High-energy neutron emission in fission: $^{235}U(n_{th},f)$ PFNS

Roberto Capote
Deputy Section Head, Nuclear Data Section, IAEA, Vienna

Thanks to my PRC coauthors:
M. Schulc, M. Kostal, J. Simon, E. Novak, T. Czakoj

Centrum výzkumu Řež s.r.o.
Research Centre Řež

FIESTA 2024, 18-22 November 2024, Los Alamos, NM

Outlook

- Basic concepts, Spectrum Average Cross Sections (SACS) in a neutron field
- IRDFF library of eval. dosimetry reactions, e.g., $^{90}Zr(n,2n)$
- Reference PFNS of $^{252}Cf(sf)$ and $^{235}U(n_{th},f)$

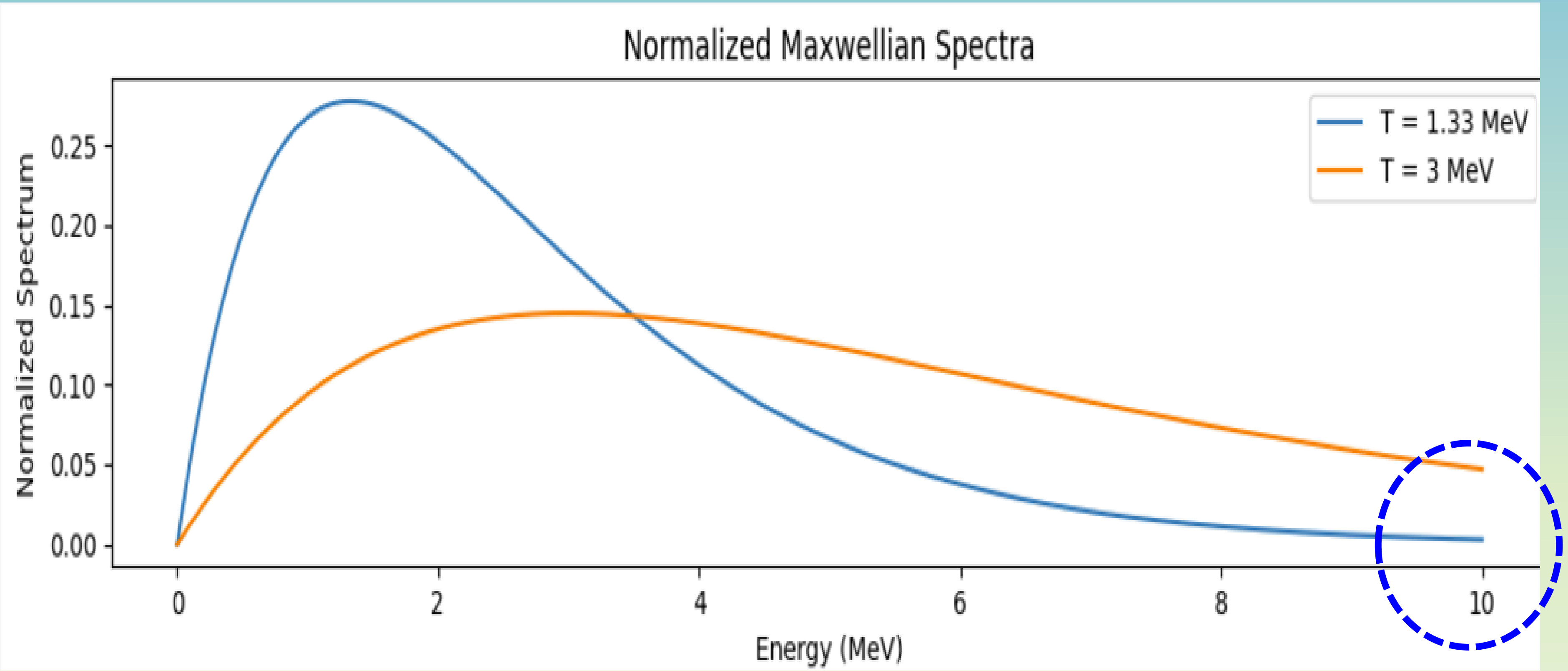
  assumption: $^{252}Cf(sf)$ PFNS Mannhart 1989 eval is good!
- SACS-Cf/SACS-U5 ratio measurements

"It doesn't matter how beautiful your theory is,
it doesn't matter how smart you are.
If it doesn't agree with experiment, it's wrong."

Richard Philips Feynman, Nobel Prize in Physics 1965

Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

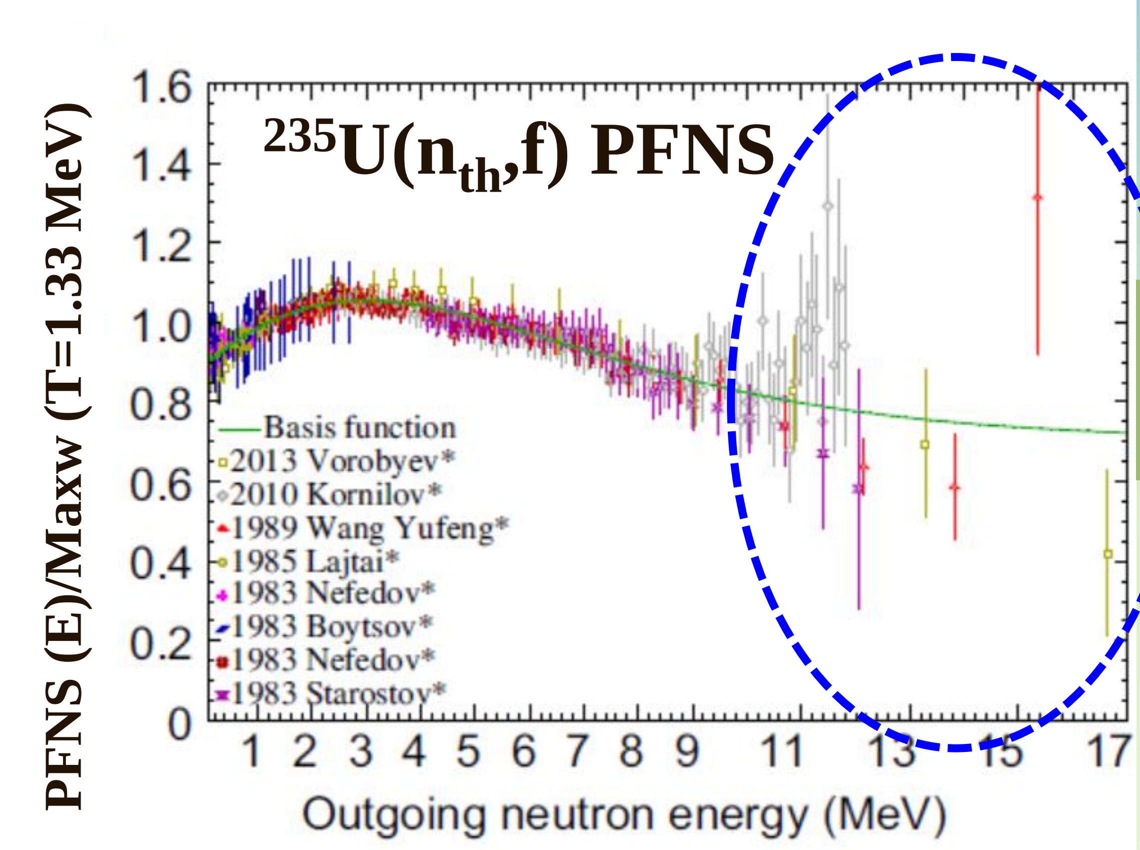
Maxwell-Boltzmann distribution



High-energy neutrons (En>10 MeV) < 2% of all fission neutrons

Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

$^{235}U(n_{th},f)$ PFNS evaluated at IAEA CRP (2016) adopted by Neutron Standards & ENDF/B-VIII.0



Discrepant ToF data above 10 MeV!

No HE PFNS data meas. for $^{235}U(n_{th},f)$ since 2013

Idea: to probe evaluated $^{235}U(n_{th},f)$ PFNS using SACS in this field

*** better statistics than in direct PFNS meas.**

Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

SACS in a neutron field: clean integral data

$$SACS = \frac{\int \sigma(E)\varphi(E)dE}{\int \varphi(E)dE}$$

SACS depends on $\sigma(E)$ and $\varphi(E)$ (PFNS) shape

$$if \int \varphi(E)dE \equiv 1 \qquad SACS = \int [\sigma(E)\varphi(E)]dE$$

$$\sigma(E)\varphi(E) \equiv \text{reaction rate}$$

Two neutron fields considered, one tested, Cf standard

SACS-Cf = SACS in ^{252}Cf(sf) PFNS

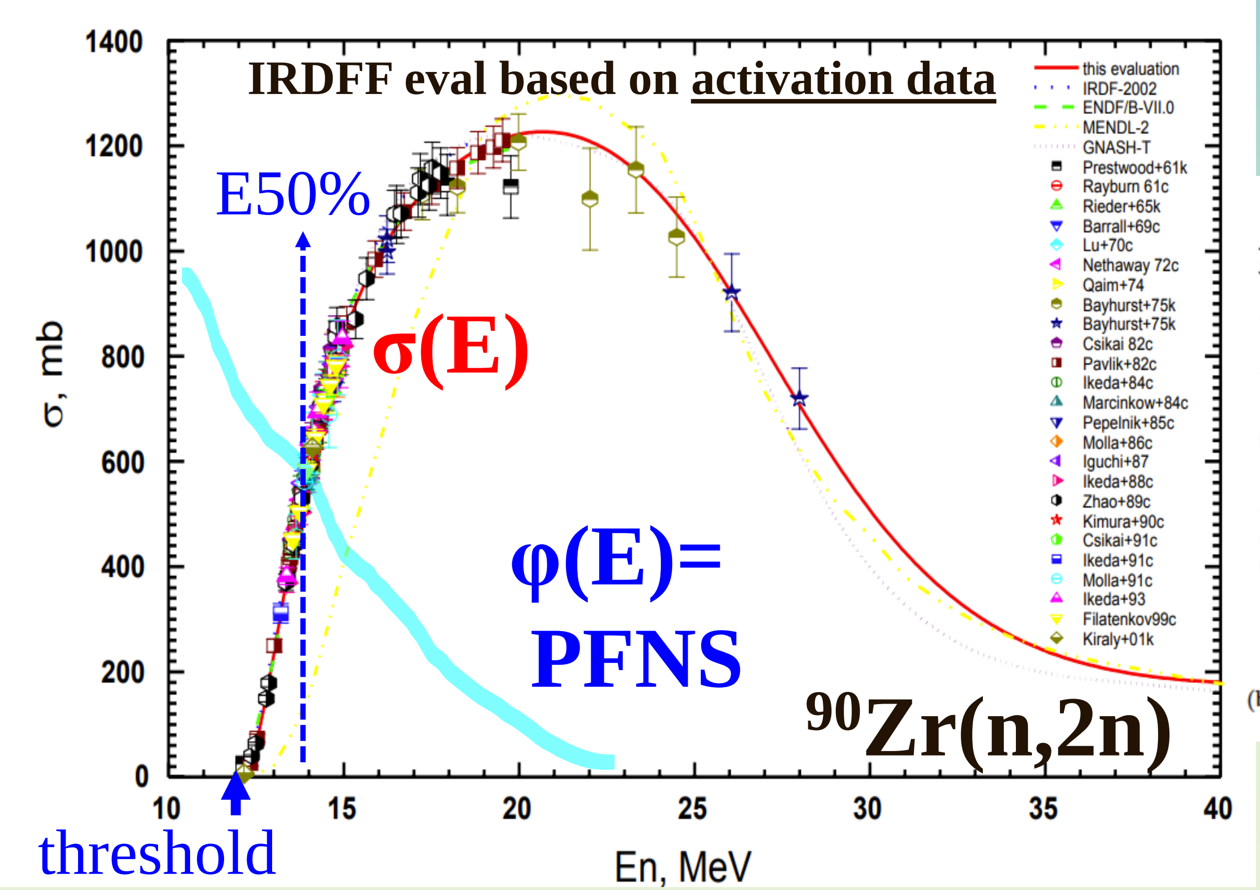
SACS-U5 = SACS in ^{235}U(n_{th},f) PFNS

For uncertainty reduction: ratio meas. in the two neutron fields: same Ge(Li) detector; same reaction; correlated measurement

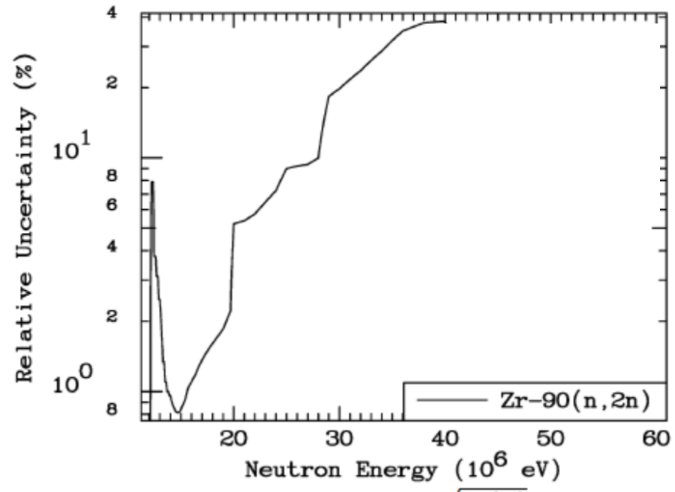
FIESTA 2024, Fuller Lodge, Los Alamos, NM
November 18-22, 2024
Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

$\sigma(E)$: IRDFF dosimetry cross sections

GLSQ evaluations: 13 (n,2n)-E50%>10 MeV



Eval. Uncert.



(b) One-sigma uncertainties in % ($\equiv 100 \times \frac{\sqrt{cov(i,i)}}{\mu_i}$), being μ_i the corresponding cross section mean value.

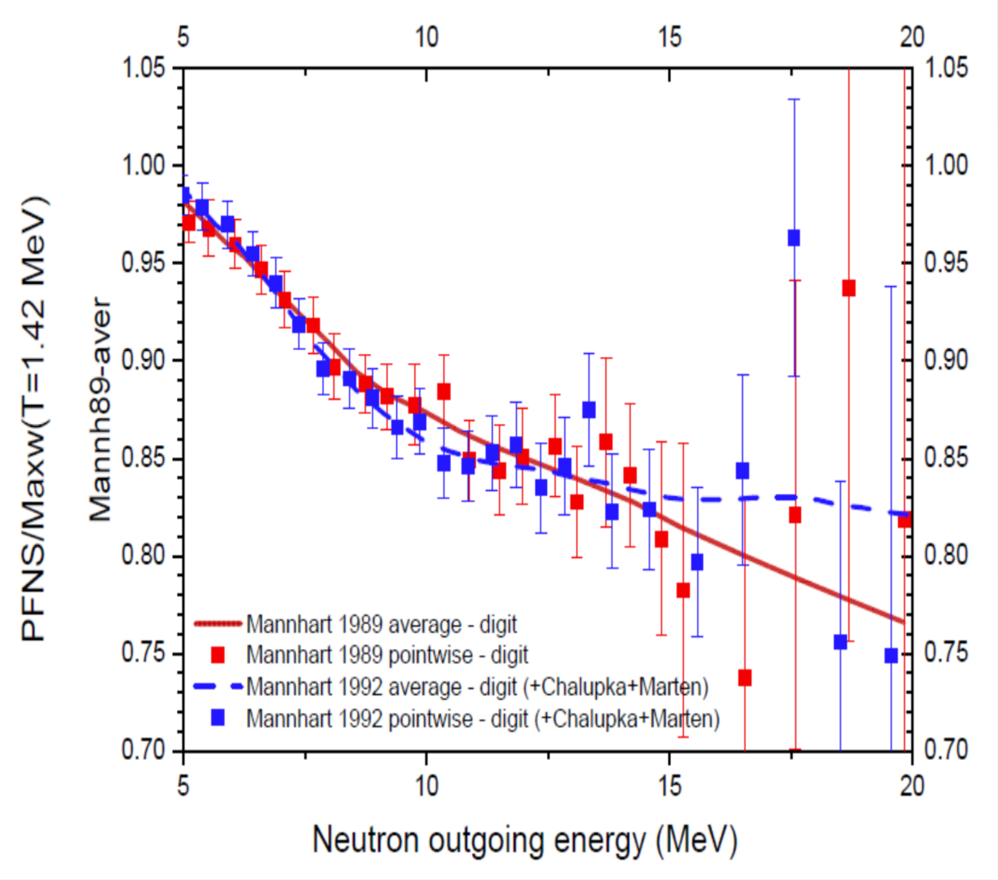
σ(E) well known!

K. Zolotarev, INDC(NDS)-0546, IRDFF-II evaluation

^{90}Zr(n,2n) reaction cross section independently evaluated

Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

$\varphi(E)$: ^{252}Cf (sf) PFNS reference spectrum GLSQ evaluations by Mannhart 1989,1992 based on ToF data!



1) **W. Mannhart, INDC(NDS)-220, 1989, p.305 (IRDFF)**
2) **W. Mannhart, Int. Symp. on Nuclear Data Evaluation Methodology, 12-19 Oct.1992, BNL, NY, USA, C. Dunford editor, p.247**

Unfortunately NOT reproducible !!

AIACHNE new evaluation on-going at LANL, Neudecker et al

Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

IRDFF eval validation in a ^{252}Cf(sf) PFNS

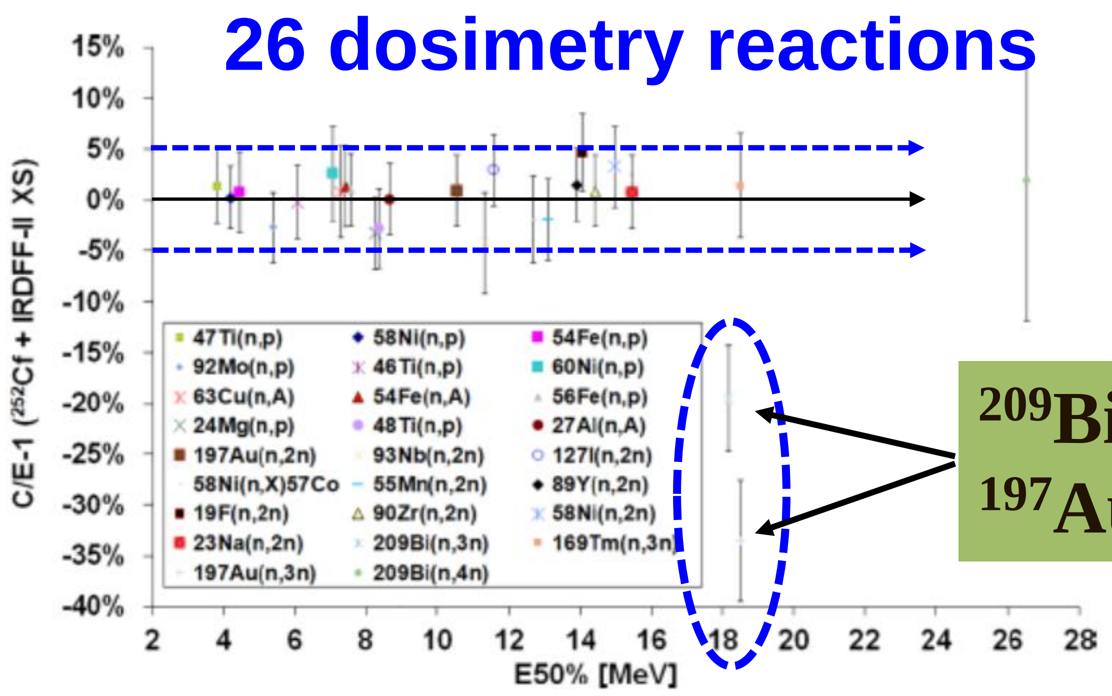


FIG. 2. Calculation to experiment (C/E) ratio for SACS of dosimetry reactions in the ^{252}Cf(sf) reference neutron field as a function of the mean response neutron energy $E50\%$.

^{209}Bi(n,3n)
^{197}Au(n,3n) dropped

M. Schulc et al, Phys. Rev.C109 (2024) 054616

24 XS eval. validated in ^{252}Cf(sf) PFNS (M 89)

Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

SACS ratio in ^{252}Cf(sf) and ^{235}U(n_{th},f) PFNS derived with ^{reduced} uncertainty

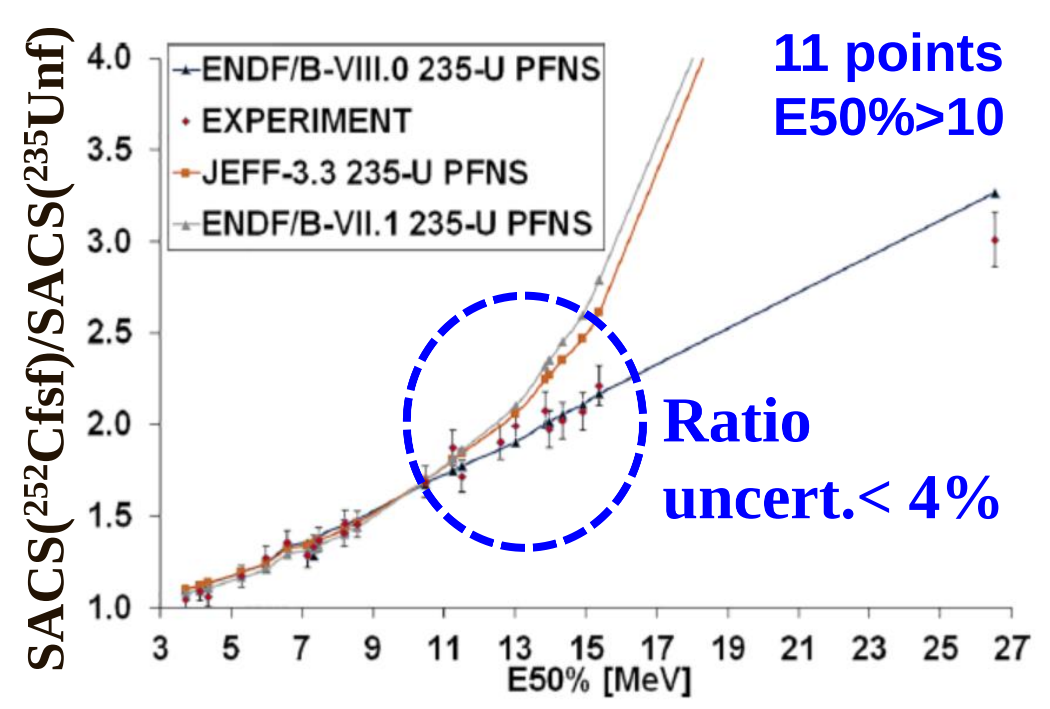


FIG. 3. SACS ratios and uncertainties as a function of the mean neutron response energy *E*50% of each dosimetry reaction listed in Table 2.

TABLE II. Mean response neutron energies in MeV for dosimetry reactions and corresponding experimental SACS ratios and their relative uncertainties. ^{169}Tm(*n*, 3*n*) was not measured in reactors.

Reaction	*E*50% (MeV)	SACS Ratio	Unc. (%)
^{47}Ti(*n*, *p*)^{47}Sc	3.73	1.042	2.7
^{58}Ni(*n*, *p*)^{58}Co	4.12	1.088	2.8
^{54}Fe(*n*, *p*)^{54}Mn	4.36	1.056	2.6
^{92}Mo(*n*, *p*)^{92m1}Nb	5.29	1.170	2.4
^{46}Ti(*n*, *p*)^{46}Sc	5.98	1.273	2.9
^{60}Ni(*n*, *p*)^{60}Co	6.57	1.352	4.2
^{63}Cu(*n*, α)^{60}Co	7.14	1.282	3.2
^{54}Fe(*n*, α)^{51}Cr	7.31	1.327	3.0
^{56}Fe(*n*, *p*)^{56}Mn	7.46	1.367	2.2
^{24}Mg(*n*, *p*)^{24}Na	8.19	1.404	2.2
^{48}Ti(*n*, *p*)^{48}Sc	8.22	1.460	2.8
^{27}Al(*n*, α)^{24}Na	8.56	1.454	2.8
^{197}Au(*n*, 2*n*)^{196}Au	10.47	1.686	3.7
^{93}Nb(*n*, 2*n*)^{92m1}Nb	11.26	1.872	2.5
^{127}I(*n*, 2*n*)^{126}I	11.51	1.715	4.6
^{58}Ni(*n*, *X*)^{57}Co	12.60	1.900	5.3
^{55}Mn(*n*, 2*n*)^{54}Mn	13.02	1.990	2.7
^{89}Y(*n*, 2*n*)^{88}Y	13.84	2.076	2.6
^{19}F(*n*, 2*n*)^{18}F	13.96	1.973	2.6
^{90}Zr(*n*, 2*n*)^{89}Zr	14.35	2.022	3.9
^{58}Ni(*n*, 2*n*)^{57}Ni	14.91	2.070	3.0
^{23}Na(*n*, 2*n*)^{22}Na	15.37	2.211	4.3
^{209}Bi(*n*, 4*n*)^{206}Bi	26.54	3.007	9.1

M. Schulc et al, Phys. Rev.C109 (2024) 054616

Excess of HE neutrons seen in exp., described by B/VIII.0

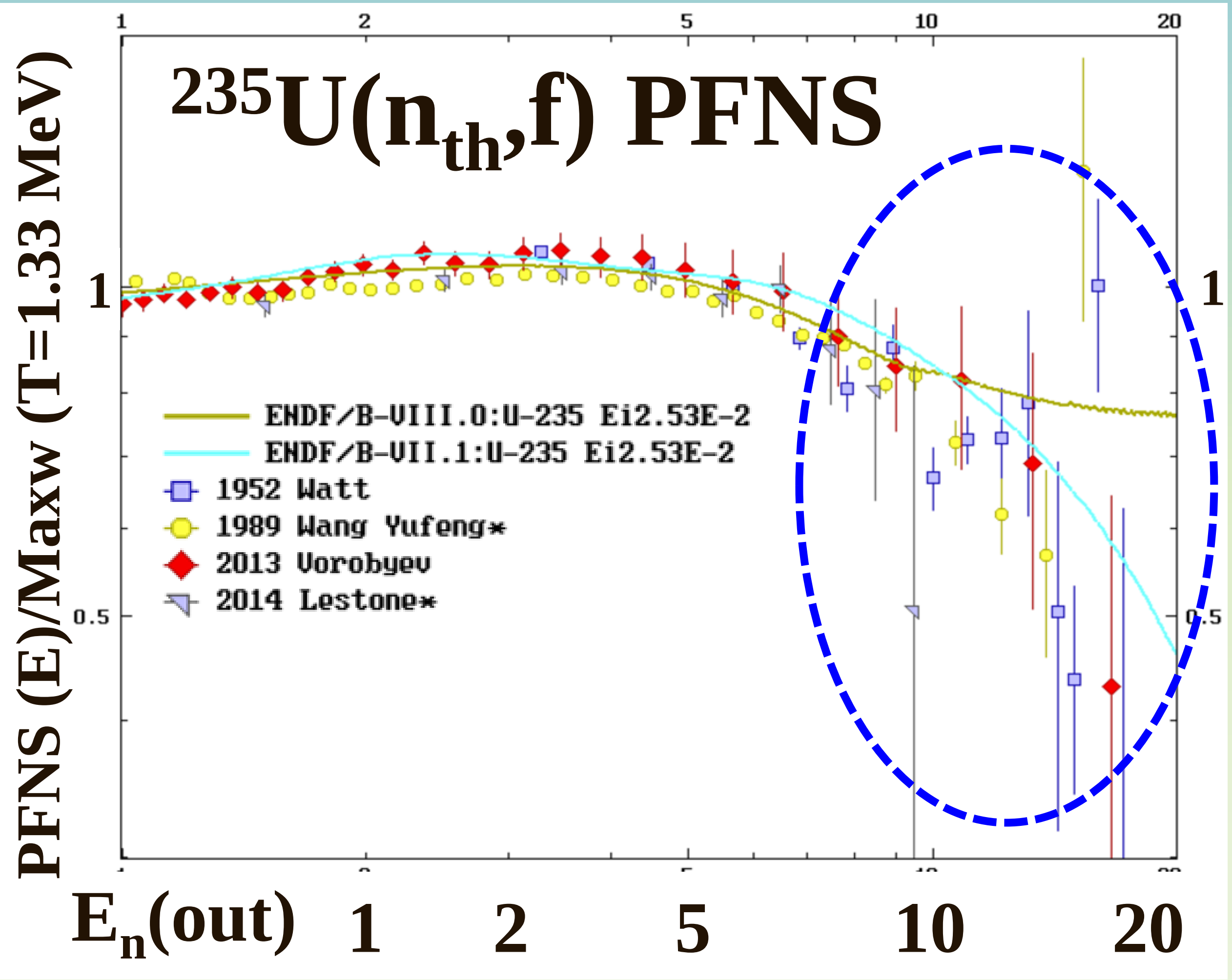
Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

Selected PFNS data vs ENDF/B evals

Watt 1952:
CR39 detectors
Traceable to H(n,el)
Low backg E>3 MeV

Watt measur. show lower uncert. than modern data !!

Propose new experiment:
*CR39 or similar detector
(track detector)
*Secondary U5 target
*High flux reactor
Detect outgoing neutrons
(En>3MeV)



Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

SUMMARY

- ENDF/B-VIII.0 $^{235}U(n_{th},f)$ PFNS evaluation validated by SACS ratio data
- Measured SACS(Cf(sf))/SACS($^{235}U(n_{th},f)$) ratio uncertainties below 4%
- High-energy fission neutron excess identified (e.g., respect to ENDF/B-VII.1)
- Origin unknown, FF equilibrium emission unlikely
- Scission neutrons may be a good explanation

Roberto Capote, IAEA Nuclear Data Section
e-mail: **R.CapoteNoy@iaea.org**
Web: **http://www-nds.iaea.org**

Thank you!

SACS ratio as a function of PFNS eval

$^{252}Cf(sf)$ PFNS

1) W. Mannhart, INDC(NDS)-220, 1989, p.305 (IRDFF)
2) W. Mannhart, Int. Symp. on Nuclear Data Evaluation Methodology, 12-19 Oct.1992, BNL, NY, USA, C. Dunford editor, p.247

Low sensitivity of SACS ratio to $^{252}Cf(sf)$ PFNS evaluation !

n,2n reac	E_{50}	SACS exp SACS 89 SACS 92	^{252}Cf 1989	^{252}Cf 1992	^{235}U B8.0
^{197}Au	10.5 MeV	1.69(6)-3.7% 1.67 1.67	5.5(1)	5.5(1)	3.3(1)
^{127}I	11.5 MeV	1.72(8) -4.6% 1.75 1.74	2.10(8)	2.09(6)	1.2(9)
^{89}Y	13.8 MeV	2.08(6)- 2.6% 2.00 2.06	.34(2)	.35(4)	.17(1)
^{19}F	14.0 MeV	1.97(5)- 2.6% 2.00 2.00	1.6(9) x0.01	1.6(5) x0.01	0.80(7) x0.01
^{90}Zr	14.3 MeV	2.02(8)- 3.9% 2.10 2.20	.21(1)	.22(2)	0.10(9)
^{58}Ni	14.9 MeV	2.07(6)-3.0% 2.10 2.17	8.4(5) x0.001	8.7(1) x0.001	4.0(4) x0.001
^{23}Na	15.4 MeV	2.21(9)-4.3% 2.18 2.26	8.3(6) x0.001	8.6(1) x0.001	3.8(4) X0.001

e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org

(γ,n) contributing reactions to SACS

S. Simakov, nds.iaea.org/publications/indc/indc-nds-0904/

Impact of Photonuclear Reactions on Neutron Dosimetry in ^{252}Cf(s.f.) and ^{235}U(n_{th},f) Neutron-gamma Mixed Radiation Fields

(n,2n) and (γ,n) reactions on the same target and leading to production of the same isotope							
^{19}F(n,2n)^{18}F	10.986	IRDFF-II	16	^{19}F(γ,n)^{18}F	10.432	IAEA/PD-2019	9018
^{23}Na(n,2n)^{22}Na	12.965	IRDFF-II	16	^{23}Na(γ,n)^{22}Na	12.420	IAEA/PD-2019	11022
^{27}Al(n,2n)^{26}Al	13.546	IRDFF-II	16	^{27}Al(γ,n)^{26}Al	13.058	IAEA/PD-2019	10/5/1
^{46}Ti(n,2n)^{45}Ti	13.479	IRDFF-II	16	^{46}Ti(γ,n)^{45}Ti	13.189	IAEA/PD-2019	22045
^{55}Mn(n,2n)^{54}Mn	10.414	IRDFF-II	16	^{55}Mn(γ,n)^{54}Mn	10.227	IAEA/PD-2019	25054
^{54}Fe(n,2n)^{53}Fe	13.629	IRDFF-II	16	^{54}Fe(γ,n)^{53}Fe	13.378	IAEA/PD-2019	26053
^{59}Co(n,2n)^{58}Co	10.633	IRDFF-II	16	^{59}Co(γ,n)^{58}Co	10.454	IAEA/PD-2019	27058
^{58}Ni(n,2n)^{57}Ni	12.429	IRDFF-II	16	^{58}Ni(γ,n)^{57}Ni	12.216	IAEA/PD-2019	28057
^{63}Cu(n,2n)^{62}Cu	11.038	IRDFF-II	16	^{63}Cu(γ,n)^{62}Cu	10.864	IAEA/PD-2019	29062
^{65}Cu(n,2n)^{64}Cu	10.065	IRDFF-II	16	^{65}Cu(γ,n)^{64}Cu	9.911	IAEA/PD-2019	29064
^{75}As(n,2n)^{74}As	10.383	IRDFF-II	16	^{75}As(γ,n)^{74}As	10.245	IAEA/PD-2019	33074
^{89}Y(n,2n)^{88}Y	11.612	IRDFF-II	16	^{89}Y(γ,n)^{88}Y	11.482	IAEA/PD-2019	4
^{90}Zr(n,2n)^{89}Zr	12.103	IRDFF-II	16	^{90}Zr(γ,n)^{89}Zr	11.968	IAEA/PD-2019	10/5/1
^{93}Nb(n,2n)^{92m}Nb	9.063	IRDFF-II	41092m	^{93}Nb(γ,n)^{92m}Nb	8.966	IAEA/PD-2019	41092m
^{115}In(n,2n)^{114m}In	9.311	IRDFF-II	49114m	^{115}In(γ,)^{115m}In	9.230	IAEA/PD-2019	49114m
^{127}I(n,2n)^{126}I	9.217	IRDFF-II	16	^{127}I(γ,n)^{126}I	9.144	IAEA/PD-2019	53126
^{141}Pr(n,2n)^{140}Pr	9.464	IRDFF-II	16	^{141}Pr(γ,n)^{140}Pr	9.397	IAEA/PD-2019	59140
^{169}Tm(n,2n)^{168}Tm	8.082	IRDFF-II	16	^{169}Tm(γ,n)^{168}Tm	8.034	IAEA/PD-2019	4
^{197}Au(n,2n)^{197}Au	8.114	IRDFF-II	16	^{197}Au(γ,n)^{196}Au	8.072	IAEA/PD-2019	79196
^{209}Bi(n,2n)^{208}Bi	7.496	IRDFF-II	16	^{209}Bi(γ,n)^{208}Bi	7.460	IAEA/PD-2019	83208
^{238}U(n,2n)^{237}U	6.180	IRDFF-II	16	^{238}U(γ,n)^{237}U	6.154	IAEA/PD-2019	92237

Eventually the impact of (γ,x) on the total residual production was shown to be less than ≈ 1% for most of the considered reaction pairs and thus could be neglected since 1% is the highest accuracy presently achievable. The

Roberto Capote, IAEA Nuclear Data Section
e-mail: R.CapoteNoy@iaea.org
Web: http://www-nds.iaea.org