Prompt Fission Neutron Spectra of ^{240}Pu(n,F)

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Collaboration on PFNS of 2000-2011

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EXPERIMENTS on

- **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**

^{235}U+n; ^{239}Pu+n; ^{238}U+n – first observed by

Kammerdiener J.L., UCRL-51232, **1972**.

- **Asymmetry in neutron emission spectra of ^{232}Th+n**

and ^{238}U+n at En=6, 12,14, 18 MeV(measured)

- **Asymmetry of pre-fission neutron emission in**

^{238}U(n,F) vis ^{232}Th(n,F) (predicted)

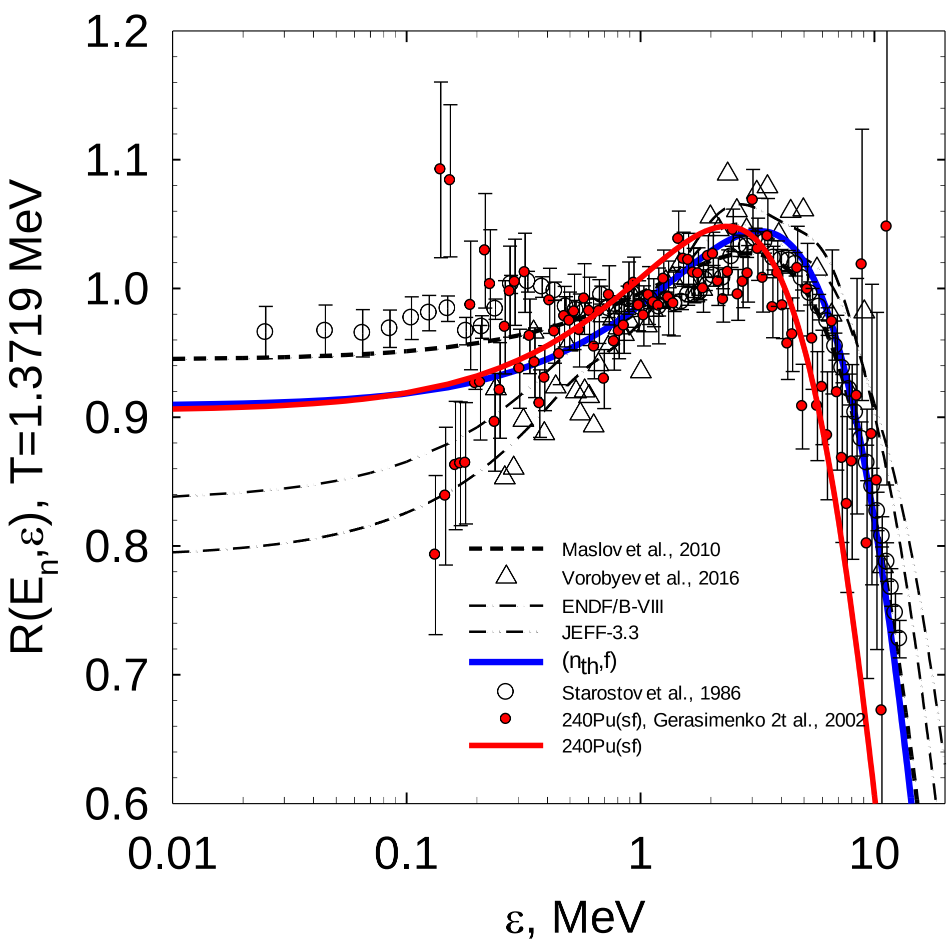
For $^{240,242}Pu$

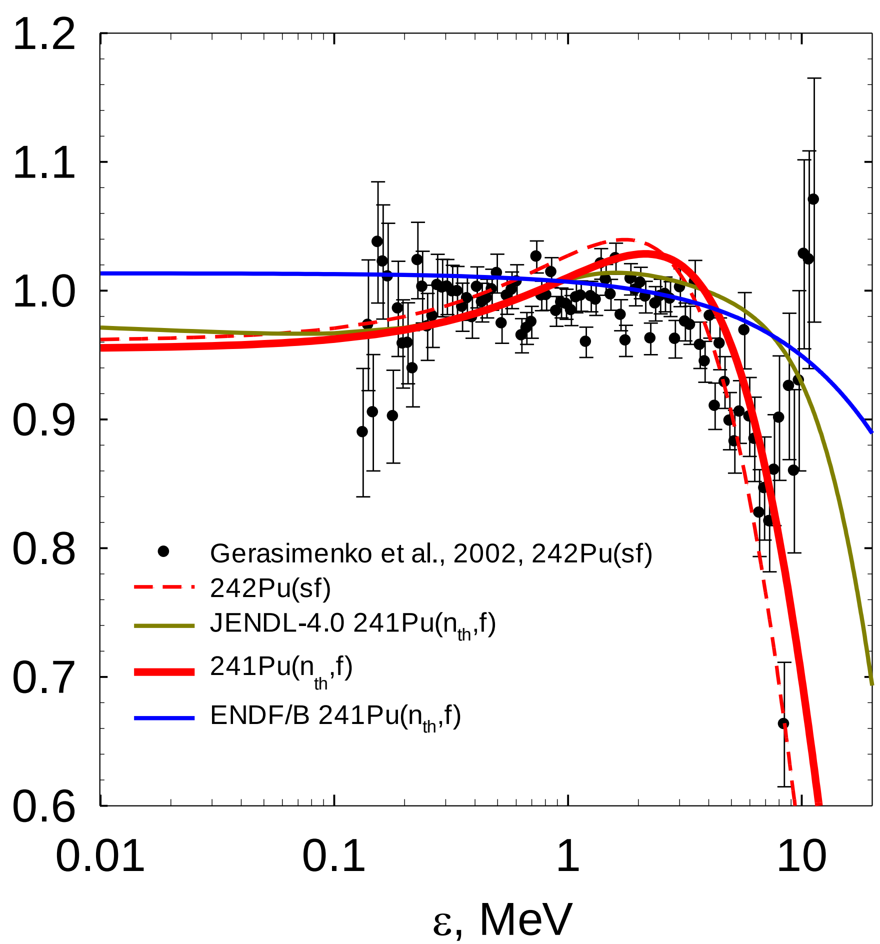
$^{240}Pu(sf)$, $^{242}Pu(sf)$ --SFNS only

$^{240}Pu(sf)$ **$^{241}Pu(sf)$** **$^{242}Pu(sf)$**

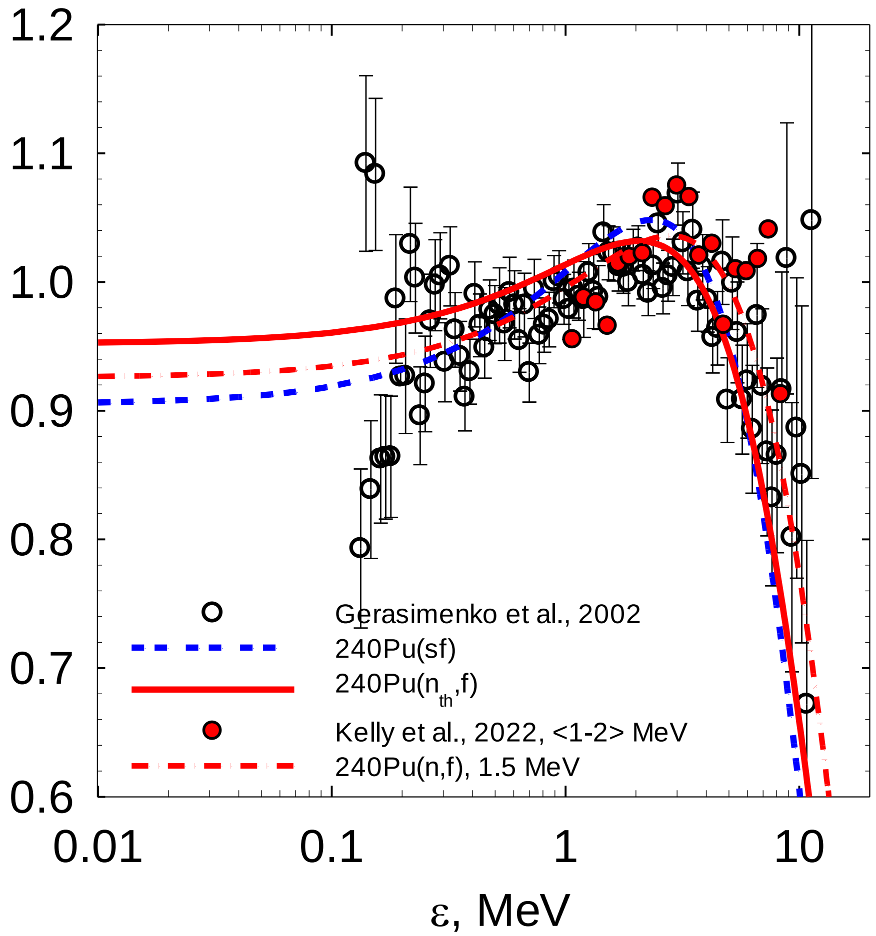
$^{239}Pu(n_{th},f)$ **$^{240}Pu(n_{th},f)$** **$^{241}Pu(n_{th},f)$**

$^{239}Pu(n_{th},f)$ $^{240}Pu(sf)$ $^{241}Pu(n_{th},f)$ $^{242}Pu(sf)$

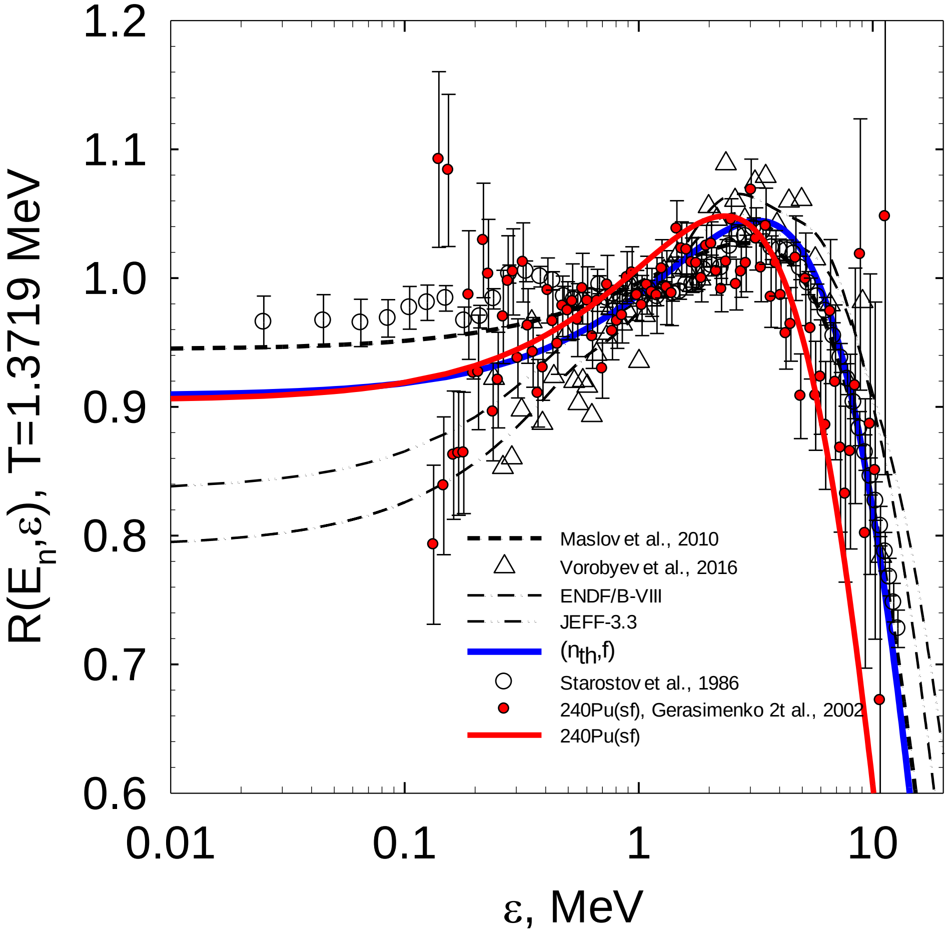




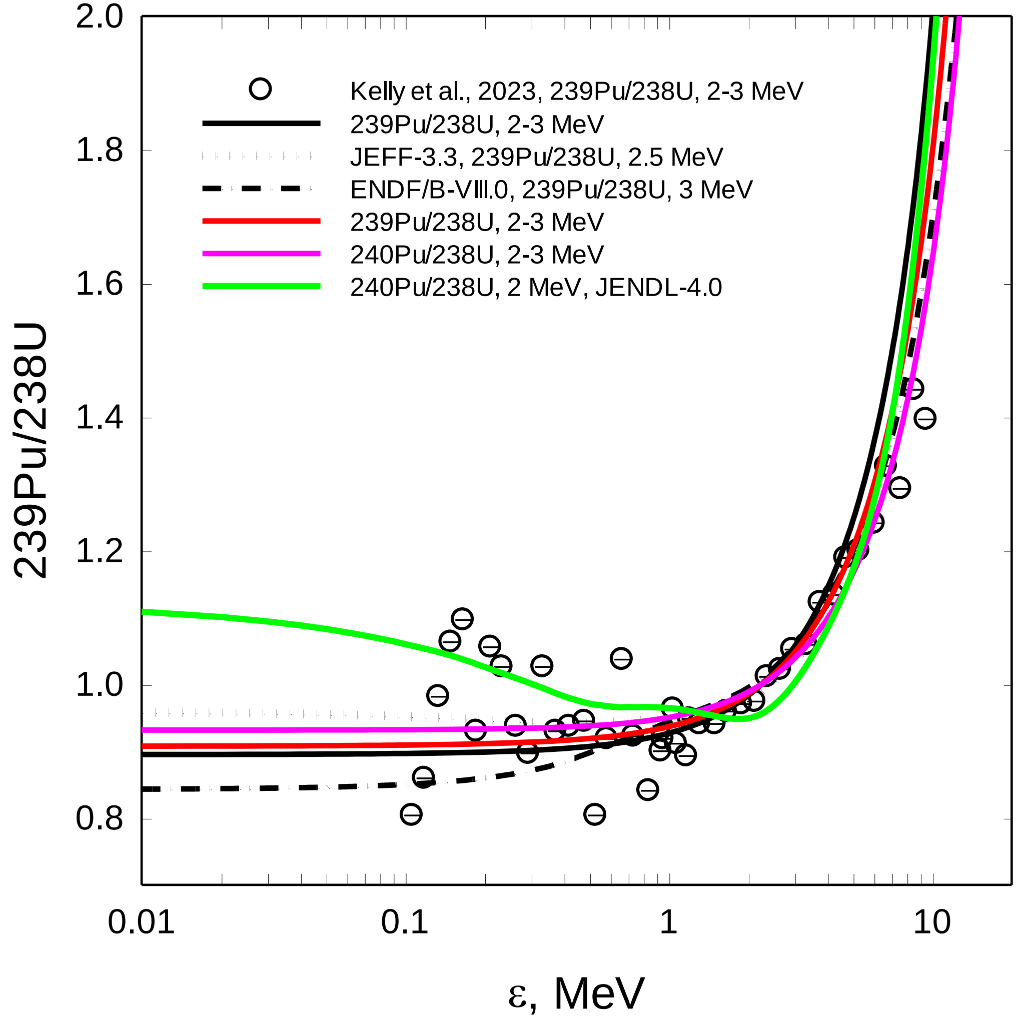
$^{240}Pu(n_{th},f)$ $^{240}Pu(\mathit{sf})$



$^{239}Pu(n_{th},f)$ $^{240}Pu(\mathit{sf})$



^{239}Pu(n,f)/^{238}U(n,f) E_n=2-3MeV ^{240}Pu(n,f)/ ^{238}U(n,f)



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

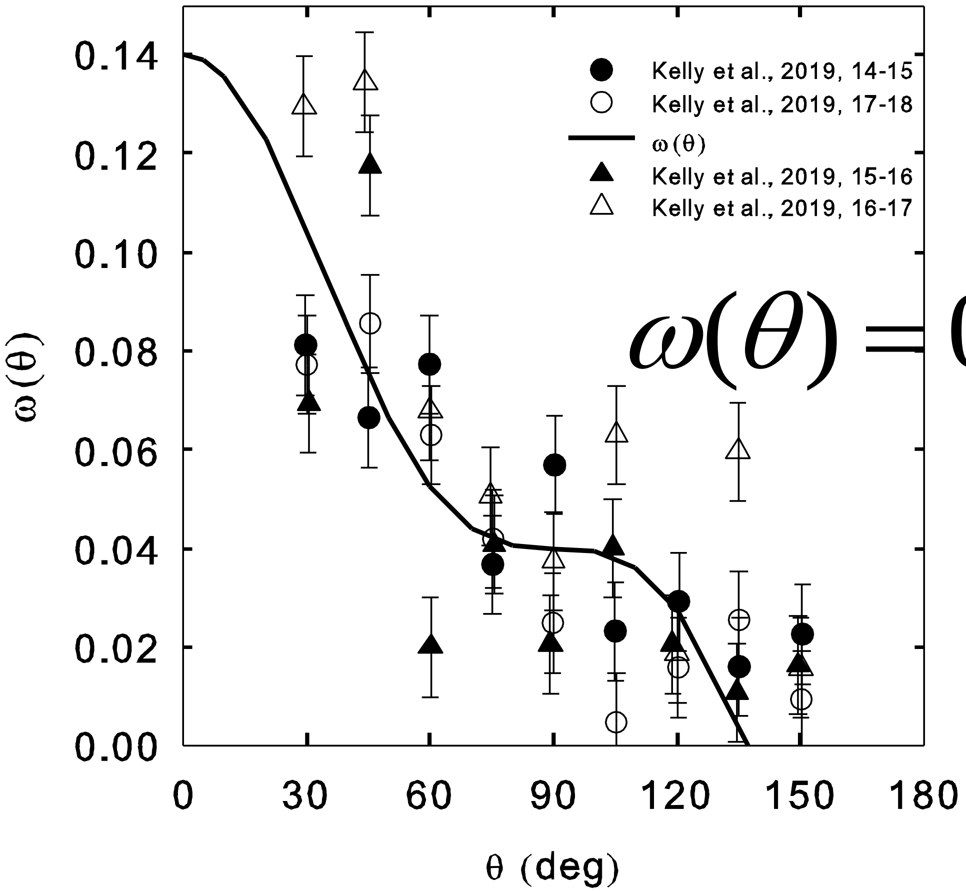
$$\sigma_{n,xnf}\left(E_n\right)=\sum_{J\pi}^{J}\int_0^{U_x}W_{A+1-x}^{J\pi}(U)P_{f\,(A+1-x)}^{J\pi}(U)dU$$

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

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

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

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



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

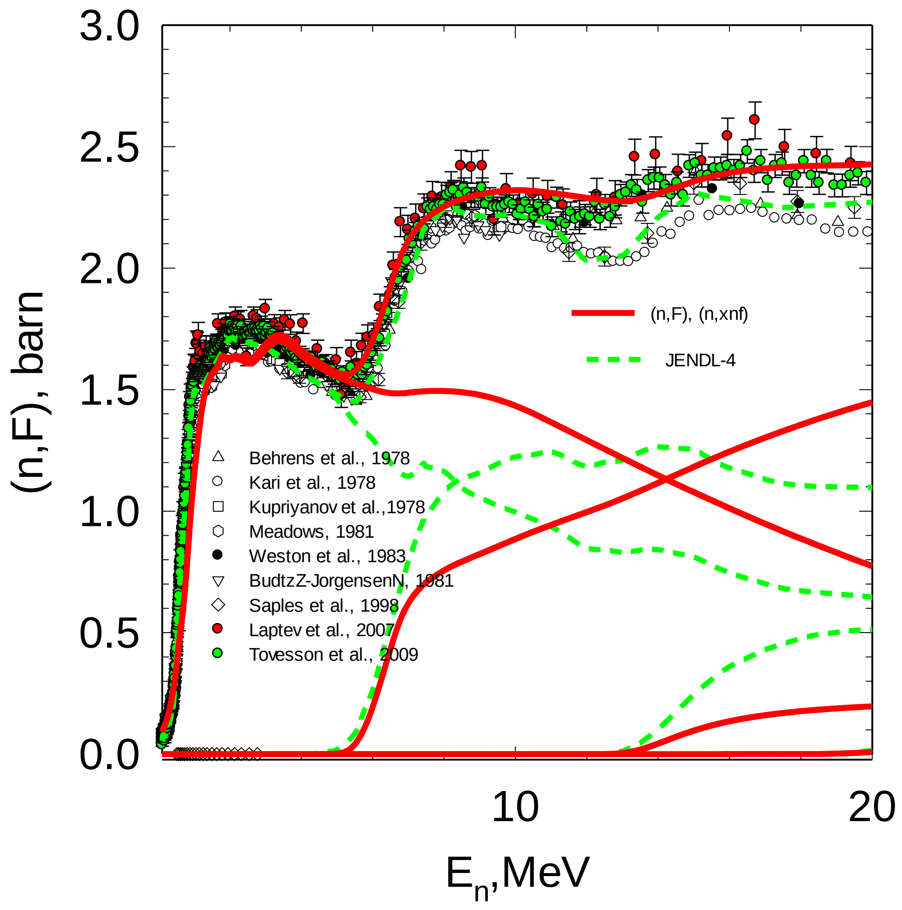
Angular anisotropy (AA) of secondary neutrons is evidenced in neutron emission spectra (NES) due to

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)

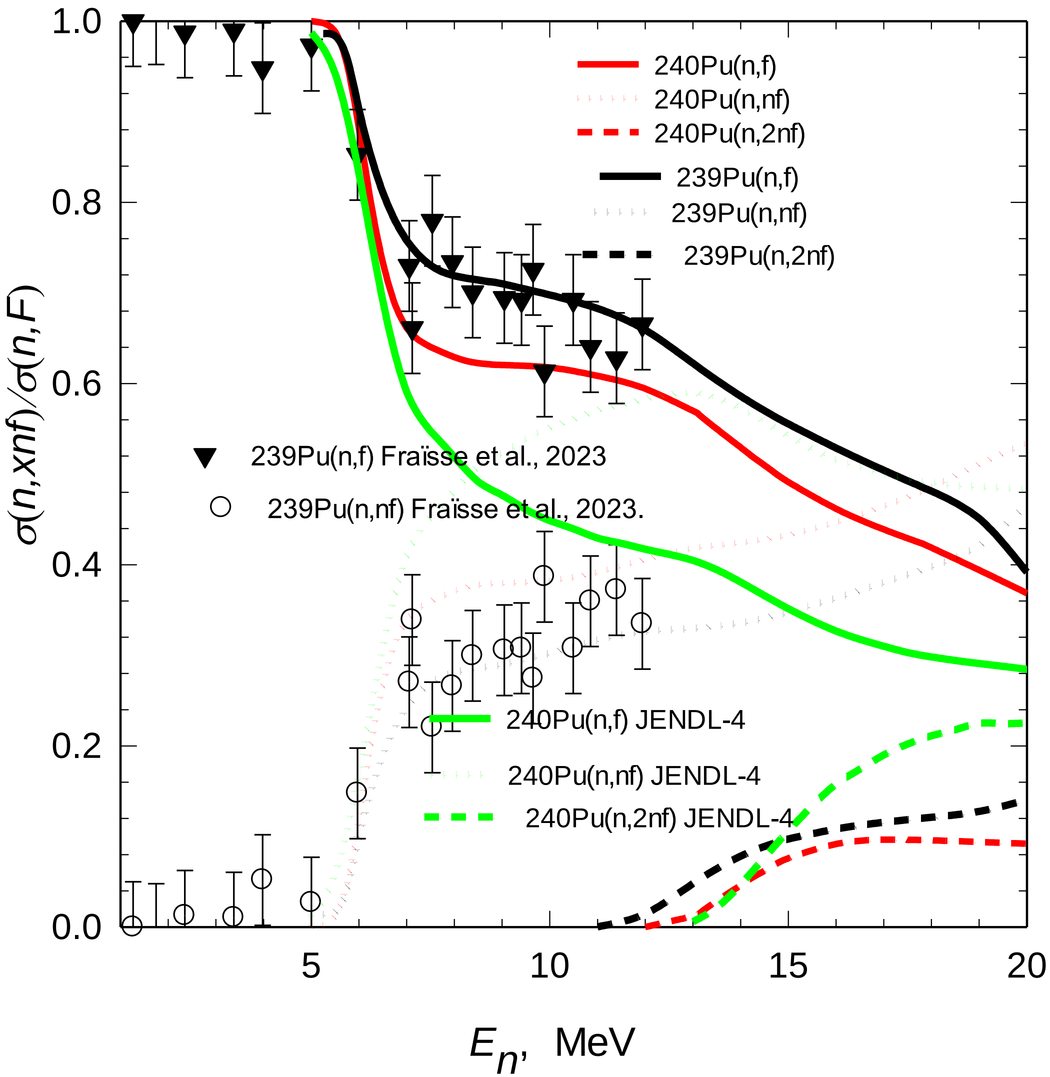
NES **AA** is due to PE/semi-direct $(n,nX)^1$

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

$^{240}Pu(n,F)$, $^{240}Pu(n,xnf)$



$^{240}Pu(n,xnf)/^{240}Pu(n,F)$



PFNS as a superposition of (n,f) &(n,xnf)

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

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

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

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

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

Exclusive neutron spectra of (n,xnf)$^{1,..x}$, ($n,n\gamma$) 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 ^{240}Pu being included via $\left\langle \omega(\theta) \right\rangle_{\vartheta} \approx \omega(\theta \approx 90^{o})$

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

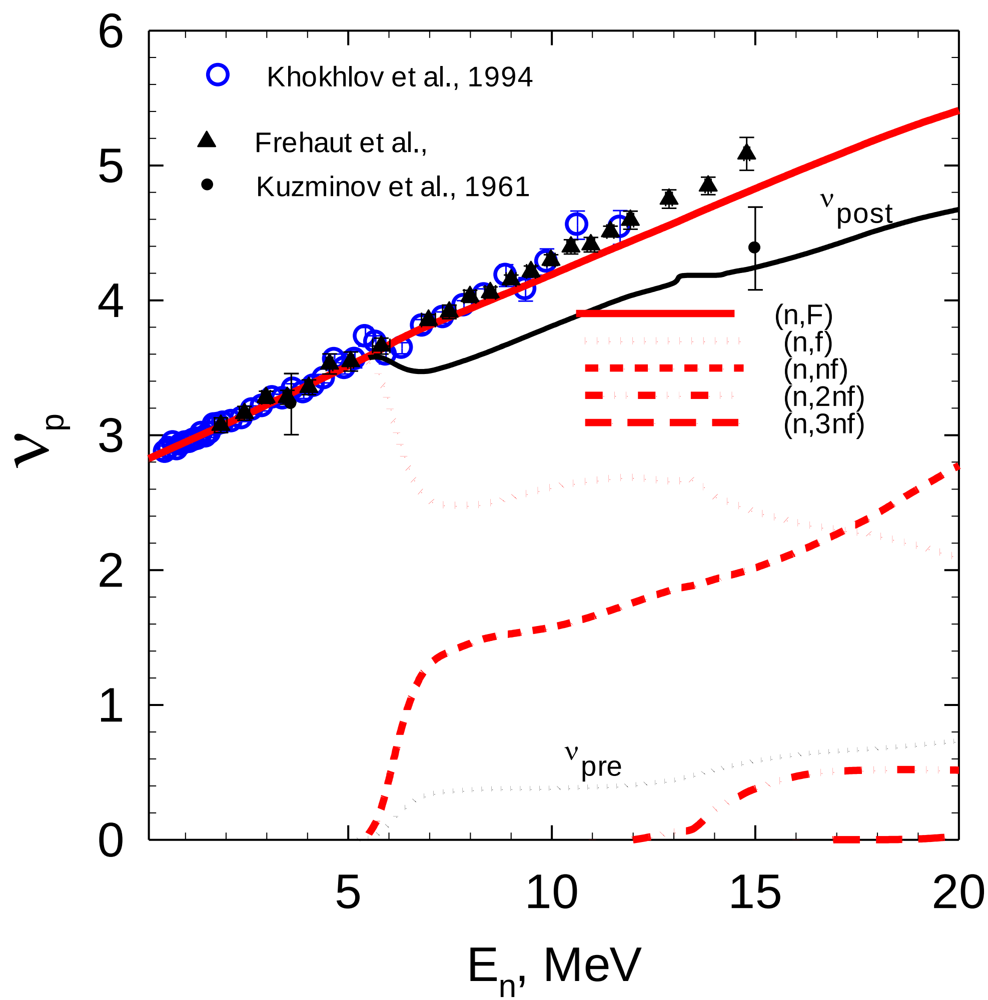
$$E_{nx} = E_r - E_{fx}^{pre} + E_n + B_n - \sum_{x,1\le k\le x}\left(\left\langle E_{nxnf}^{k}(\theta)\right\rangle + B_{nx}\right)$$

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

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

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

$^{240}Pu(n,F)$, $^{240}Pu(n,xnf)$, pre- and post-fission neutrons multiplicity



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

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

$$\sigma_c(E_n) = \sigma_a(E_n)\left(1-q-\tilde{q}\right),$$

$$\tilde{q} = \int_0^{E_n-E_d} \frac{d\tilde{\sigma}^1_{nnx}}{d\varepsilon}\,d\varepsilon = \int_0^{E_n-E_d} \sqrt{\frac{\varepsilon}{E_n}}\,\frac{\left\langle \omega(\theta) \right\rangle_{\theta}}{E_n-\varepsilon}\,d\varepsilon = \left\langle \omega(\theta) \right\rangle_{\theta}\left[\ln\left(\frac{1+\sqrt{1-\delta}}{1-\sqrt{1-\delta}}\right) - 2\sqrt{1-\delta}\right]$$

$\delta = E_d/E_n$, E_d -upper discrete level energy

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

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

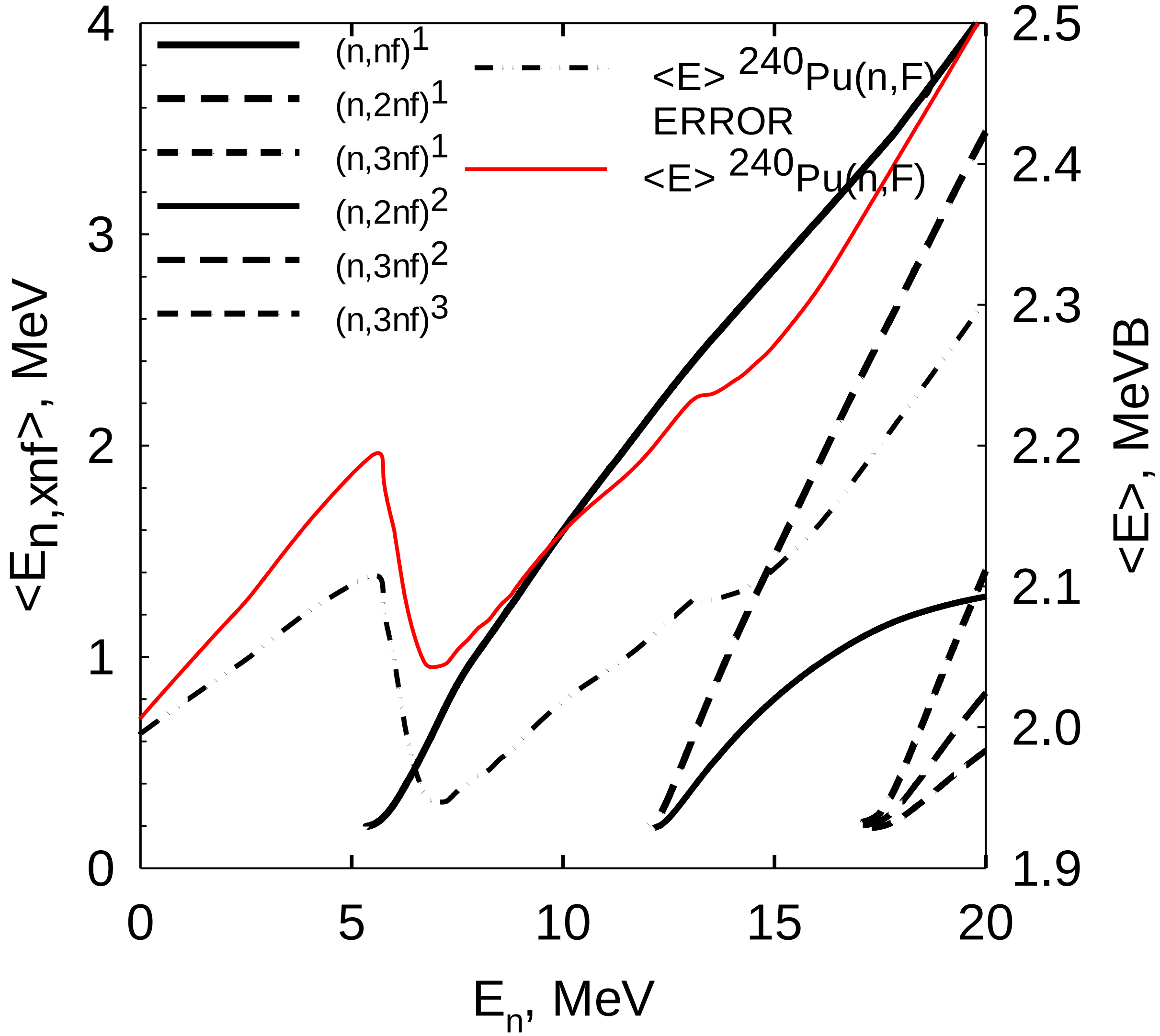
$$\frac{d^2\sigma^1_{n2nx}\left(\varepsilon,E_n,\theta\right)}{d\varepsilon d\theta}=\frac{d^2\sigma^1_{nnx}\left(\varepsilon,E_n,\theta\right)}{d\varepsilon d\theta}\frac{\Gamma^A_n(E_n-\varepsilon,\theta)}{\Gamma^A(E_n-\varepsilon,\theta)}$$

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

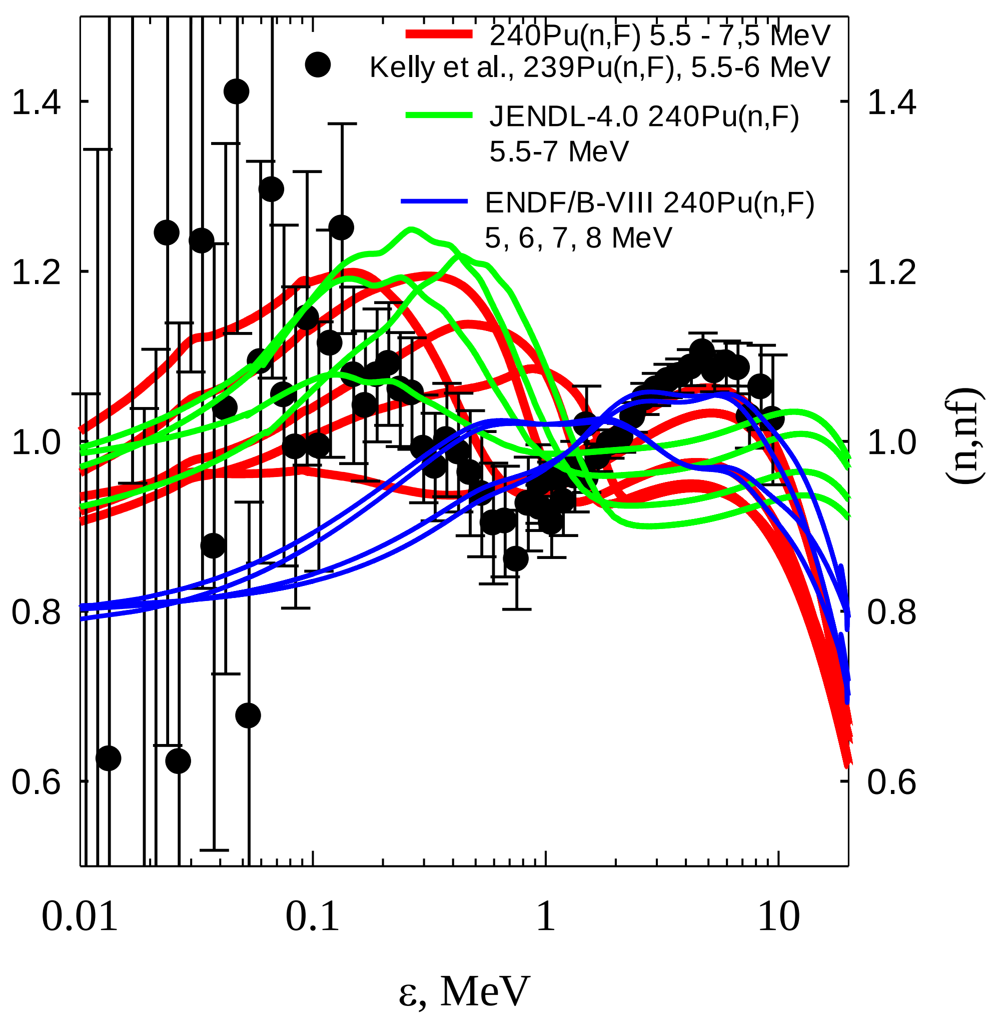
Exclusve pre-fission neutron contribution to the neutron emission spectra

$$\frac{\sigma_{n,2nf}(E_n,\theta)}{4\pi}\frac{d\sigma^{1,2}_{n2nf}(\varepsilon,E_n,\theta)}{d\varepsilon}$$

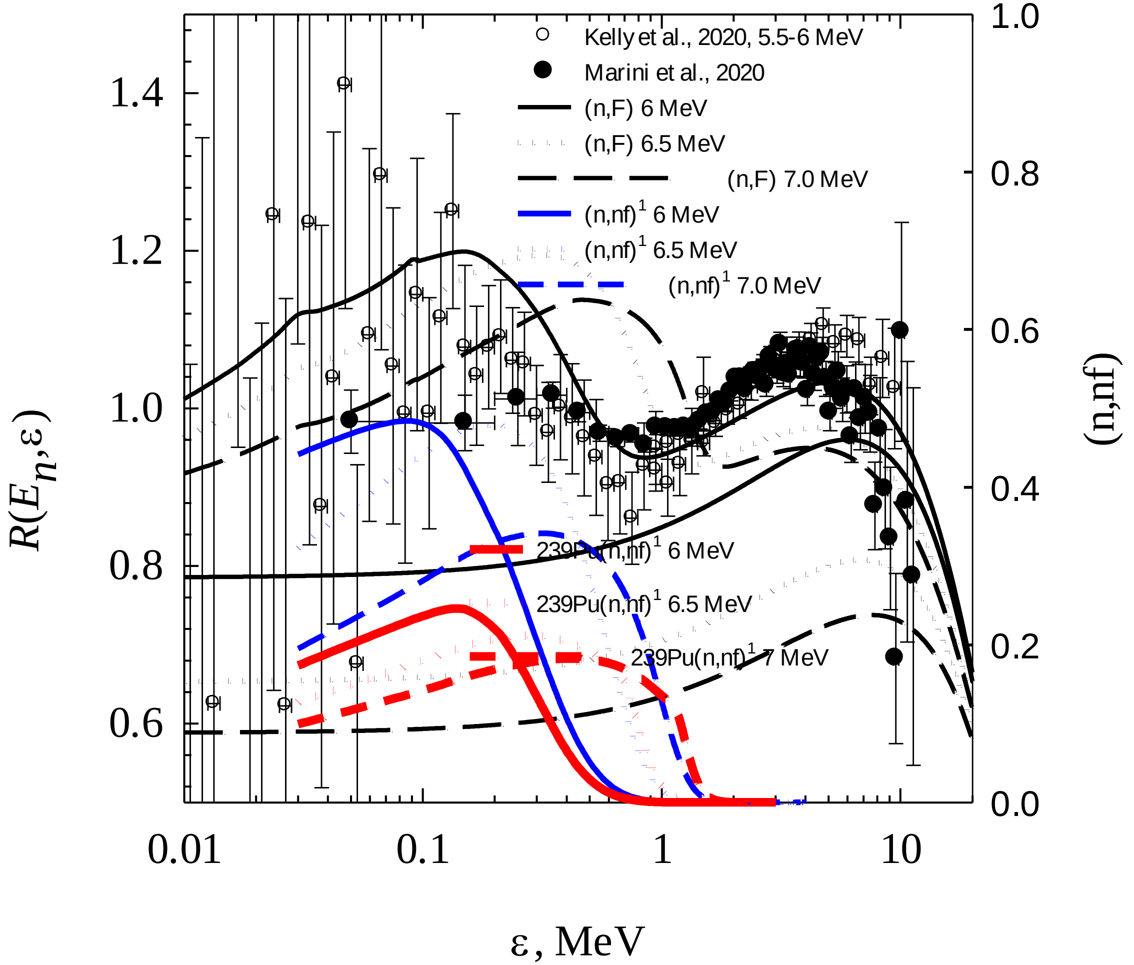
<Enxnf>, <E> of PFNS



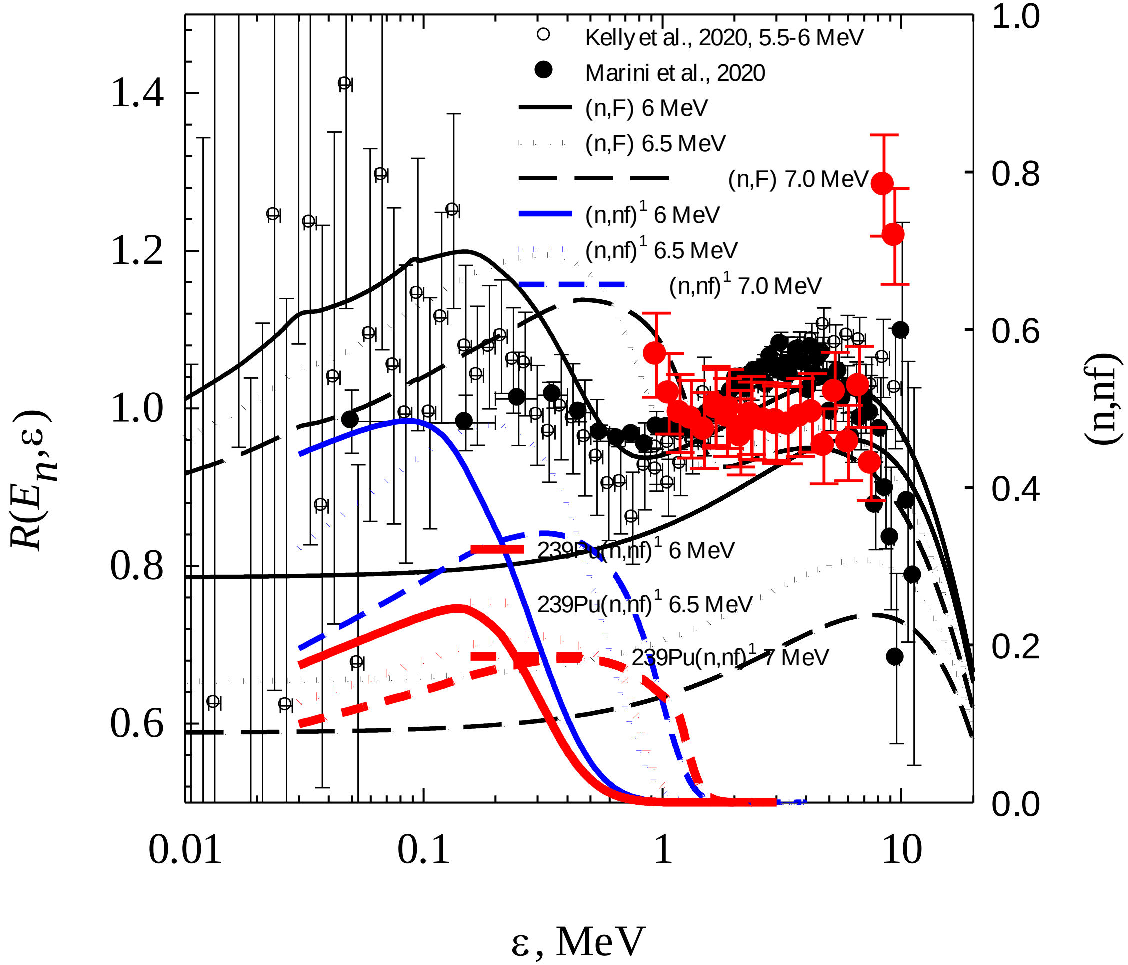
^{240}Pu(n,F) 5.5-7 MeV ^{239}Pu(n,F)



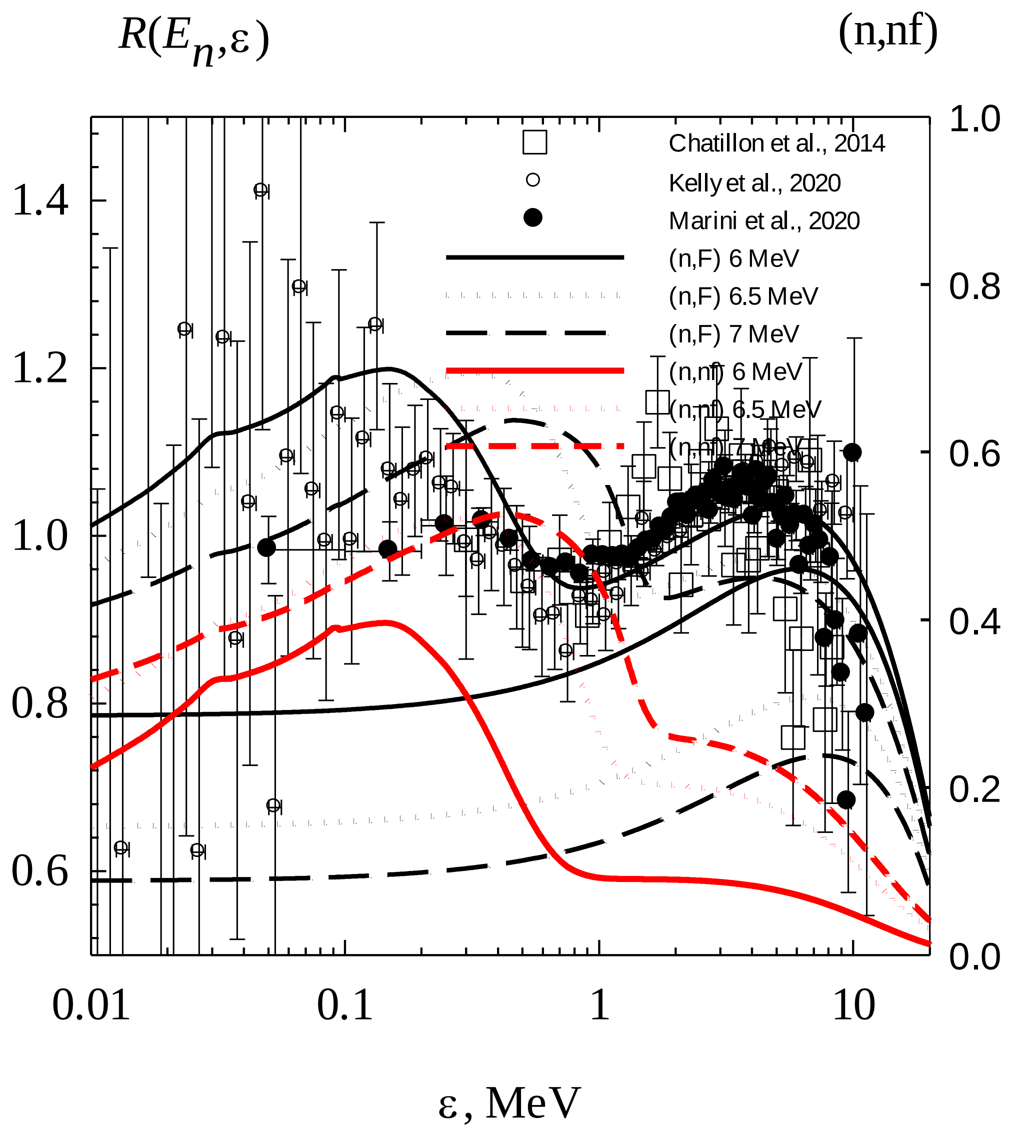
^{239}Pu(n,xnf) 6-7 MeV ^{240}Pu(n,xnf)



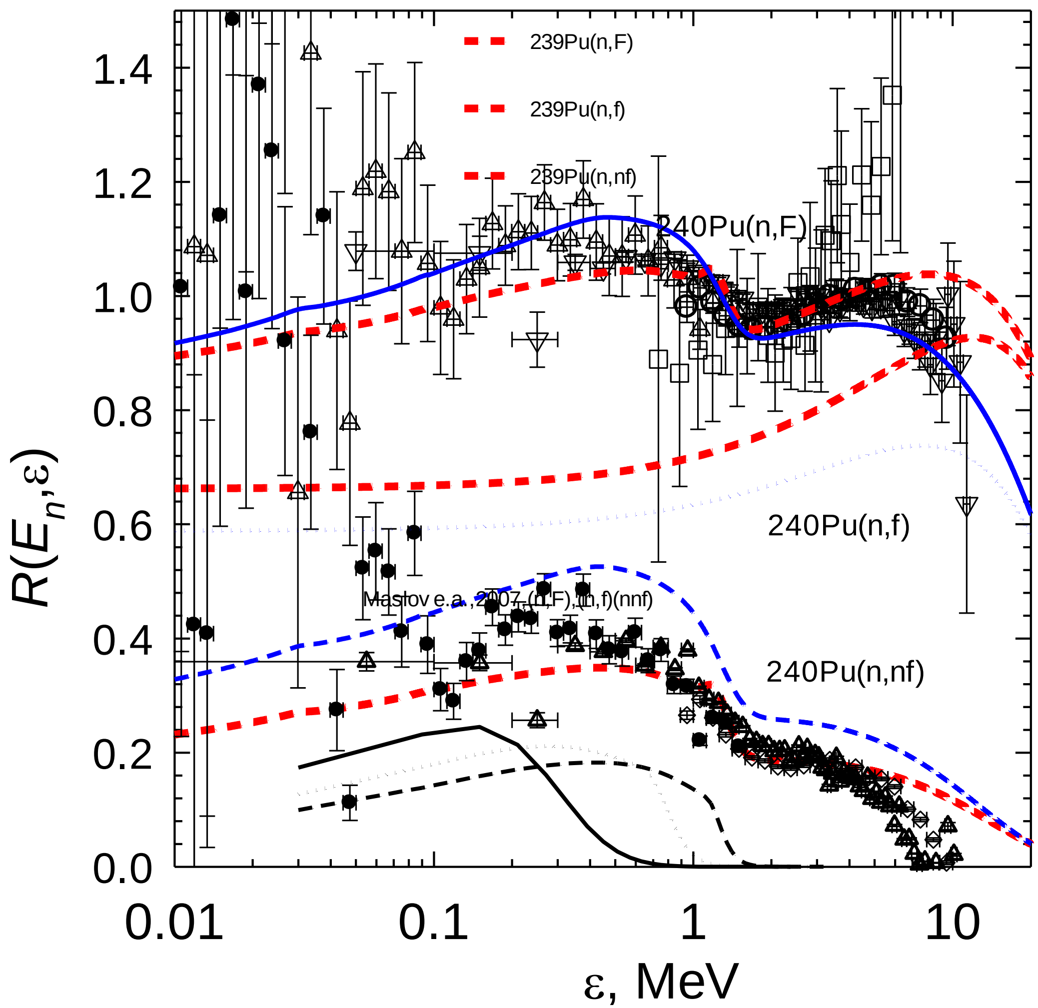
^{239}Pu(n,F) 5.5-7 MeV ^{240}Pu(n,F)



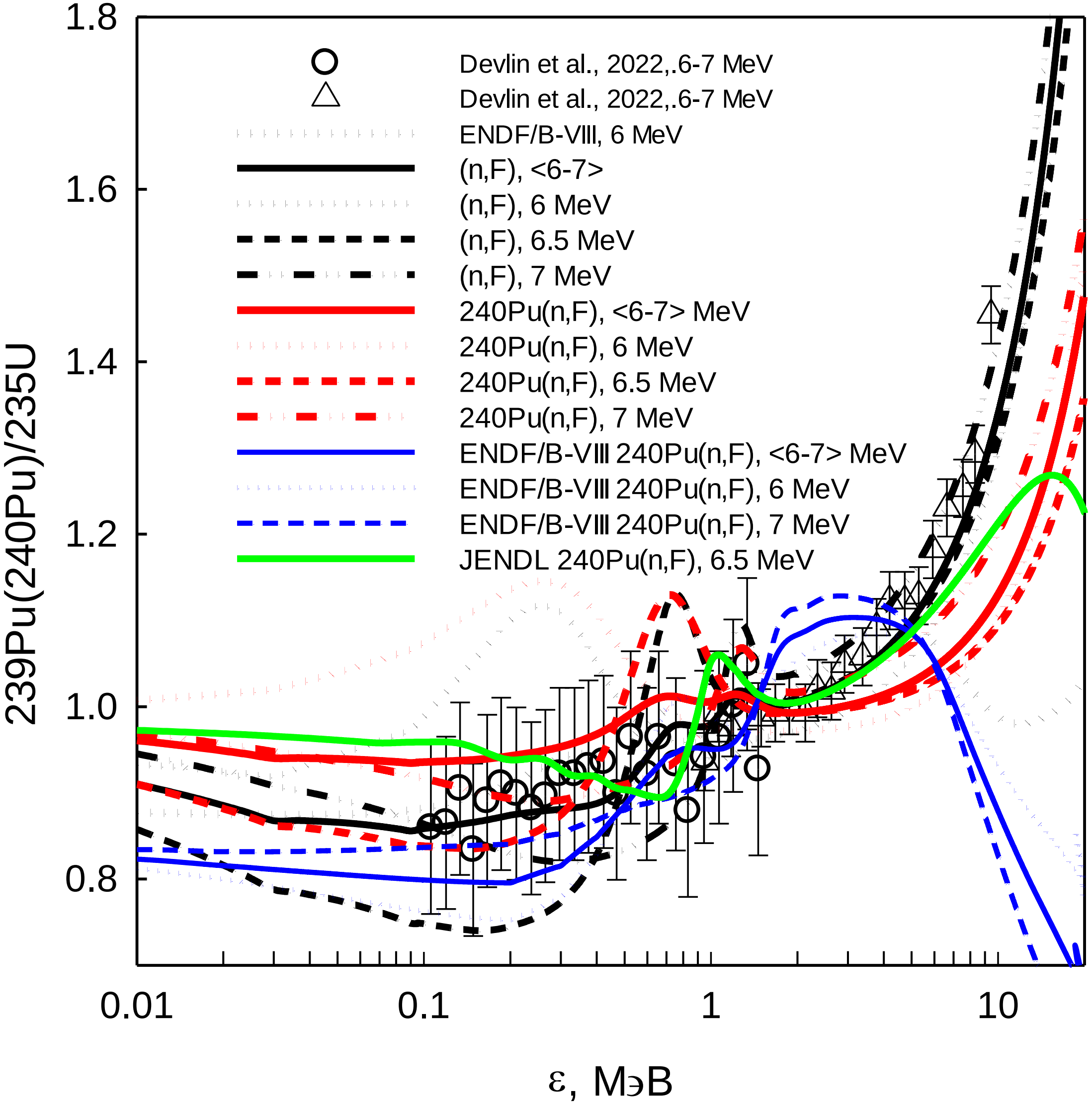
^{240}Pu(n,F) 6-7 MeV ^{240}Pu(n,nf)



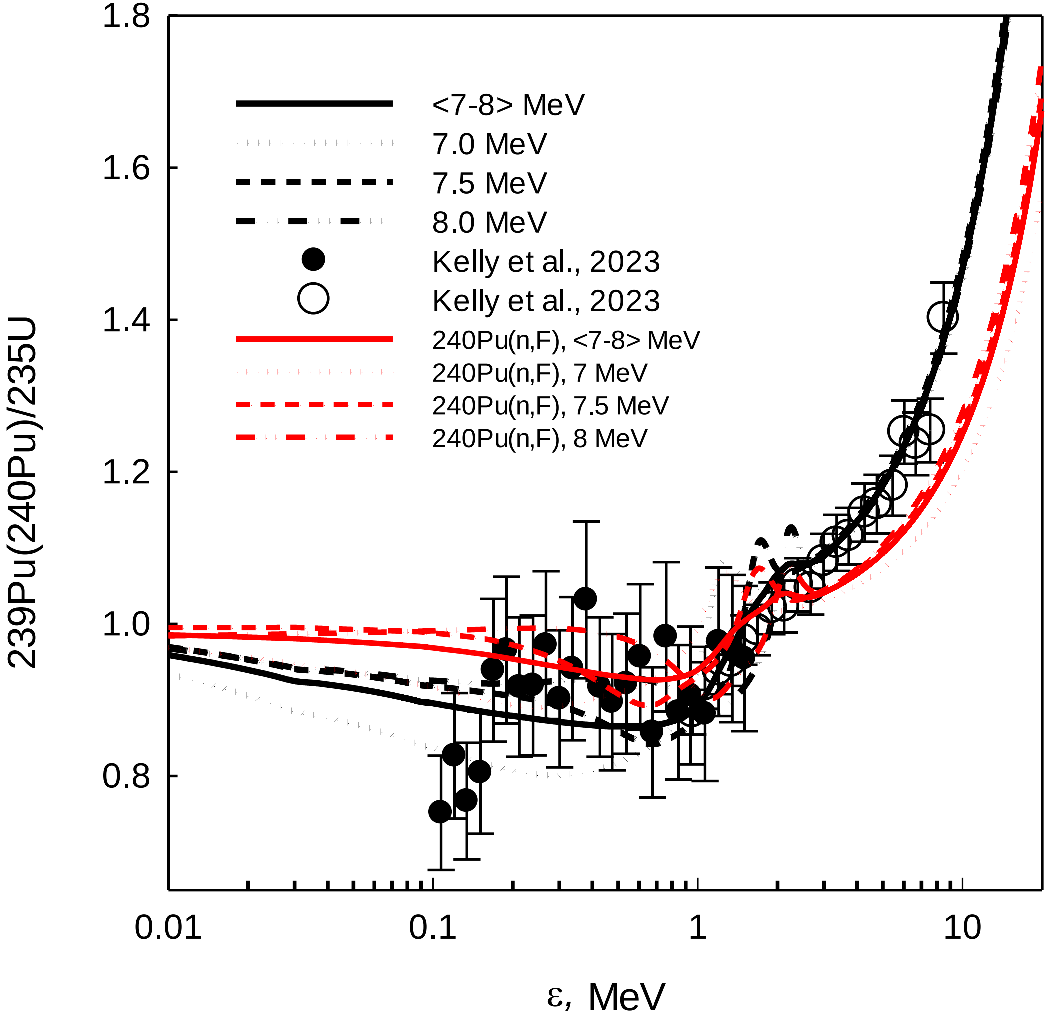
^{239}Pu(n,F) E_n=7 MeV ^{240}Pu(n,F)



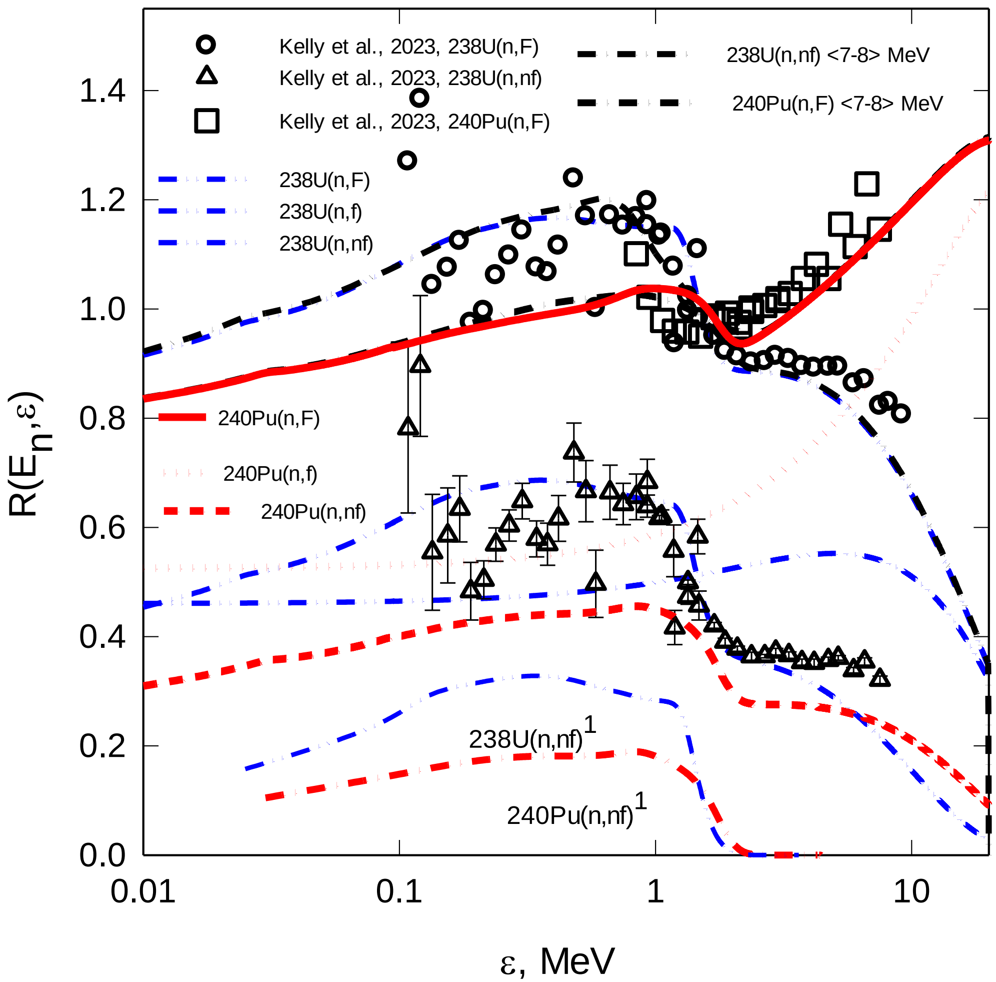
$^{239}Pu/^{235}U$ 6-7 MeV $^{240}Pu/^{235}U$



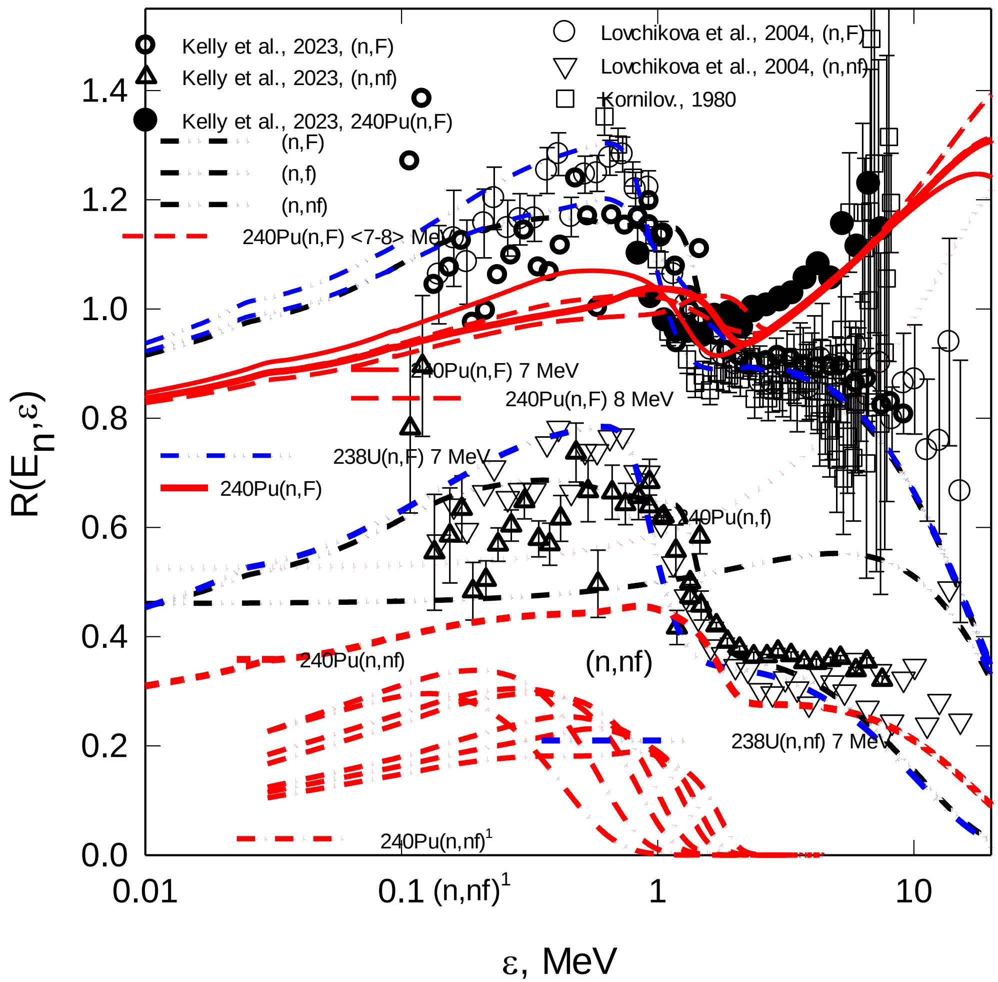
$^{239}Pu/^{235}U$ 7-8 MeV $^{240}Pu/^{235}U$



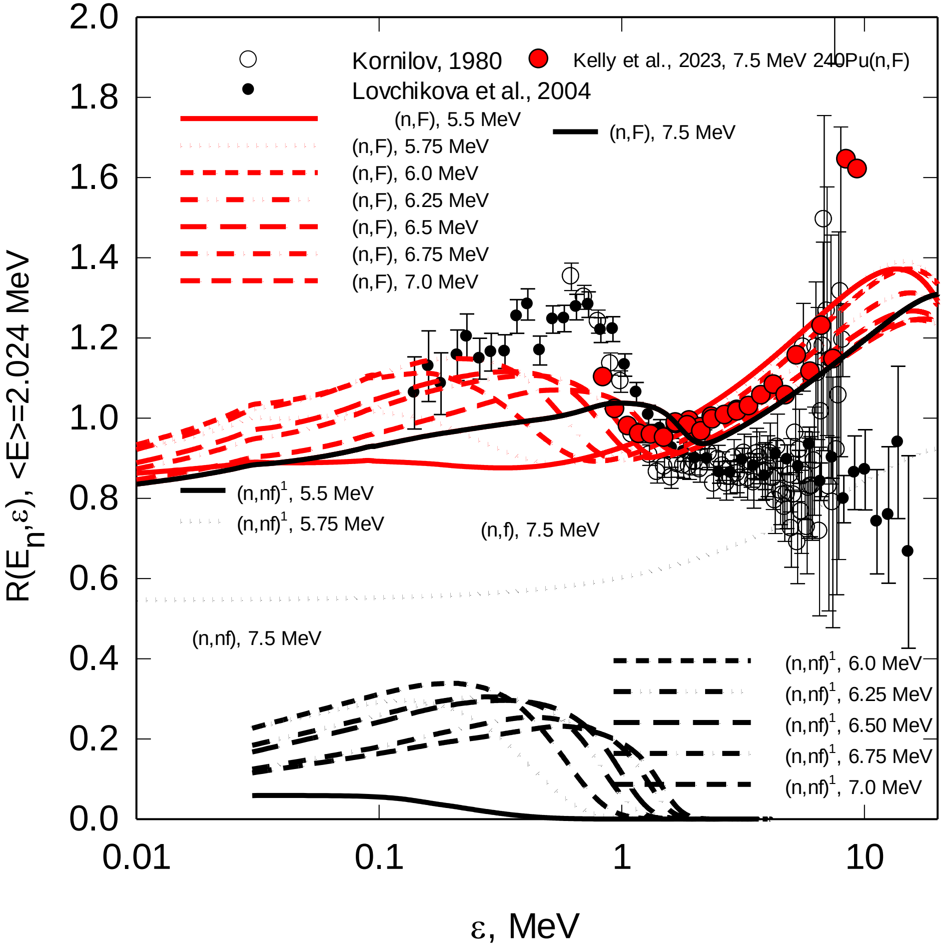
^{238}U(n,F) 7-8 MeV ^{240}Pu(n,F)

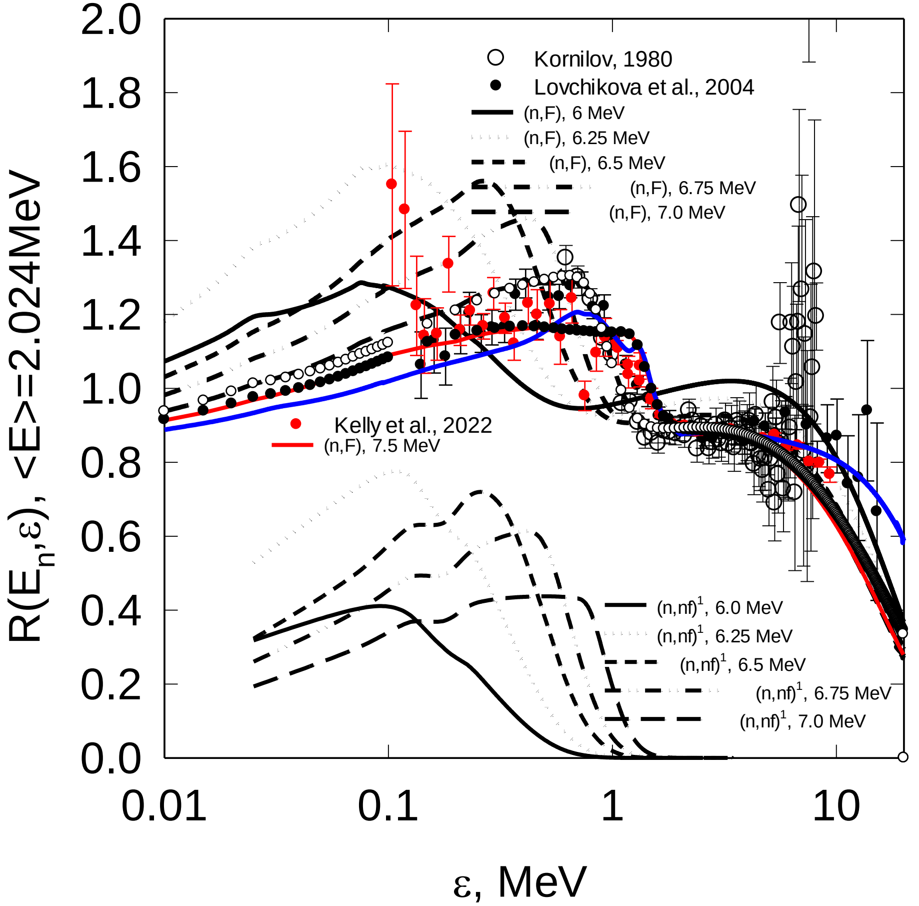


^{238}U(n,F) 7-8 MeV ^{240}Pu(n,F)

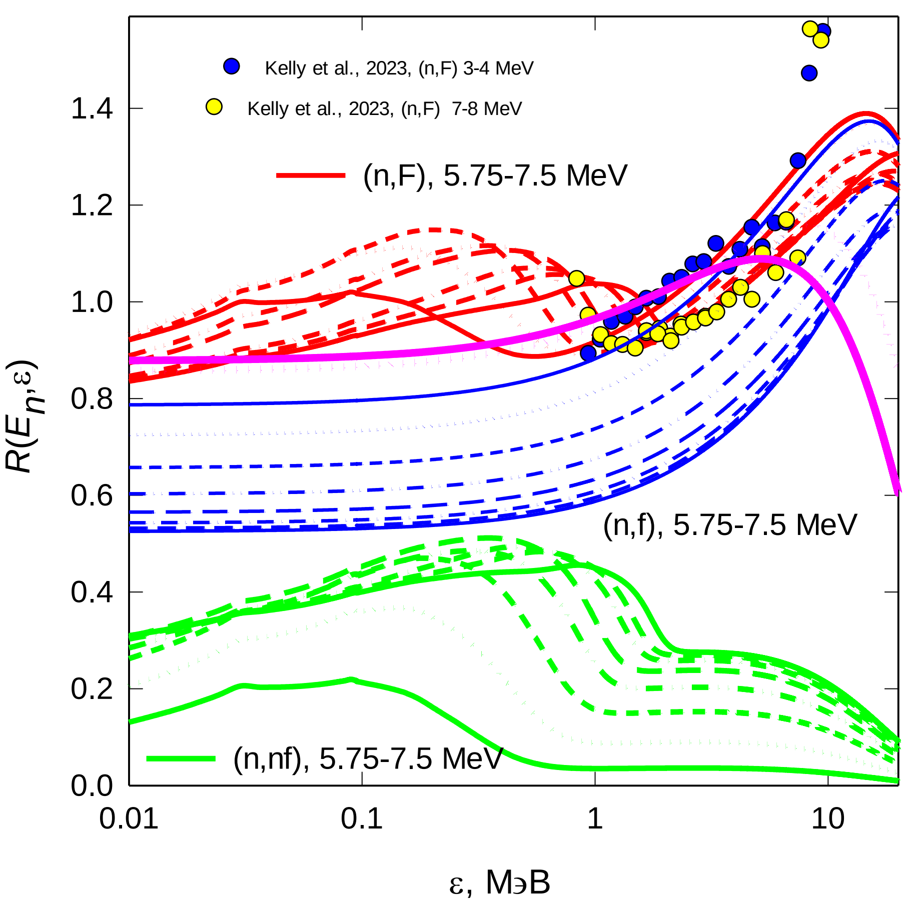


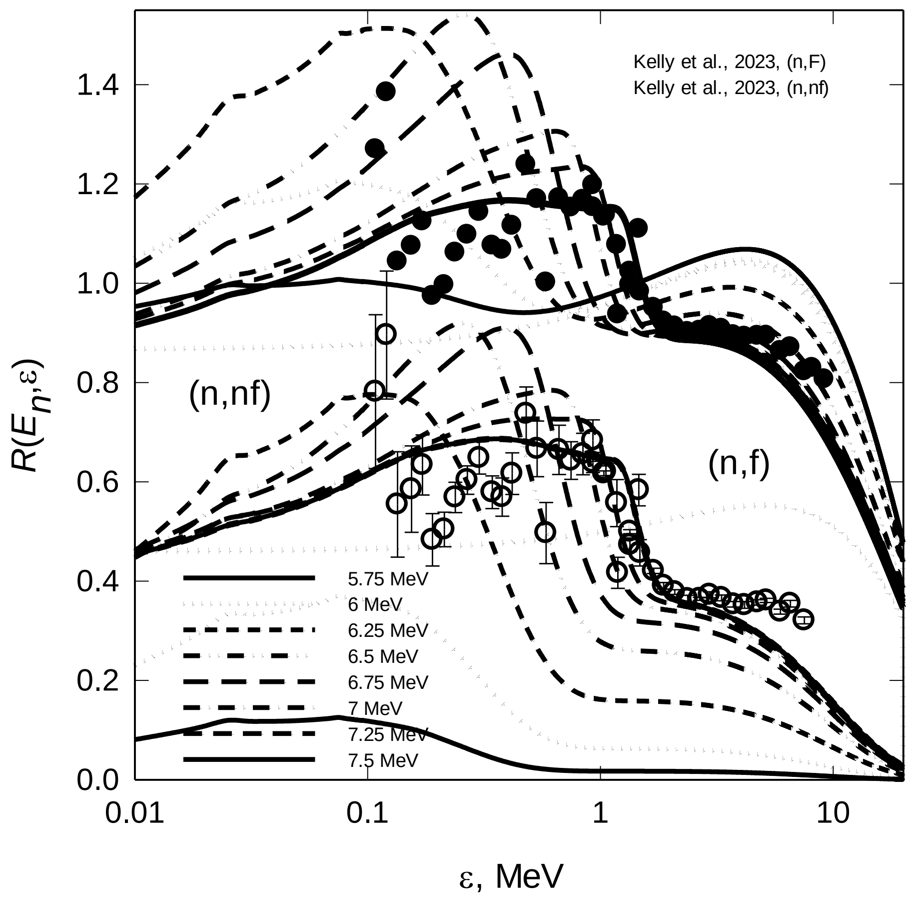
^{240}Pu(n,F)   6-7 MeV ^{238}U(n,F)



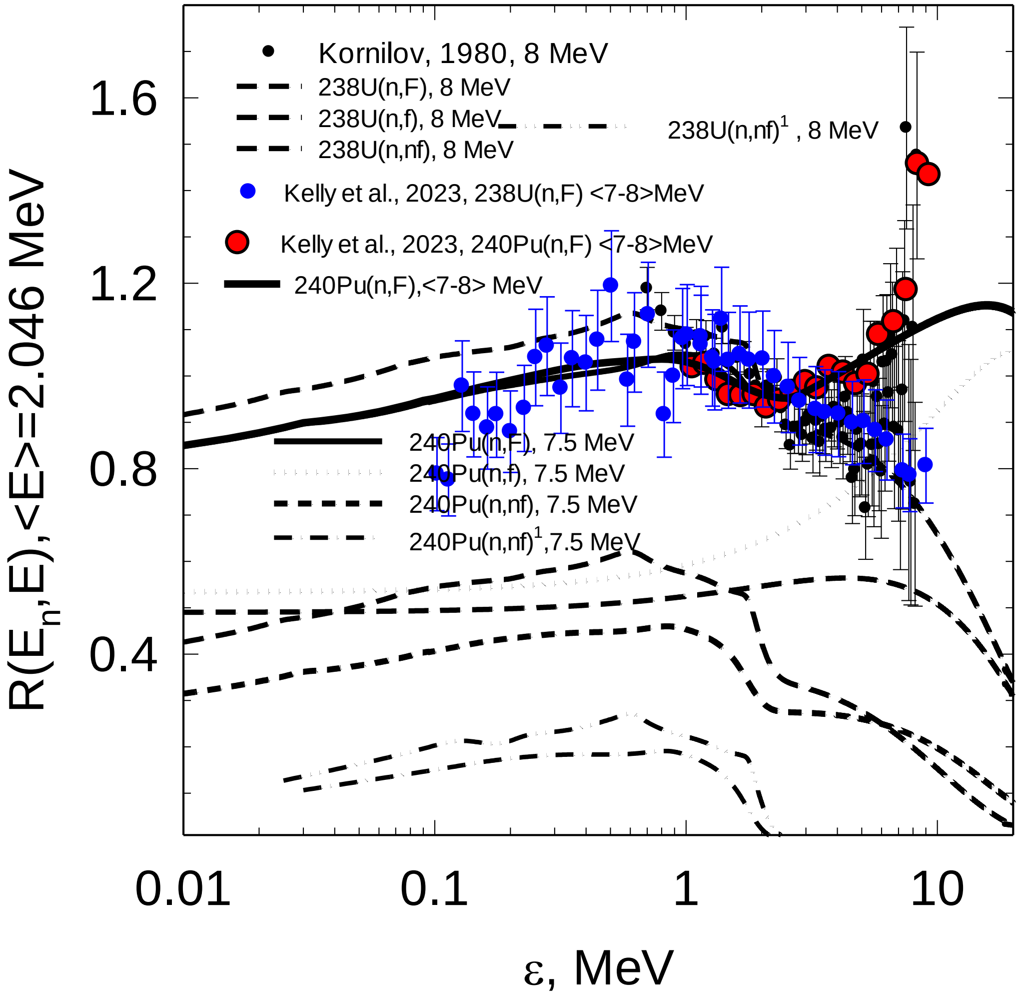


^{240}Pu(n,F) En=5.75-7.5 MeV ^{238}U(n,F)

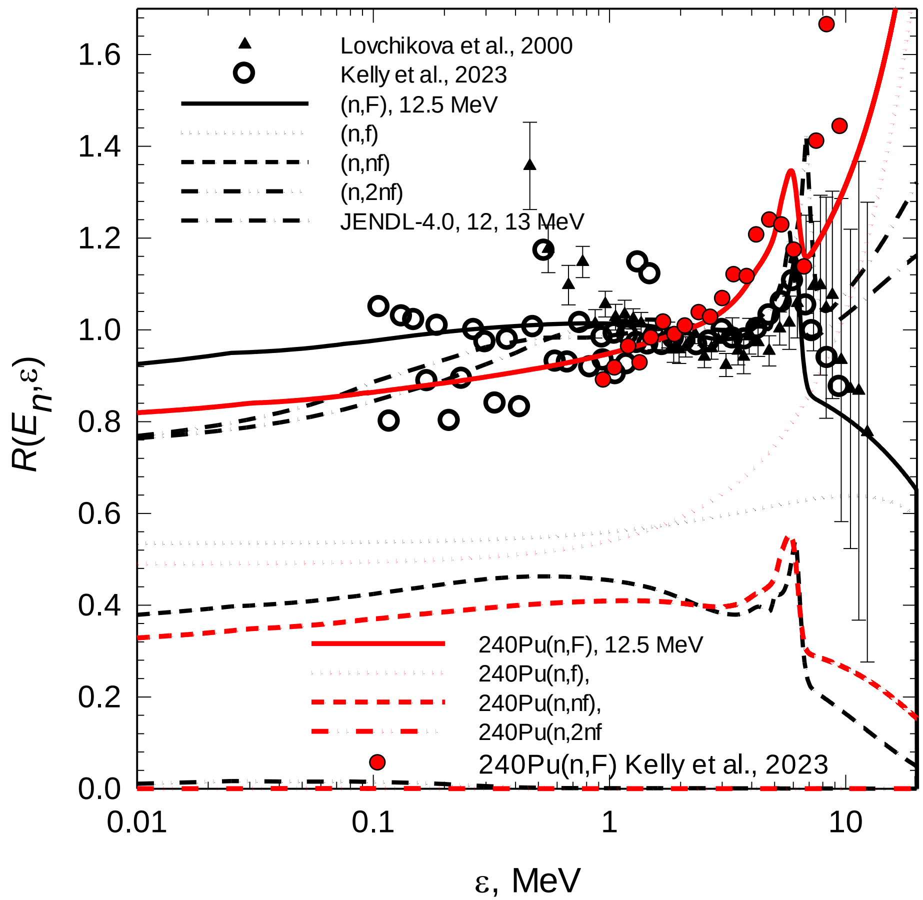




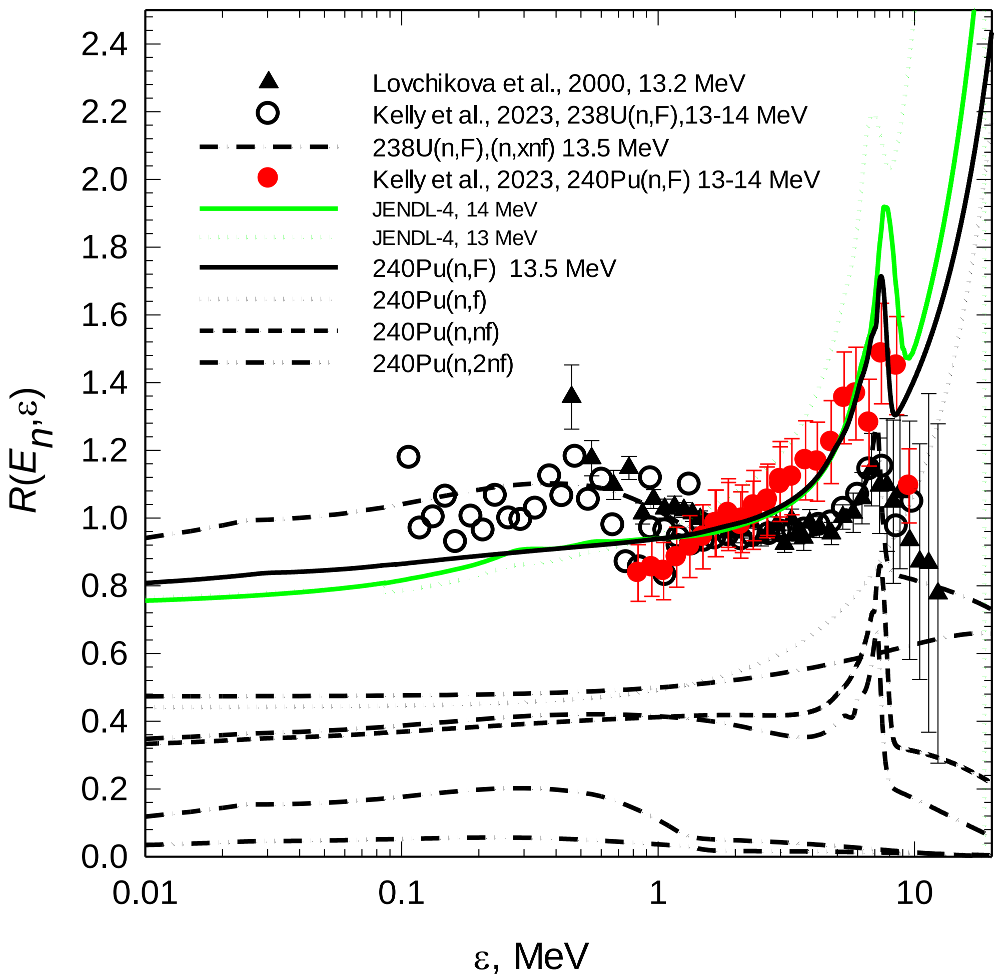
^{240}Pu(n,F) 7-8 MeV ^{238}U(n,F)



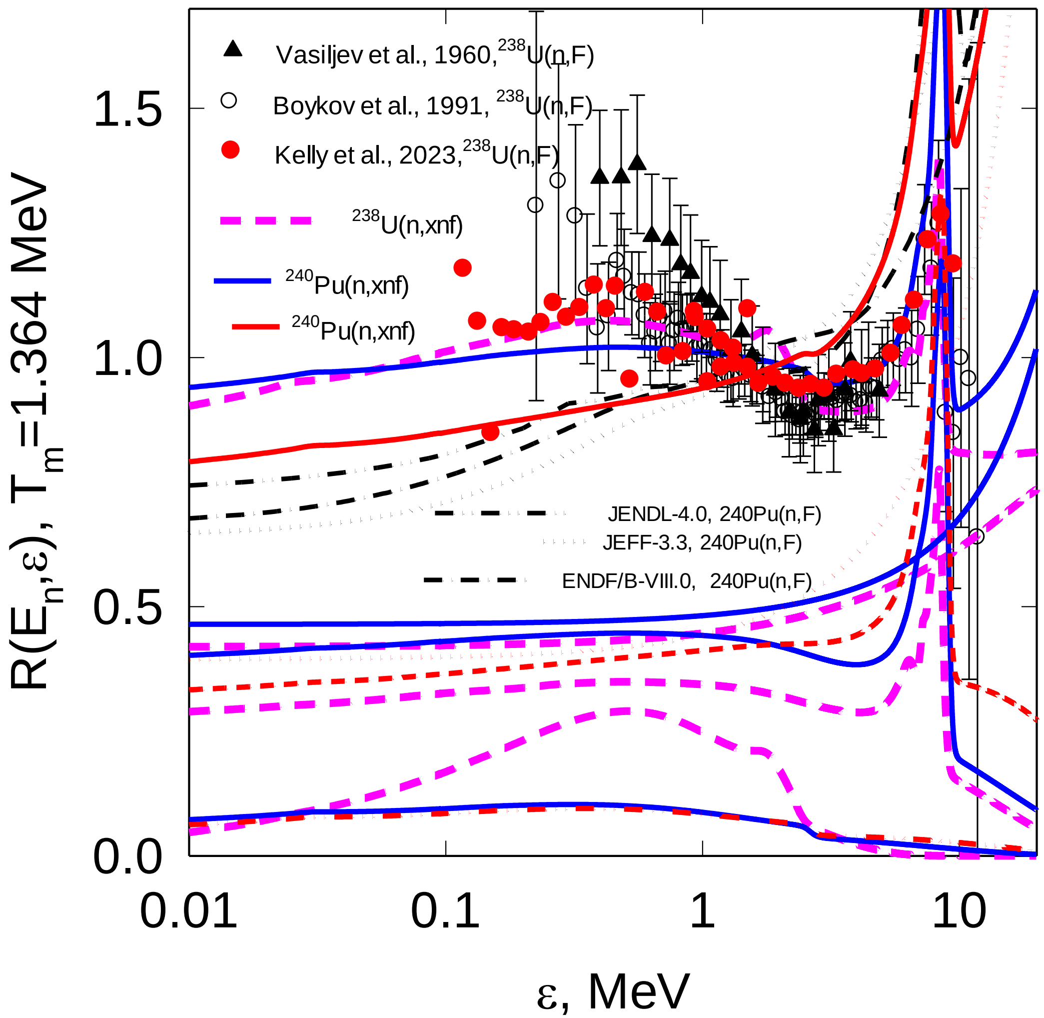
^{240}Pu(n,F) 12-13 MeV ^{238}U(n,F)



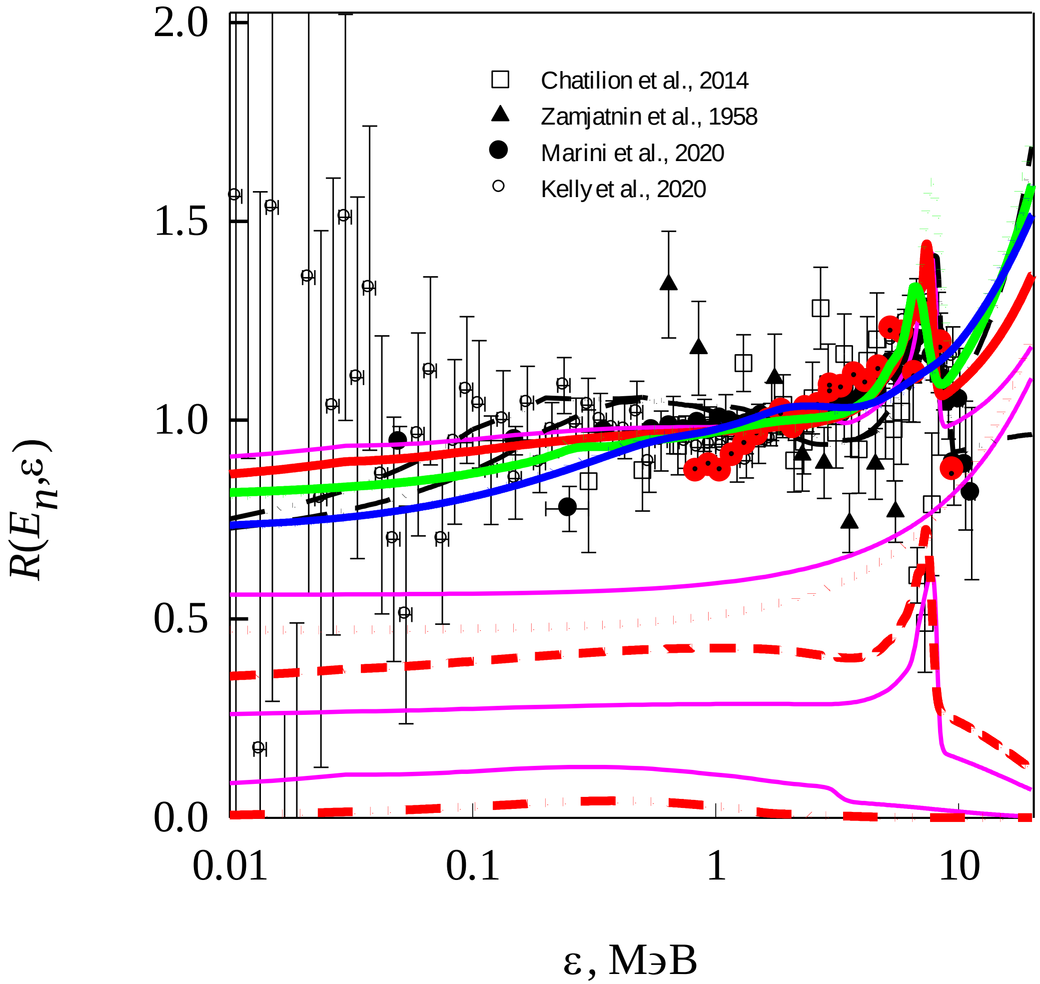
^{240}Pu(n,F) 13-14 MeV ^{238}U(n,F)



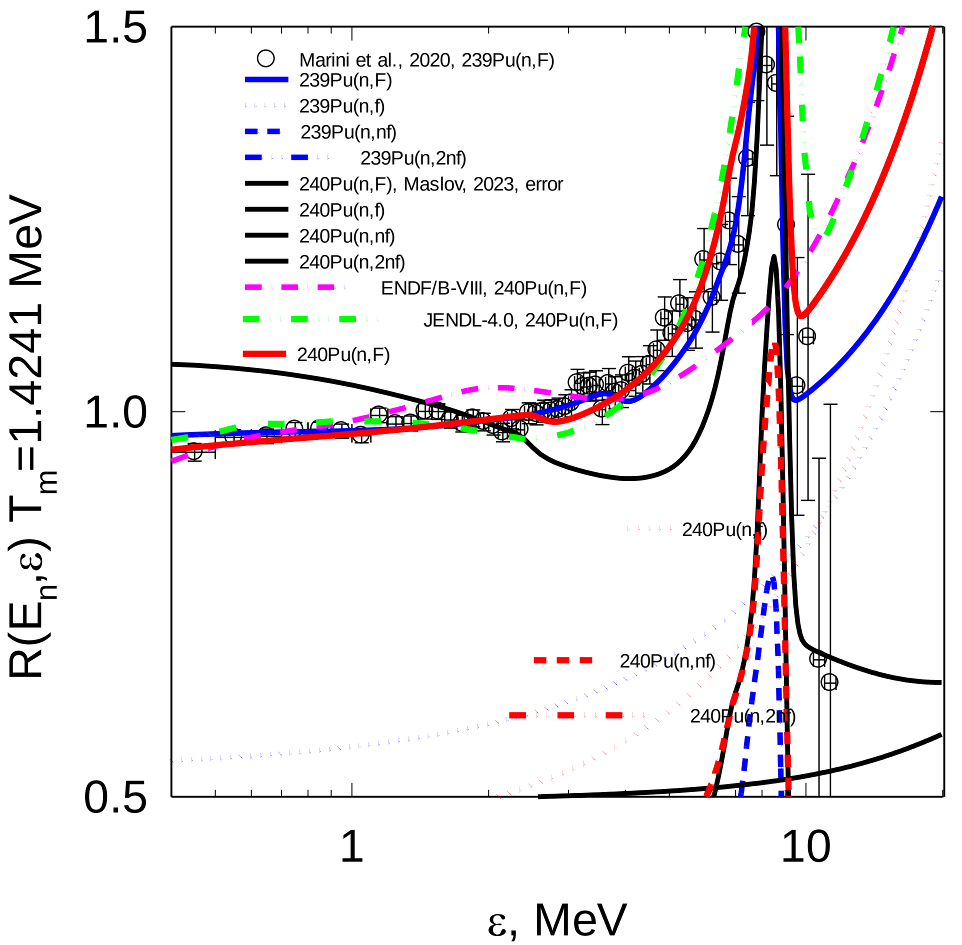
^{240}Pu(n,F) 14-15 MeV ^{238}U(n,F)



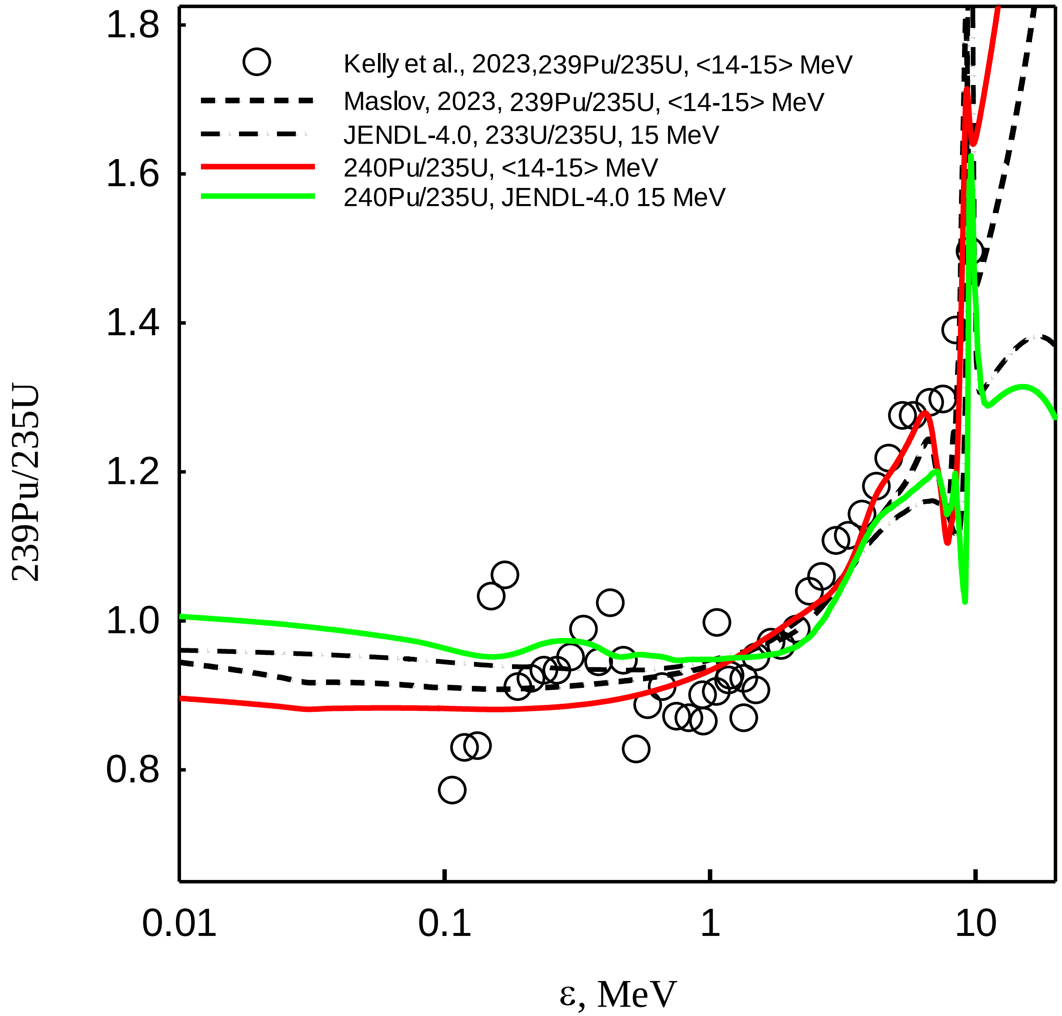
^{240}Pu(n,F) 13-14 MeV ^{239}Pu(n,F)



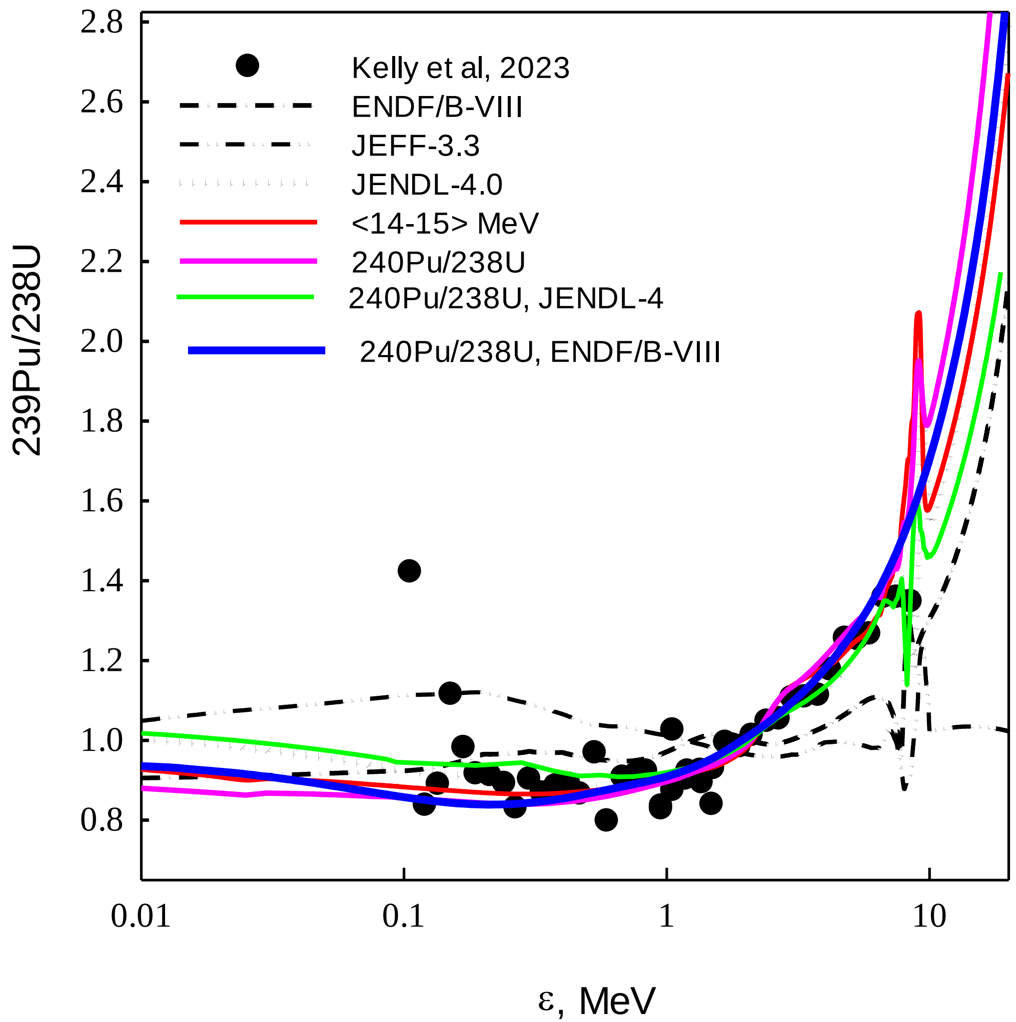
^{240}Pu(n,F) 14-15 MeV ^{239}Pu(n,F)



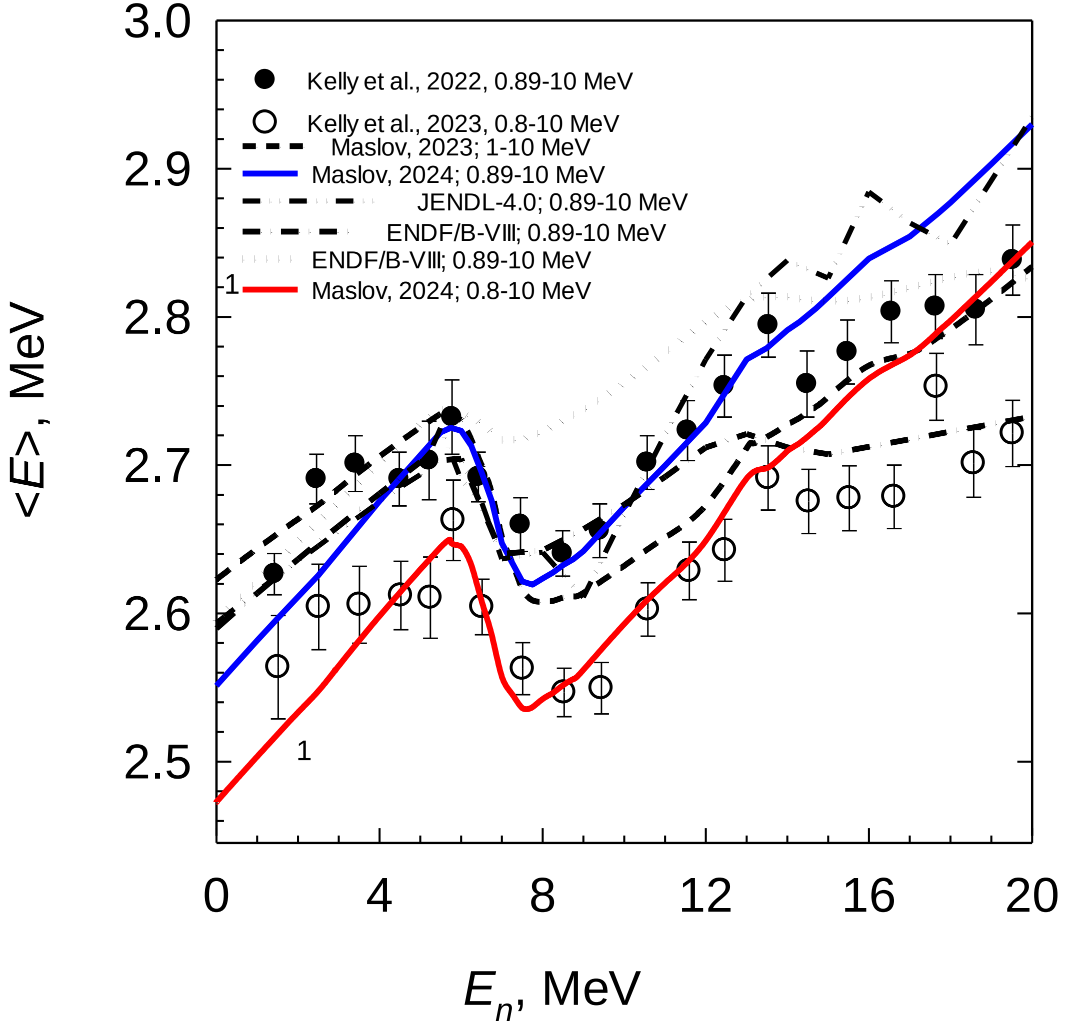
^{239}Pu/^{235}U   En=14-15 MeV ^{240}Pu/^{235}U



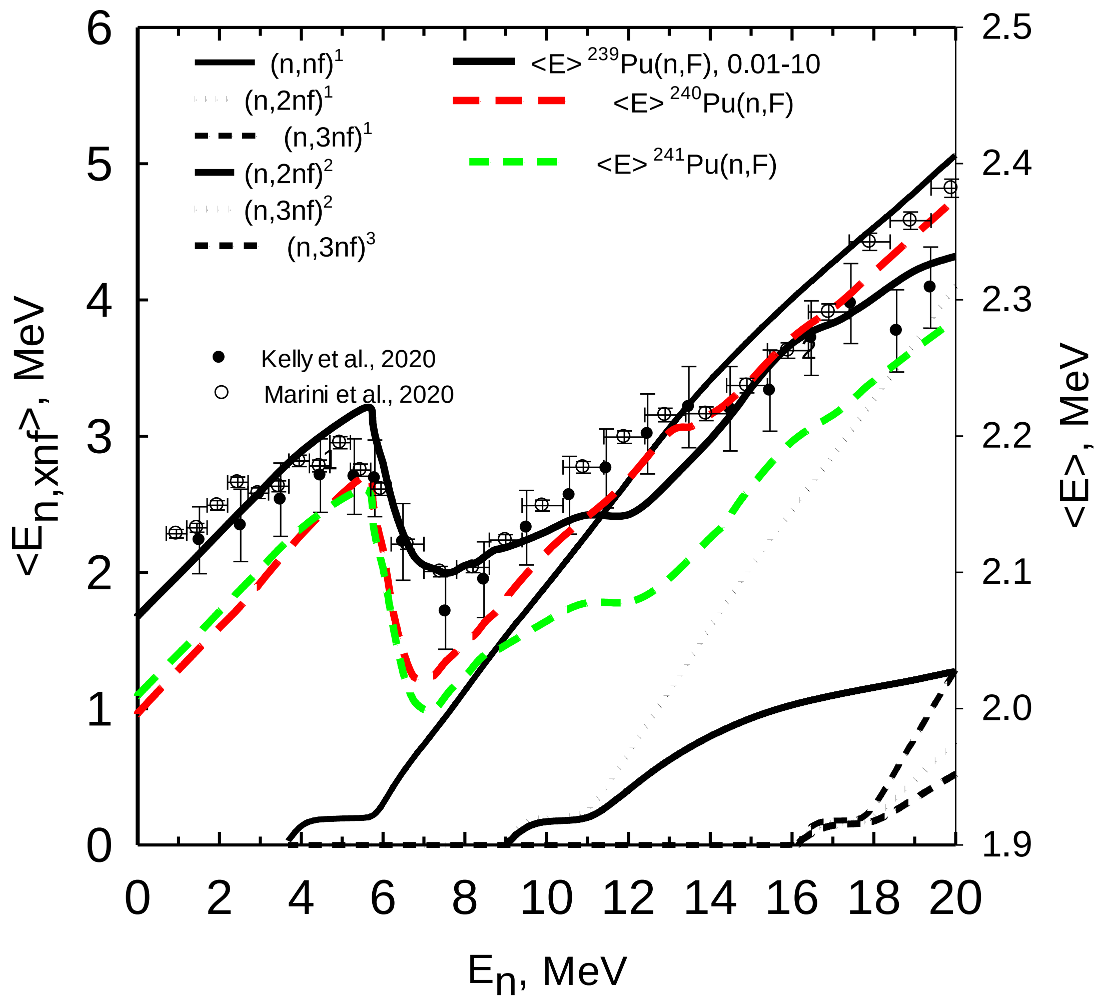
$^{239}Pu/^{238}U$ E_n=14-15 MeV $^{240}Pu/^{238}U$



^{240}Pu(n,F) <E>, ε~0.8-10 MeV



^{239}Pu(n,F), ^{240}Pu(n,F), ^{241}Pu(n,F) <E>, ε~0.01-10 MeV



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

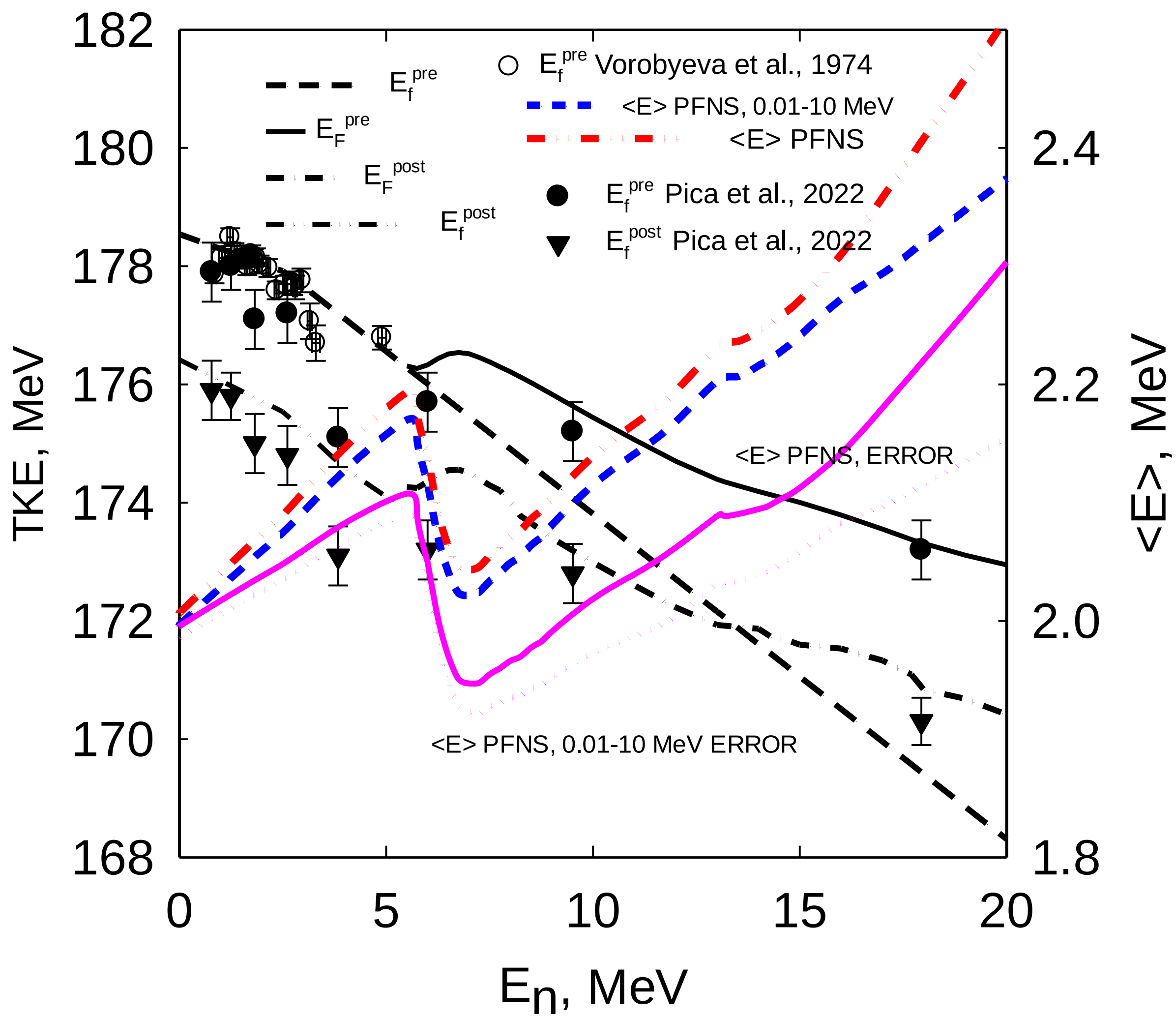
$$E_{nx} = E_r - E^{pre}_{fx} + E_n + B_n - \sum_{x,1\le k\le x} \left(\left\langle E^k_{nxnf}(\theta) \right\rangle + B_{nx} \right)$$

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

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

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

Total Kinetic Energy



Conclusions

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

<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 ^{240}Pu(n,F), ^{239}Pu(n,F) and ^{241}Pu(n,F) css within E_n~0.01–20 MeV

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

Conclusions

Approximation obtained for $\omega(\theta)$ fits the measured ^{239}Pu+n NES at En=14 MeV.

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

On that background

The PFNS shapes and energies <E> and TKE for ^{240}Pu(*n,F*)& ^{240}Pu(*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 ^{240}**Pu(*n,xnf*)**$^{1,..x}$ **and** ^{240}**Pu(*n,F*) PFNS** stronger response to forward and backward (*n,xnf*)^{1} might be predicted.