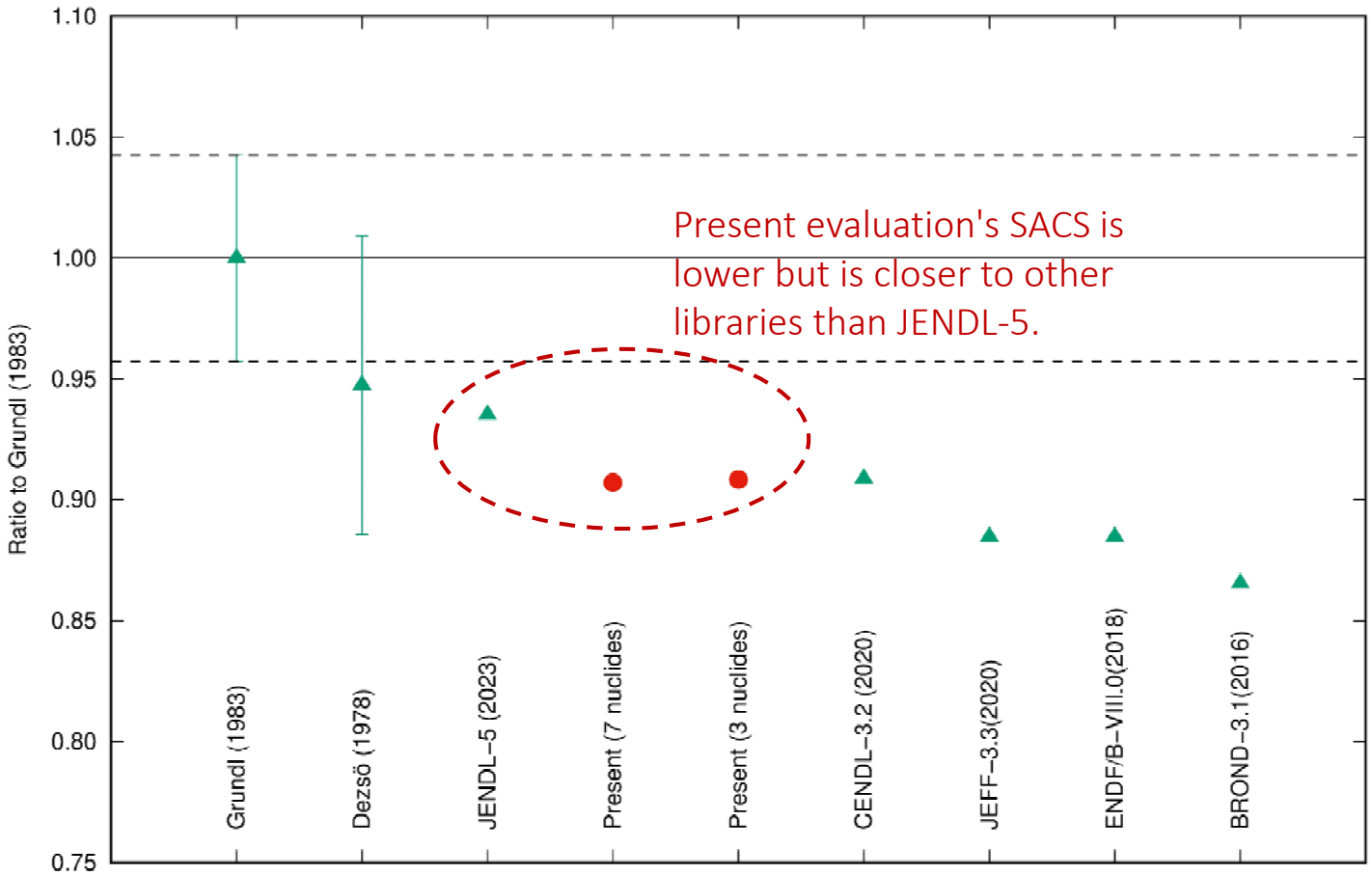
Some CERN n_TOF data points are lower but consistent with others within error bars.

Difference in ^{232}Th fission cross sections between evaluations

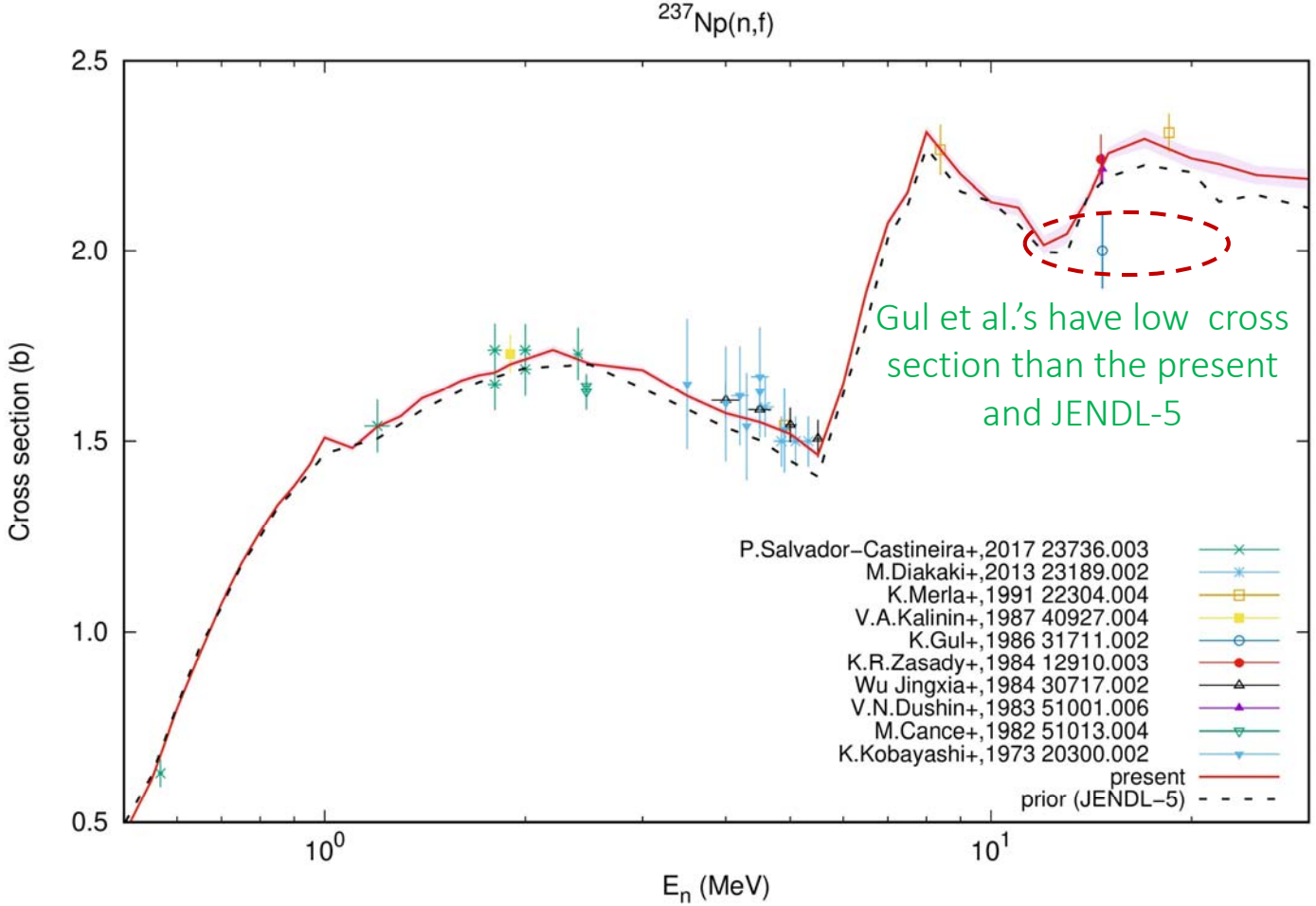


The new evaluations show a 4% reduction in ^{232}Th cross sections compared to JENDL-5 between 2 and 6 MeV.

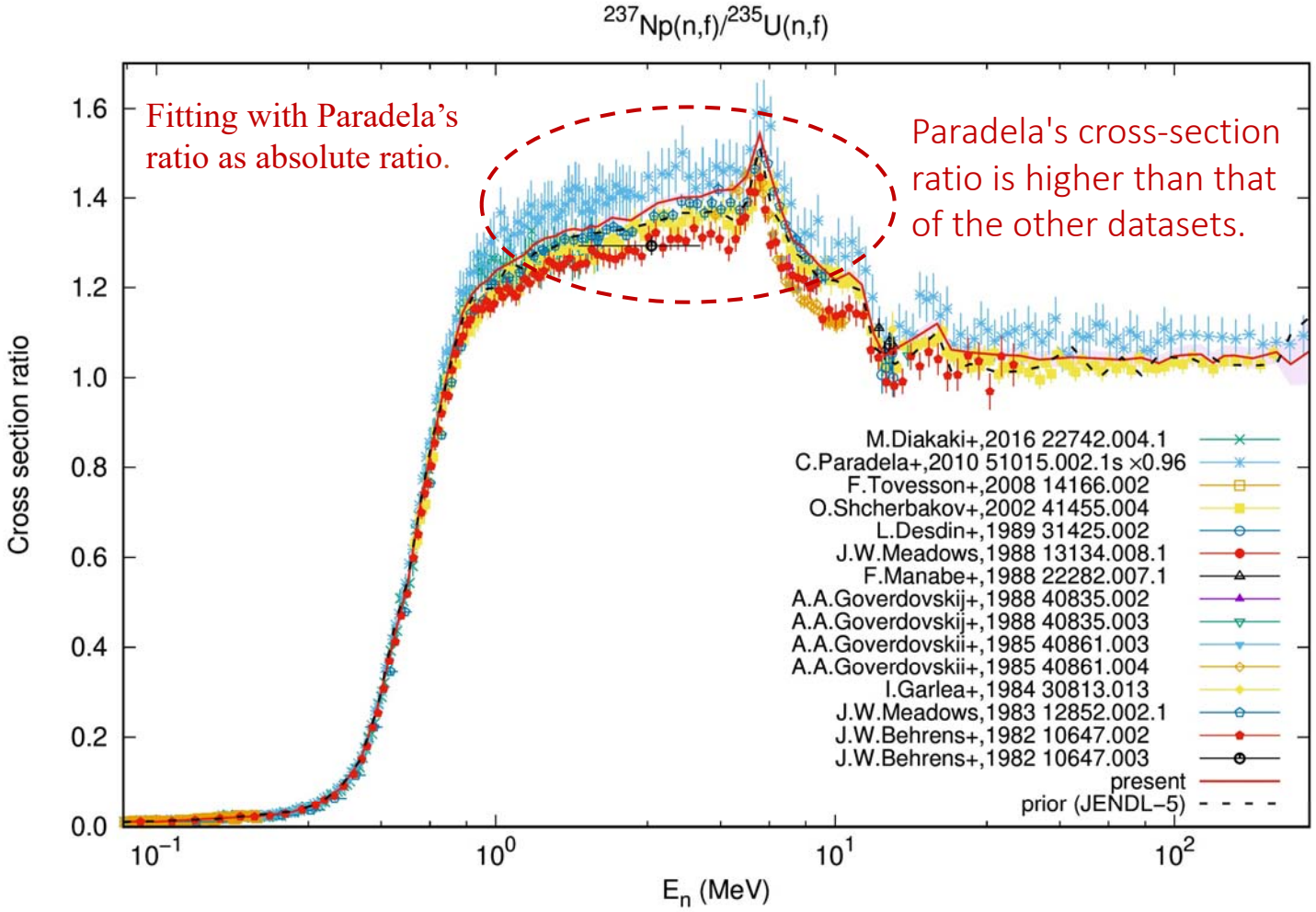
^{252}Cf(sf) fission neutron spectrum average cross sections (SACS) relative to Grundl et al.



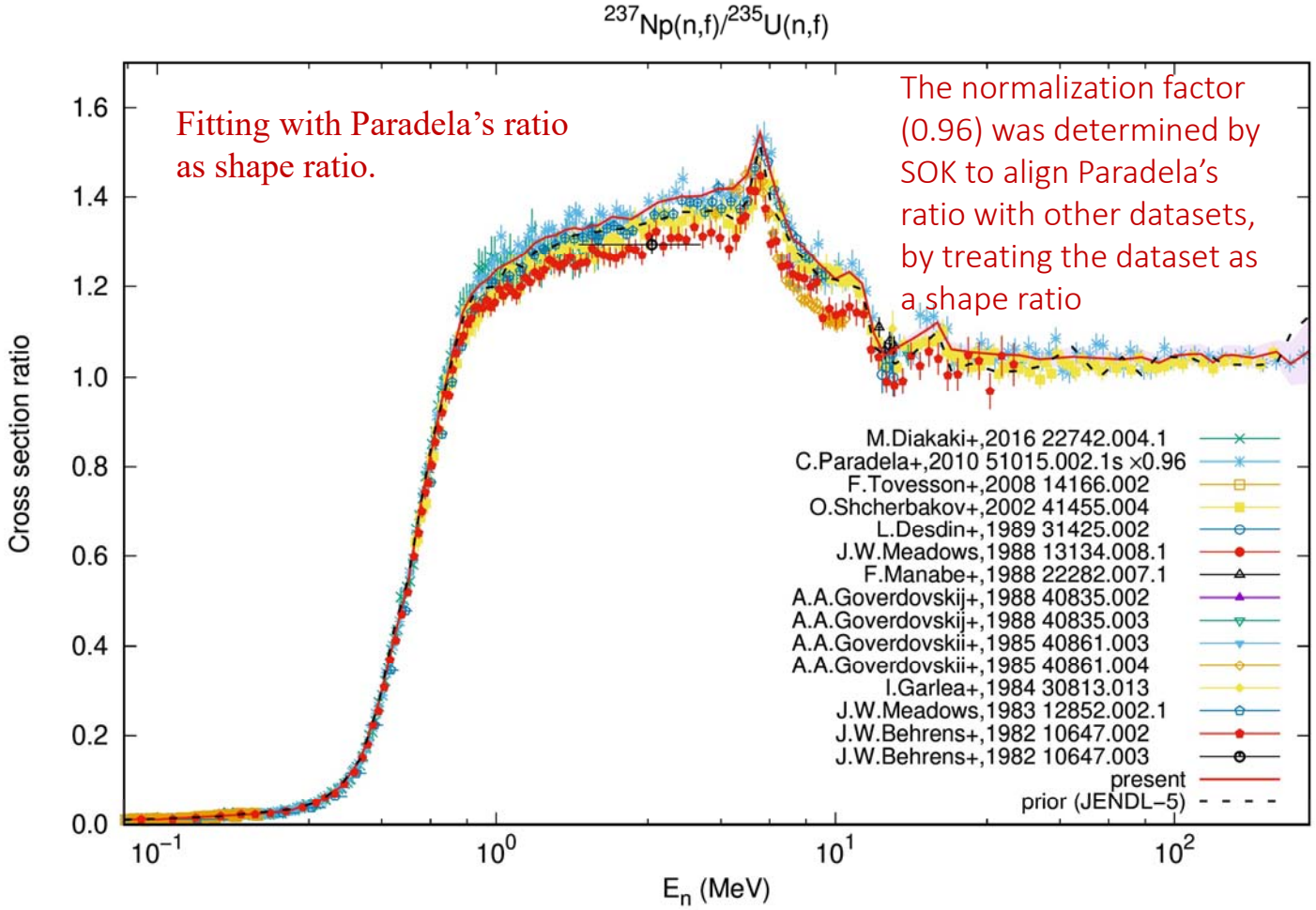
Preliminary result: Simultaneous fitting of ^{237}Np with ^{233,235,238}U, $^{239\text{-}241}$Pu fission cross section.



Preliminary result: Simultaneous fitting of ^{237}Np /^{235}U with ^{233,235,238}U, $^{239\text{-}241}$Pu fission cross section.



Preliminary result: Simultaneous fitting of ^{237}Np /^{235}U with ^{233,235,238}U, $^{239\text{-}241}$Pu fission cross section.



Summary

- **Revision of EXFOR entries** with other centres for direct use of EXFOR entries as inputs to least-squares analysis
- Simultaneous evaluation of ^{232}Th(n,f), ^{233,235,238}U and $^{239\text{-}241}$Pu till 200 MeV with SOK:
  - ^{232}Th: Our cross sections systematically lower than JENDL-5. SACS from our cross sections is 11% lower than Grundl et al.'s and closer to other libraries than JENDL-5.
  - ^{237}Np: Our cross sections are higher than JENDL-5 above 1 MeV but all datasets align better with JENDL-5 and the present evaluation below 1 MeV.

Work in progress

Future work will involve completing the study of simultaneous evaluation of ^{237}Np(n,f), ^{233,235,238}U and $^{239\text{-}241}$Pu and their validation against spectrum-averaged cross section measurements in the ^{252}Cf spontaneous fission neutron field.

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