A detailed validation of two deterministic models of prompt emission: PbP and sequential emission

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PbP and sequential emission modelings

Similarities and differences

Both modelings work with the **same fragmentation range** constructed as following:

- the initial fragment mass range A is going from symmetric fragmentation up to a very asymmetric split (with a step of 1 mass unit)
- 3 or 5 charge numbers Z are considered for each A, as the nearest integer values above and below the most probable charge $Zp(A) = Z_{UCD}(A) + \Delta Z(A)$
- for each fragmentation ($A, Z; A_0-A, Z_0-Z$) the calculations are done at TKE values covering a large range, e.g. from 100 to 200 MeV, usually with a step size of 5 MeV. Step sizes of 2 MeV or 1 MeV are used, too.

Both models use the **same TXE partition** based on modeling at scission:

- calculation of the extra-deformation energy of fragments at scission compared to full acceleration $\Delta E_{def} = E_{LDM}(\beta_{sciss}) - E_{LDM}(\beta_{full\ acc.})$
- partition of the available excitation energy at scission (obtained by subtracting ΔE_{def} of the light and heavy fragments from TXE) between the nascent fragments under the assumptions :
  - statistical equilibrium at scission (equal nuclear temperatures of nascent frag.)
  - level densities of nascent fragments in the Fermi-gas regime

- **PbP – the sequential emission is globally taken into account by a residual temperature distribution P(T)**

$$\phi(\varepsilon) = \int_0^{T\max} P(T)\,\varphi(\varepsilon,T)\,dT$$

in the center-of-mass frame

$$\varphi(\varepsilon,T) = K(T)\,\varepsilon\,\sigma_c(\varepsilon)\exp(-\varepsilon/T) \qquad K(T) = \left(\int_0^{\infty} \varepsilon\,\sigma_c(\varepsilon)\exp(-\varepsilon/T)\,d\varepsilon\right)^{-1}$$

with $\sigma_c(\varepsilon)$: optical model calc. with phenomenological potentials adequate for nuclei appearing as FF (B-G, K-D etc.) or analytical expressions or constant

A.Tudora, F.-J.Hambsch, *Eur. Phys.J A*, 53 (2017) 159 and references therein

- **Sequential emission treatment based on the successive equations of residual temperature**

$$\overline{E_r}^{(k-1)} - S_n^{(k-1)} - <\varepsilon>_k = a_k\,T_k^2$$

$$\overline{E}_r^{(0)} = E^*$$ **of the initial fragment from the TXE partition**

Solved for each emission sequence k corresponding to each initial fragment A, Z at each TKE value

All details: **A.Tudora, F.-J.Hambsch, V.Tobosaru, *Eur. Phys.J A*, 54(5) (2018) 87**

The equations of residual temperature are solved under the approximations:

- **analytical expression of $\sigma_c(\varepsilon)$** $\sigma_c(\varepsilon) = \sigma_0 (1 + \alpha / \sqrt{\varepsilon})$
- **non-energy dependent level density parameter of fragments**

(e.g. Egidy-Bucurescu systematic 2009 for BSFG, G-C systematic etc.)

Supported by :

- **a deviation of <ε> based on analytical $\sigma_c(\varepsilon)$ from <ε> based on $\sigma_c(\varepsilon)$ from OM calculation is less than 4%**
- **non-energy dependent lev. dens. parameters of the EB-2009 systematic for BSFG which deviate less than 10% from the ones of the superfluid model of Ignatiuk over the entire A range, except around 130, especially at low residual excitation energies.**

Primary results of both modelings :

- **PbP – the multi-parametric matrices of different quantities characterizing the fragments and the prompt emission q(A,Z,TKE)**
  (e.g. ν(A,Z,TKE), Eγ(A,Z,TKE), <ε>(A,Z,TKE), a(A,Z,TKE) etc.)

- **Sequential emission - q_k(A,Z,TKE) averaged over the number of sequences, i.e.**

$$\bar{q}(A,Z,TKE) = \frac{1}{k_{max}(A,Z,TKE)} \sum_{k=1}^{k\,max} q_k(A,Z,TKE)$$

I. First validation, i.e. of the prompt emission model itself

It consists of the comparison of multi-parametric matrices q(A,TKE) with the existing experimental data (e.g. ν(A,TKE), Eγ(A,TKE) etc.)
In this case the Y(A,TKE) distributions are not involved.

II. Second validation, i.e. of a prompt emission model together with the Y(A,TKE) distribution

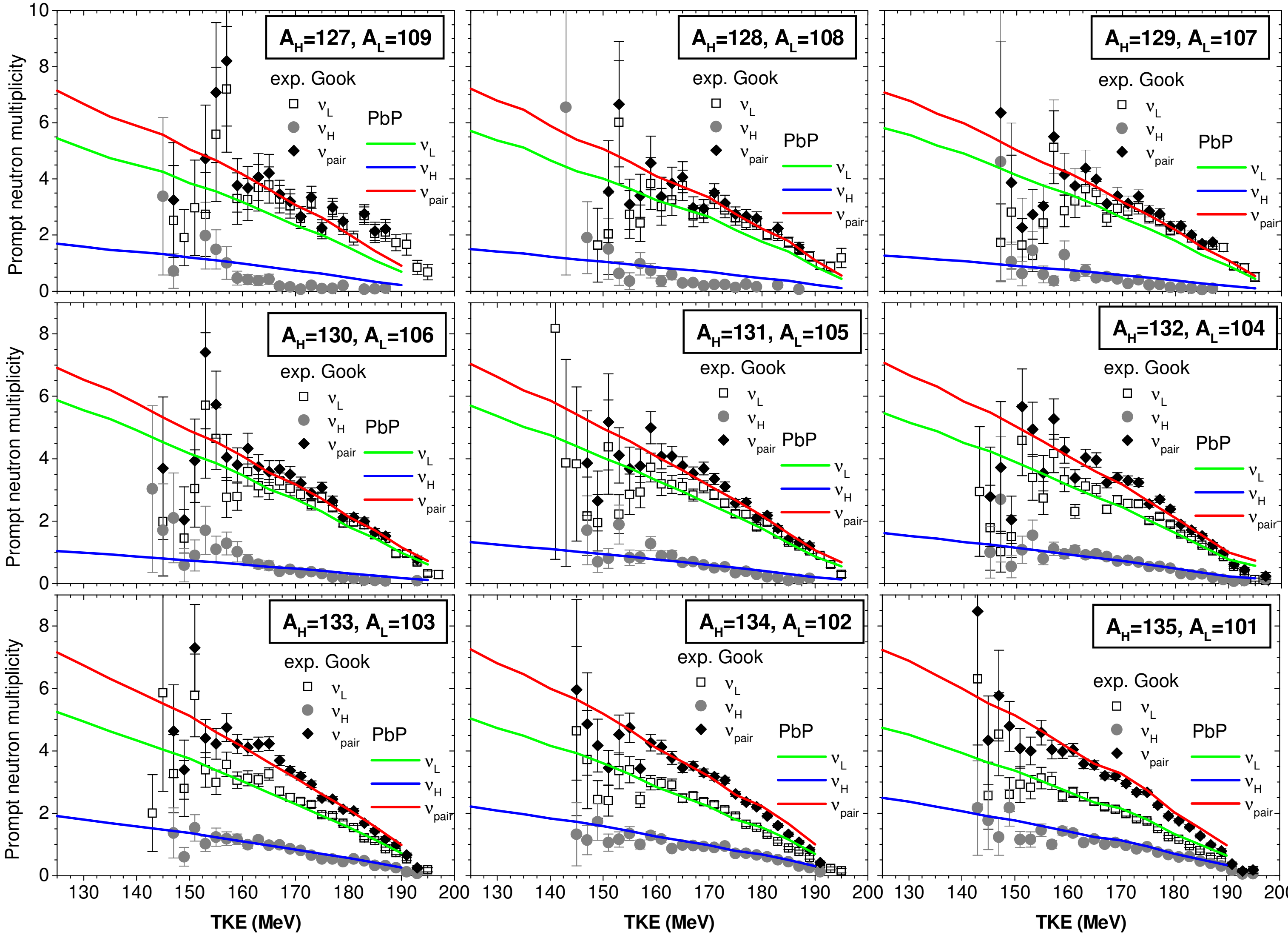
It consists of the comparison of different single distributions and total average values of prompt emission quantities with the available experimental data (e.g. ν(A), <ν>(TKE), <Eγ>(A), <Nγ>(A), <ε>(A), <ε>(TKE), PFNS, $<\nu_p>_{tot}$, $<E\gamma>_{tot}$ etc.)

Both PbP and sequential emission modelings were submitted to both validations mentioned above, being compared with the exp. data available in the last 10 years. The most recent refs are:

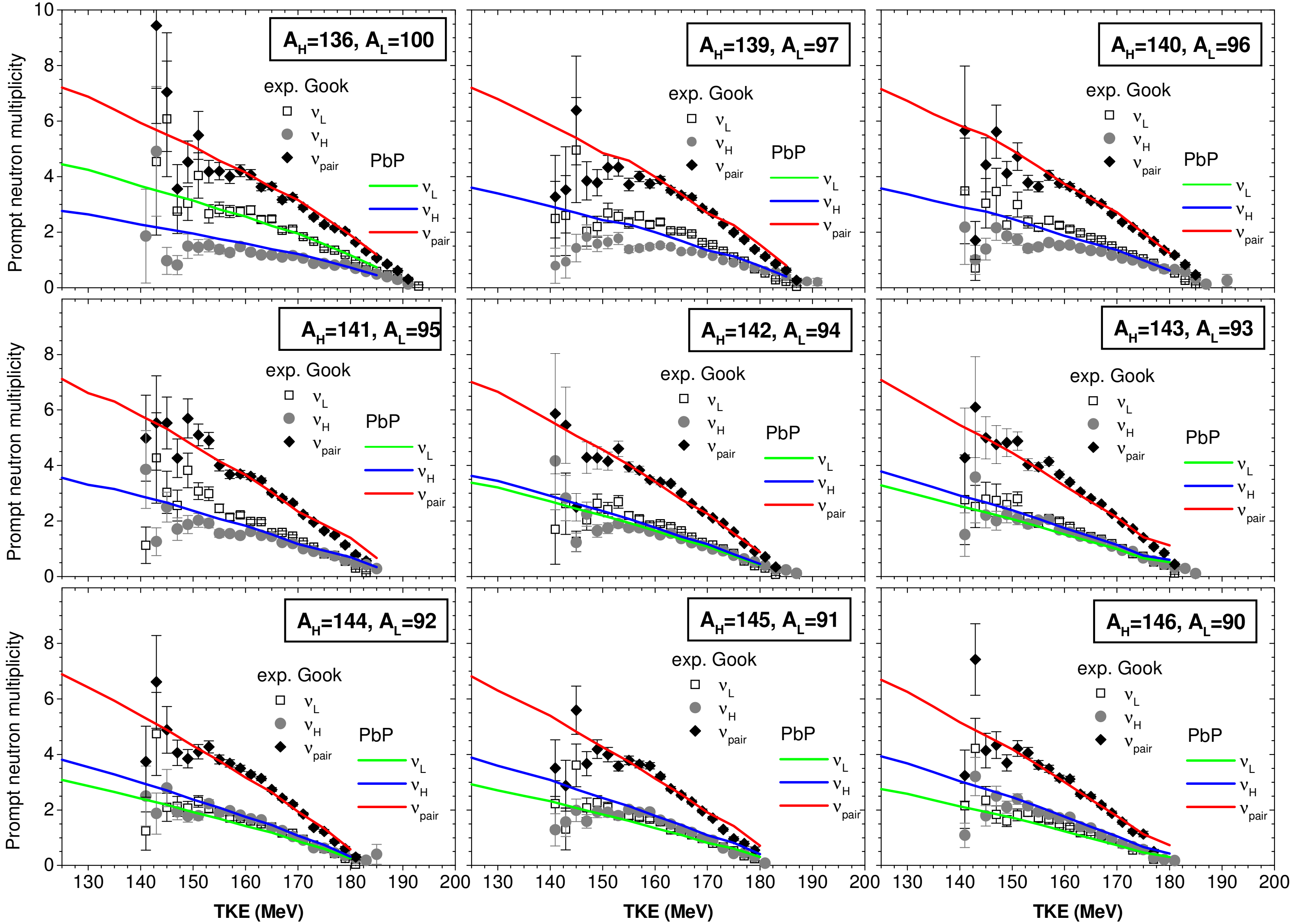
- ***"Comprehensive overview of the Point-by-Point model of prompt emission in fission"*, A.Tudora, F.-J.Hambsch, *Eur.Phys.J A*, 53(8) (2017) 159**
- ***"Revisiting the residual temperature distribution in prompt neutron emission in fission"* A.Tudora, F.-J.Hambsch, V.Tobosaru, *Eur.Phys.J A*, 54(5) (2018) 87**
- ***"Prompt emission calculations for $^{233}U(n_{th},f)$"*, A.Tudora, A.Matei, *Roum.J.Phys.* 2018, in press**

Here, only a supplementary validation based on the very recent exp. data for $^{235}U(n,f)$ measured at JRC-Geel (Göök et al., Phys.Rev.C. 2018)

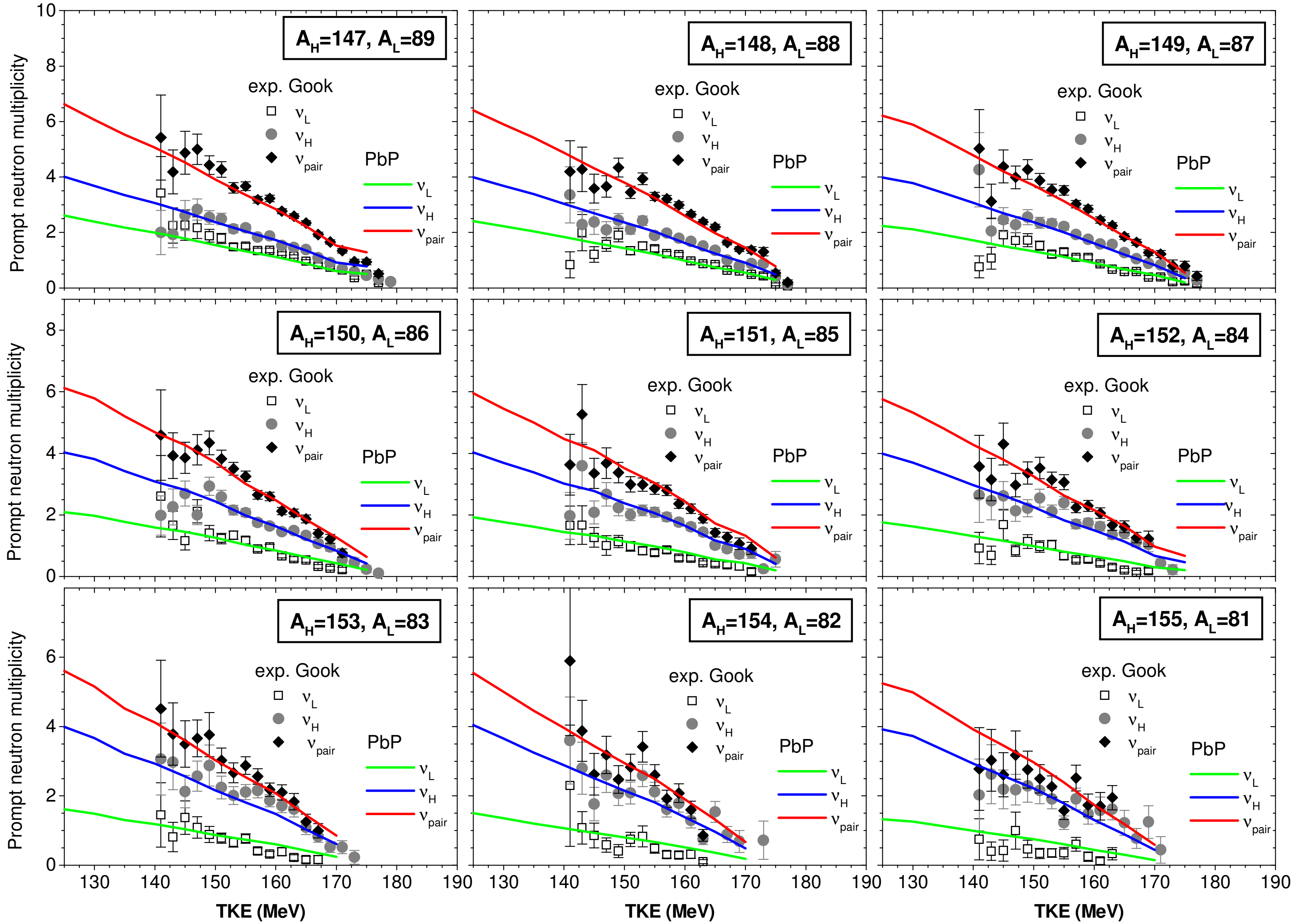
PbP result of ν(A,TKE) for $^{235}U(n_{th},f)$ compared with the recent data of Göök et al. (measured in the En range 0.26 eV – 45 keV)



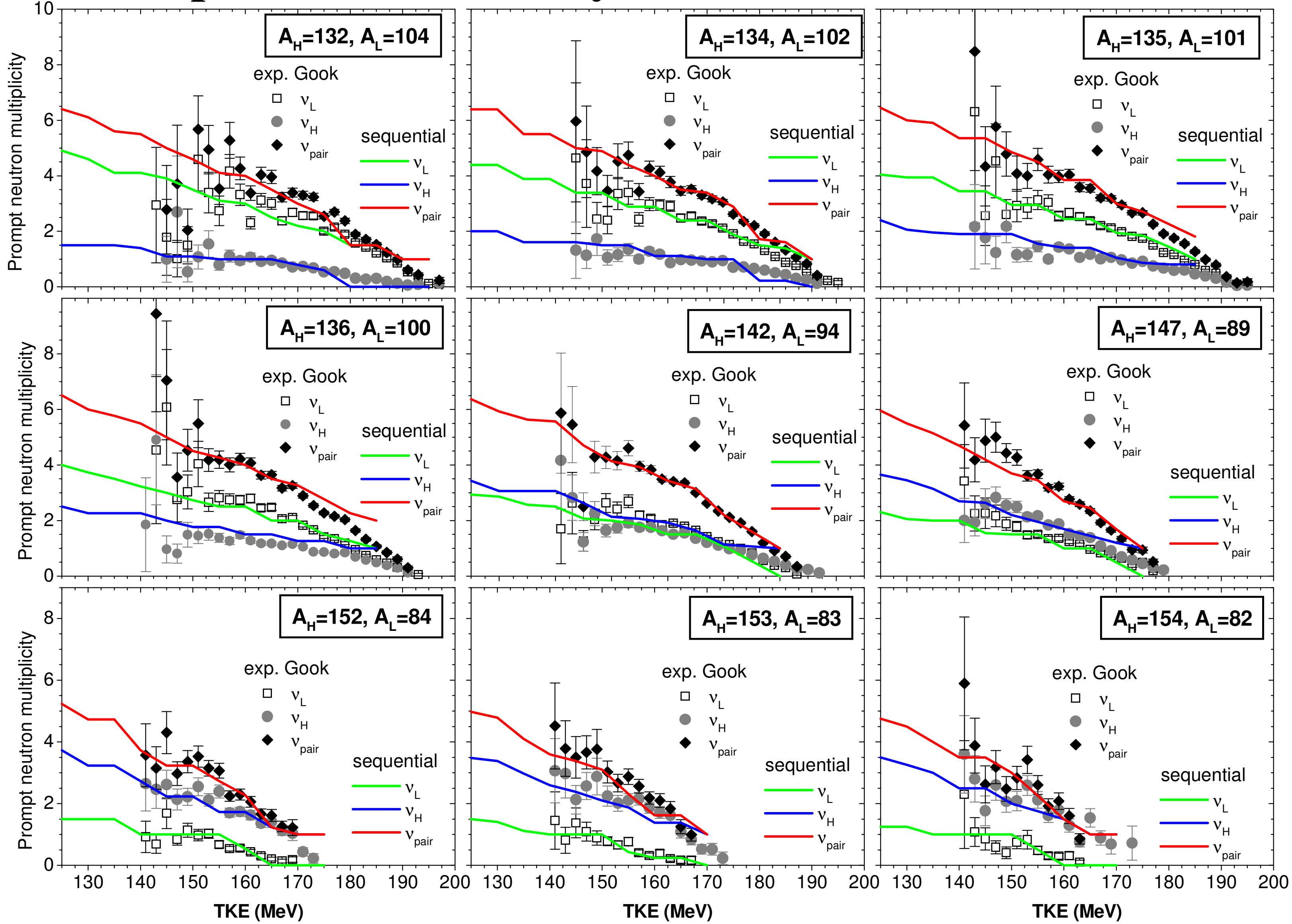
PbP result of ν(A,TKE) for $^{235}U(n_{th},f)$ compared with the very recent data of Göök et al.



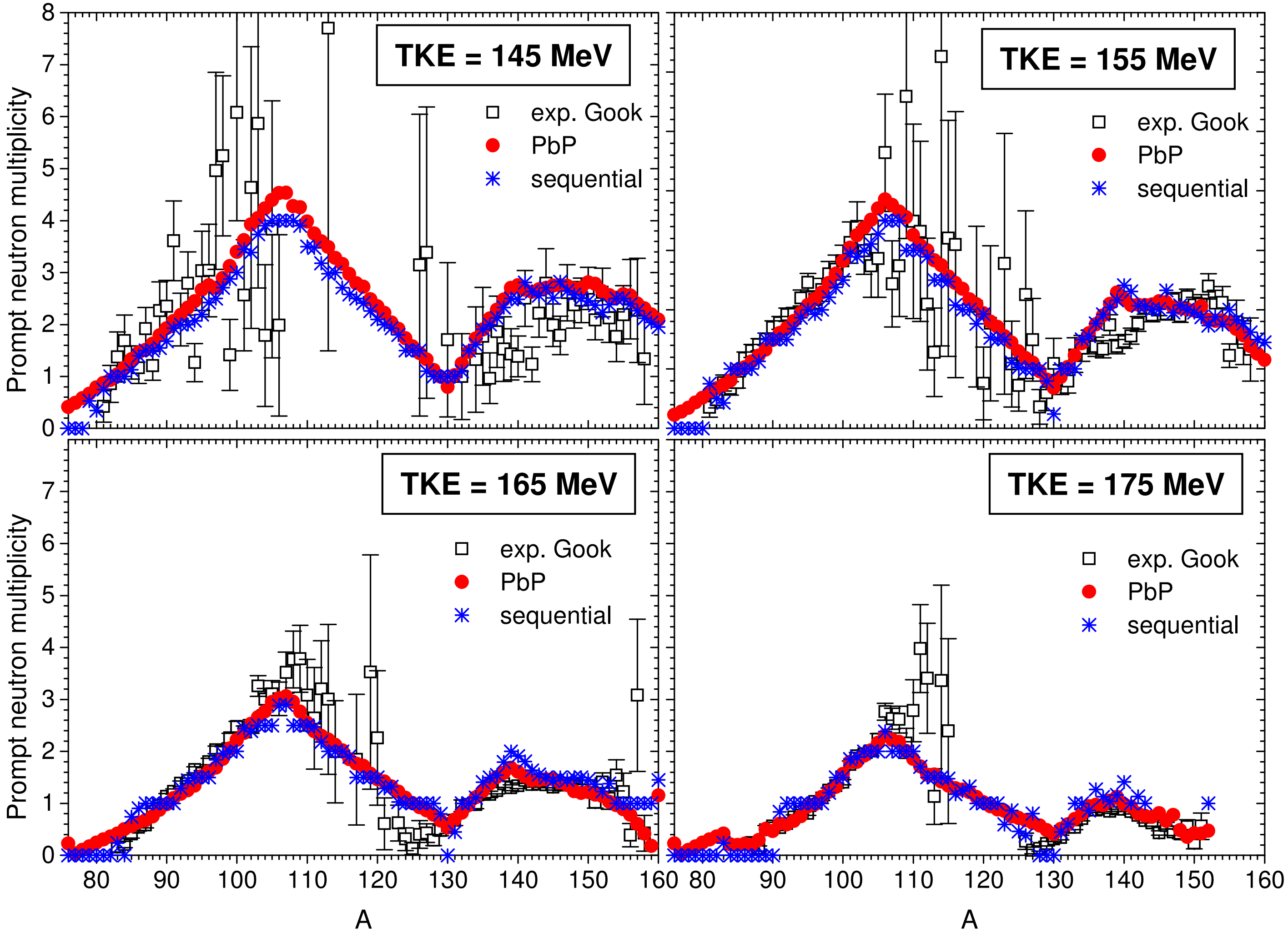
PbP result of ν(A,TKE) for $^{235}U(n_{th},f)$ compared with the very recent data of Göök et al.



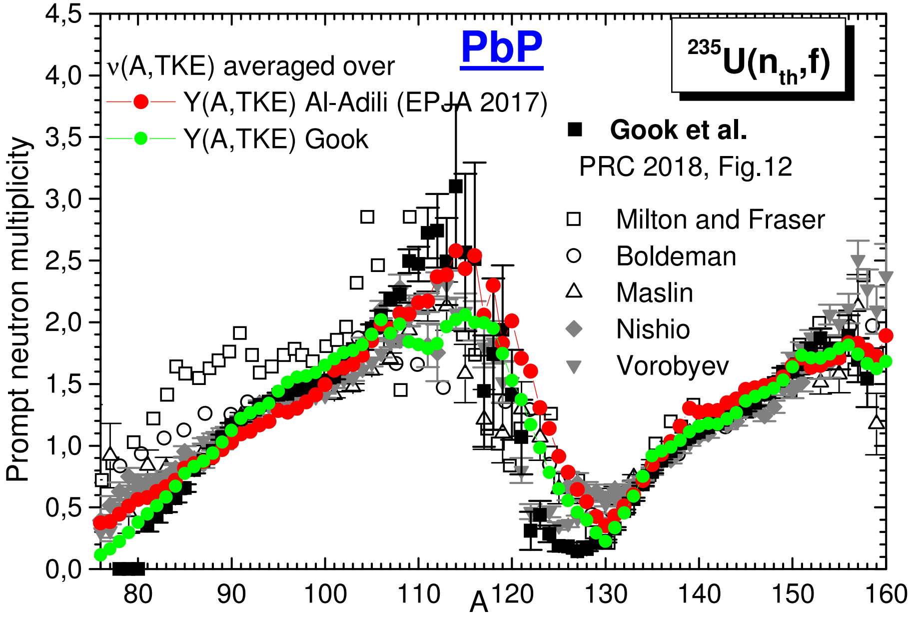
Sequential emission result of ν(A,TKE) for $^{235}U(n_{th},f)$ compared with the very recent data of Göök et al.

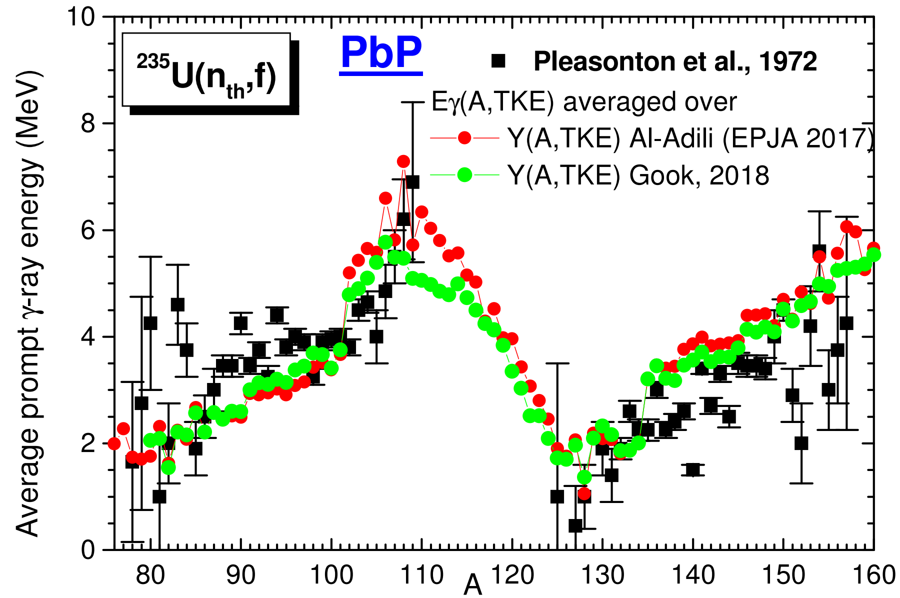


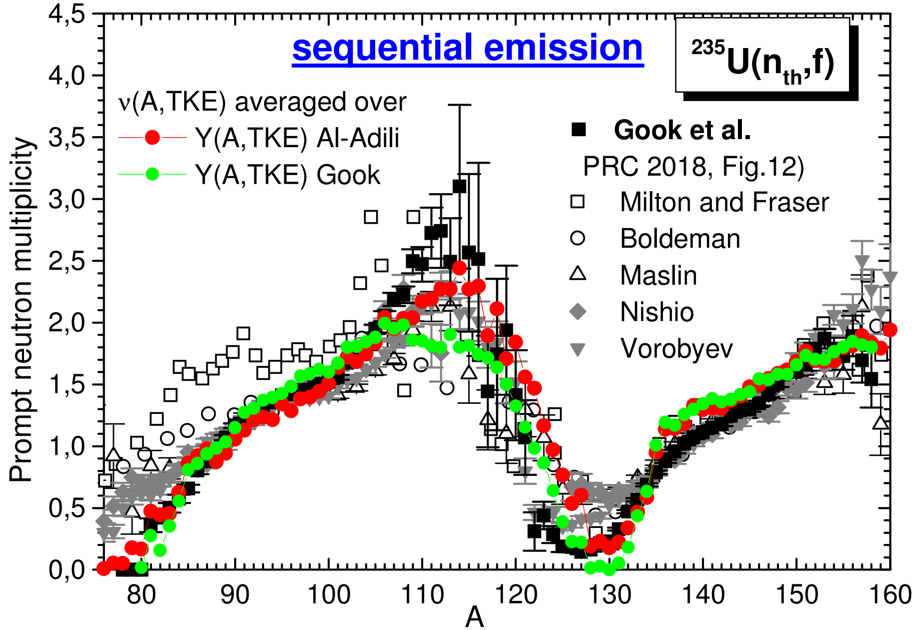
ν(A,TKE) results of PbP and sequential emission for $^{235}U(n_{th},f)$ compared with very recent data of Göök et al.

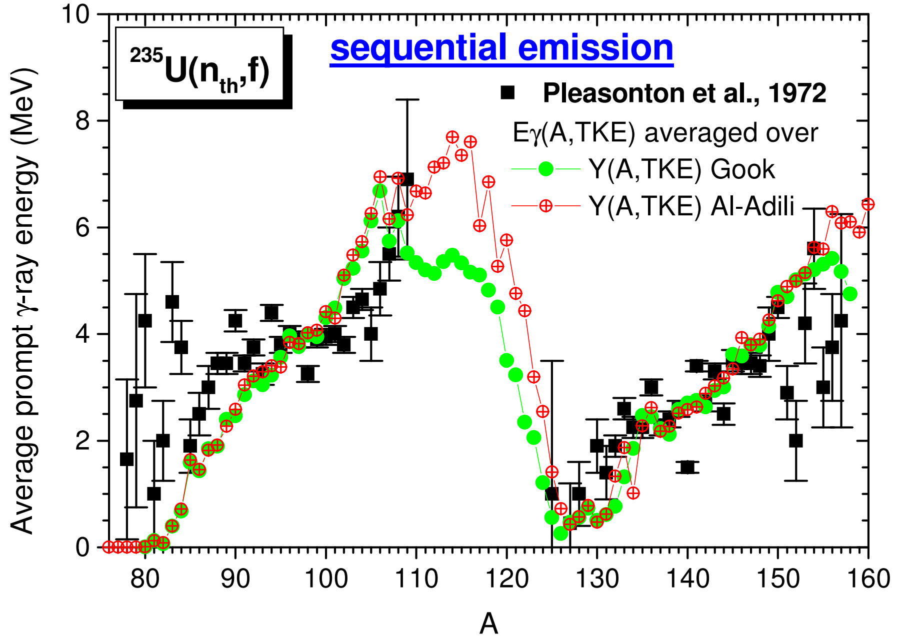


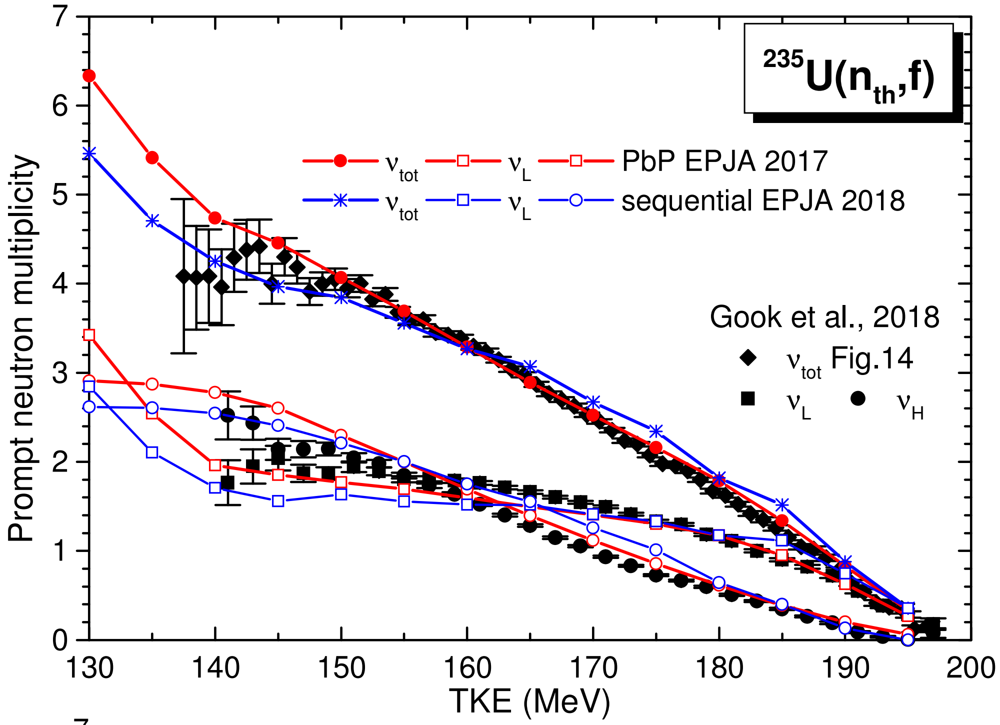
Average quantities, single distributions – influence of Y(A,TKE)



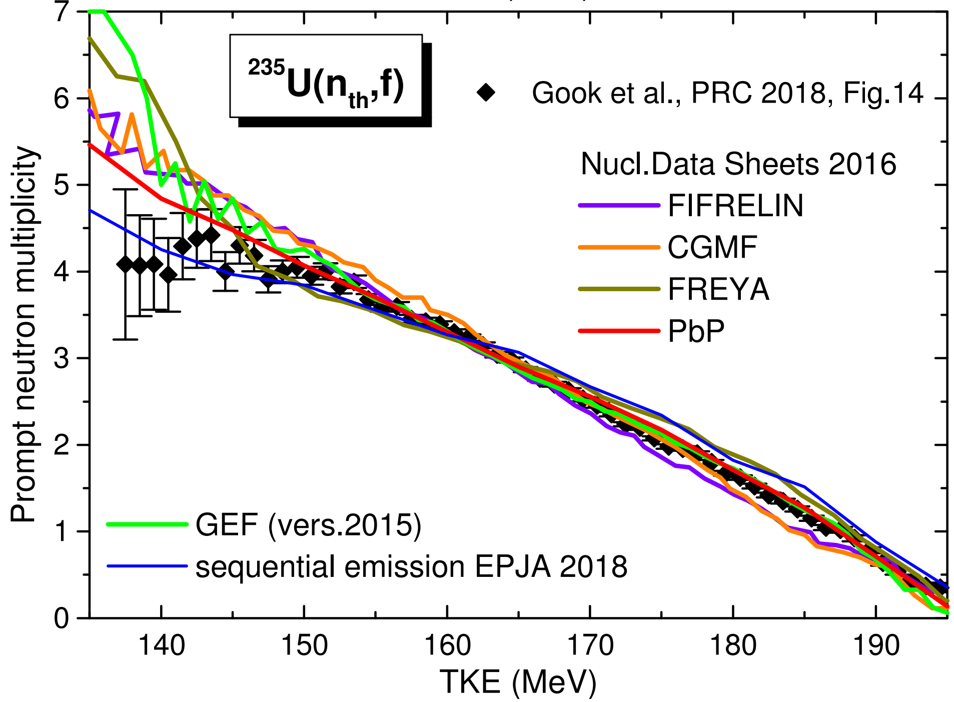








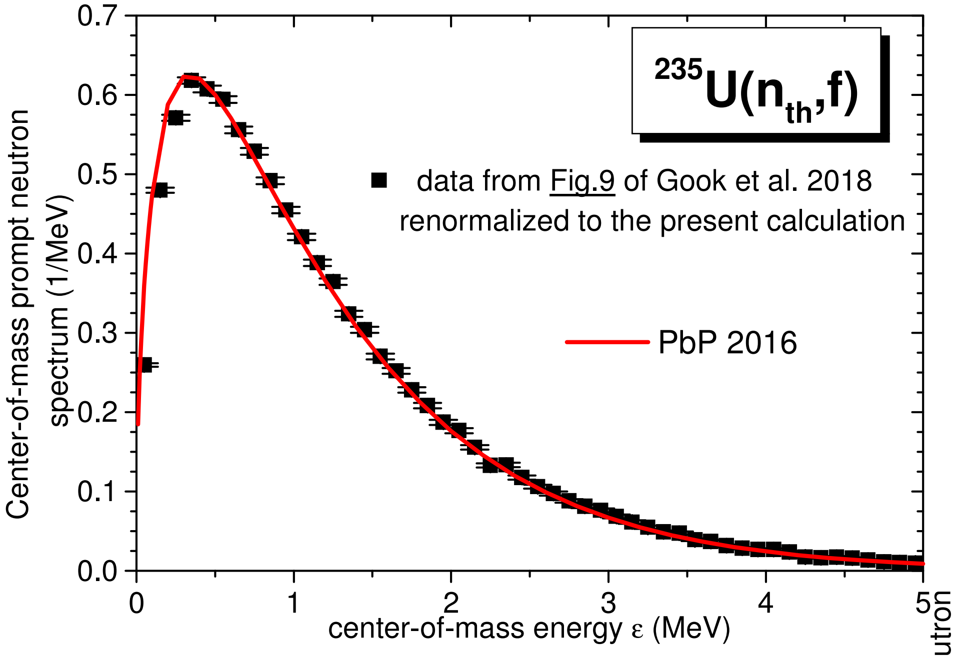
$\langle\nu\rangle$(TKE) obtained by averaging ν(A,TKE) over Y(A,TKE) of Göök et al. and of Al-Adili et al. do not differ significantly from each other because the difference between their Y(TKE) projections are very low, almost insignificant. Consequently here only the PbP and sequential emission results based on Y(A,TKE) of Al-Adili are given.



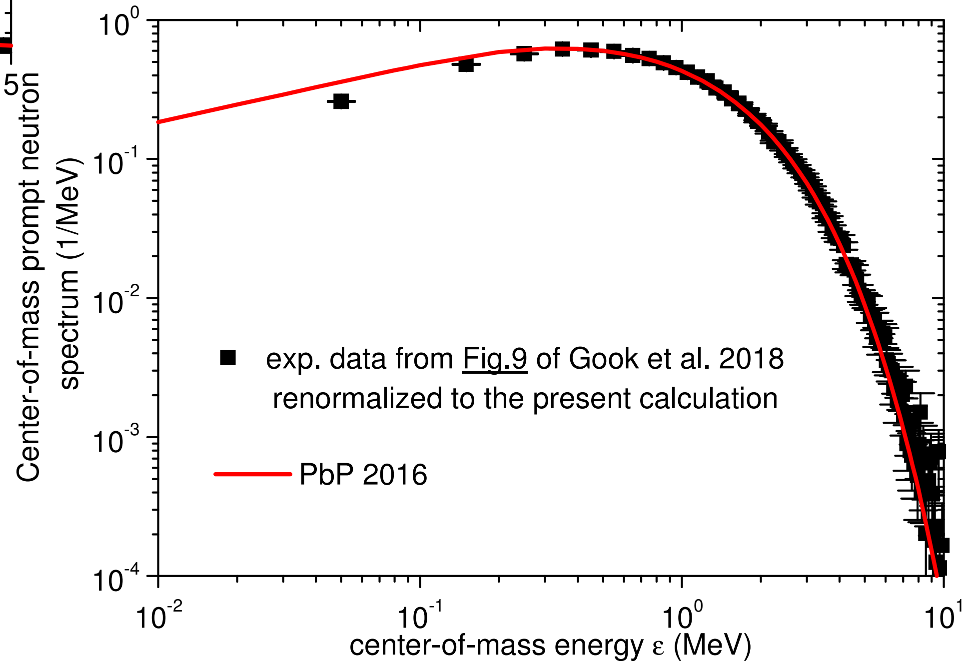
The $\langle\nu\rangle$(TKE) predictions of FIFRELIN, CGMF, FREYA and PbP reported in 2016, of GEF (vers. 2015) and of the sequential emission treatment (EPJA 2018) are confirmed by the recent data of Göök et al.

The best description of these exp.data is given by the results of PbP and GEF.

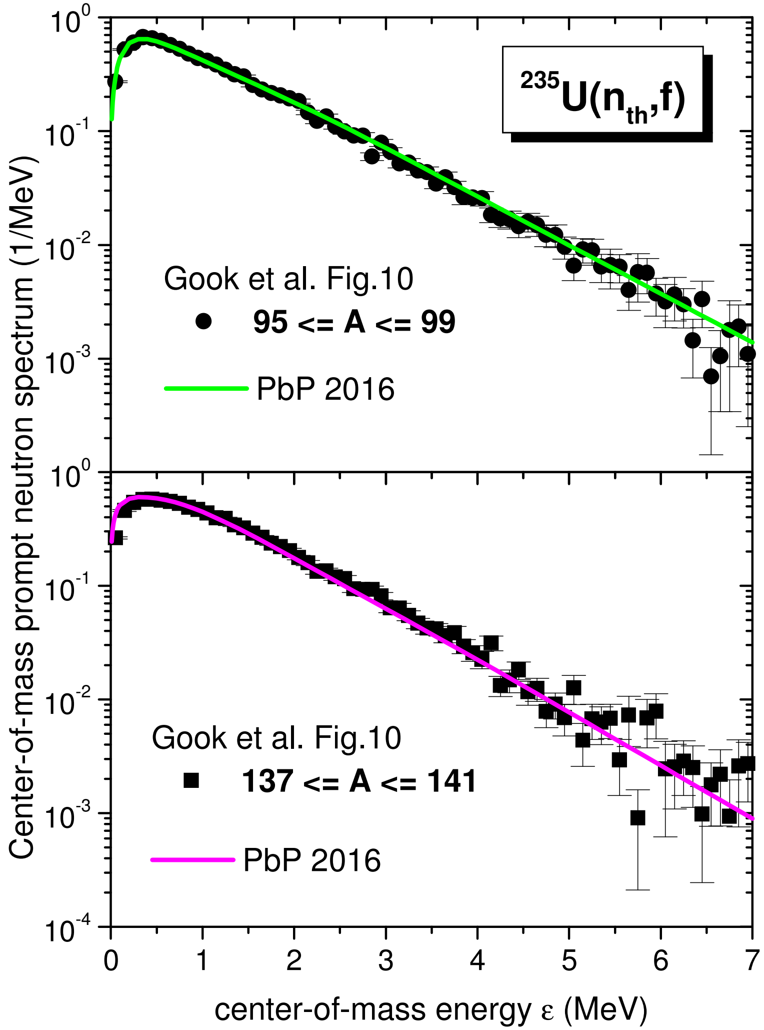
PbP result of the prompt neutron spectrum in the center-of-mass frame compared with the data of Göök et al.

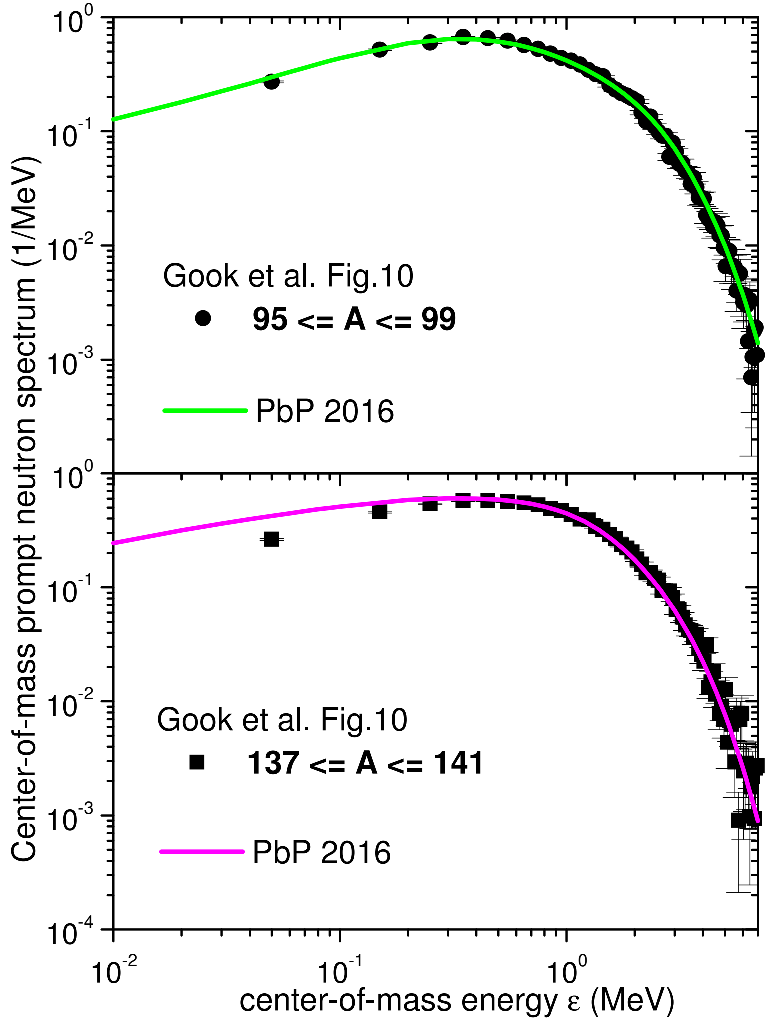


The recent data of Göök et al. from Fig.9 (PRC 2018) are very well described by the previous PbP result.
(calculated in 2016 and published in EPJA 2017)



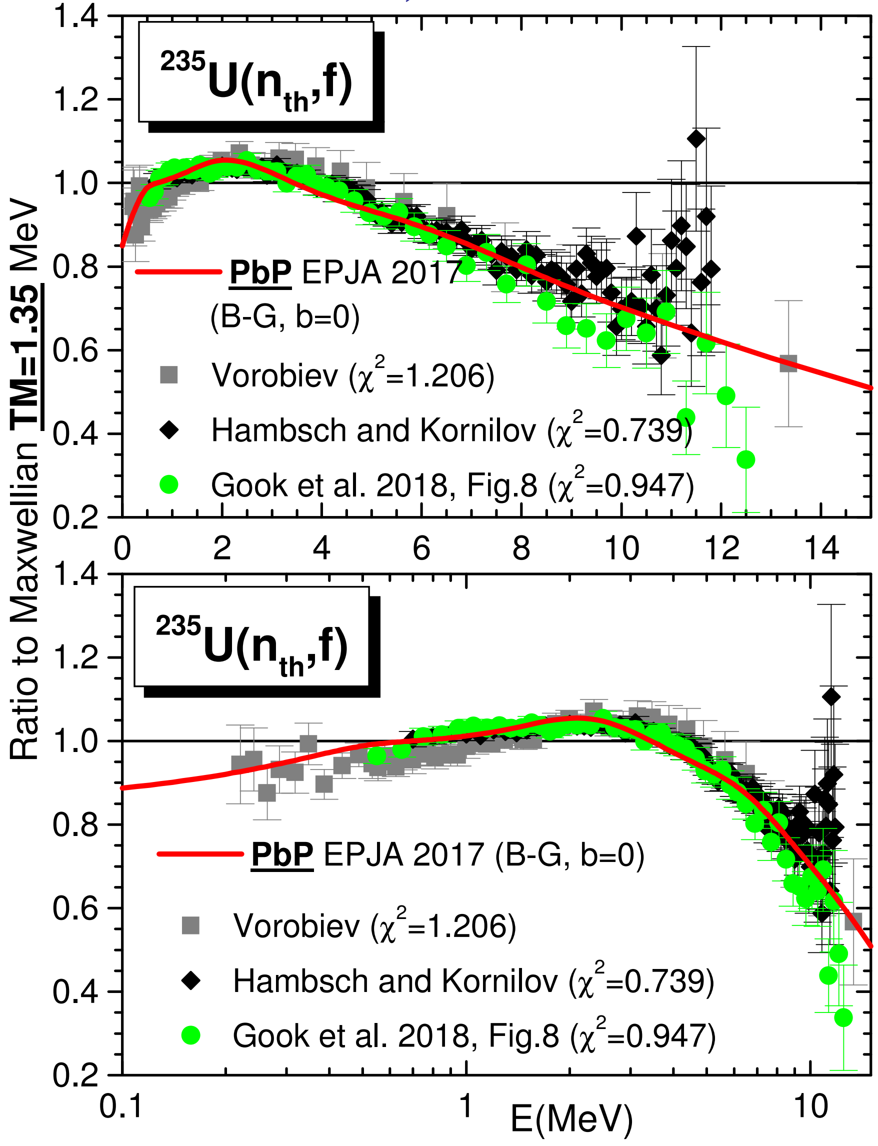
The data of Göök et al. (Fig.10 of PRC 2018) regarding the prompt neutron spectrum in the **center-of-mass frame** for selected fragment mass ranges around the most probable fragmentation (LF upper part, HF lower part) are **very well described by the PbP results** (representing the spectrum obtained by averaging over the light and heavy fragment groups, respectively).



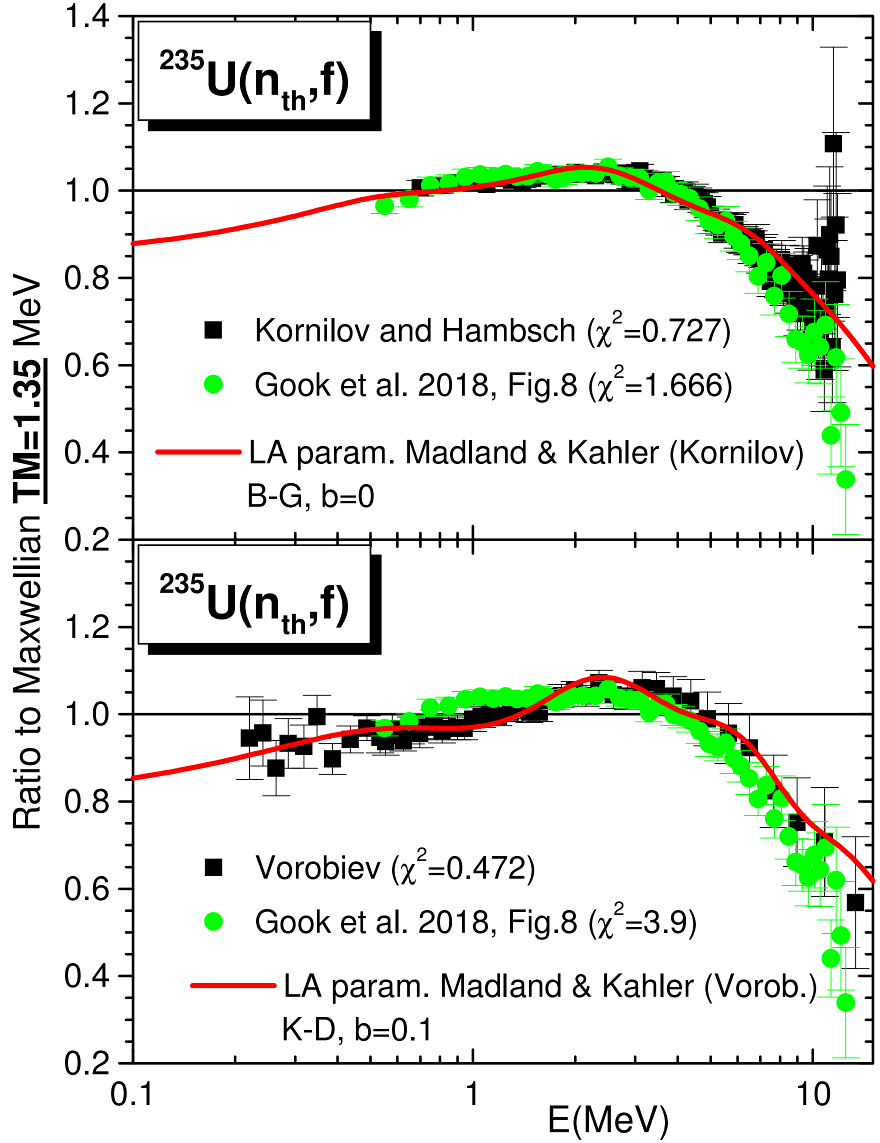


PFNS in the laboartory frame - previous results of PbP and LA (EPJA 2017) compared with the data of Göök et al. (PRC 2018, Fig.8)

PbP, EPJA 2017



LA param. Madland & Kahler 2017



- **The recent experimental data of Göök et al. for ^{235}U(n,f) confirm the predictions of the PbP and sequential emission modelings.**

- **The very good description of the experimental ν(A,TKE) data for ^{235}U(n,f) by the PbP and sequential emission results is a valuable supplementary validation of these models themselves.**

- **The very good agreement of PbP and sequential emission results for different single distributions (e.g. ν(A), ν(TKE), <ε> etc.) and total average prompt emission quantities (e.g. prompt fission neutron spectrum in the centre-of-mass and laboratory frame) validates these models together with the Y(A,TKE) distribution.**