Neutron Reference Data for high energy applications

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nBHEAM 2025: Neutron Beams at High Energy: Applications and Metrology

Outlook

- IAEA neutron data standards adopted by ENDF/B-VIII.0
- IAEA high-energy reference cross sections
- Reference neutron fields
- IRDFF-II: a neutron metrology library up to 60 MeV

**"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

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IAEA Neutron Standard XS evaluation

https://nds.iaea.org/standards **rel. 2017**

TABLE II. Neutron Cross Section Standards.

Reaction	Standards Energy Range
H(n,n)	1 keV to 20 MeV
^{3}He(n,p)	0.0253 eV to 50 keV
^{6}Li(n,t)	0.0253 eV to 1.4 MeV
^{10}B(n,α)	0.0253 eV to 1 MeV
^{10}B(n,$\alpha_1\gamma$)	0.0253 eV to 1 MeV
C(n,n)	10 eV to 1.8 MeV
Au(n,γ)	0.0253 eV, 0.2 to 2.5 MeV, 30 keV MACS
^{235}U(n,f)	0.0253 eV, 0.15 MeV to 200 MeV, 7.8-11 eV
^{238}U(n,f)	2 MeV to 200 MeV

Based on Bayesian (GLSQ) fit of exp. data

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High-Energy Reference Fission Cross sections

Reaction	Energy Range	ENDF-6 formatted data
^{235}U(n,f)	0.0253 eV - 1 GeV (reference above 200 MeV)	235U-Ref-HighErg.endf
^{238}U(n,f)	0.0253 eV - 1 GeV (reference above 200 MeV)	238U-Ref-HighErg.endf
^{239}Pu(n,f)	0.0253 eV - 300 MeV (reference above 200 MeV)	239Pu-Ref-HighErg.endf
^{209}Bi(n,f)	34 MeV - 1 GeV	209Bi-Ref-HighErg.endf
^{nat}Pb(n,f)	34 MeV - 1 GeV	natPB-Ref-HighErg.endf

Reference Prompt Fission Neutron Spectra

#	Reaction	Energy Range	ENDF-6 formatted data
10	^{252}Cf(sf) PFNS from the IRDFF-II library W. Mannhart 1987-1989	0.00001-30 MeV (outgoing)	PFNS-Cf252sf-ENDF.txt
10	^{235}U(n_{th},f) from the IRDFF-II library A. Trkov, V.G. Pronyaev, R. Capote, 2017	Thermal energy (incident), 0.00001-30 MeV (outgoing)	PFNS-U235nth-ENDF.txt

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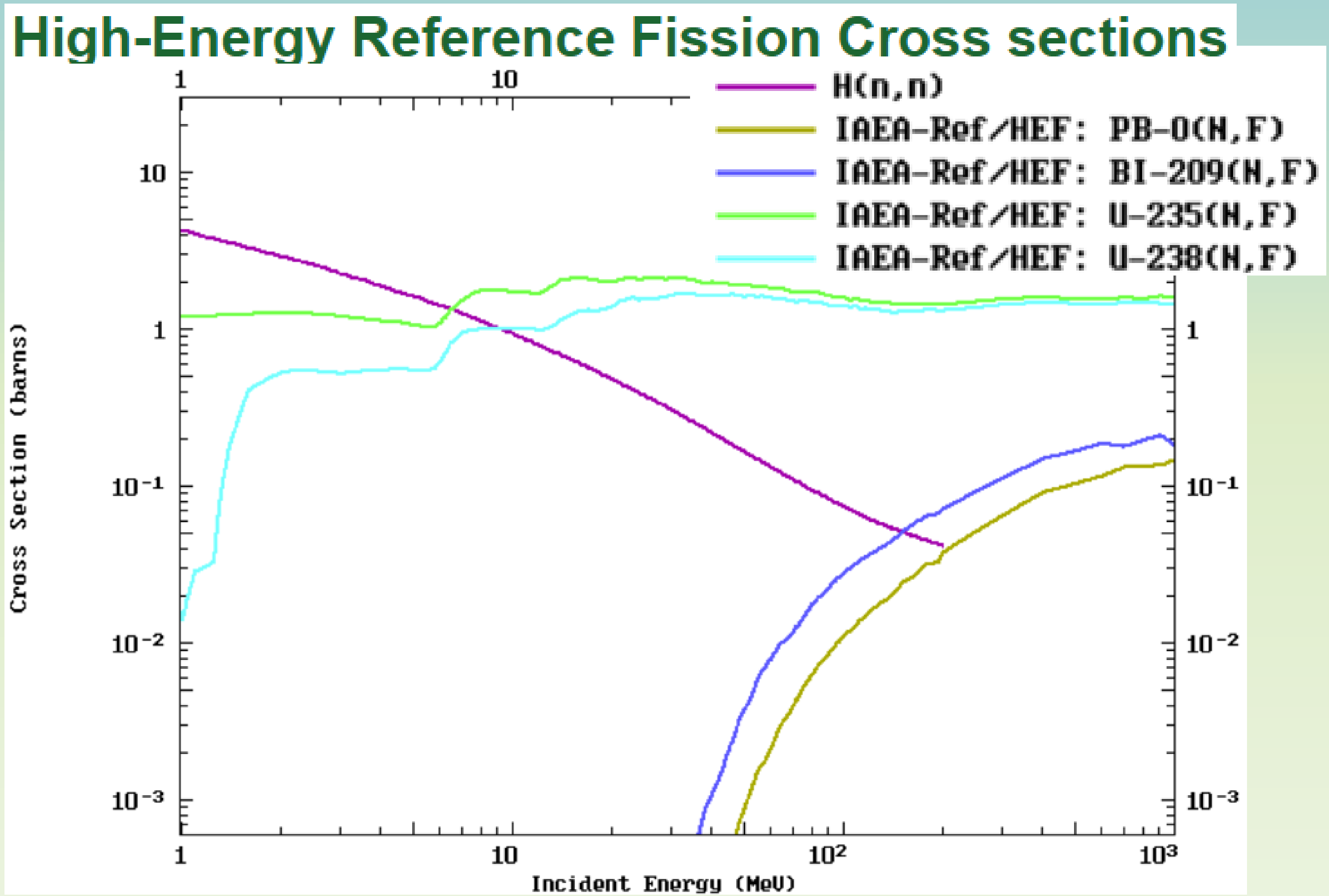

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Updated IAEA standards to be released in 2026

- ✓ Extended energy range of H(n,p) up to 50-100 MeV
- ✓ Updated ^{235,238}U(n,f) reference XS up to 450 MeV
- ✓ New evaluation of ^{252}Cf(sf) neutron reference field (Mannhart evaluation made in 1989, not reproducible)

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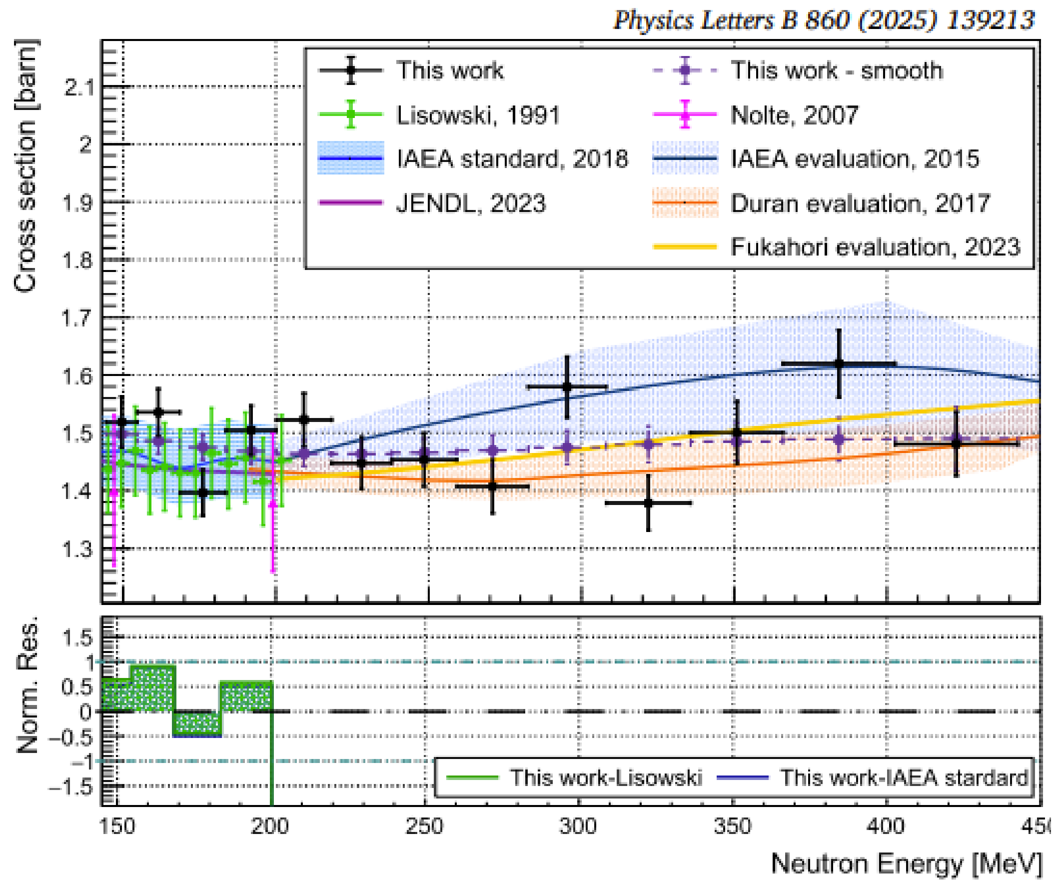
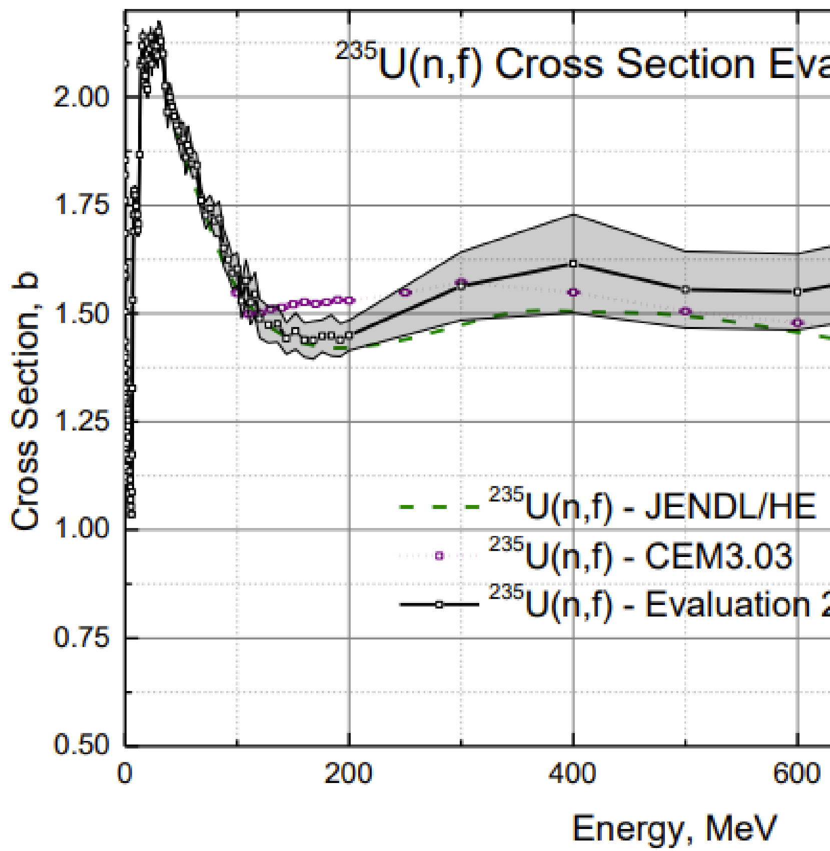
IAEA Neutron HE reference XS: $^{235}U(n,f)$





n_TOF collab. Phys. Lett B860 (2025) 139213

https://doi.org/10.1016/j.physletb.2024.139213

B. Marcinkevicius et al, INDC(NDS)-0681 (2015)

https://doi.org/10.61092/iaea.mx8f-tz39

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IAEA Neutron HE reference XS: ^{235}U(n,f)

JENDL/HE-2007 formatting problem

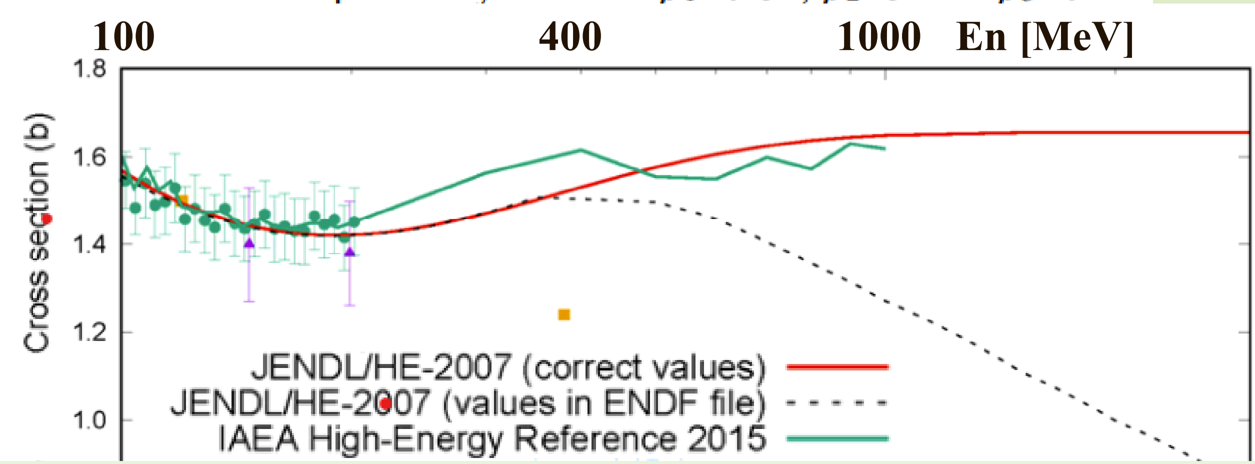
1. ^{235}U(n,f) cross section

The high energy part of the ^{235}U(n,f) cross section for the JENDL/HE-2007 library [1] above 200 MeV was evaluated by using the FISCAL code [2]. This code calculates fission cross sections by using the following systematics on the fission probability P_f (fission cross section divided by the total reaction cross section):

$$P_f(x, E_{\mathrm{exc}}) = p_1\left[1 - e^{-(E_{\mathrm{exc}} - p_2)\, p_3}\right],$$

where $x = Z^2/A$ with Z and A are the atomic and mass numbers of the compound nucleus (Z = 92 and A = 236 for ^{235}U(n,f) cross section) and E_{exc} is the excitation energy of the compound nucleus. The three parameters for the ^{236}U compound system are p_1=0.81, p_2=5 and p_3=0.1.

JENDL/HE-2007 corrected



T. Fukahori, INDC(JPN)-0210 https://nds.iaea.org/publications/indc/indc-jpn-0210.pdf

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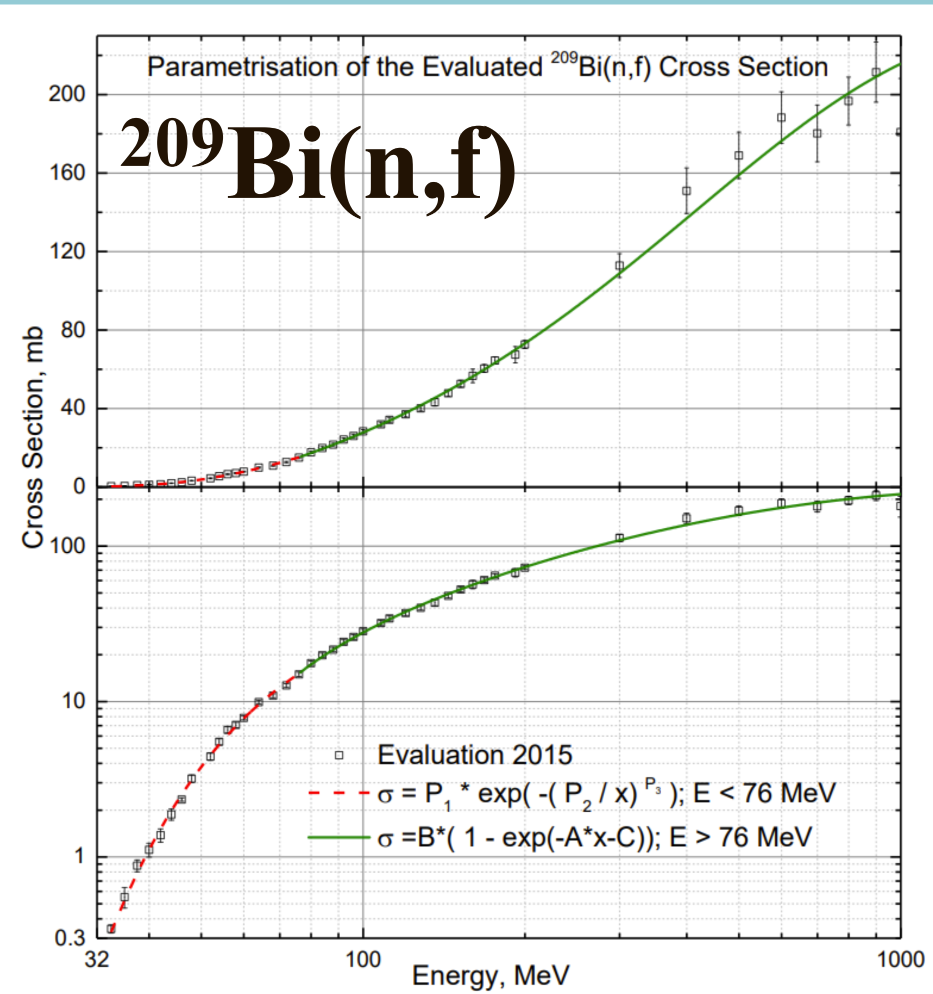
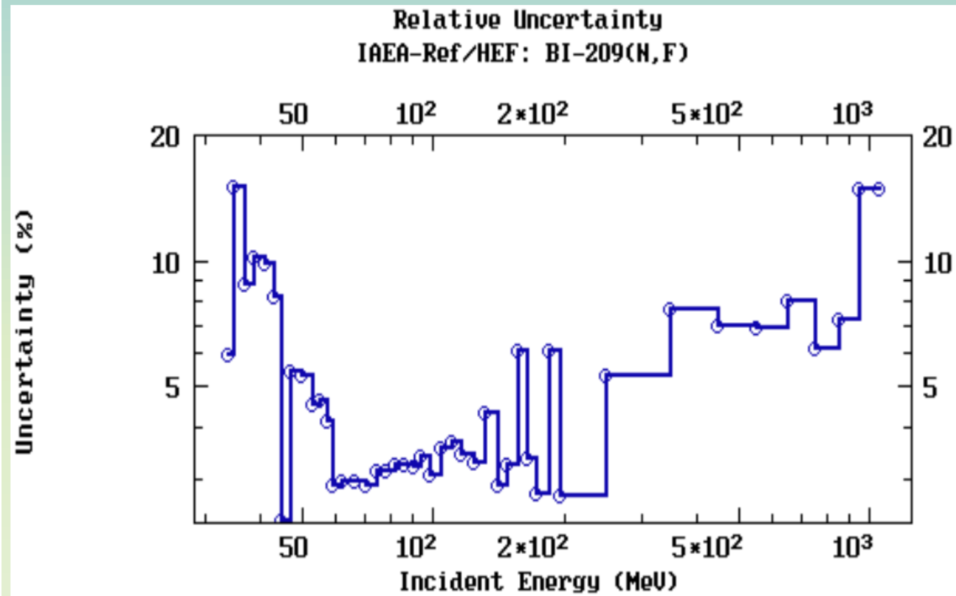
IAEA Neutron HE reference XS



Uncertainties



B. Marcinkevicius, S. Simakov, V.G. Pronyaev, INDC(NDS)-0681 (2015)
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IRDFF-II released in January 2020

https://nds.iaea.org/IRDFF

ELSEVIER

Nuclear Data Sheets
Volume 163, January 2020, Pages 1-108

IRDFF-II: A New Neutron Metrology Library

A. Trkov [a], P.J. Griffin [b], S.P. Simakov [c], L.R. Greenwood [d], K.I. Zolotarev [e], R. Capote [a], D.L. Aldama [f], V. Chechev [g], C. Destouches [h], A.C. Kahler [i], C. Konno [j], M. Koštál [k], M. Majerle [l], E. Malambu [m], M. Ohta [n], V.G. Pronyaev [o], V. Radulović [p], S. Sato [n], M. Schulc [k], E. Šimečková [q]…
H. Yashima [s]

https://doi.org/10.1016/j.nds.2019.12.001

Also available as arXiv 1909.03336 (2019)

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IRDFF-II contents

https://nds.iaea.org/IRDFF

- ~~CFPY of 7 FPs at thermal, fast, and 14 MeV~~
- ~~Metrology (dosimetry) metrics: damage XS~~
- 199 reaction cross-section and decay data files (ENDF pointwise, groupwise, ACE, ASCII)

  includes XS on natural targets
- IRDFF-II reference neutron spectra

See A. Trkov et al, IRDFF-II paper
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Dosimetry cross sections: 119 react

See A. Trkov et al, IRDFF-II paper
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TABLE 1: (continued). IRDFF-II nuclear data contents and evaluation sources. (r) denotes renormalization.

No.	Reaction	Reaction ID	MAT	Energy Interval	Evaluation source	Eval. Date	Consistency v2002 to v-1.05[1]	Consistency v-1.05 to IRDFF-II[2]
92	^{115}In(n,2n)^{114m}In	In1152m	4931	E_{th}-20 MeV	INDC(NDS)-0526	2008	new	old
				20–60 MeV	TENDL-2010(r)		new	old
93	^{115}In(n,n')^{115m}In	In115nm	4931	E_{th}-20 MeV	IRDF-2002	2005	old	old
				20–60 MeV	TENDL-2010(r)		–	old
94	^{115}In(n,γ)^{116m}In	In115gm	4931	0–20 MeV	INDC(NDS)-0657	2013	new	old
				20–60 MeV	TENDL-2010(r)		–	old
95	^{127}I(n,2n)^{126}I	I1272	5325	E_{th}-32 MeV	INDC(NDS)-0526	2008	new	old
				32–60 MeV	TENDL-2010(r)		new	old
96	^{139}La(n,γ)^{140}La	La139g	5728	0–20 MeV	INDC(CCP)-0431	2002	old	old
				20–60 MeV	TENDL-2010(r)		old	old
97	^{141}Pr(n,2n)^{140}Pr	Pr1412	5925	E_{th}-20 MeV	IRDF-2002	2005	old	old
				20–60 MeV	TENDL-2010(r)		–	old
98	^{169}Tm(n,2n)^{168}Tm	Tm1692	6925	E_{th}-40 MeV	INDC(NDS)-0584	2010	new	old
				40–60 MeV	TENDL-2013(r)		new	old
99	^{169}Tm(n,3n)^{167}Tm	Tm1693	6925	E_{th}-60 MeV	INDC(NDS)-0657	2013	new	old
100	^{181}Ta(n,γ)^{182}Ta	Ta181g	7328	0–20 MeV	JENDL-3.2	1994	old	old
				20–60 MeV	TENDL-2010(r)		–	old
101	^{186}W(n,γ)^{187}W	W186g	7443	0–60 MeV	ENDF/B-VII.1 [34, 37]	2009	new	old
102	^{197}Au(n,2n)^{196}Au	Au1972	7925	E_{th}-40 MeV	INDC(NDS)-0526	2008	new	old
				40–60 MeV	TENDL-2010(r)		new	old
103	^{197}Au(n,γ)^{198}Au	Au197g	7925	0–60 MeV	IAEA STD 2017 [33]	2018	new	new
104	^{199}Hg(n,n')^{199m}Hg	Hg199nm	8034	E_{th}-20 MeV	INDC(NDS)-0526	2008	new	old
				20–60 MeV	TENDL-2010(r)		new	old
105	^{204}Pb(n,n')^{204m}Pb	Pb204nm	8225	E_{th}-20 MeV	INDC(CCP)-0431	2002	new	old
				20–60 MeV	TENDL-2011(r)		new	old
106	^{209}Bi(n,2n)^{208}Bi	Bi2092	8325	E_{th}-400MeV	V.G.Pronyaev	2019	–	new
107	^{209}Bi(n,3n)^{207}Bi	Bi2093	8325	E_{th}-400MeV	V.G.Pronyaev	2019	–	new
108	^{209}Bi(n,4n)^{206}Bi	Bi2094	8325	E_{th}-400MeV	V.G.Pronyaev	2019	–	new
109	^{209}Bi(n,5n)^{205}Bi	Bi2095	8325	E_{th}-400MeV	V.G.Pronyaev	2019	–	new
110	^{209}Bi(n,6n)^{204}Bi	Bi2096	8325	E_{th}-400MeV	V.G.Pronyaev	2019	–	new

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Reference neutron spectra

https://nds.iaea.org/IRDFF

TABLE 5. List of IRDFF-II benchmark neutron fields. Note that "adhoc" MAT numbers have been assigned (unrelated to the charge of the decaying nucleus).

No.	Name	MAT	$E_{\mathrm{aver}}[MeV]$	Description
	Measured by Time-of-Flight neutron fields including the ^{252}Cf(sf) standard			
1	^{252}Cf(sf)	9861	2.121	Spontaneous fission neutron spectrum from ^{252}Cf
2	^{235}U(n_{th},f) PFNS	9228	2.000	Thermal-neutron induced prompt fission spectrum from ^{235}U
3	^{9}Be(d,n) 16MeV	9408	5.608	Spectrum of neutrons from 16 MeV deuterons incident on a beryllium target
4	^{9}Be(d,n) 40MeV	9409	15.58	Spectrum of neutrons from 40 MeV deuterons incident on a beryllium target
	Measured by Time-of-Flight neutron fields not accepted as benchmark fields			
1	^{233}U(n_{th},f) PFNS	9222	2.030	Thermal-neutron induced prompt fission spectrum from ^{233}U
2	^{239}Pu(n_{th},f) PFNS	9437	2.073	Thermal-neutron induced prompt fission spectrum from ^{239}Pu

SACS measured in these spectra are tabulated in the IRDFF-II paper

See A. Trkov et al, IRDFF-II paper
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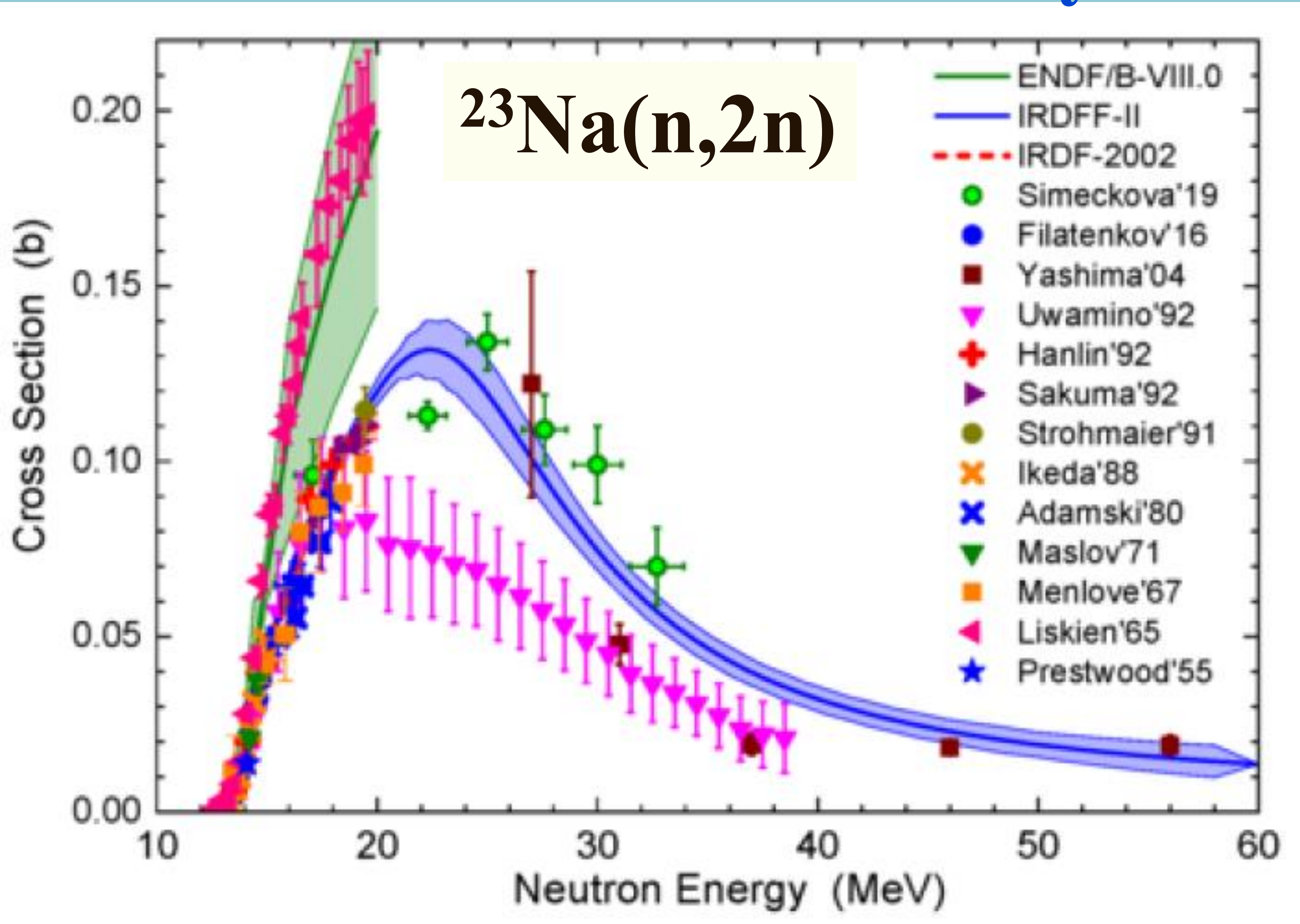

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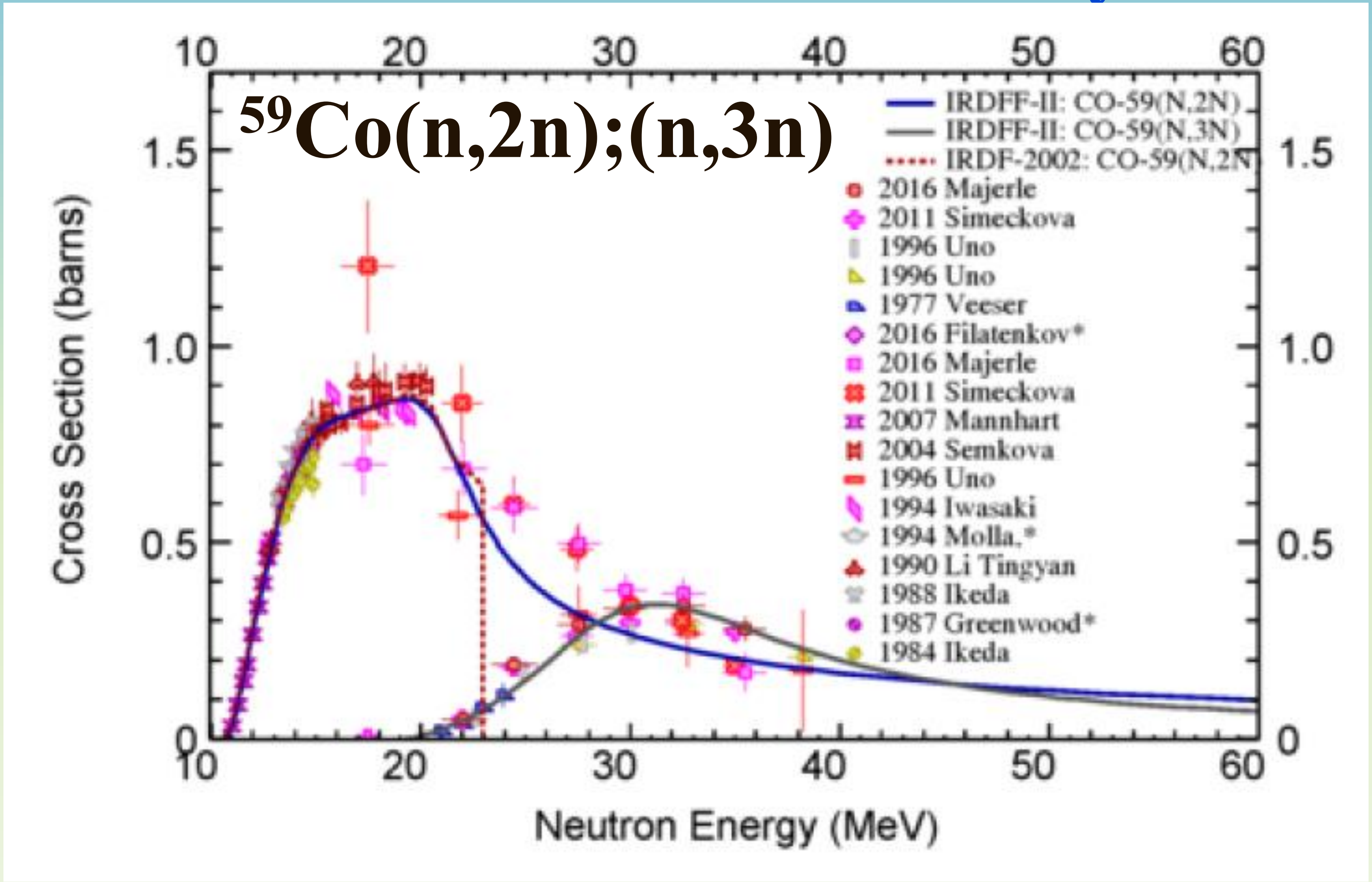

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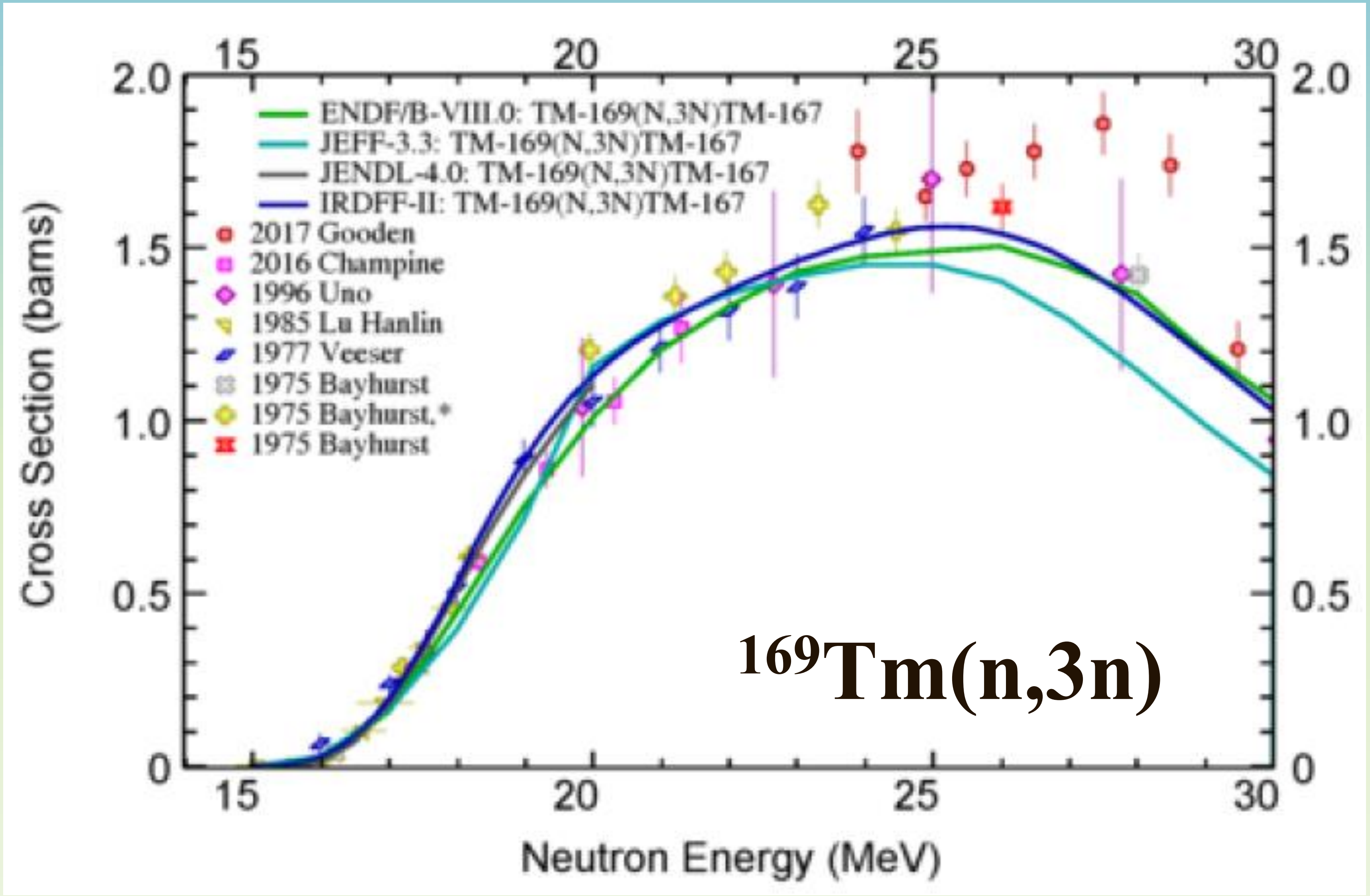

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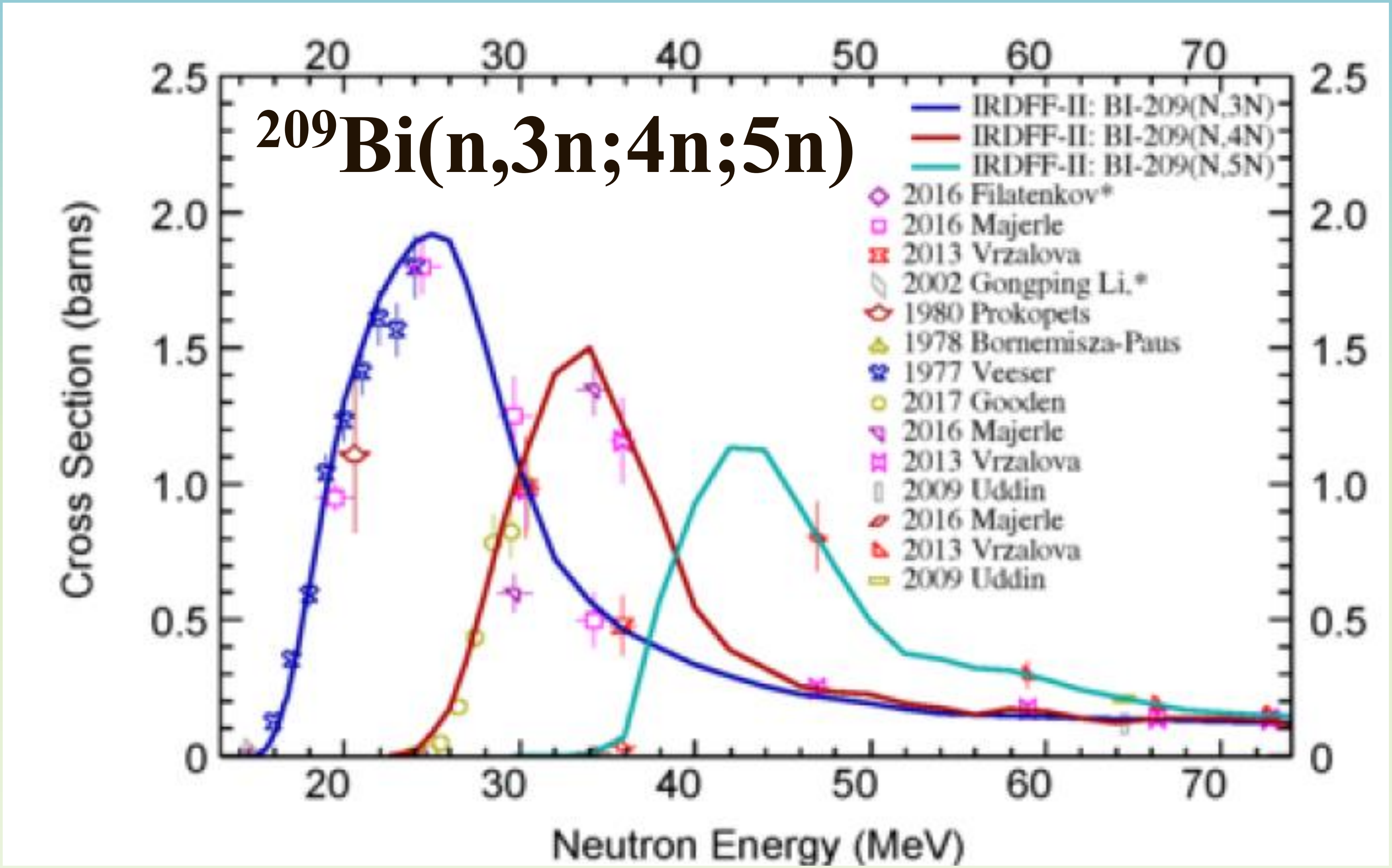

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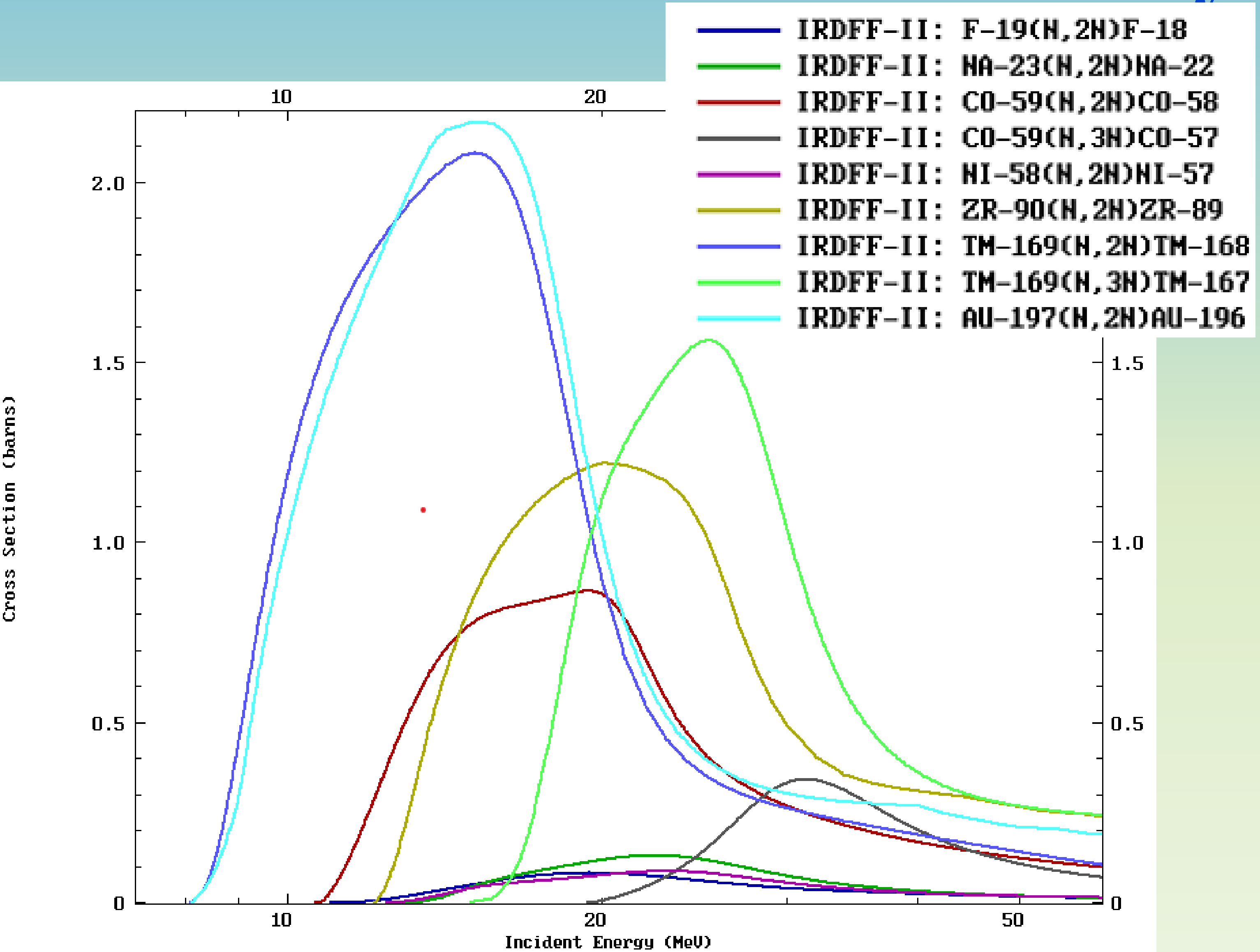

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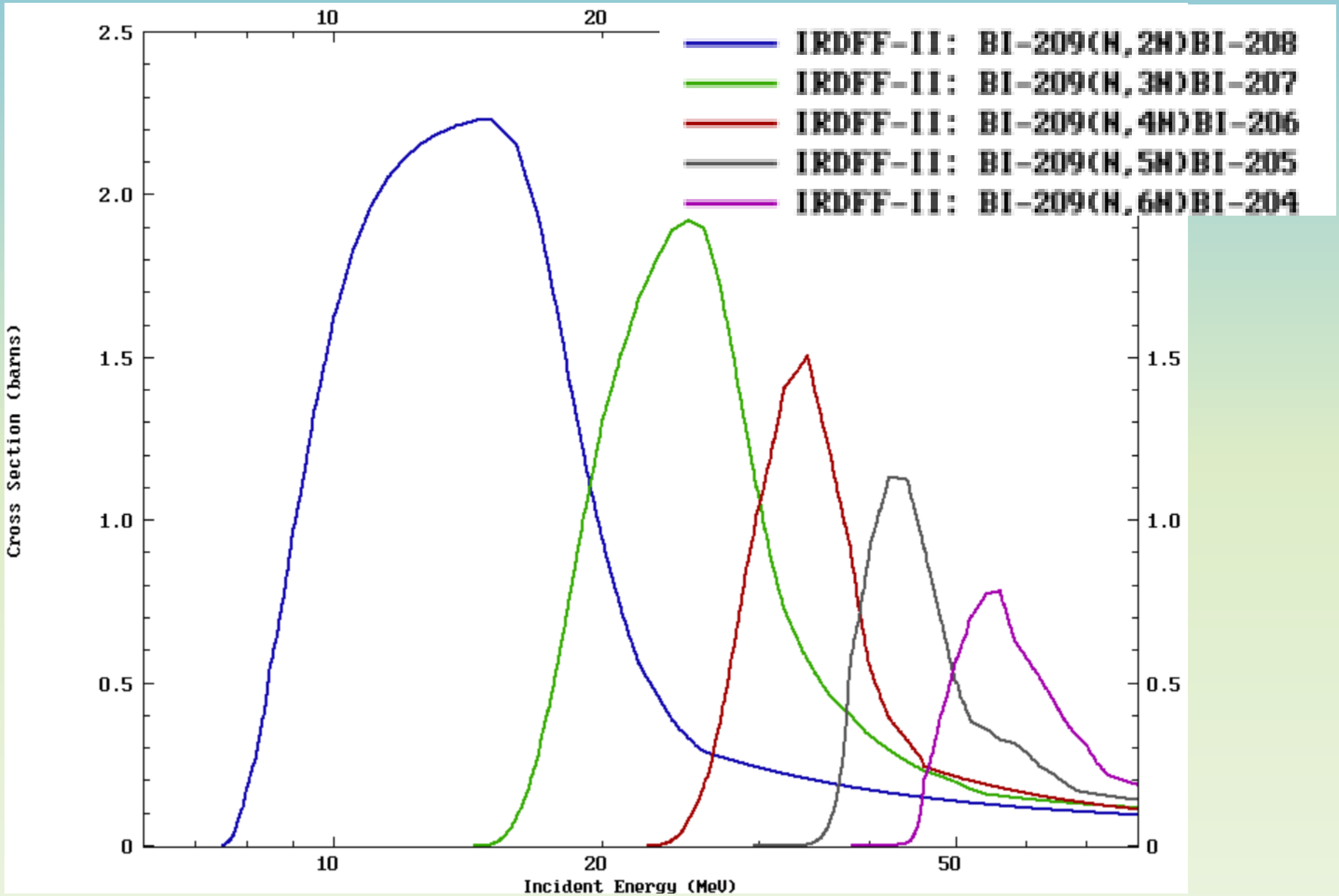

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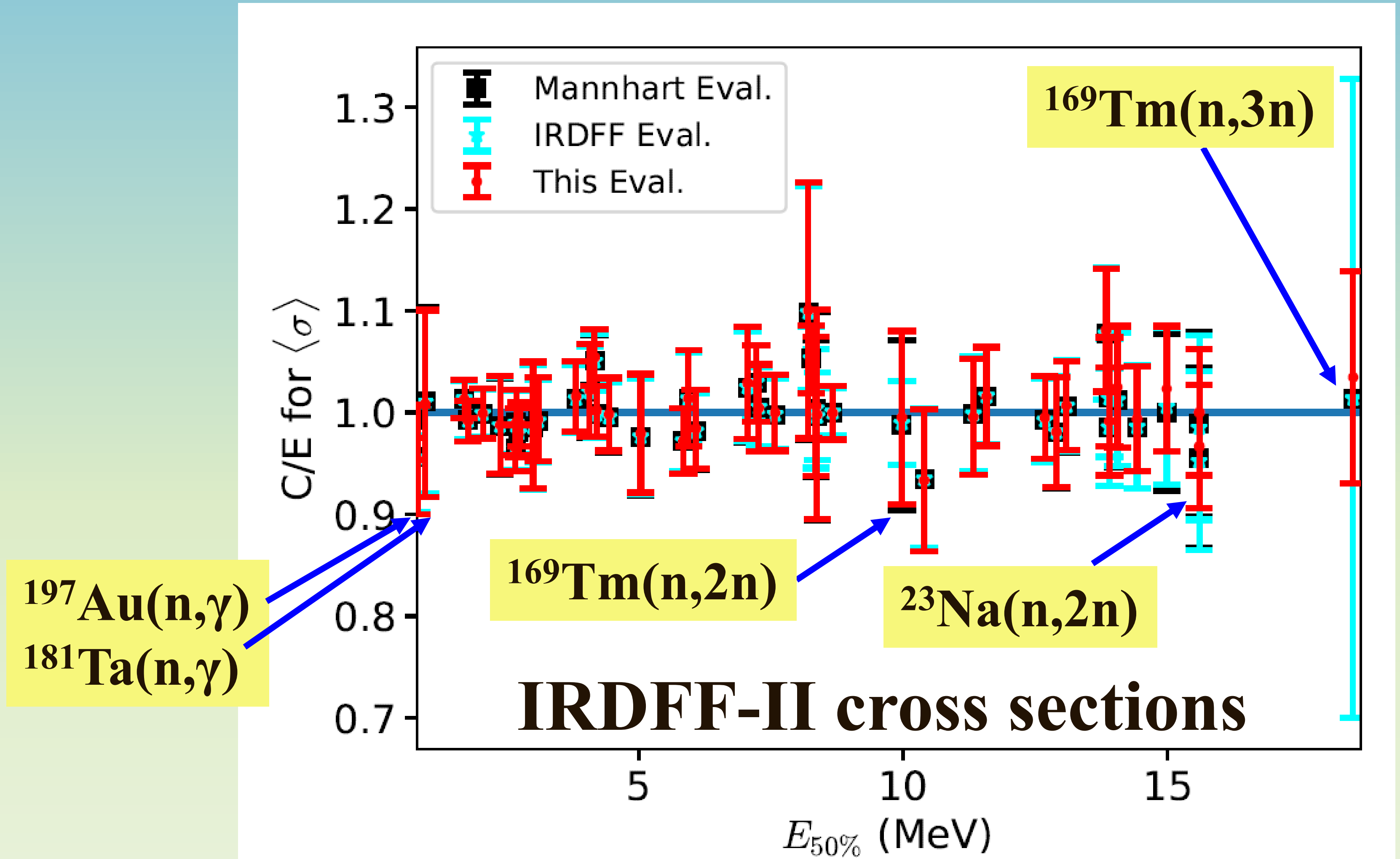
New evaluation of ^{252}Cf(sf) neutron field



D. Neudecker et al, "Reevaluating the PFNS of ^{252}Cf(sf)"
May 2025, submitted to EPJN

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What we can learn from established neutron dosimetry E<20 MeV?

DATA needs:

- ToF measured (& eval) broad spectrum ref beam - ^{252}Cf(sf)
- Measured SACS by activation in this reference beam
- Well measured (& eval) threshold cross sections (dosimeters) covering the whole energy range (n,xn)
- Evaluated XS : both mean & covar for spectrum unfolding

n,xn covers up to ~60 MeV

Neutron dosimetry does not depend on reaction models !!

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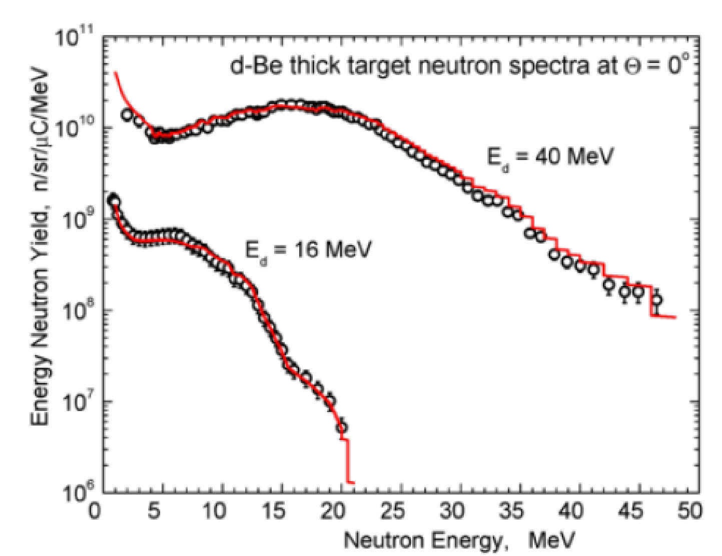
HE neutron data status for dosimetry

- Standard cross sections (XS) ^{235,238}U(n,f) up to 200 MeV
- Reference HE XS ^{nat}Pb(n,f),^{209}Bi(n,f) up to 1 GeV, ^{235,238}U(n,f) …
- IRDFF-II: A comprehensive neutron dosimetry library for fission and fusion applications up to **60 MeV** is available
- More than 20 dosimetry reactions and associated decay data included in the energy range from 14 up to 60 MeV
- Reference spectra are given with corresponding SACS data - most used ^{252}Cf(sf), but

Be(d,n) spectra available for Ed=16,40 MeV

See A. Trkov et al, IRDFF-II paper Nucl. Data Sheets 163 (2020) 1-108



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HE neutron data needs

- We need a high-energy broad-spectrum neutron reference field (reproducible, MC simulation validated by ToF measurement)
- We need SACS activation measurements in this HE reference field
- We need XS measurements in HE quasi-monoen. neutron fields to extend IRDFF-II up to 150 MeV (eg in Li(p,n) fields)

  potential candidate reactions: ^{209}Bi(n,7n),^{209}Bi(n,8n), ^{209}Bi(n,9n), ^{59}Co(n,4n), ^{59}Co(n,5n), ^{181}Ta(n,xn), x=2-8, …
- **We can use existing Li(p,n) spectra up to 60 MeV to validate existing HE IRDFF-II if we undertake activation measurements of (n,xn) dosimeters in the Li(p,n) field**

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**"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

Thank you!