Prompt Fission Neutron Spectra of 233U(n,F)

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Collaboration on PFNS of 2000-2011

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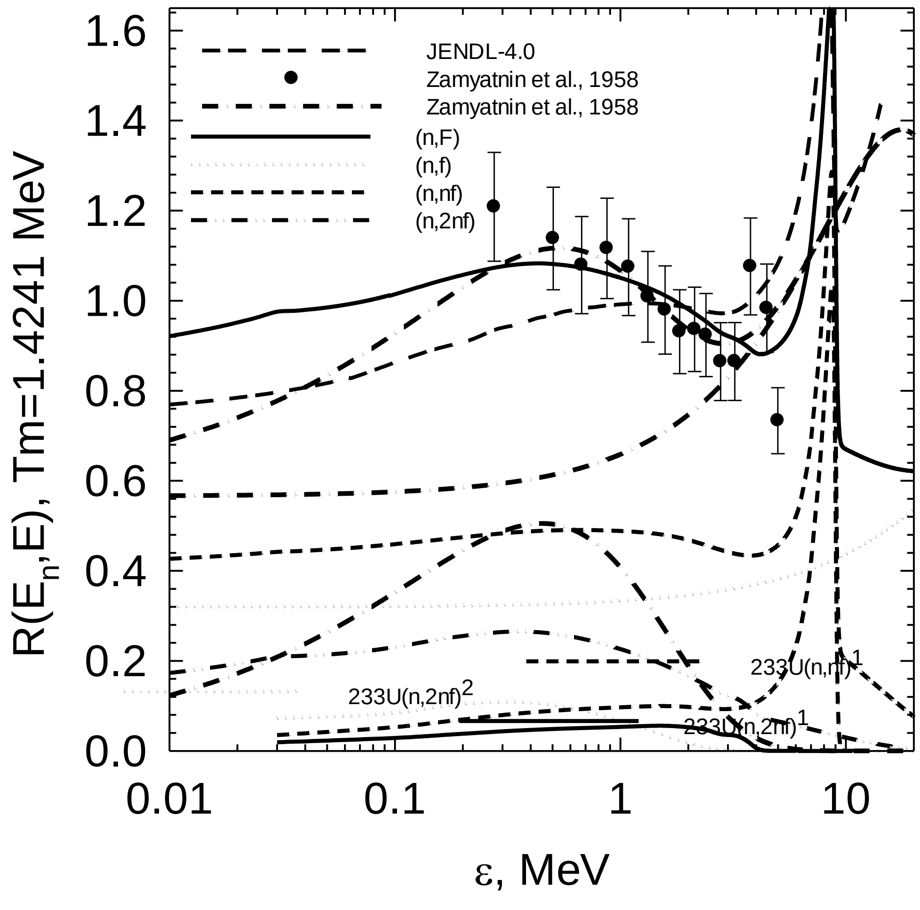
EXPERIMENTS on

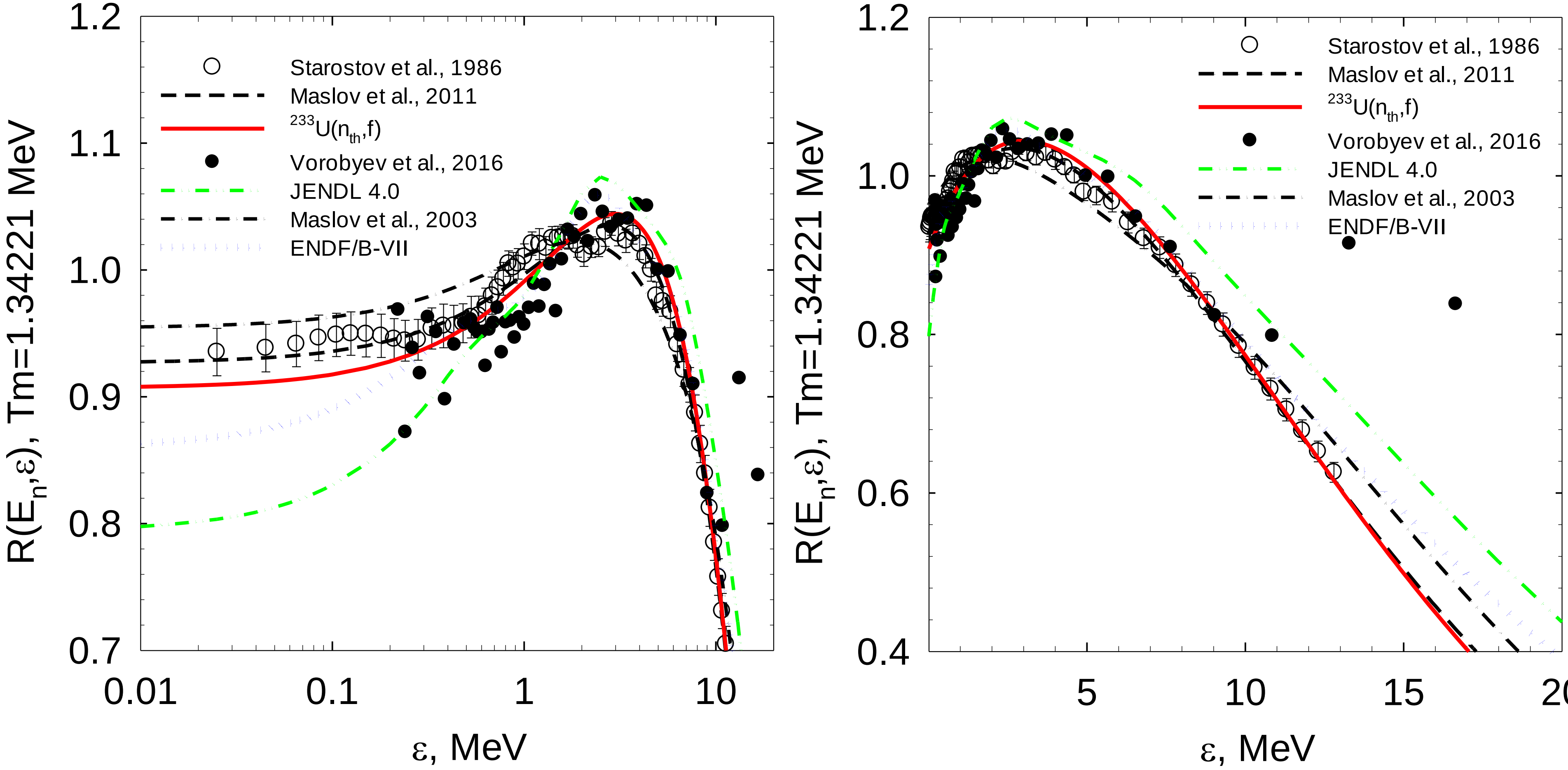
- **PFNS of 235-U(n,F) 238-U(n,F) 239-Pu(n,F)**
  LANSCE, 2019-2023
- **Asymmetry PFNS in 239-Pu(n,F) 235-U(n,F) PFNS**
  Kelly e. a., Phys. Rev. Lett., **2019**, v. 122, p. 072503
- **Asymmetry in neutron emission spectra E_n=14 MeV**
  235U+n; 239Pu+n; 238U+n – first observed by
  Kammerdiener J.L., UCRL-51232, **1972**.
- **Asymmetry in neutron emission spectra of 232Th+n**
  and 238U+n at E_n=6, 12,14, 18 MeV

For 233U(n,F) PFNS next to nothing

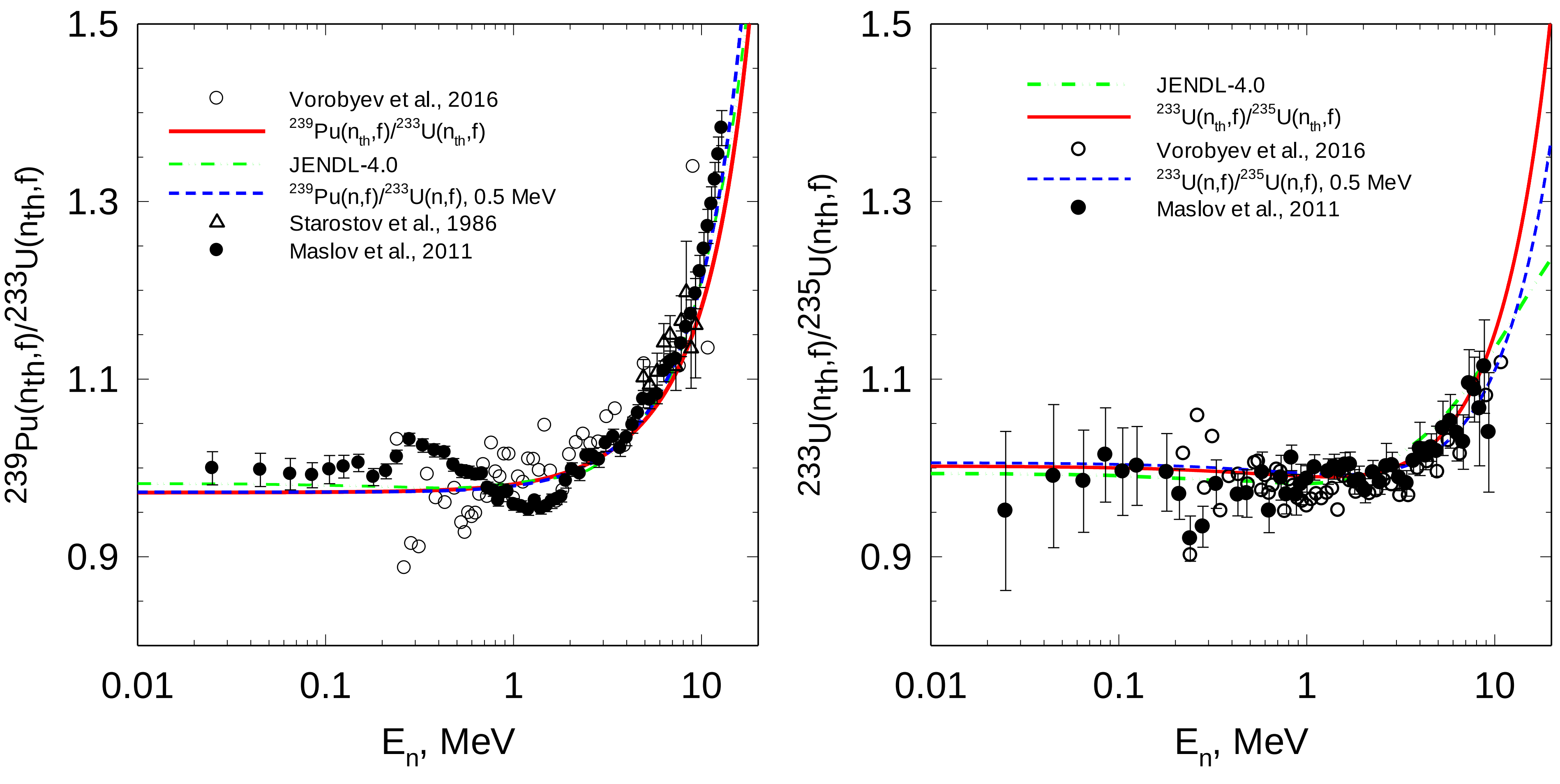
233U(n,F) PFNS En=14 MeV



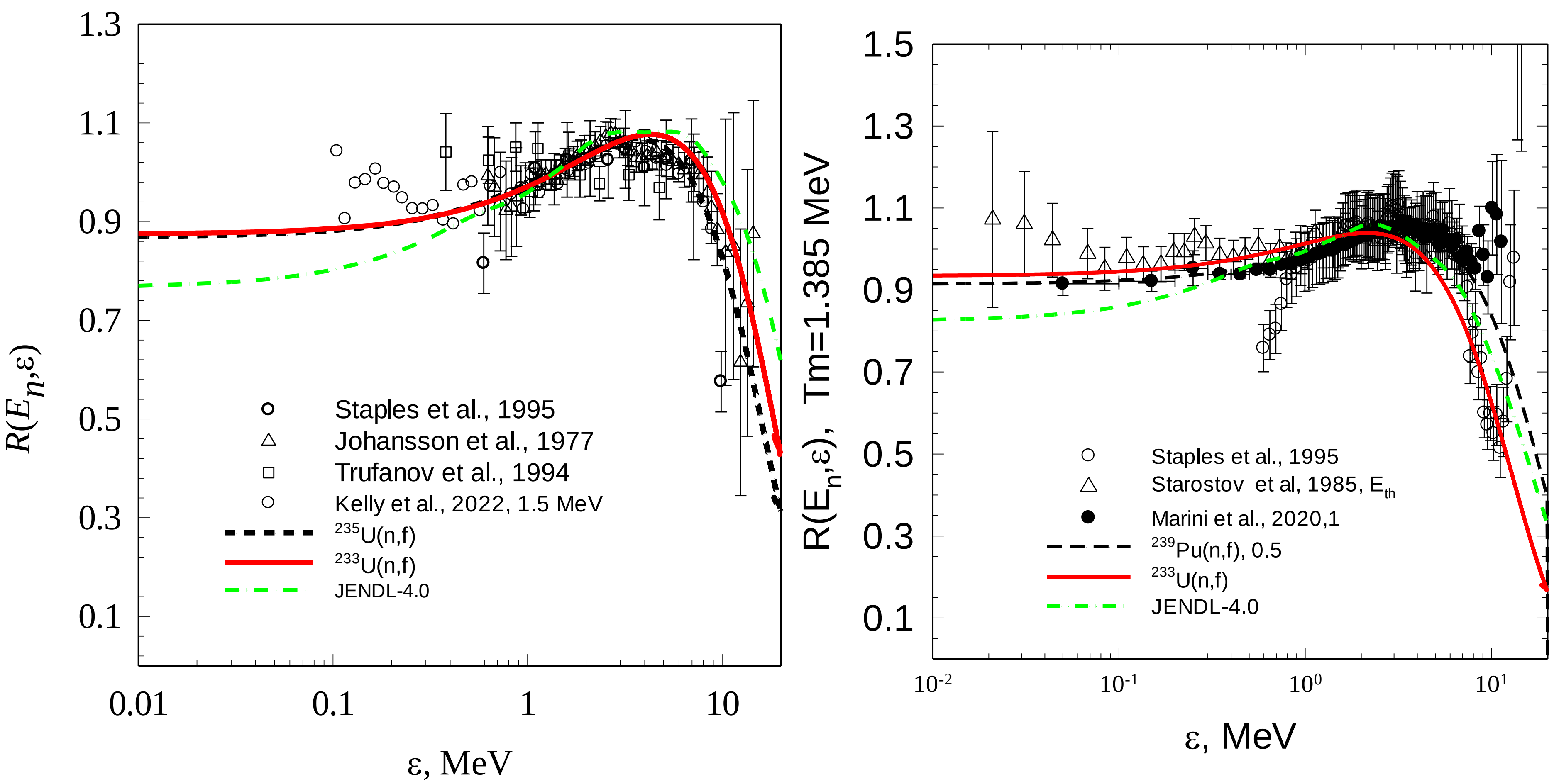
En=0.02536 eV   233U(n,F) PFNS En=0.02536 eV



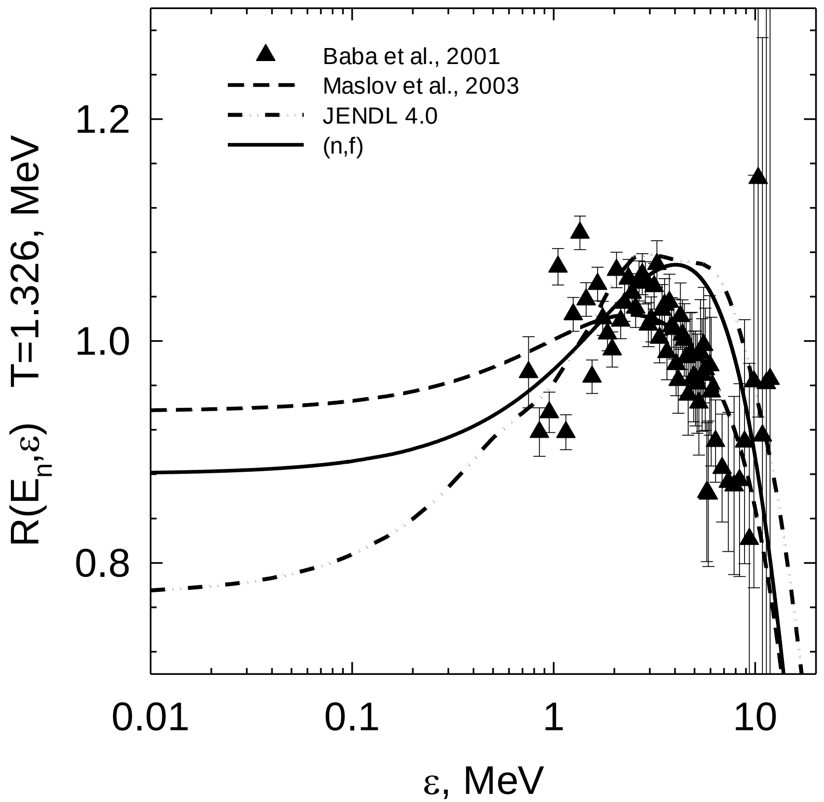
En=0.5 MeV 239Pu/233U PFNS ratio 233U/235U En=0.5 MeV



En=0.5 MeV, 1.5 MeV 233U(n,F) PFNS En=0.02536 eV 233U(n,F)
235U(n,F) 1.5 MeV 239Pu(n,F)

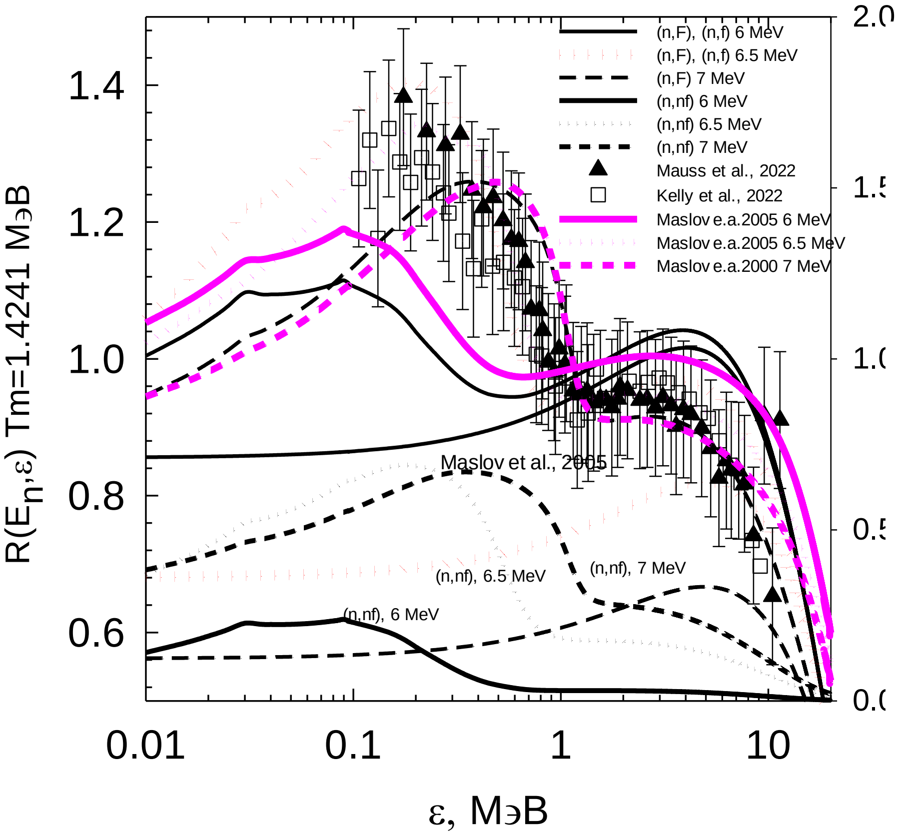


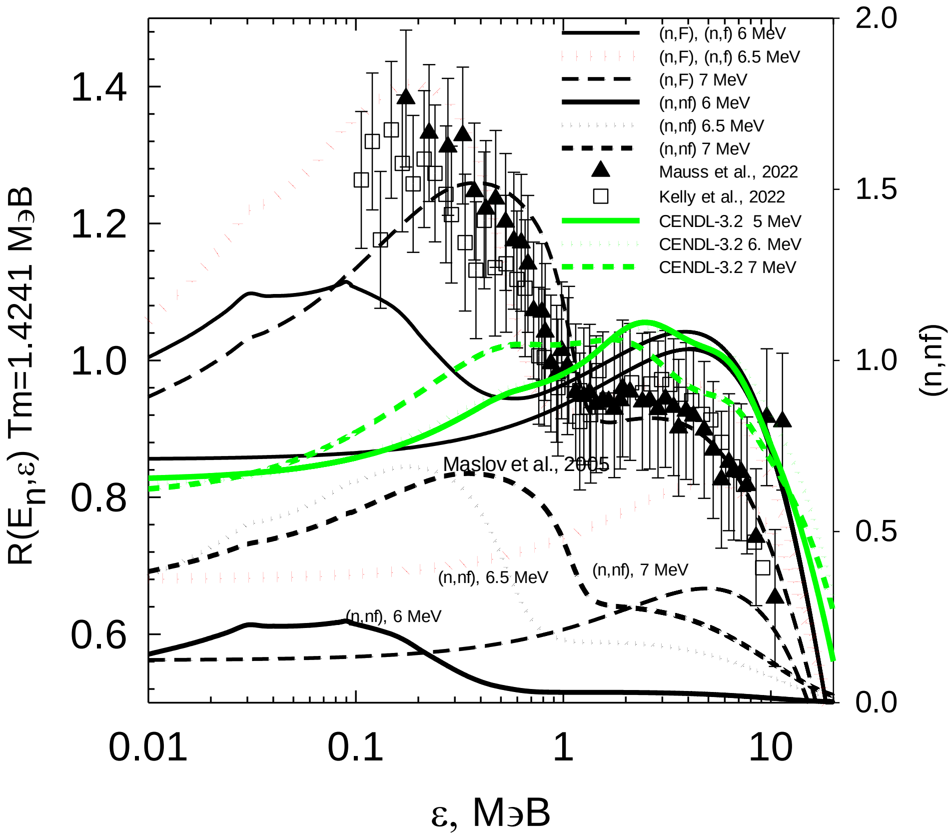
233U(n,F) PFNS En=0.5 MeV



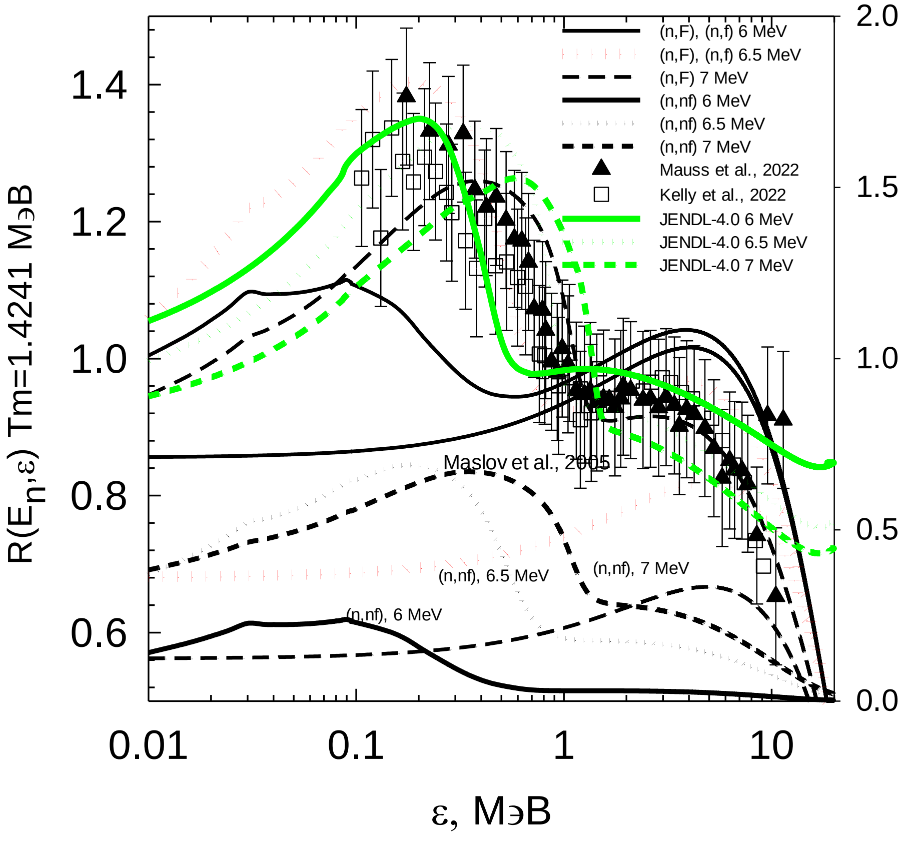
Maslov V.M. Physics of Atomic Nuclei, 2023, Vol. 86, pp. 627–669.

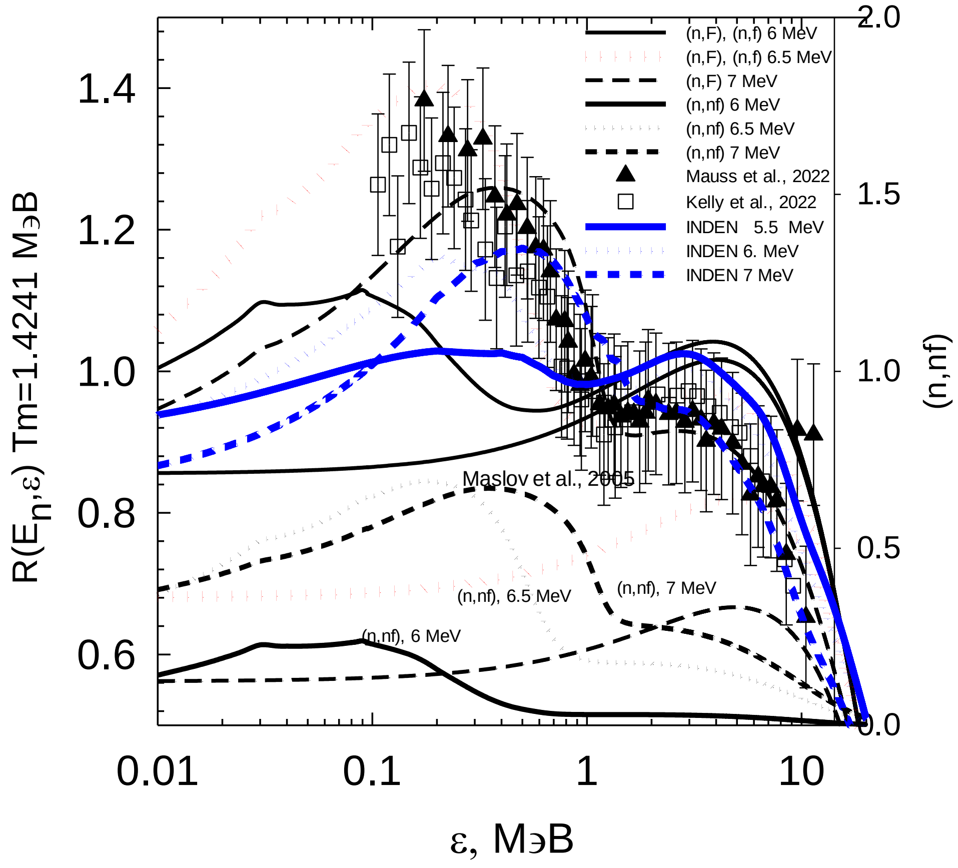
En=6.5 MeV 235U(n,F) PFNS En=6.5 MeV 235U(n,F)





Maslov V.M. Phys. At. Nucl. 2023, Vol. 86, pp. 627–669.
En=6.5 MeV 235U(n,F) PFNS En=6.5 MeV 235U(n,F)





$$\sigma_{nF}\left(E_n\right)=\sigma_{nf}\left(E_n\right)+\sum_{x=1}^{X}\sigma_{n,xnf}\left(E_n\right)$$

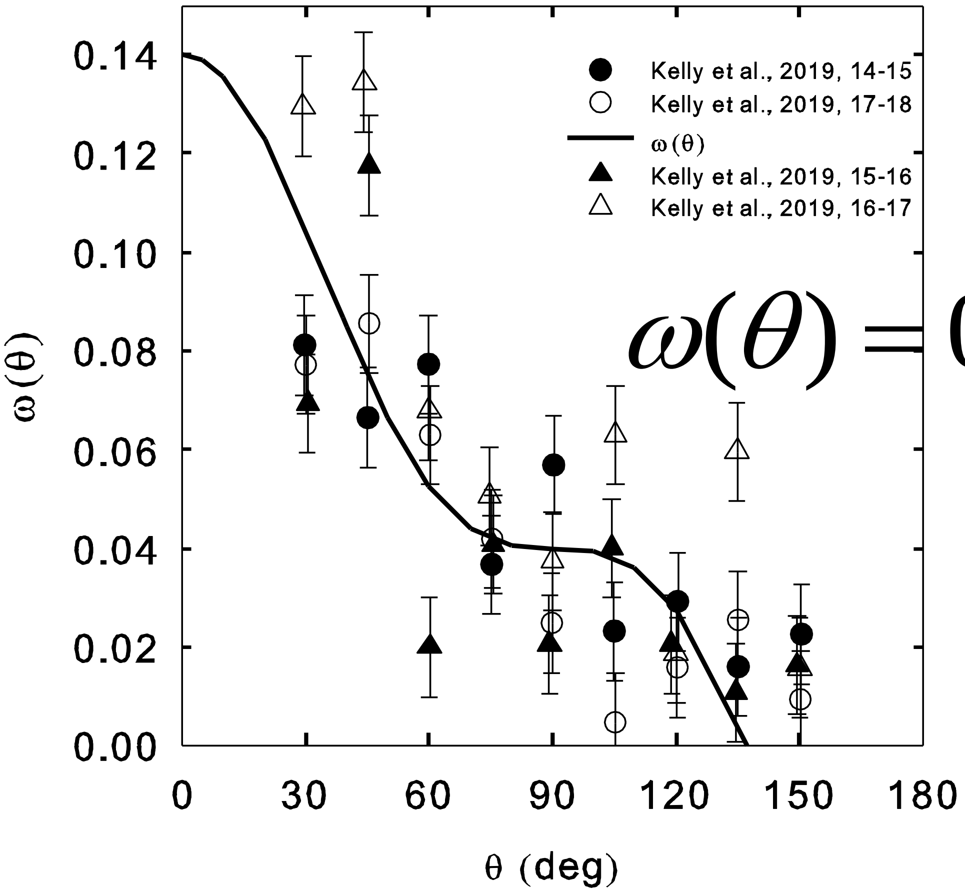
$$\sigma_{n,xnf}\left(E_n\right)=\sum_{J\pi}^{J}\int_0^{U_x}W_{A+1-x}^{J\pi}(U)P_{f(A+1-x)}^{J\pi}(U)dU$$

$$\frac{d\sigma^1_{nnx}(\varepsilon,E_n)}{d\varepsilon}\approx\frac{d\tilde{\sigma}^1_{nnx}(\varepsilon,E_n)}{d\varepsilon}+\sqrt{\frac{\varepsilon}{E_n}}\frac{\left\langle\omega(\theta)\right\rangle_\theta}{E_n-\varepsilon}$$

$$\left\langle\omega(\theta)\right\rangle_\vartheta\approx\omega(\theta\approx90^o)$$

$$\omega(\theta)=0.4\cos^3(\theta)+0.16$$

Angular distribution of 239Pu(n,F) pre-fission neutrons



$$\omega(\theta) = 0.4\cos^3(\theta) + 0.16$$

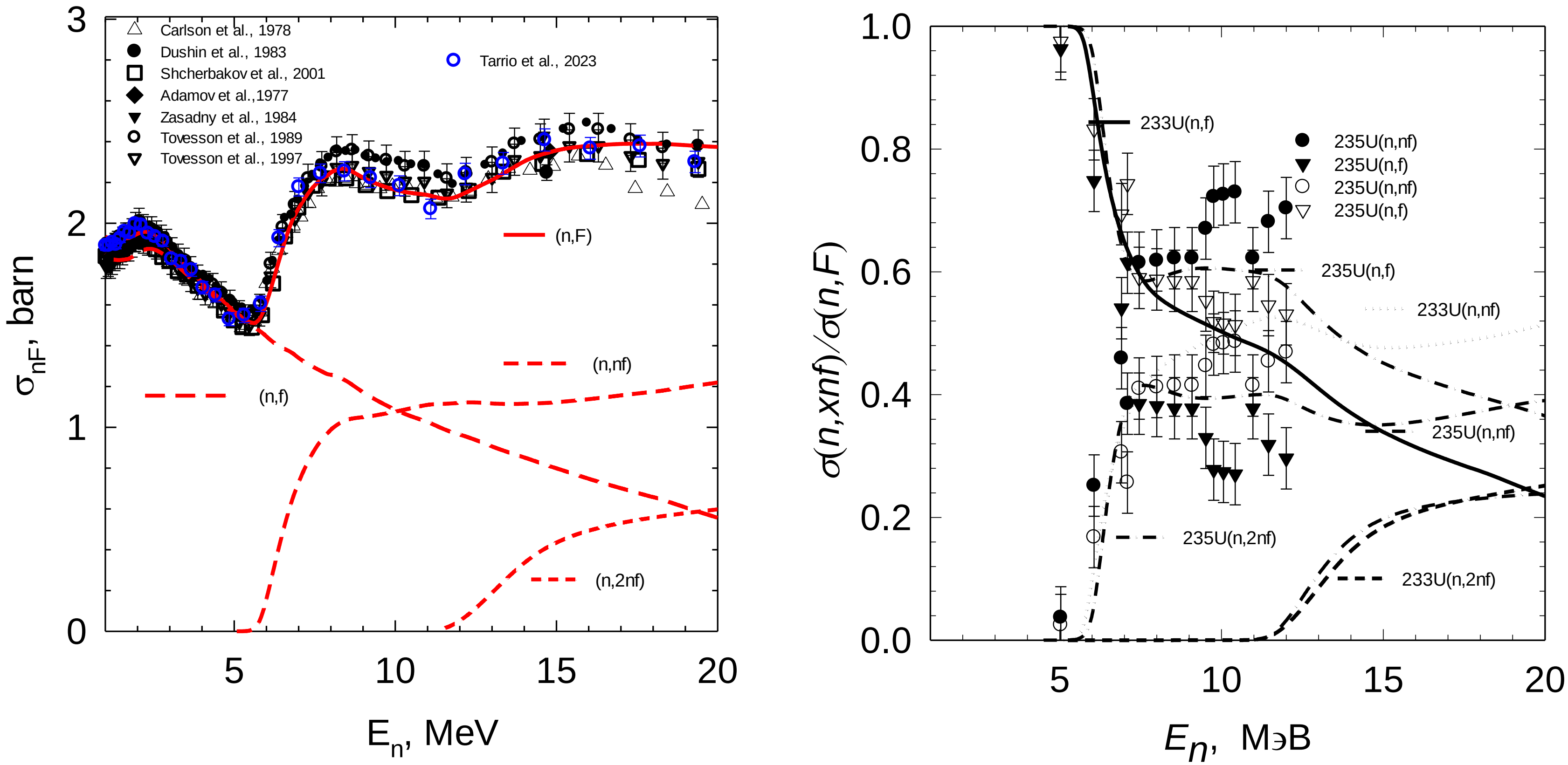
Angular anisotropy (AA) of secondary neutrons is evidenced in neutron emission spectra (NES) 232Th, 235U, 238U,239Pu, due to

1. (n,n)
2. **g.s. band levels** $J^{\pi}= 0^+, 2^+, 4^+, 6^+, 8^+$ (e-e)
3. γ–bands with $K^{\pi}=0^+, 2^+$, octupole bands $K^{\pi}=0^-$ (e-e)
4. (n,nγ)

NES **AA** is due to PE/semi-direct $(n,nX)^1$

Angular anisotropy of PFNS due to tiny part of $(n,nX)^1$ neutrons in exclusive pre-fission neutrons in $(n,xnf)^{1,\ldots,x}$.

σ(n,F), σ(n,xnf) σ(n,xnf)/σ(n,F)



PFNS as a superposition

$$S(\varepsilon,E_n,\theta)=\tilde{S}_{A+1}(\varepsilon,E_n,\theta)+\tilde{S}_{A}(\varepsilon,E_n,\theta)+\tilde{S}_{A-1}(\varepsilon,E_n,\theta)+\tilde{S}_{A-2}(\varepsilon,E_n,\theta)=$$

$$\nu_p^{-1}(E_n,\theta)\cdot\Big\{\ \nu_{p1}(E_n)\cdot\beta_1(E_n,\theta)S_{A+1}(\varepsilon,E_n,\theta)+\nu_{p2}(E_n-\left\langle E_{nnf}(\theta)\right\rangle)\beta_2(E_n,\theta)S_A(\varepsilon,E_n,\theta)+$$

$$+\beta_2(E_n,\theta)\frac{d^2\sigma^1_{nnf}(\varepsilon,E_n,\theta)}{d\varepsilon d\varepsilon}+\nu_{p3}(E_n-B_n^A-\left\langle E^1_{n2nf}(\theta)\right\rangle-\left\langle E^2_{n2nf}(\theta)\right\rangle)\beta_3(E_n,\theta)S_{A-1}(\varepsilon,E_n,\theta)+\beta_3(E_n,\theta)\cdot$$

$$\left[\frac{d^2\sigma^1_{n2nf}(\varepsilon,E_n,\theta)}{d\varepsilon d\theta}+\frac{d^2\sigma^2_{n2nf}(\varepsilon,E_n,\theta)}{d\varepsilon d\theta}\right]+\nu_{p4}(E_n-B_n^A-B_n^{A-1}-\left\langle E^1_{n3nf}(\theta)\right\rangle-\left\langle E^2_{n3nf}(\theta)\right\rangle-\left\langle E^3_{n3nf}(\theta)\right\rangle)\cdot$$

$$\beta_4(E_n,\theta)S_{A-2}(\varepsilon,E_n,\theta)+\beta_4(E_n,\theta)\left[\frac{d^2\sigma^1_{n3nf}(\varepsilon,E_n,\theta)}{d\varepsilon d\theta}+\frac{d^2\sigma^2_{n3nf}(\varepsilon,E_n,\theta)}{d\varepsilon d\theta}+\frac{d^2\sigma^3_{n2nf}(\varepsilon,E_n,\theta)}{d\varepsilon d\theta}\right]\Big\}.$$

$$\nu_{\mathrm{p}}(E_n)=\nu_{post}+\nu_{pre}=\sum_{x=1}^{X}\nu_{px}(E_{nx})+\sum_{x=1}^{X}(x-1)\cdot\beta_x(E_n)$$

Exclusive neutron spectra of (*n,xnf*)$^{1,..x}$, (*n,nγ*) and (*n,xn*)$^{1,..x}$ are calculated within Hauser-Feshbach formalism alongside with (*n,F*) and (*n,xn*) reaction cross sections, angular dependence of first (*n,nX*)^{1} emission $\omega(\theta)$ being included.

$$U_x = E_n + B_n - \sum_{x,1\le k\le x}(< E^k_{nxnf}(\theta) > + B_{nx})$$

$$E_{nx} = E_r - E^{pre}_{fx} + E_n + B_n - \sum_{x,1\le k\le x}\left(\left\langle E^k_{nxnf}(\theta)\right\rangle + B_{nx}\right)$$

$$E^{pre}_F(E_n) = \sum_{x=1}^{X} E^{pre}_{fx}(E_n)\sigma_{n,xnf} / \sigma_{n,F}$$

$$E^{post}_F \approx E^{pre}_F\left(1 - \nu_{post} / (A + 1 - \nu_{pre})\right)$$

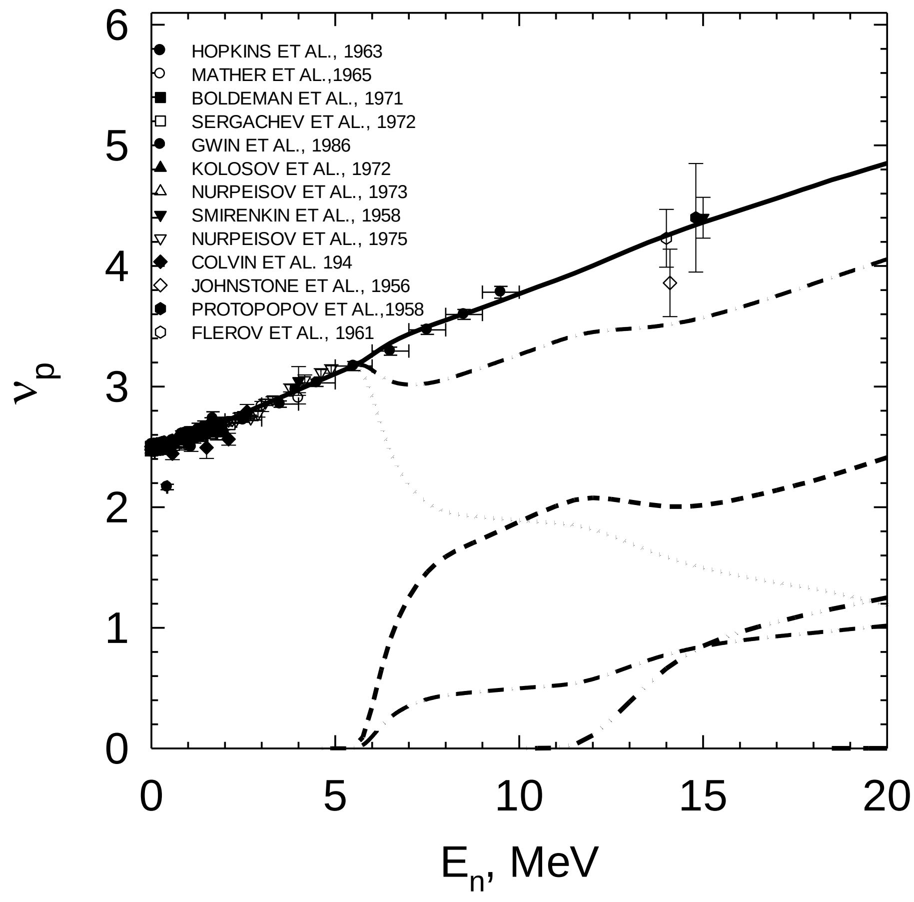
$$\nu_{\mathrm{p}}(E_n) = \nu_{post} + \nu_{pre} = \sum_{x=1}^{X} \nu_{px}(E_{nx}) + \sum_{x=1}^{X}(x-1)\cdot\beta_x(E_n)$$

$$\frac{d^2\sigma^1_{nnx}(\varepsilon, E_n, \theta)}{d\varepsilon d\theta} \approx \frac{d^2\tilde{\sigma}^1_{nnx}(\varepsilon, E_n, \theta)}{d\varepsilon d\theta} + \sqrt{\frac{\varepsilon}{E_n}}\frac{\omega(\theta)}{E_n - \varepsilon}$$

$$\left\langle \omega(\theta) \right\rangle_{\vartheta} \approx \omega(\theta \approx 90^o)$$

Maslov V.M. Anisotropy of Prompt Fission Neutron Spectra of 239Pu(n, F) and 235U(n, F), Physics of Particles and Nuclei Letters, 2023, Vol. 20, No. 6, pp. 1373–1384.

233U(n,F), 233U(n,xnf) pre- and post-fission neutrons multiplicity



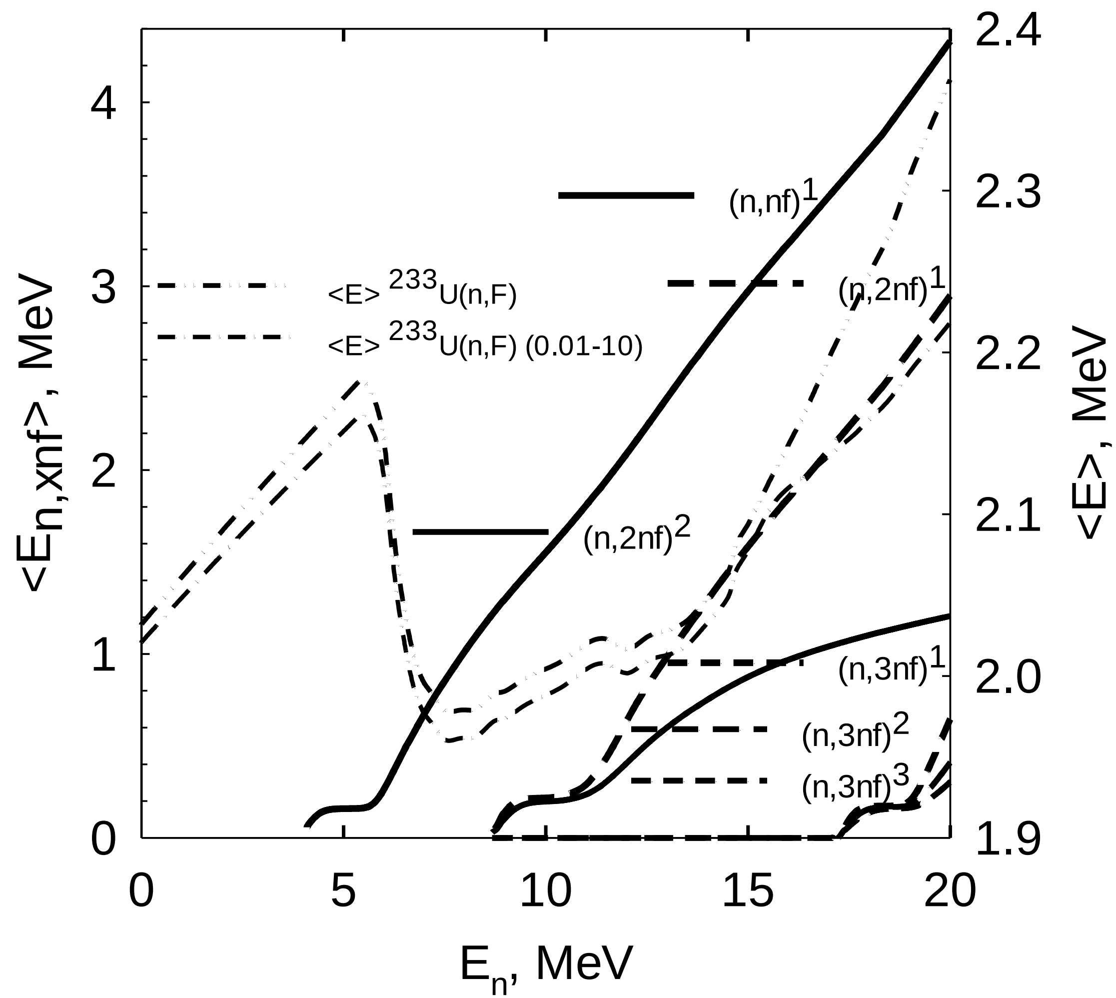
$$\frac{d\tilde{\sigma}^1_{nnx}(\varepsilon, E_n)}{d\varepsilon} = \sum_{J,\pi} W^A(E_n - \varepsilon, \theta, J^\pi)$$

$$\frac{d^2\sigma^1_{nnf}(\varepsilon, E_n, \theta)}{d\varepsilon d\theta} = \frac{d^2\sigma^1_{nnx}(\varepsilon, E_n, \theta)}{d\varepsilon d\theta} \frac{\Gamma^A_f(E_n - \varepsilon, \theta)}{\Gamma^A(E_n - \varepsilon, \theta)}.$$

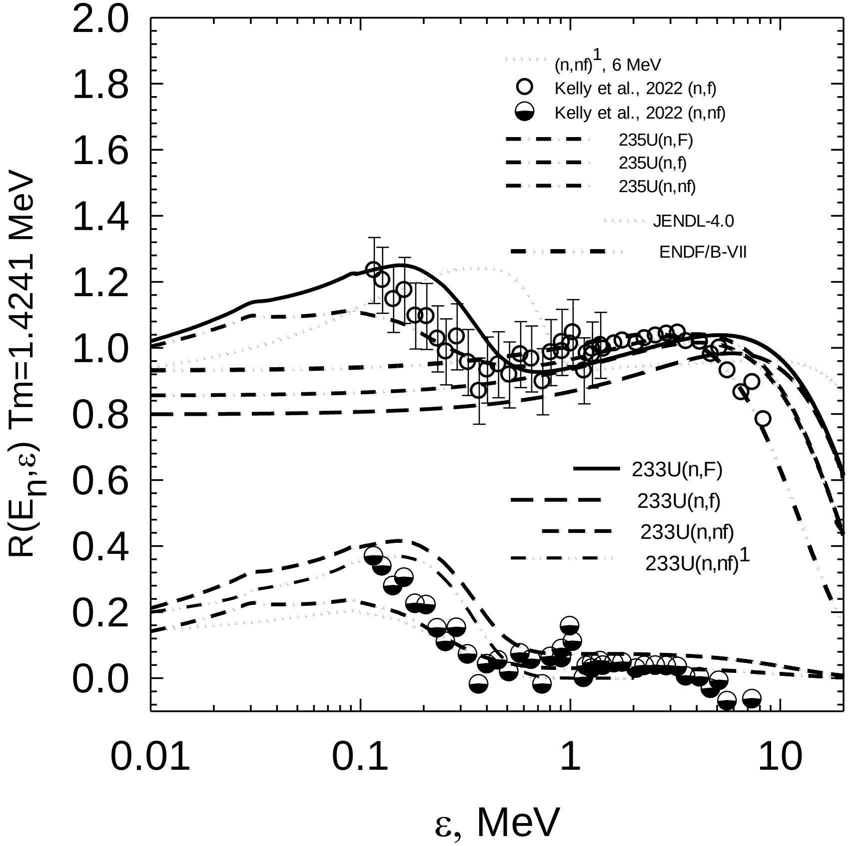
$$\frac{d^2\sigma^1_{n2nx}\left(\varepsilon, E_n, \theta\right)}{d\varepsilon d\theta} = \frac{d^2\sigma^1_{nnx}\left(\varepsilon, E_n, \theta\right)}{d\varepsilon d\theta} \frac{\Gamma^A_n(E_n - \varepsilon, \theta)}{\Gamma^A(E_n - \varepsilon, \theta)}$$

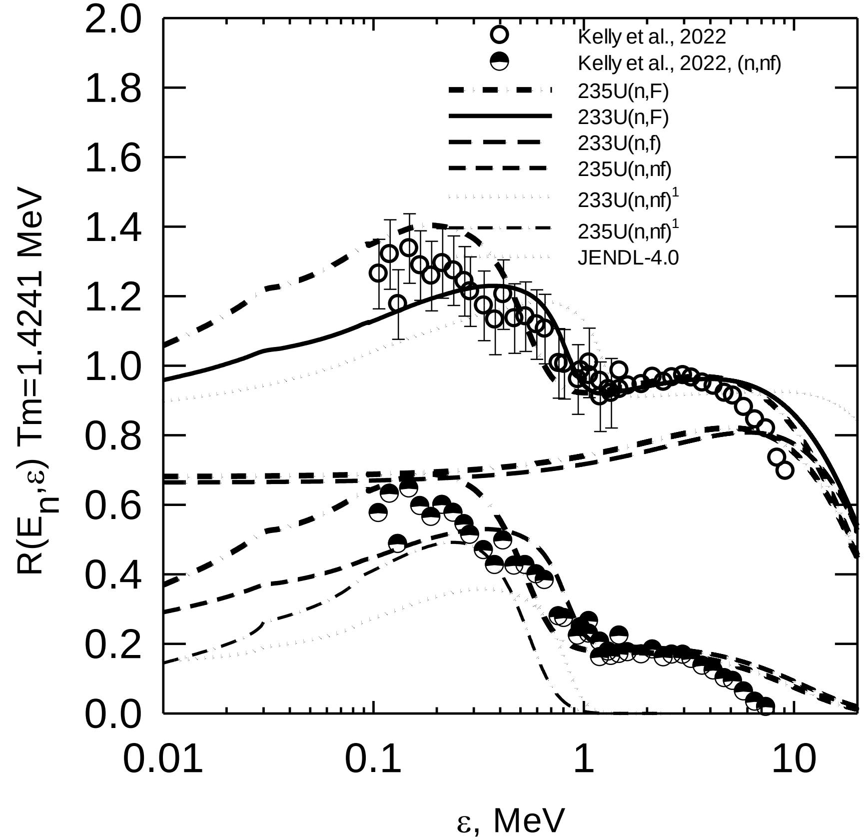
$$\frac{d^2\sigma^1_{n2nf}\left(\varepsilon, E_n, \theta\right)}{d\varepsilon d\theta} = \int_0^{E\ -B_n^A} \frac{d^2\sigma^1_{n2nx}\left(\varepsilon, E_n, \theta\right)}{d\varepsilon d\theta} \frac{\Gamma^{A-1}_f(E_n - B_n^A - \varepsilon - \varepsilon_1)}{\Gamma^{A-1}(E_n - B_n^A - \varepsilon - \varepsilon_1)} d\varepsilon_1$$

233U(n,xnf) pre-fission neutrons <Enxnf> , <E> of PFNS

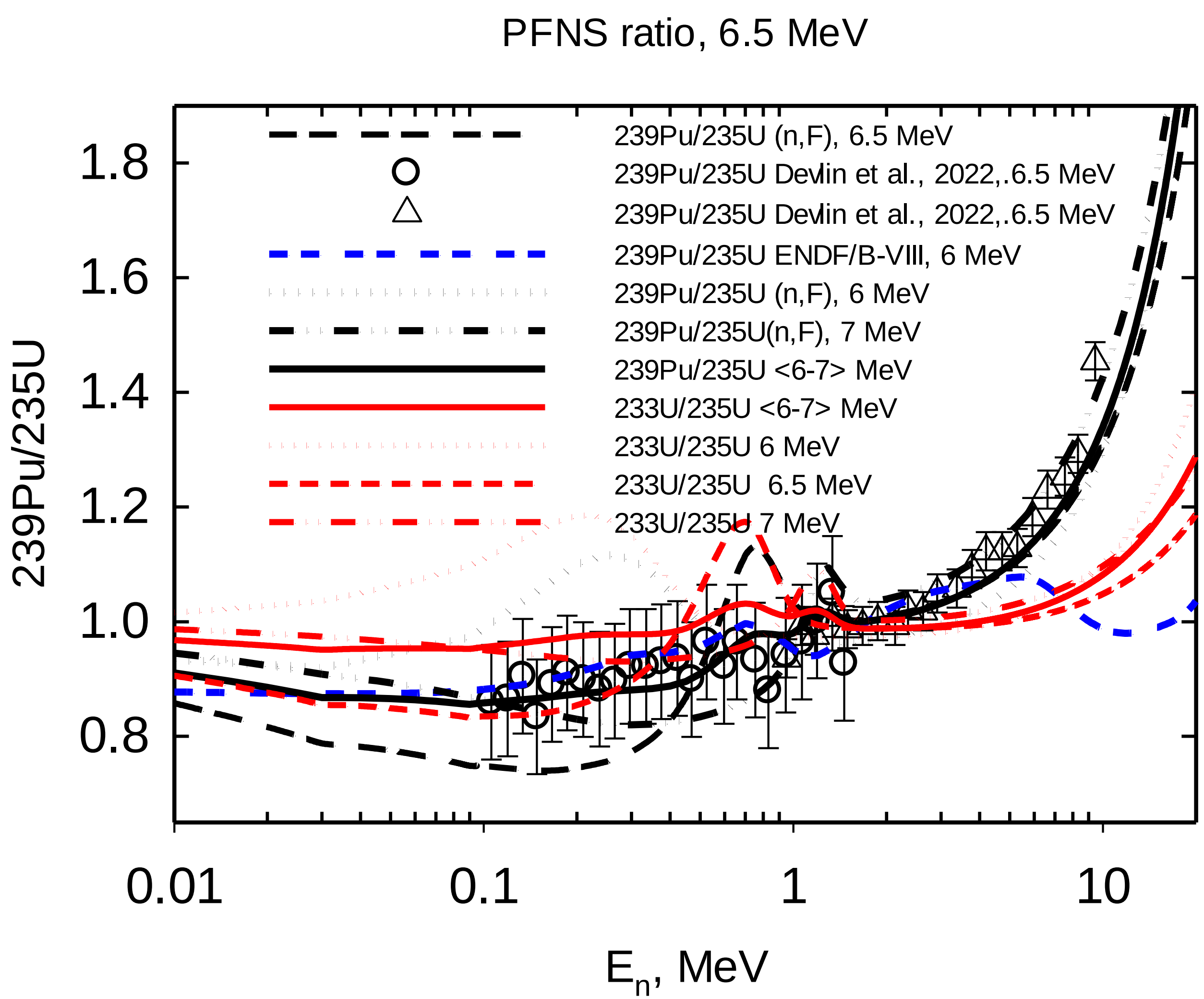


En=6 MeV 233U(n,F)&235U(n,F) PFNS En=6.5 MeV

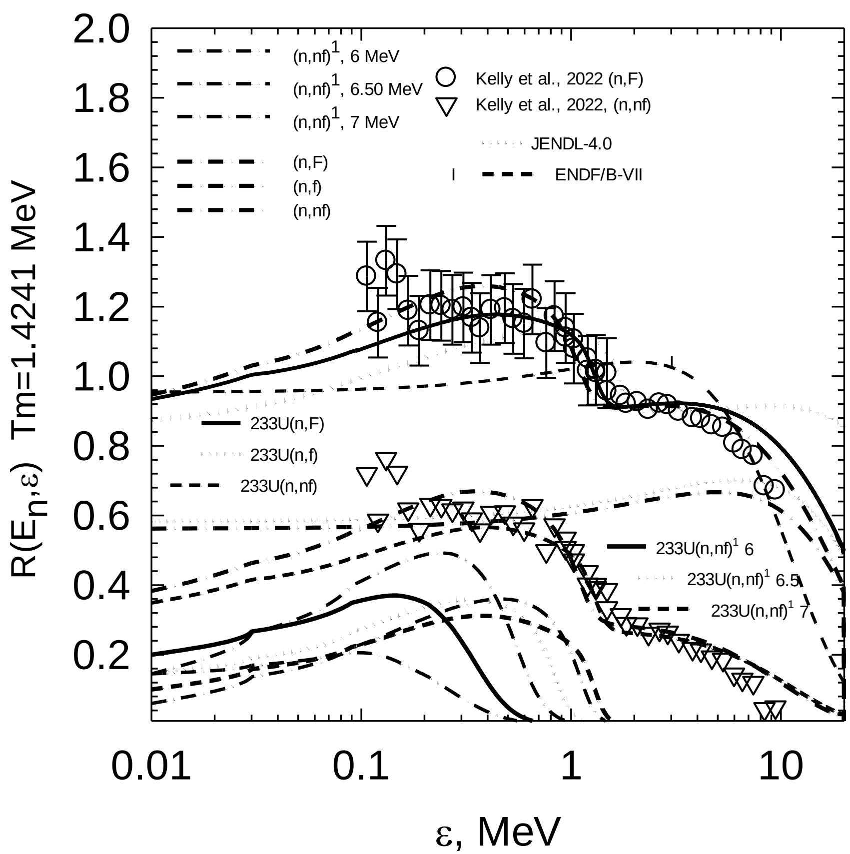


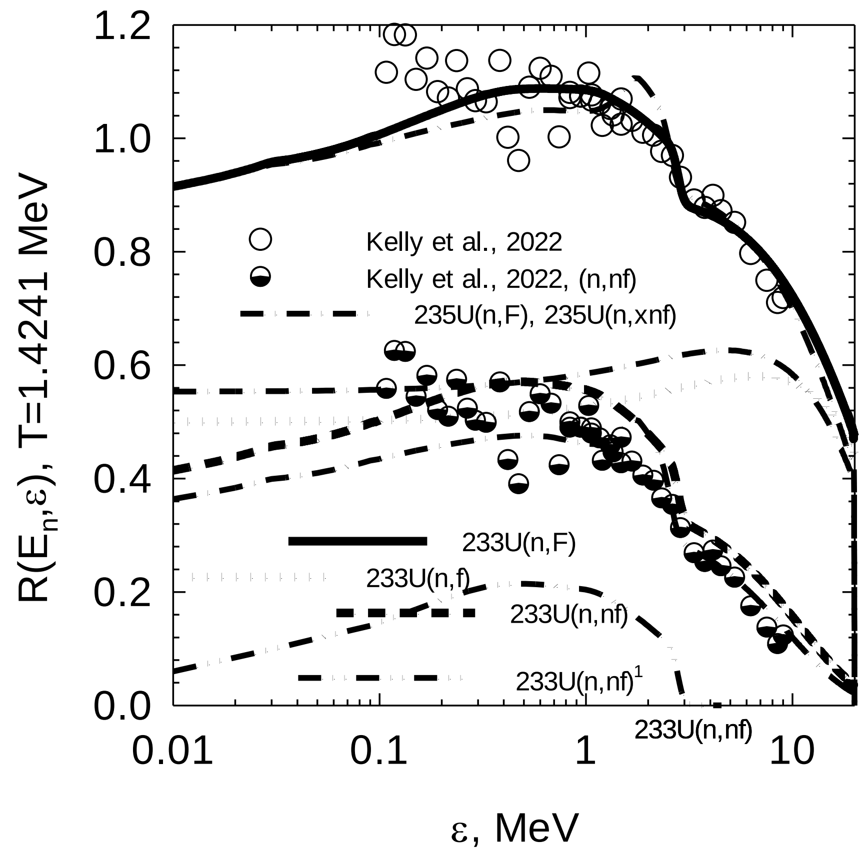


En=6-7 MeV 239Pu/235U   PFNS ratio   233U/235U

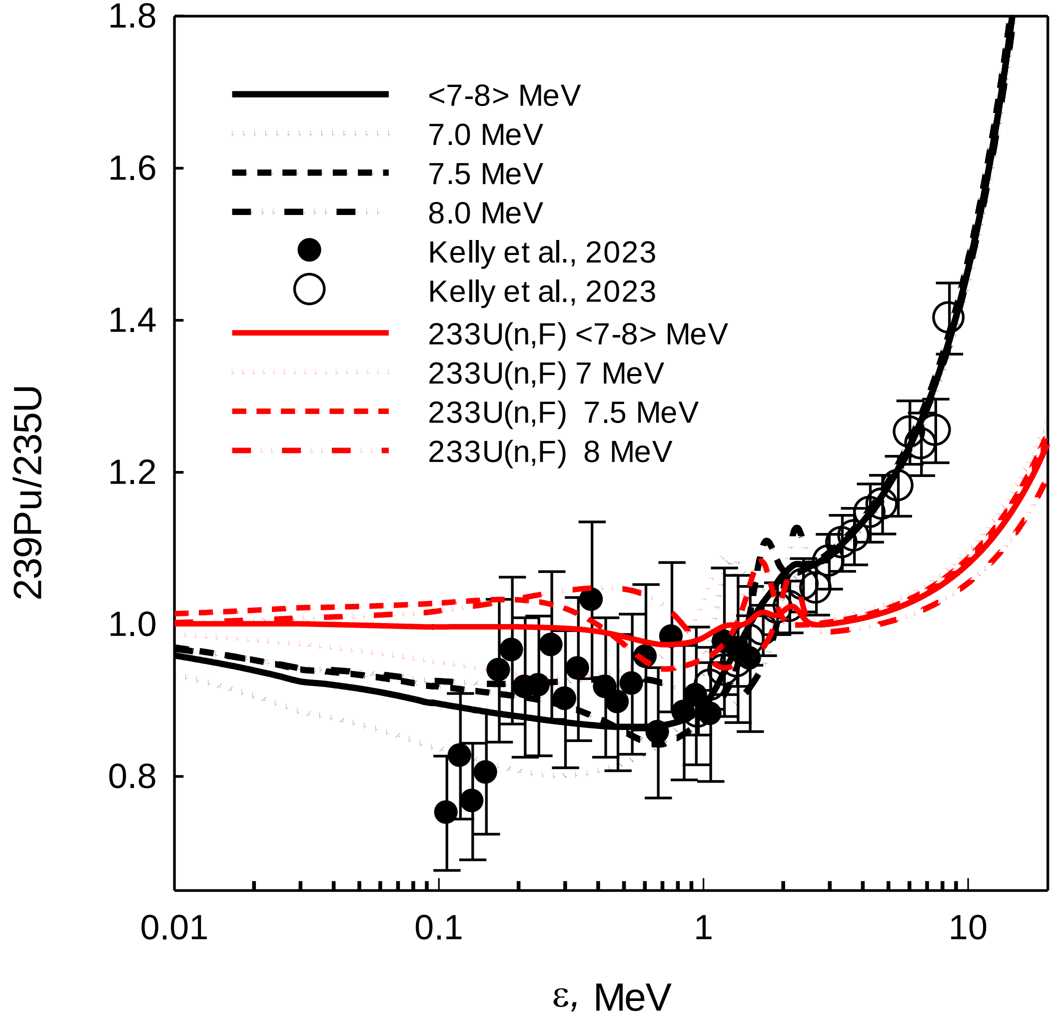


En=7 MeV 233U(n,F)&235U(n,F) PFNS En=8.5 MeV

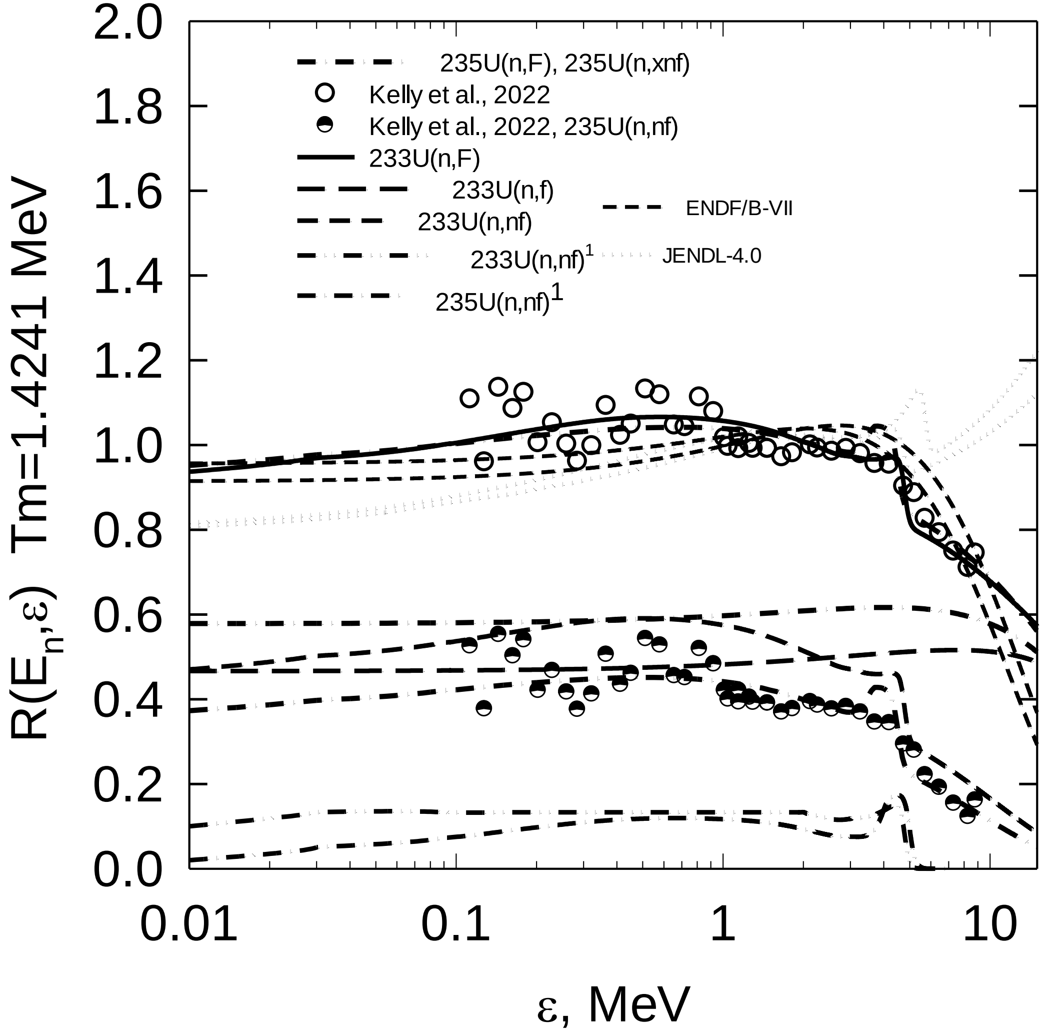


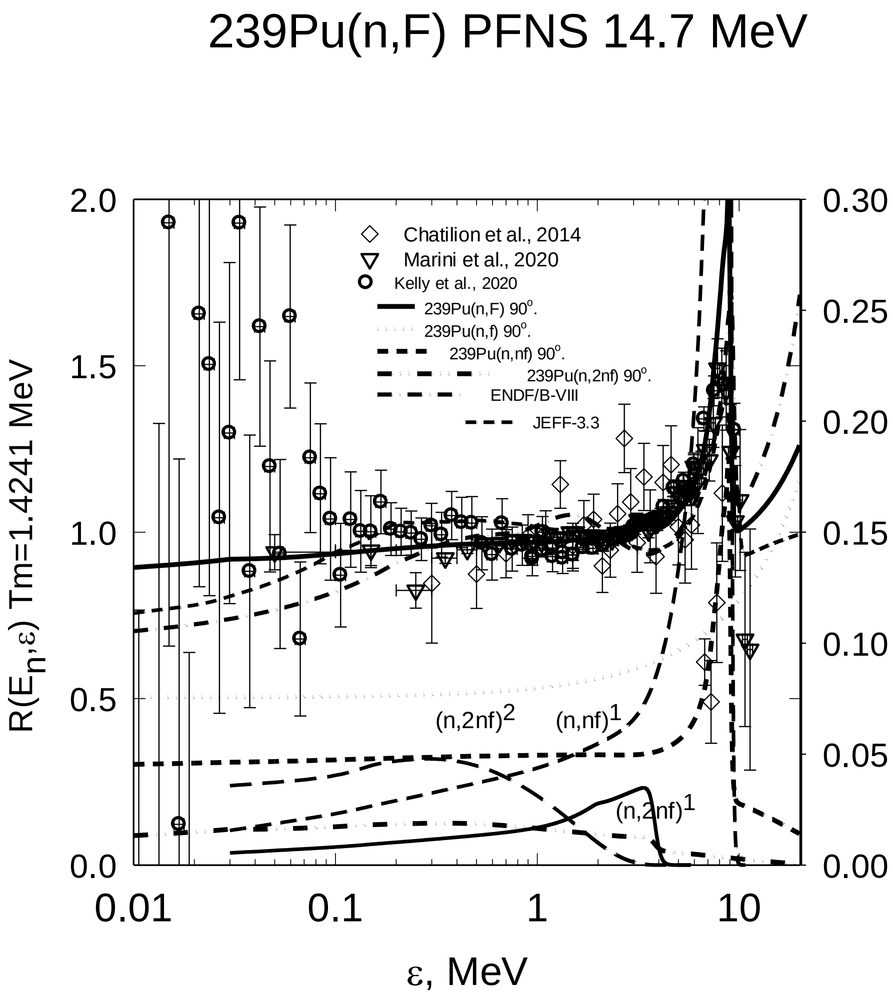


En=7-8 MeV 239Pu/235U PFNS ratio 233U/235U

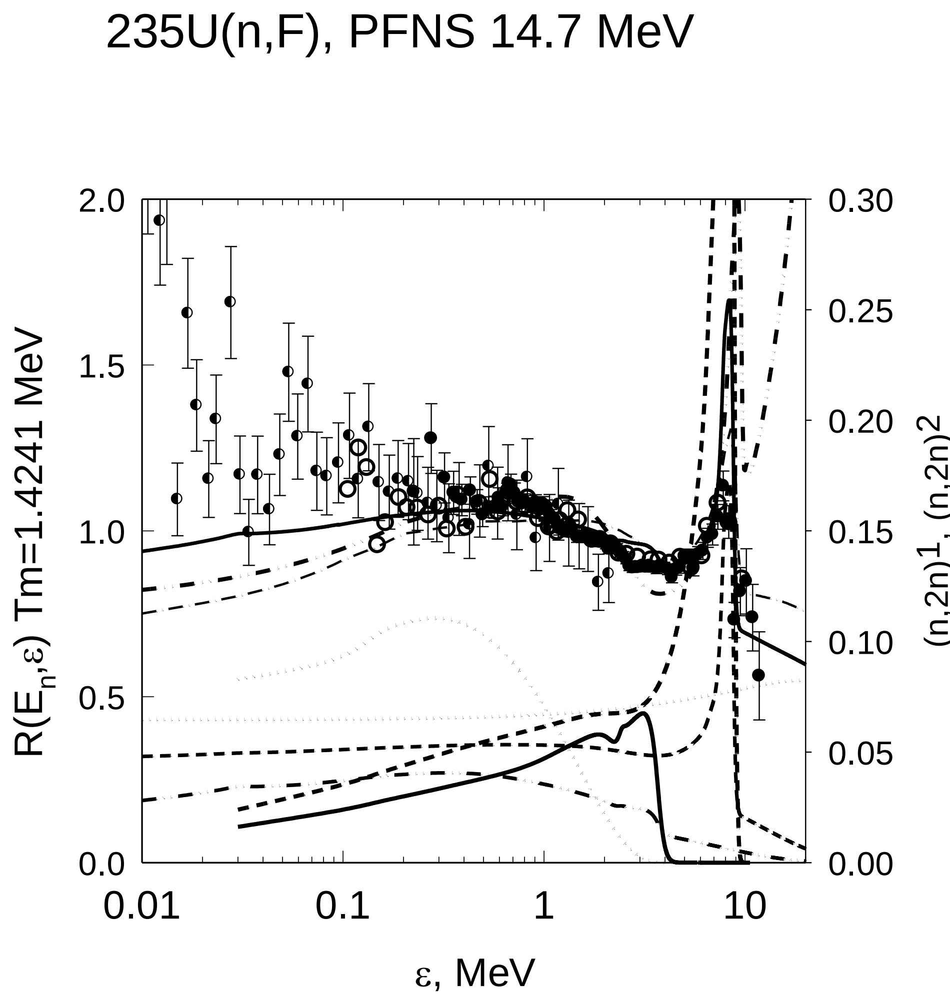


233U(n,F)&235U(n,F) PFNS En=10.5 MeV



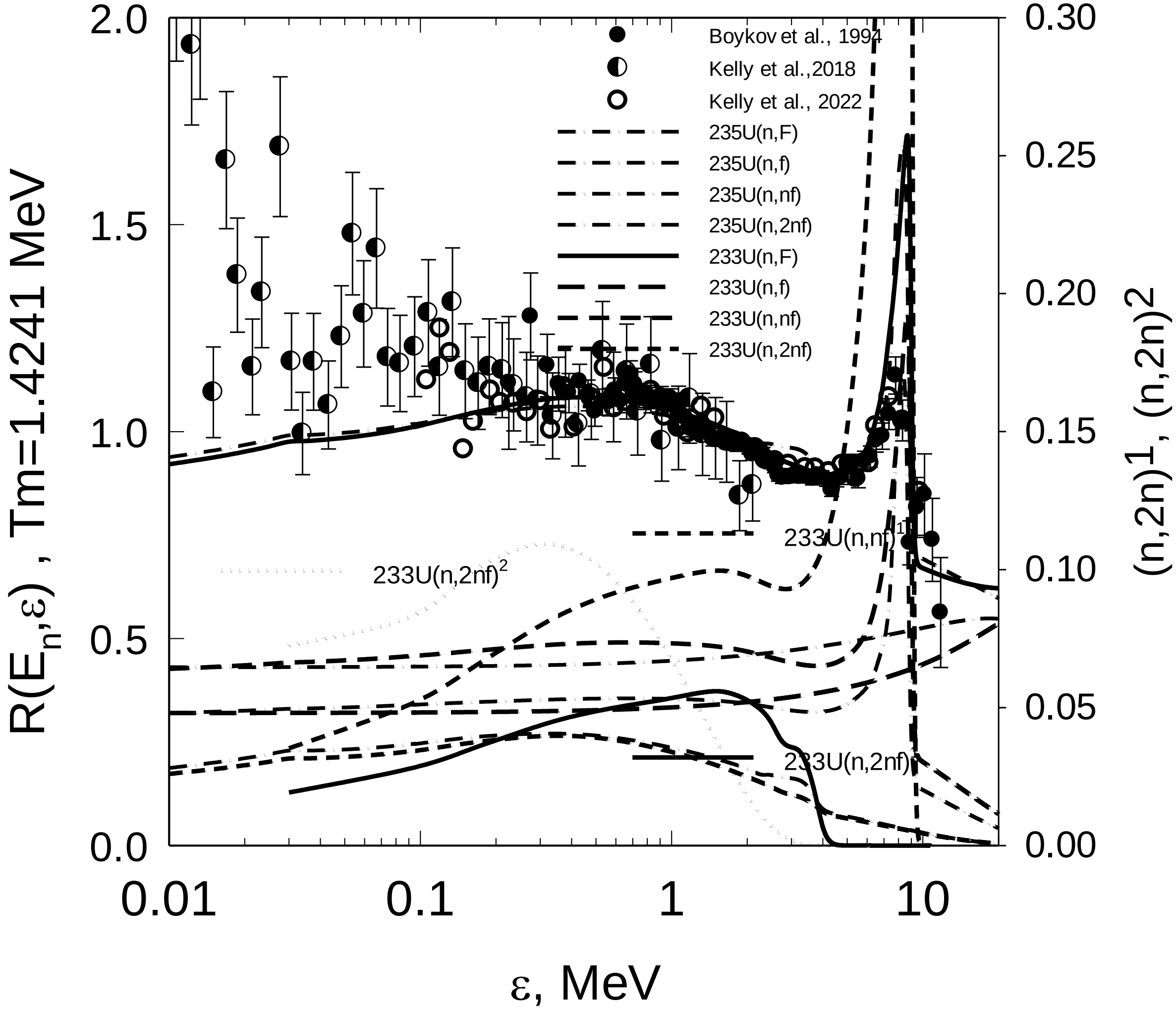


239Pu(n,F) PFNS 14.7 MeV
Chatilion et al., 2014
Marini et al., 2020
Kelly et al., 2020
239Pu(n,F) 90°.
239Pu(n,f) 90°.
239Pu(n,nf) 90°.
239Pu(n,2nf) 90°.
ENDF/B-VIII
JEFF-3.3
(n,2nf)2
(n,nf)1
(n,2nf)1
R(En,ε) Tm=1.4241 MeV
ε, MeV

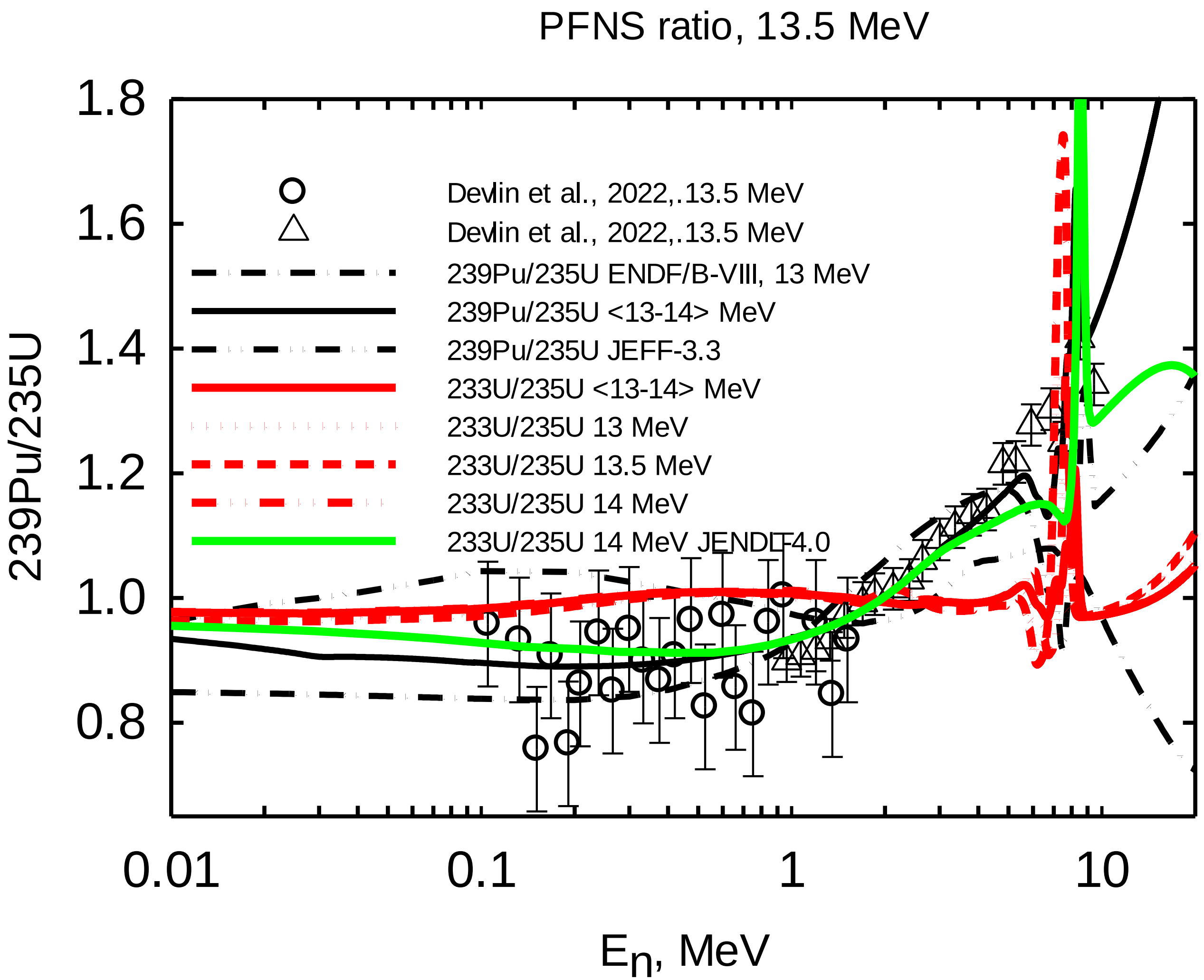


235U(n,F), PFNS 14.7 MeV
R(En,ε) Tm=1.4241 MeV
(n,2n)1, (n,2n)2
ε, MeV

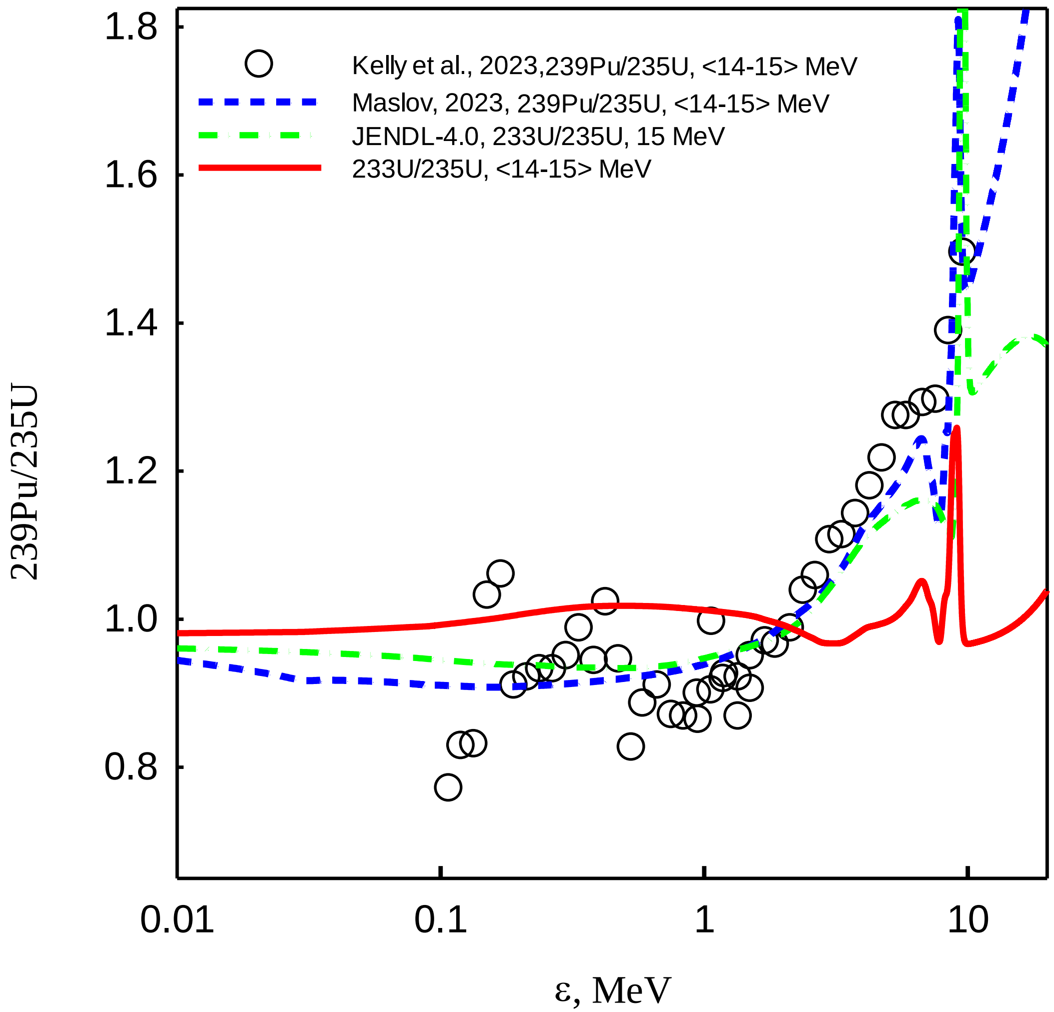
233U(n,F)&235U(n,F) PFNS En=14.5 MeV



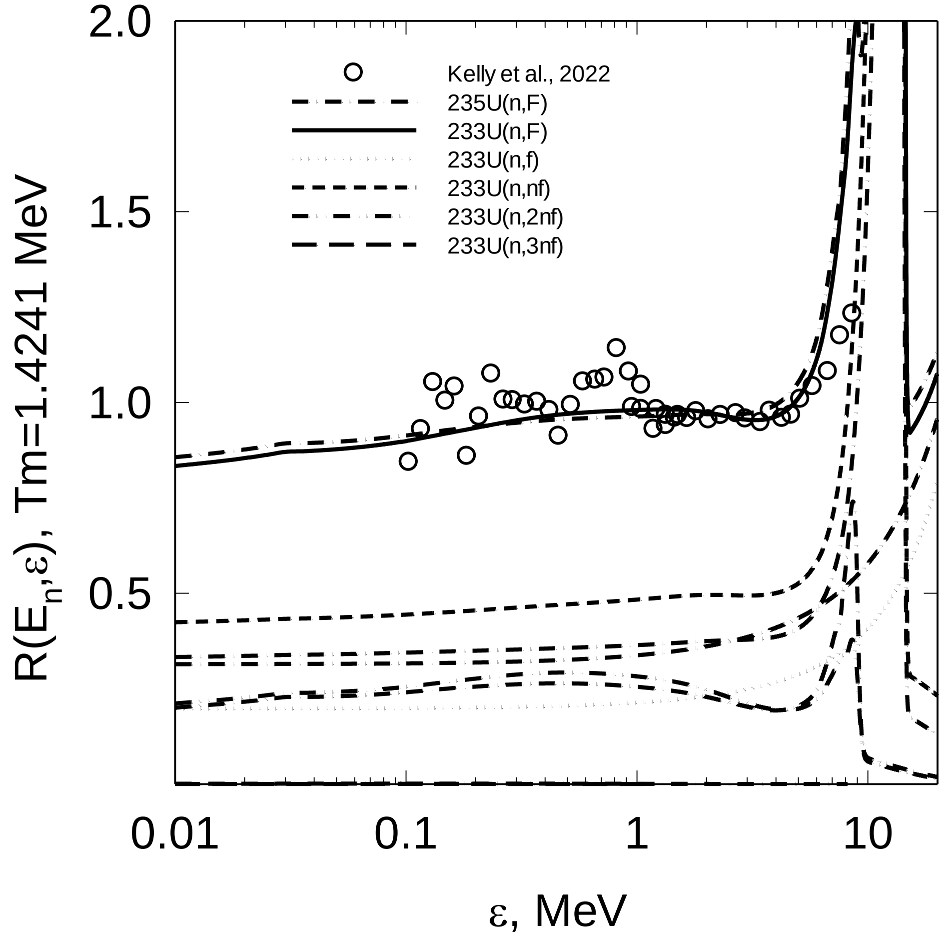
En=13-14 MeV 239Pu/235U PFNS ratio 233U/235U



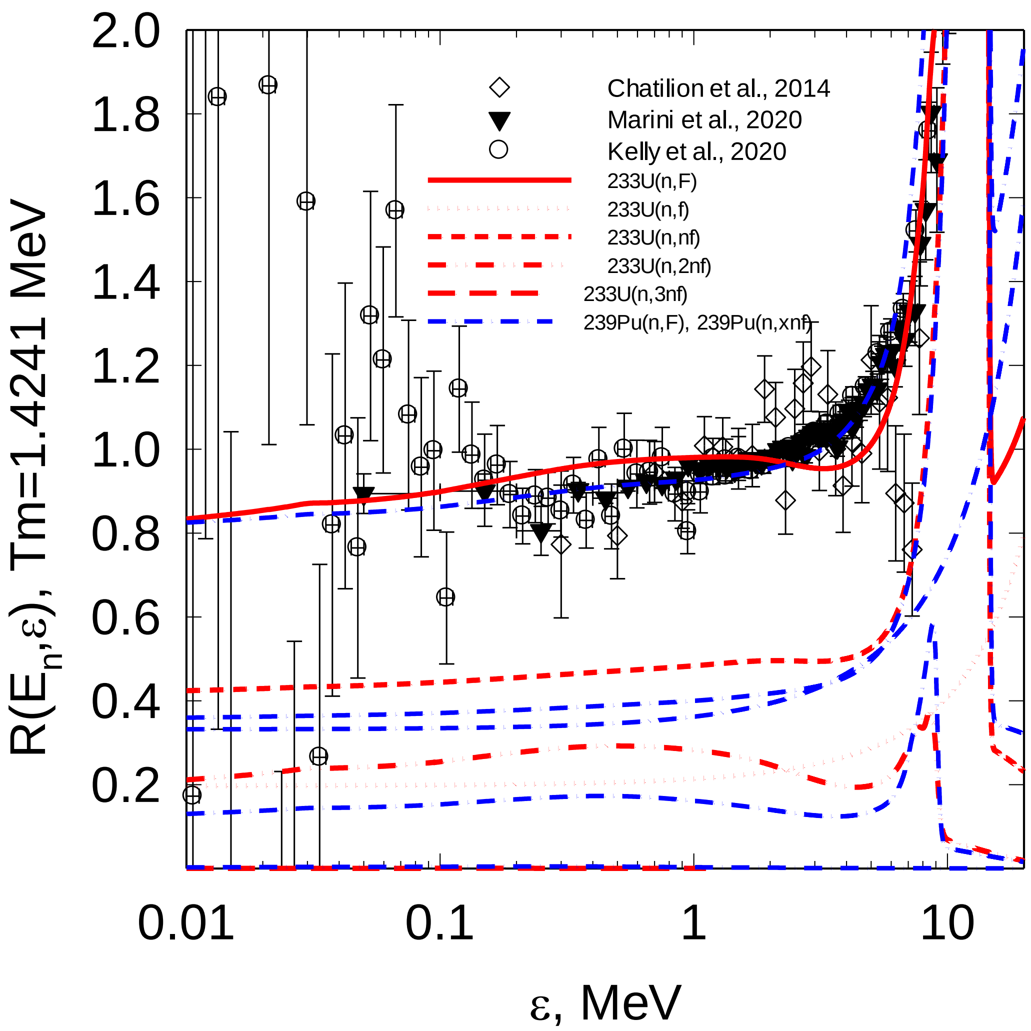
En=14-15 MeV 239Pu/235U PFNS ratio 233U/235U



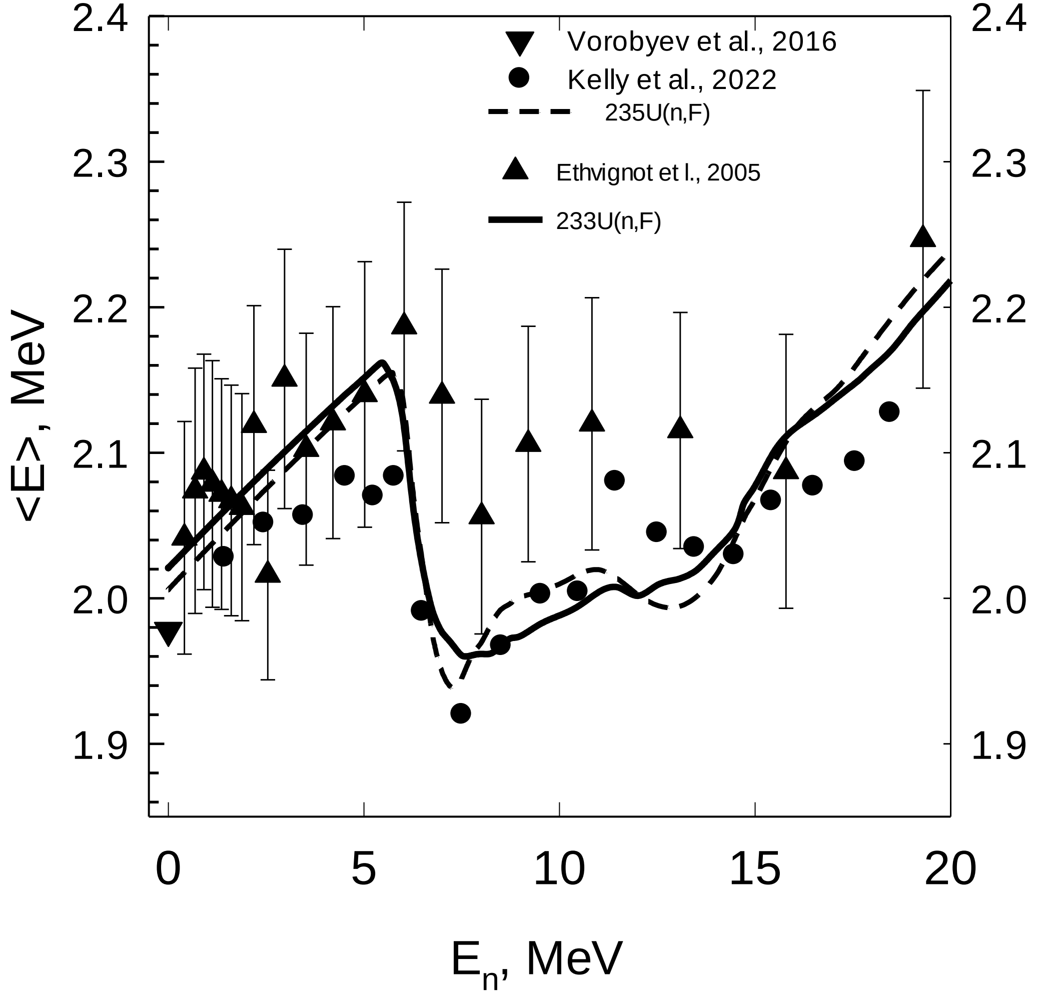
233U(n,F)&235U(n,F) PFNS   En=19-20 MeV



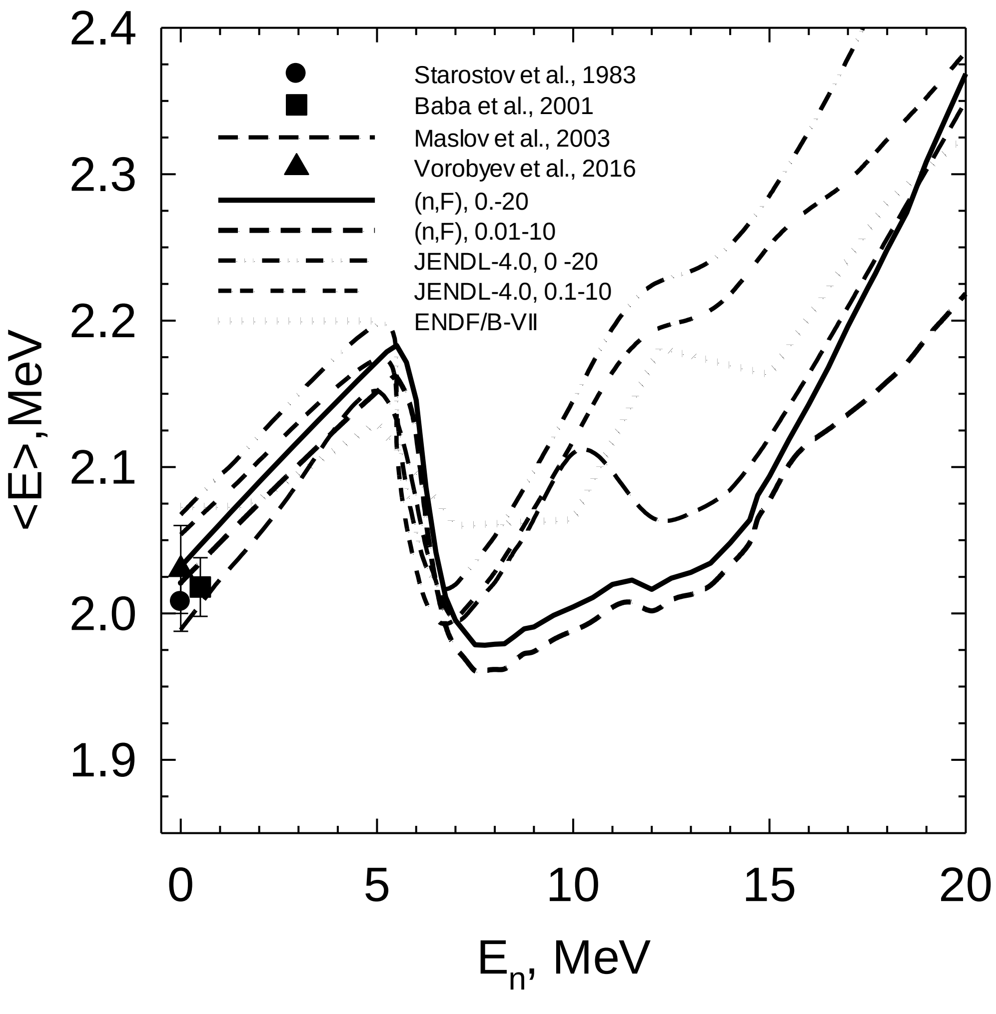
233U(n,F)&239Pu(n,F) PFNS En=19-20 MeV



<E> PFNS 233U(n,F)



<E> PFNS 233U(n,F)



$$U_x = E_n + B_n - \sum_{x,1\le k\le x} (< E_{nxnf}^{k}(\theta) > + B_{nx})$$

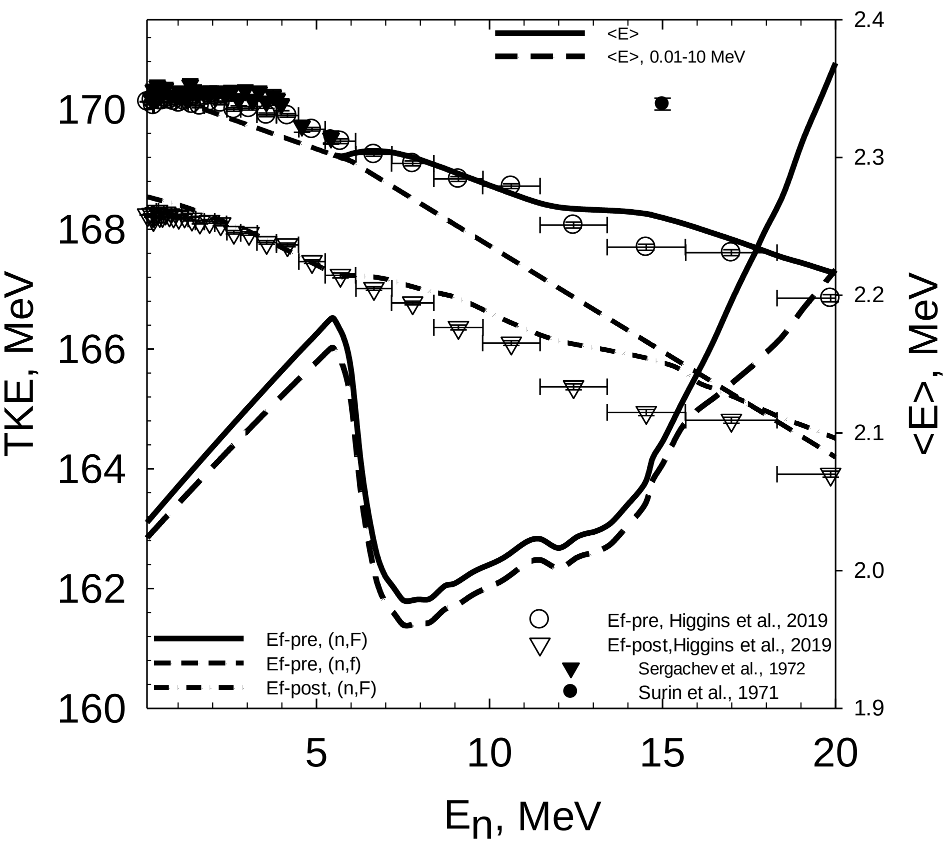
$$E_{nx} = E_r - E_{fx}^{pre} + E_n + B_n - \sum_{x,1\le k\le x} \left(\left\langle E_{nxnf}^{k}(\theta) \right\rangle + B_{nx} \right)$$

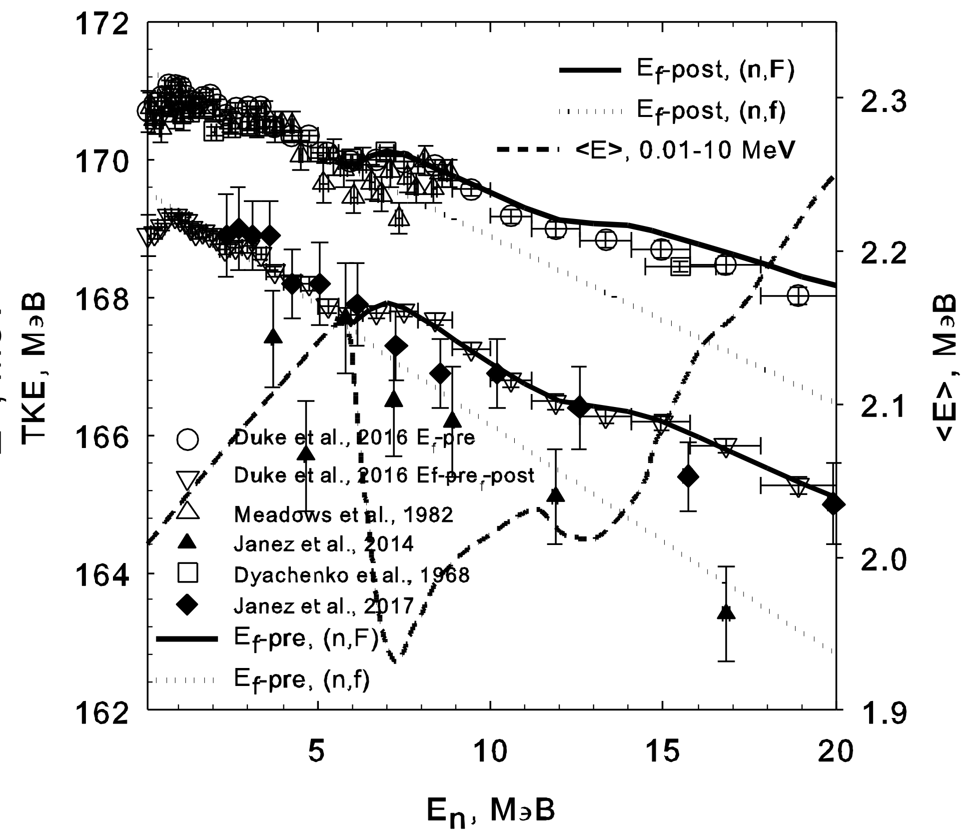
$$E_F^{pre}(E_n) = \sum_{x=1}^{X} E_{fx}^{pre}(E_n)\sigma_{n,xnf} / \sigma_{n,F}$$

$$E_F^{post} \approx E_F^{pre}\left(1 - \nu_{post} / \left(A + 1 - \nu_{pre}\right)\right)$$

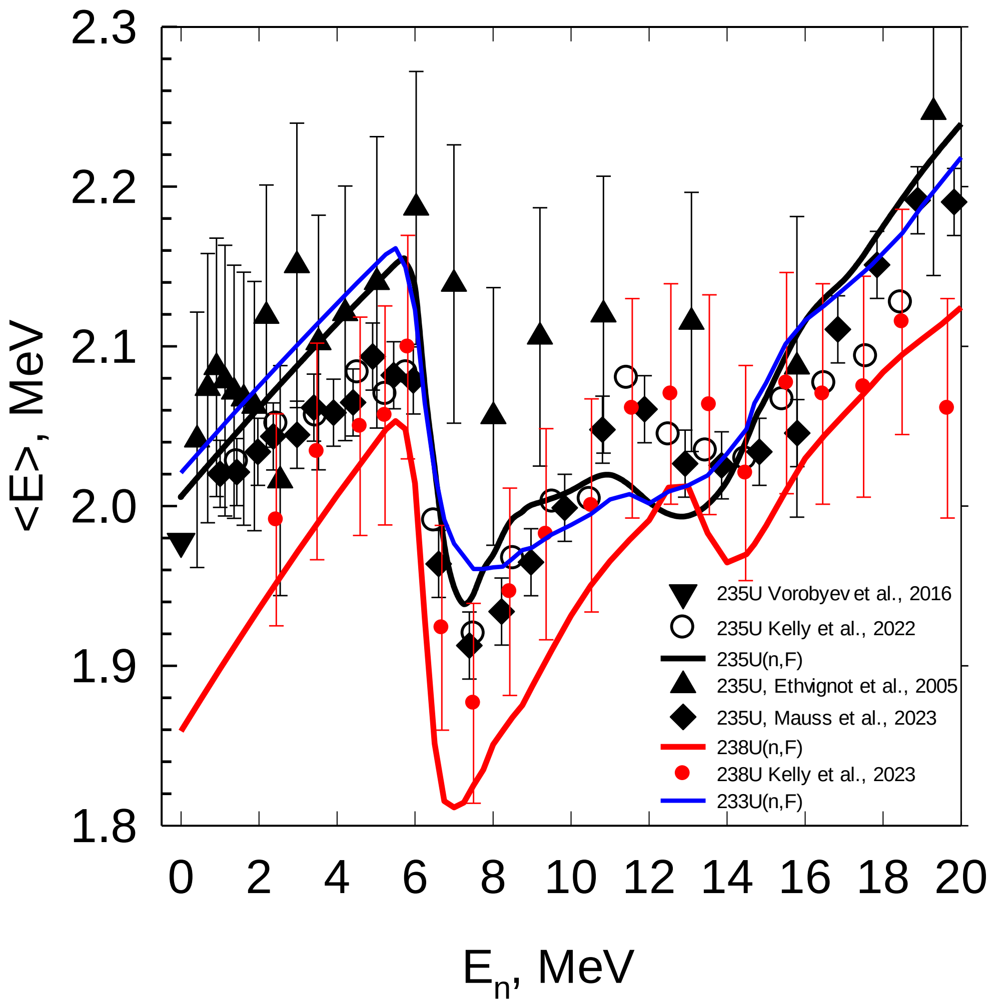
$$\nu_{\mathrm{p}}(E_n) = \nu_{post} + \nu_{pre} = \sum_{x=1}^{X} \nu_{px}(E_{nx}) + \sum_{x=1}^{X} (x-1)\cdot \beta_x(E_n)$$

TKE&<E> PFNS 233,235U(n,F)





<E> PFNS 233U(n,F), 235U(n,F), 238U(n,F)



Conclusions

Angular dependence of first $(n,nX)^1$ emission $\omega(\theta)$

<E> of $(n,nf)^1$ neutrons depends on emission angle θ

Fission cross section, prompt neutron number and total kinetic energy depend on θ as well

Exclusive neutron spectra $(n,xnf)^{1,..x}$ at θ~90^o are consistent with ^{235}U(n,F)(^{235}U(n,xn)) and ^{239}Pu(n,F)(^{239}Pu(n,xn)) css within E_n~0.01–20 MeV

Exclusive neutron spectra of $(n,xnf)^{1,..x}$, $(n,n\gamma)$ and $(n,xn)^{1,..x}$ – by Hauser-Feshbach formalism

Conclusions

Approximation obtained for $\omega(\theta)$ fits the measured 235U+n & 235U+n NES at 14 MeV.

The correlation of angular dependence of (*n,xnf*)[1] neutron emission with emissive fission (*n,xnf*) and angular anisotropy of 235U+n & 239Pu+n NES is established.

On that background

The PFNS shapes and energies <E> and TKE for ^{233}U(*n,F*)& ^{233}U(*n,xnf*) provided

Conclusions

In ^{239}**Pu(*n,xnf*)$^{1,..x}$ and** ^{235}**U(*n,xnf*)$^{1,..x}$ PFNS** demonstrate different responses to forward and backward (*n,xnf*)^{1} neutrons emission with respect to the incident neutron momentum

In ^{233}**U(*n,xnf*)$^{1,..x}$ and** ^{233}**U(*n,F*) PFNS** stronger response to forward and backward (*n,xnf*)^{1} neutrons emission ?

Conclusions

•Maslov V.M. Anisotropy of Prompt Fission Neutron Spectra of 239Pu(n, F) and 235U(n, F), Physics of Particles and Nuclei Letters, 2023, Vol. 20, No. 6, pp. 1373–1384. https://pepan.jinr.ru/index.php/PepanLetters/Issue/20/6; https://rdcu.be/dsLEl;

•Maslov V.M. Anisotropy of Prompt Fission Neutron Spectra of 233U(n, F), Physics of Particles and Nuclei Letters, 2024, in press.