Fusion Related Activities at CV Rez

Michal Kostal, LR-0 reactor lab, Rez

"Consultancy Meeting on Further Development of the Fusion Evaluated Nuclear Data Library„

Vienna 30.10.2023 - 2.11.2023

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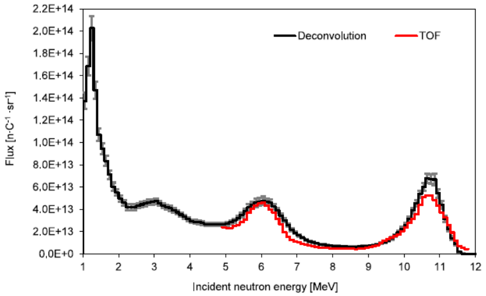
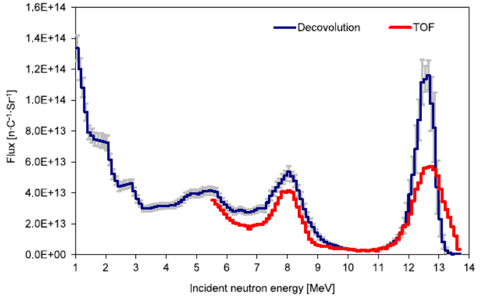
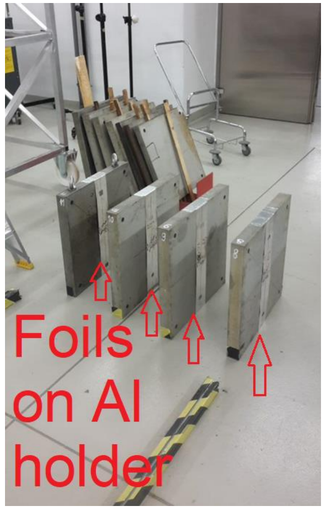
Fusion related research in Rez

Accelerator based experiments



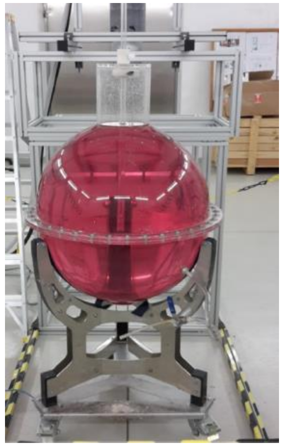


Benchmarking with ^{252}Cf(s.f) source



Experiments with D-T generator

Prompt gamma issue



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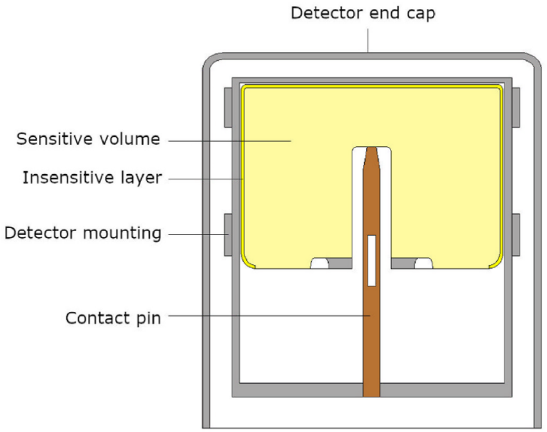
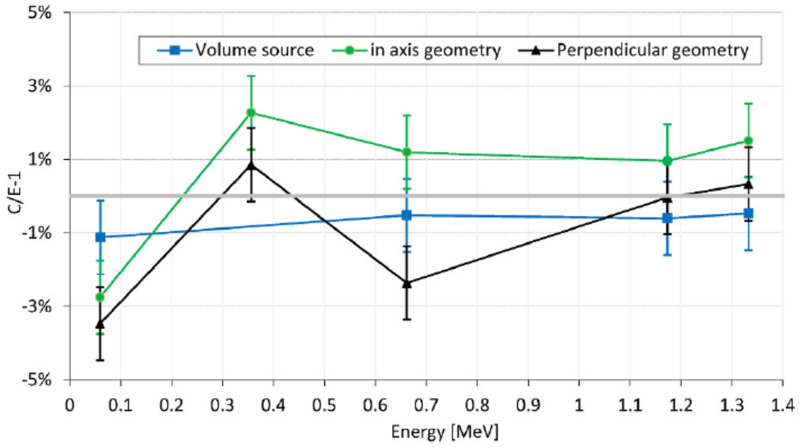
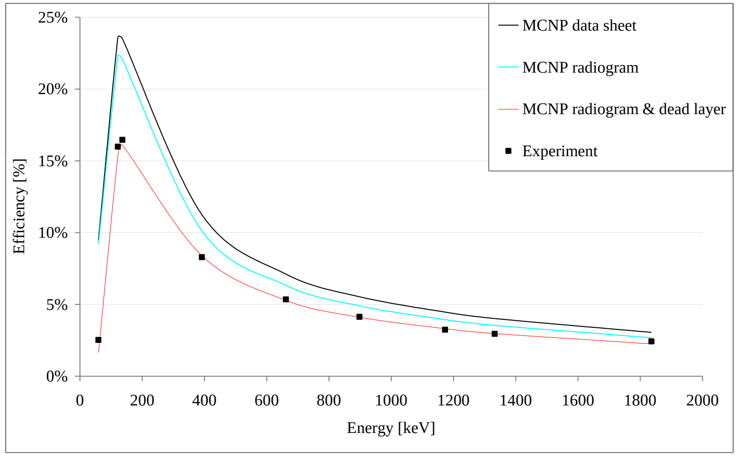
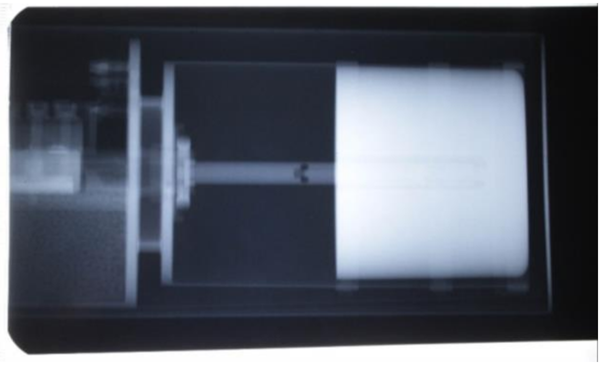
Gamma spectrometry - HPGe

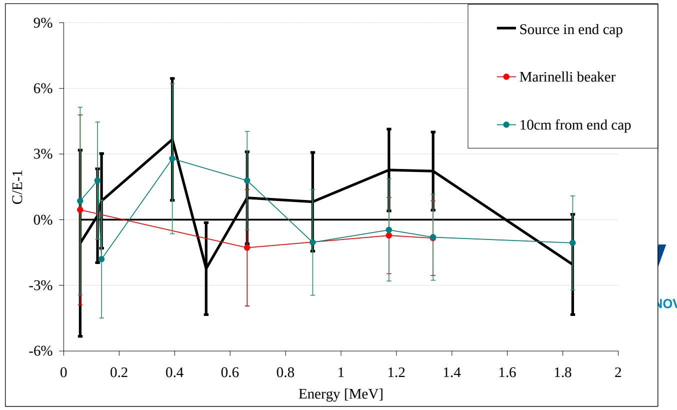
- **Most important is detector sensitivity**
- **Foil measurement**
  - Mathematical model allows even large samples on detector cap
  - Determination of coincidence summing correction
- **Gamma flux measurement**
  - Model allows evaluation of gamma flux (only the directionality needed)











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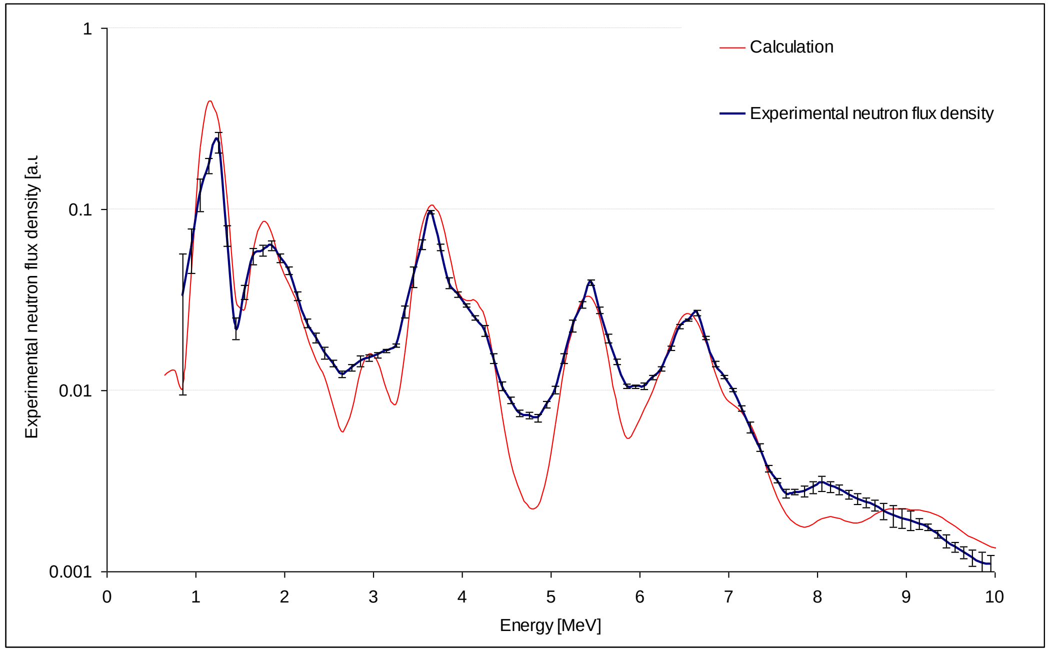
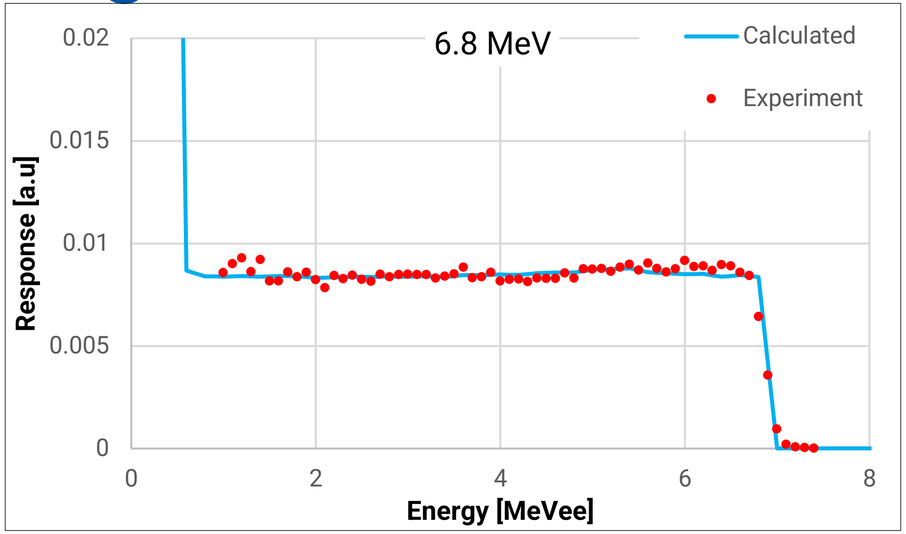
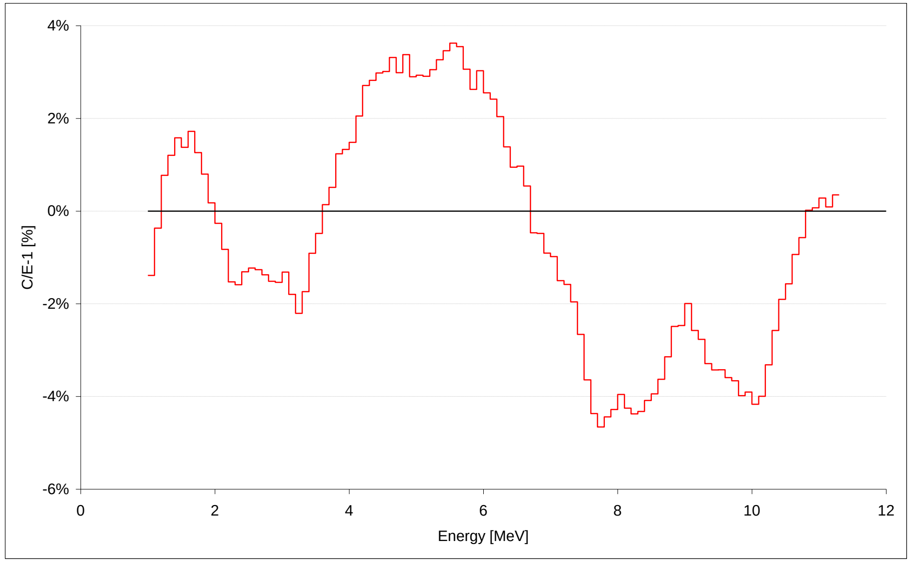
Czakoj et al., Rad. Phys. and Chem. 202 (2023) 110542

Neutron spectrometry

- Validation in PTB
- Validation in ^{252}Cf
- Verified in Si filtered spectrum







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Radulovic et al., IAEA, INDC(NDS)-0746, 2018

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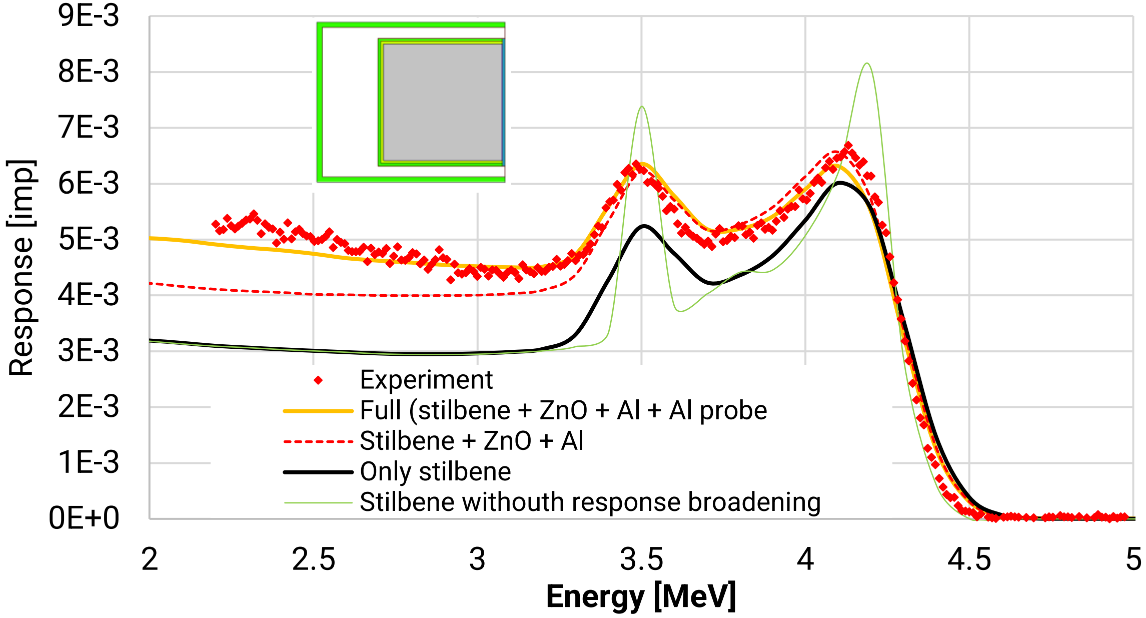
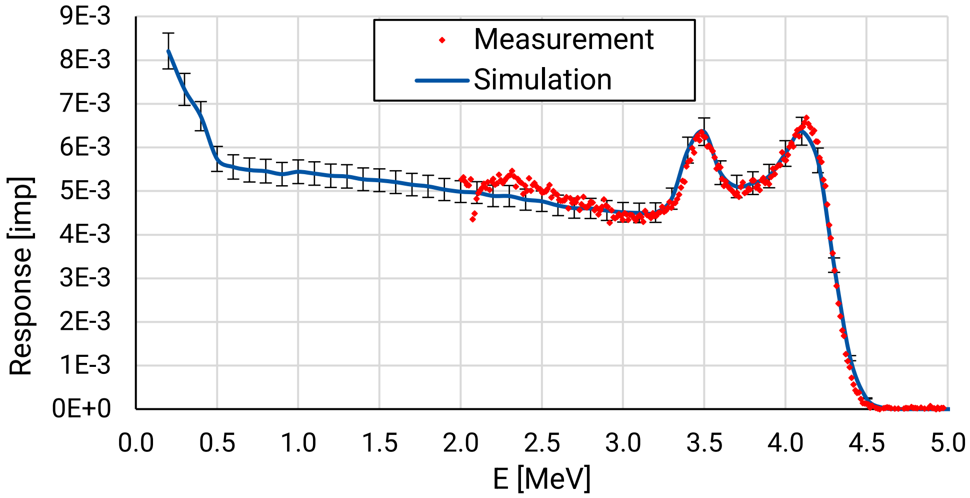
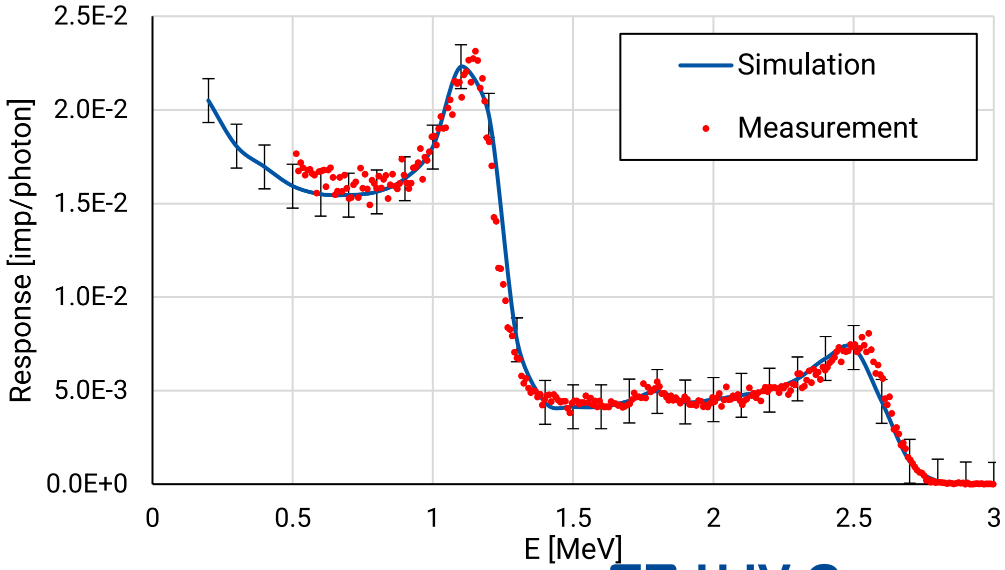
Gamma spectrometry stilbene

- Newly developed response matrix
- Simulation uses precise probe parameters
  - In gamma transport surrounding materials are essential
- Validation in AmBe + ^{24}Na







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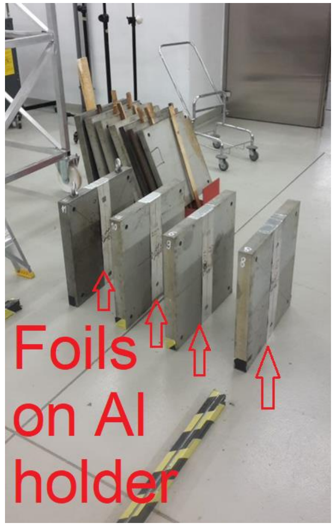
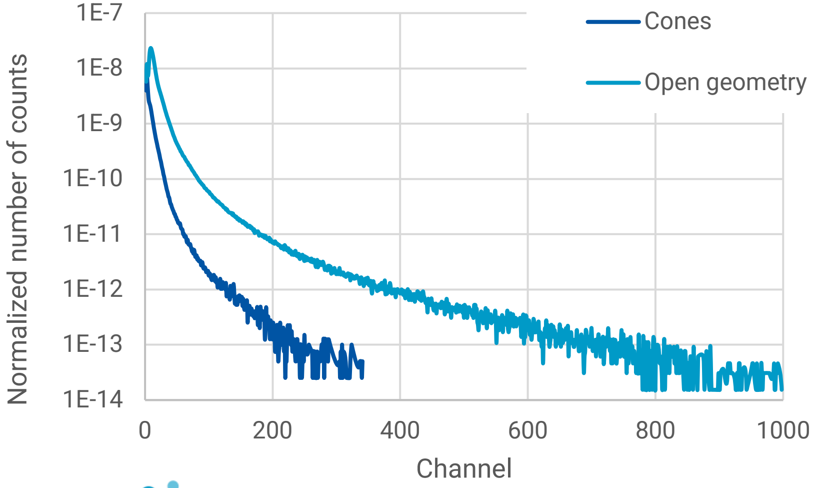
Benchmarking (stainless steel (A-320))

- Integral experiments are suitable for tuning of evaluations due to „low“ uncertainties
- The leakage experiments with $^{252}Cf(s.f)$ are ideal for validations due to low source uncertainties
- Even in fusion lower energies are essential to cover the slowing down process

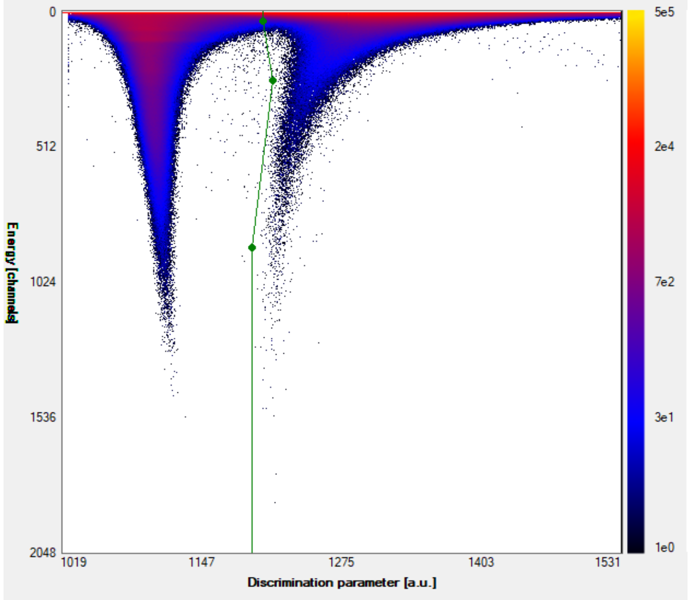


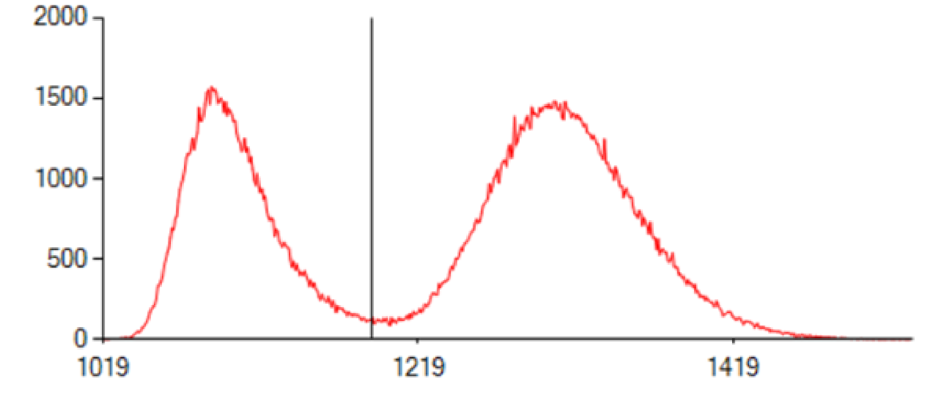
Fe	0.6783
Cr	0.1965
Ni	0.0925
Mn	0.0180
Mo	0.00403
Si	0.00344
Cu	0.00343
Ti	0.00267
V	0.000563
Sn	0.000131

Relatively low background



Good separation in metallic benchmarks – cut in ~ 0.8 MeV





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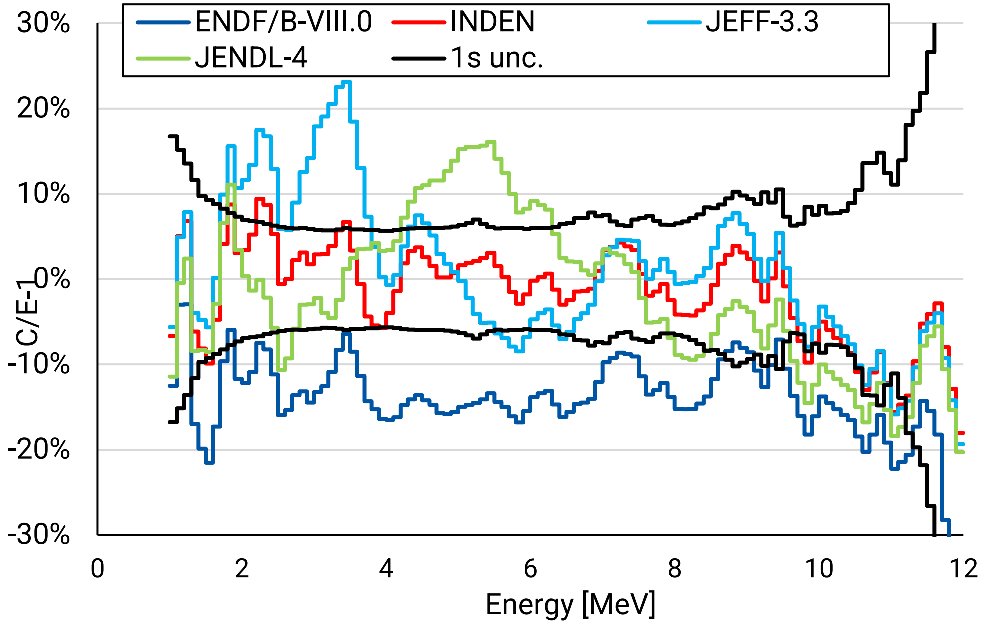
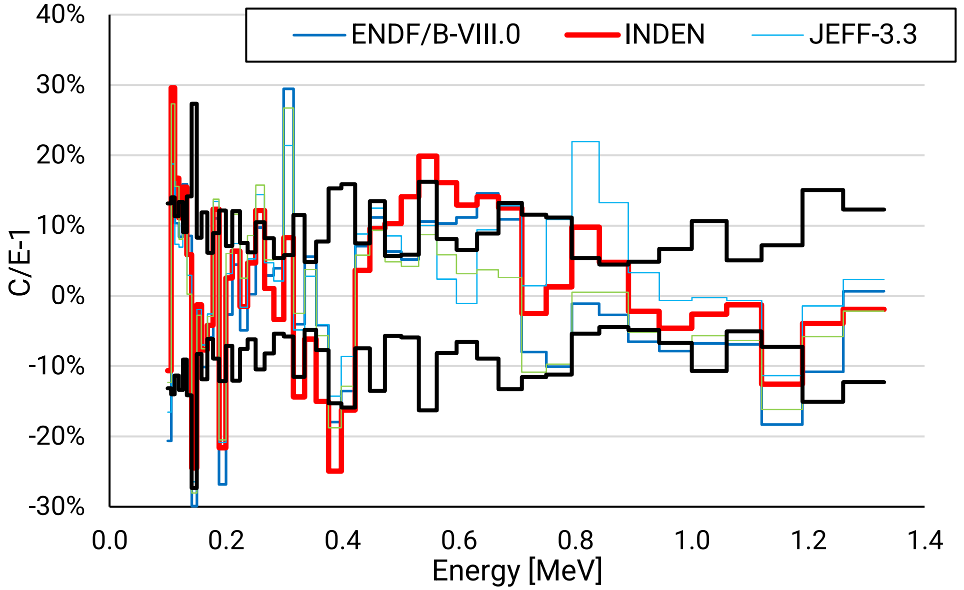
Benchmarking results

- The results for ENDF/B-VIII.0 show discrepancies
- New INDEN evaluation will be part of ENDF/B-VIII.1
- It is good to combine independent integral experiments

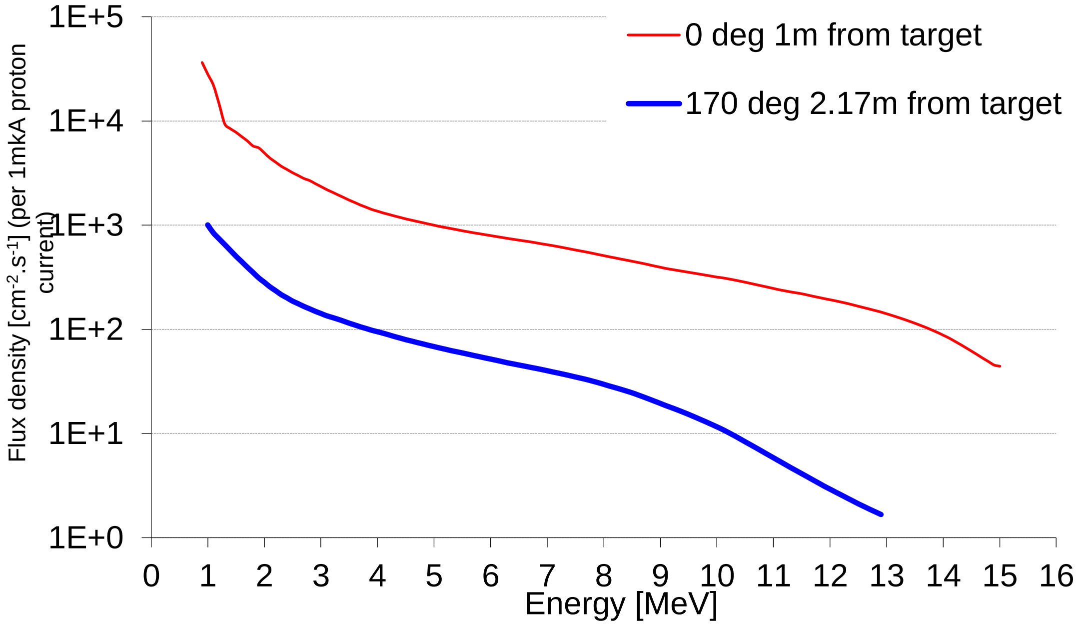
Steel thickness (cm)	Reaction	C/E-1 (%)				u_r (%)
		ENDF/B-VIII.0	INDEN	JEFF-3.3	JENDL-4	
5.04	$^{197}Au(n,\gamma)^{198}Au$	4.4	-4.4	-2.8	6.0	2.6
10.08		3.9	-6.3	-3.7	5.7	3.0
15.12		3.7	-5.7	-2.6	6.0	3.1
20.16		5.4	-5.6	0.0	7.7	3.2
5.04	$^{58}Ni(n,p)^{58}Co$	-8.6	-5.4	-3.4	-6.0	7.1
10.08		-8.4	-2.3	1.3	-3.0	3.3
15.12		-9.1	0.4	5.5	-0.4	4.0
20.16		-12.9	-0.1	5.3	-1.2	3.7
5.04	$^{181}Ta(n,\gamma)^{182}Ta$	2.1	-9.5	-3.9	3.2	3.8
10.08		4.8	-4.7	-3.3	9.6	4.0
15.12		4.8	-5.6	0.0	9.4	5.4
20.16		11.3	1.7	7.1	9.0	5.3

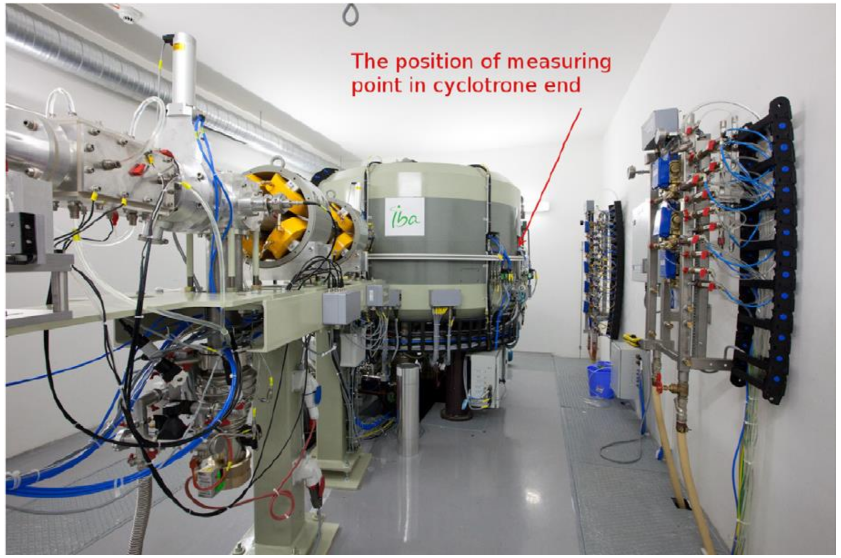


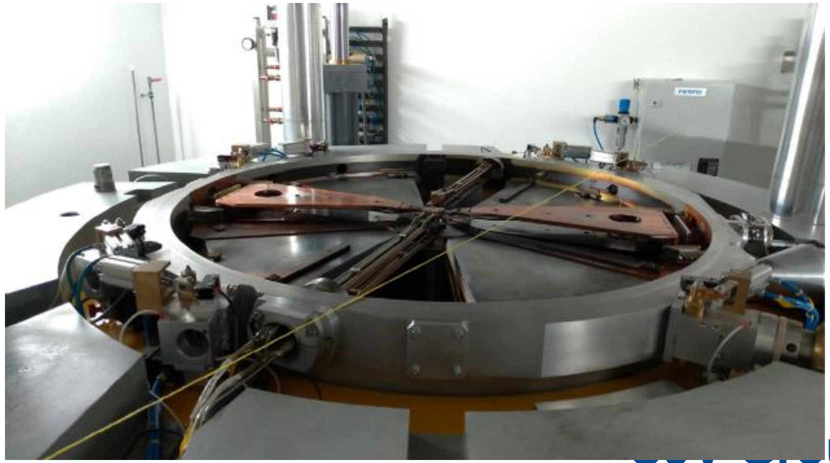


Measurements in vicinity of ^{18}F generators

- UJV (parent company of CV Rez) operating 3 IBA cyclotrons – one of them is in Rez
- Large set of measurements was realized
- Now - IAEA CRP on leakage spectra



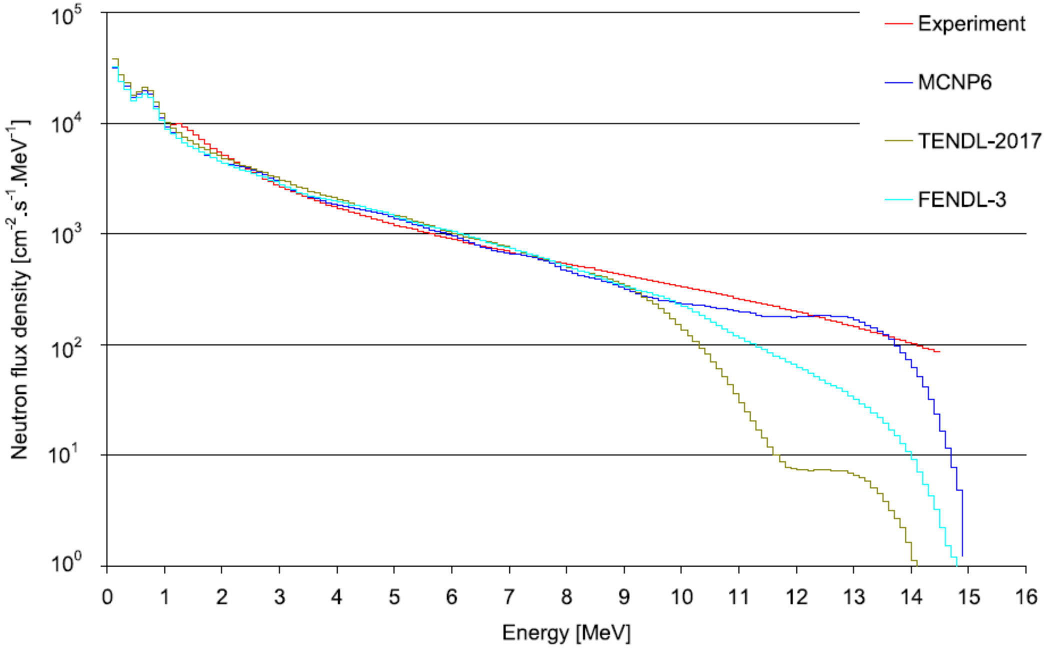


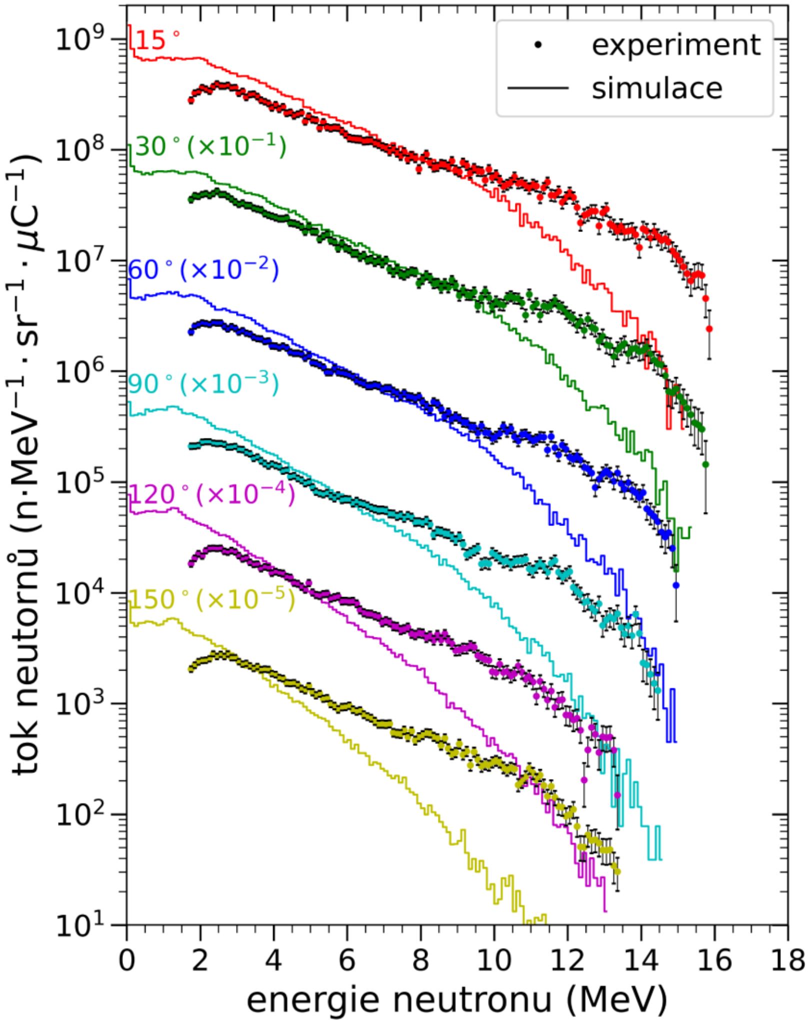


•Kostal et al, NIMA, 942, (2019), 162374

Measurements in cyclotron leakage beam

- Neutron leakage spectra measurement by stilbene in 1m distance
- Discrepancies are consistent with data presented in EXFOR (spectra from small target with $H_2{}^{18}O$

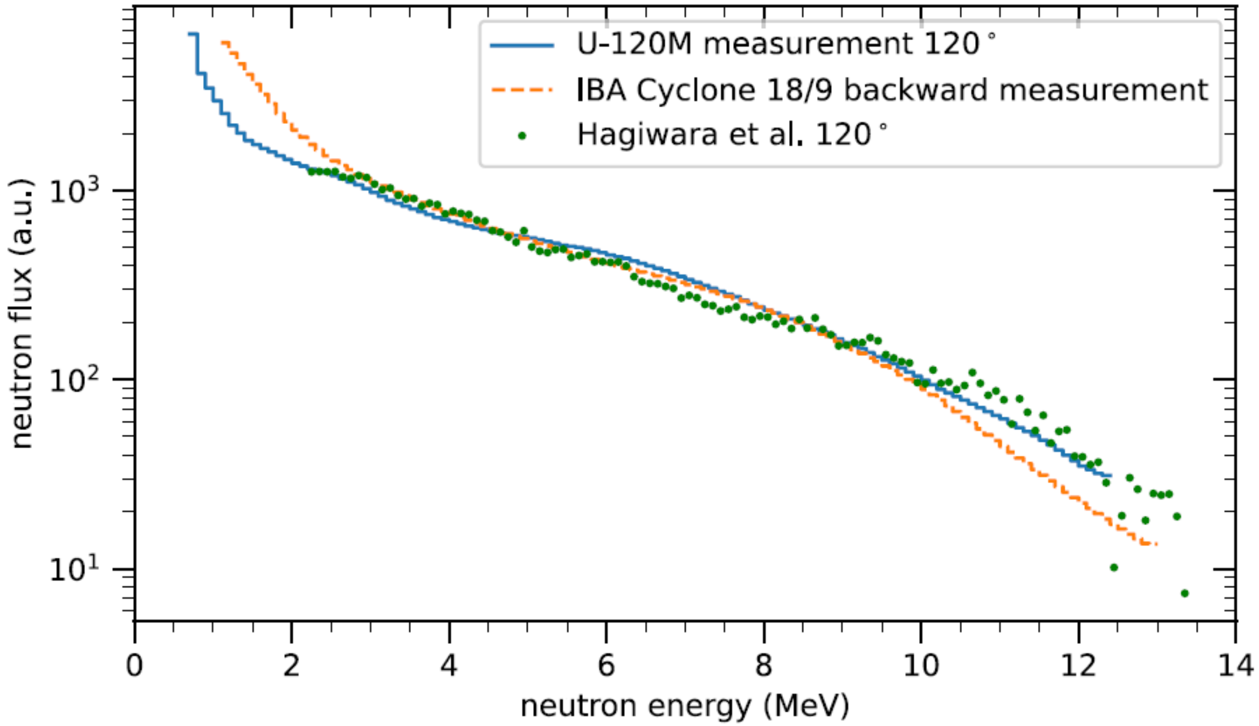




Hagiwara M. et al., Measurement of Neutrons and Gamma-Rays from Thick H18O Target Bombarded with 18 MeV Protons. JKPS 2011;59:2035-2038

Measurements in cyclotron background

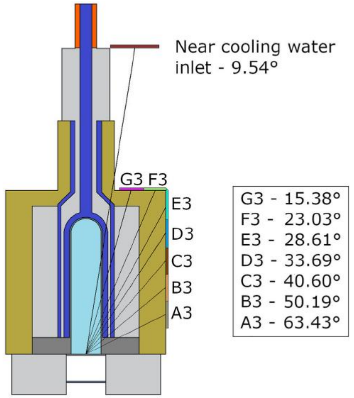
- In back-scattered neutrons significant discrepancies observed
- The measurement is reliable, as is consistent with experiment in cyclotron U-120M in Rez



Measurements on target

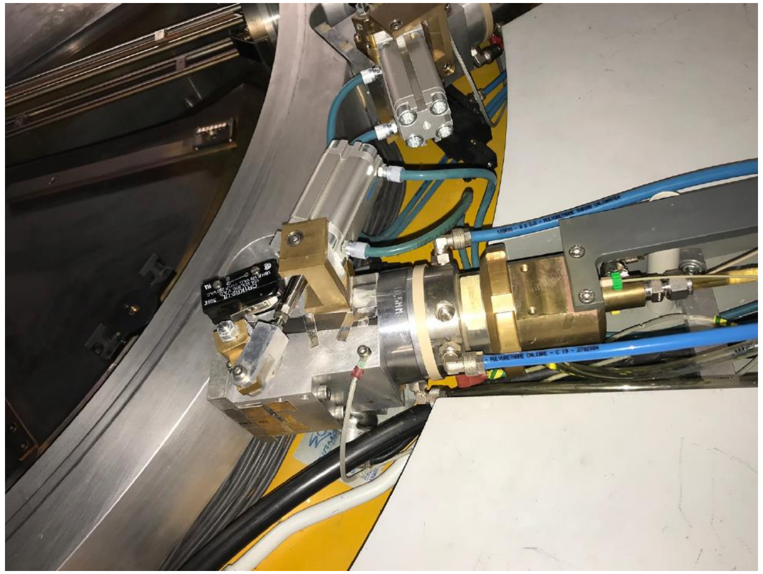
- Very large set of RR measurement performed (during routine production
- Large discrepancies in upper energy
- Use of new reaction $^{58}Ni(n,x)^{57}Co$

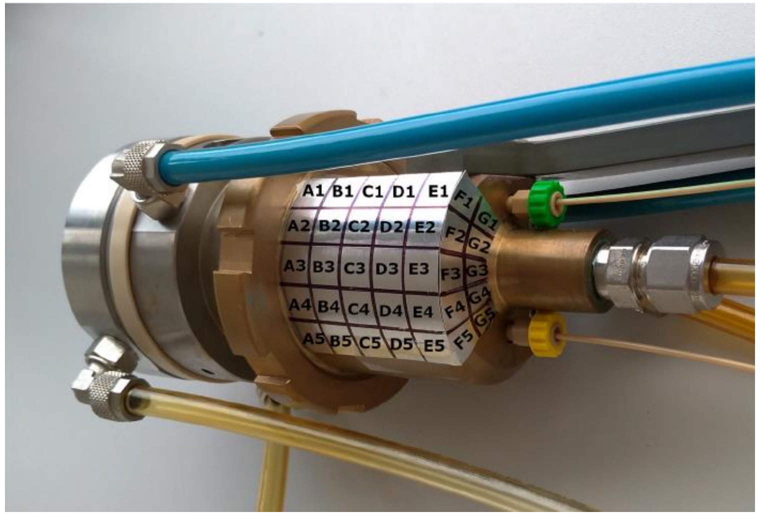
	$E_{50\%}$	63.43	50.19	40.60	33.69	28.61	23.03	15.38	9.54	0
$^{nat}Ni(n,x)^{58}Co$	5.96	3.2%	3.8%	0.3%	1.2%	−0.6%	1.6%	−2.5%	0.4%	−13.6%
$^{nat}Ti\ (n,x)^{47}Sc$	6.05	11.8%	7.4%	4.2%	−0.4%	0.2%	−1.8%	−4.7%	−2.0%	
$^{nat}Fe\ (n,x)^{54}Mn$	6.18	11.0%	8.2%	5.7%	4.7%	1.8%	−1.1%	−0.4%	−6.0%	−14.7%
$^{nat}Ti\ (n,x)^{46}Sc$	8.31	−13.5%	−14.5%	−12.3%	−11.3%	−8.8%	−9.8%	−9.9%	−15.6%	
$^{nat}Ni(n,x)^{60}Co$	9.62	−44.2%	−42.3%	−40.9%	−39.0%	−35.5%	−41.0%	−28.3%	−23.9%	−33.6%
$^{nat}Fe\ (n,x)^{51}Cr$	9.85	−44.3%	−41.3%	−38.8%	−33.6%	−31.9%	−27.3%	−22.0%		
$^{nat}Cu(n,x)^{60}Co$	9.88								−28.6%	−31.2%
$^{nat}Fe\ (n,x)^{56}Mn$	10.04	−45.4%	−43.6%	−40.1%	−35.8%	−28.6%	−27.2%	−17.0%	−25.9%	
$^{nat}Ti\ (n,x)^{48}Sc$	10.73	−58.1%	−55.4%	−51.5%	−47.7%	−42.4%	−36.5%	−30.4%	−34.3%	
$^{51}V\ (n,\alpha)^{48}Sc$	11.74	−73.6%	−69.0%	−64.0%	−58.3%	−52.3%	−45.2%	−36.6%		
$^{nat}Ni(n,x)^{57}Co$	13.06	−88.7%	−85.5%	−81.1%	−71.2%	−62.7%	−47.8%	−32.2%	−38.1%	−44.0%



MCNP 6.2	A	B	C	D	E	F	G
1	972%	533%	449%	301%	188%	108%	57%
2	836%	630%	413%	249%	185%	105%	52%
3	813%	616%	430%	252%	166%	95%	44%
4	907%	651%	411%	235%	183%	87%	40%
5	811%	623%	388%	275%	181%	112%	39%

	A	B	C	D	E	F	G
1	37.83	28.17	23.02	21.59	22.13	23.45	24.30
2	37.26	27.15	22.11	22.10	22.22	23.30	24.09
3	37.61	26.65	22.27	21.88	22.38	23.03	25.24
4	36.04	26.65	22.13	21.86	21.90	24.25	25.00
5	36.91	26.20	21.89	22.15	22.13	22.90	25.66





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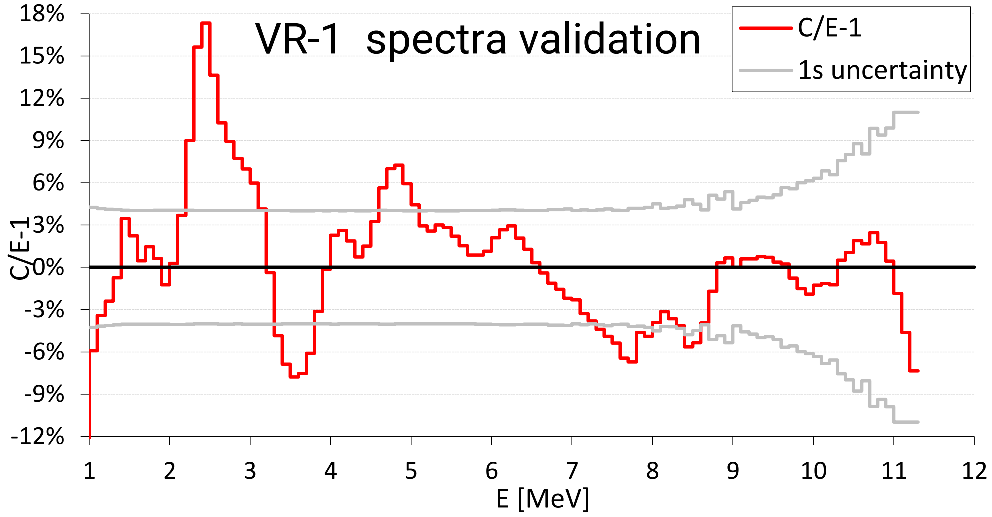
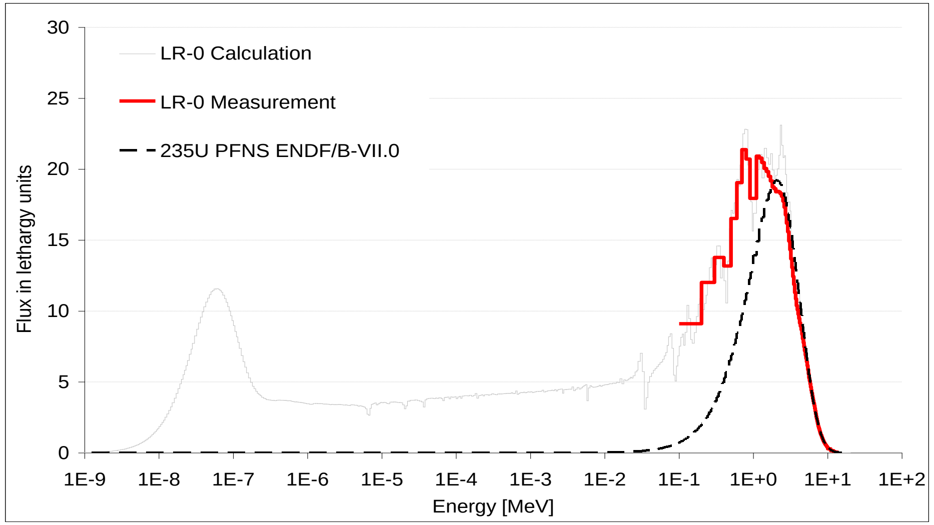
Kostal et al., Rad. Phys. and Chem., 184 (2021) 109475

$^{58}Ni(n,x)^{57}Co$ validation in ^{235}U PFNS

- High threshold reaction insensitive for gamma
- Measurements was realized in VR-1 reactor (CTU university reactor with known neutron field - identity with ^{235}U PFNS > 6 MeV)
- New measurements performed in LR-0 reference field
- Good agreement across measured set of SACS





Reference	Mean [mb]	Difference from current value
BRUGGEMAN et al., 1974	0.216 ± 0.005	-7.1%
WÖLFLE et al., 1980	0.240 ± 0.035	3.2%
HORIBE et al., 1992	0.232 ± 0.005	-0.2%
ZAIDI et al., 1993	0.253 ± 0.015	8.8%
Arribére et al., 2001	0.275 ± 0.015	18.3%
Burianova et al., 2019	0.239 ± 0.013	2.8%
Kostal et al 2021	0.241 ± 0.015	3.7%
Kostal et al 2022	0.226 ± 0.009	-2.9%
2023 measurement in LR-0	**0.233 ± 0.014**	

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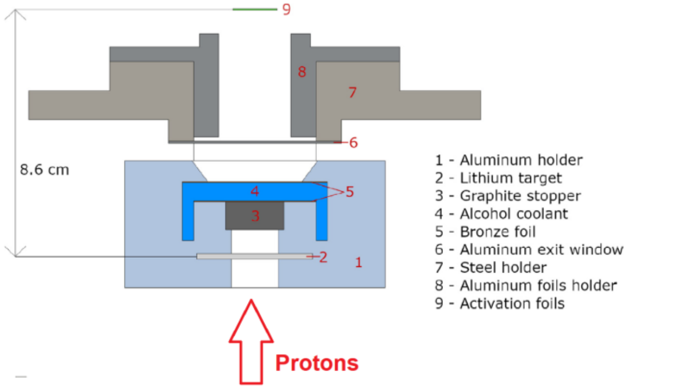
Quasi monoergetic field validation

Formed from ^{7}Li(p,n) reaction

Spectra measurement

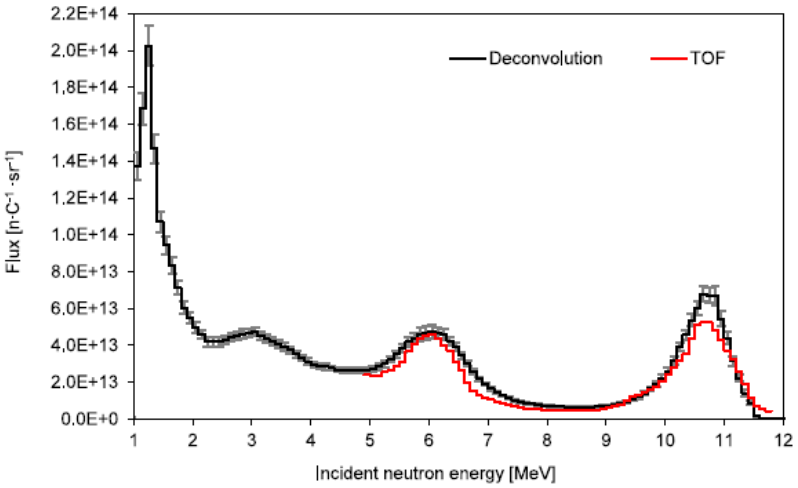
- Deconvolution
- TOF

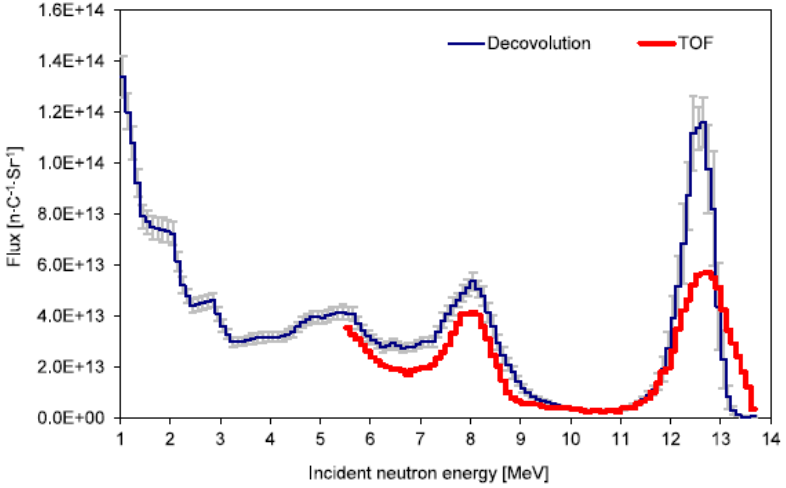
Simultaneous activation



Reaction	$E_{50\%}$ [MeV]	IRDFF-II	JEFF-3.3	JENDL-4	ENDF/B-VIII.0	Unc.
^{54}Fe(n,p)	7.75	−1.2%	−3.0%	0.6%	−1.0%	3.9%
^{47}Ti(n,p)	8.37	1.3%	1.3%	2.1%	15.9%	6.8%
^{46}Ti(n,p)	10.04	7.8%	7.8%	2.9%	4.2%	4.1%
^{59}Co(n,p)	12.13	7.2%	−1.7%	−1.3%	4.8%	4.6%
^{60}Ni(n,p)	12.24	3.8%	1.2%	7.9%	9.8%	5.3%
^{54}Fe(n, α)	12.29	−5.4%	−17.4%	−5.5%	−61.7%	6.4%
^{24}Mg(n,p)	12.31	3.0%	10.1%	10.1%	10.1%	5.0%
^{56}Fe(n,p)	12.31	−1.7%	−2.5%	−3.9%	−1.6%	5.0%
^{59}Co(n, α)	12.40	−2.9%	−5.0%	−3.2%	−0.9%	5.3%
^{48}Ti(n,p)	12.41	2.2%	2.3%	−3.9%	0.5%	5.4%
^{51}V(n, α)	12.50	−4.8%	−5.0%	−0.4%	1.5%	6.3%
^{197}Au(n,2n)	12.50	2.9%	4.2%	16.0%	4.2%	6.2%
^{58}Ni(n,x)^{57}Co	12.57	–	−7.7%	2.5%	−10.2%	6.6%
^{59}Co(n,2n)	12.58	−7.2%	−6.4%	−13.5%	−4.0%	6.7%
^{19}F(n,2n)	12.64	10.7%	40.1%	75.7%	40.1%	7.3%
^{55}Mn(n,2n)	12.58	−2.8%	4.9%	−1.0%	−3.9%	6.8%

Reaction	$E_{50\%}$ [MeV]	IRDFF-II	JEFF-3.3	JENDL-4	ENDF/B-VIII.0	Unc.
^{54}Fe(n,p)	6.78	1.9%	−2.3%	5.2%	2.0%	4.2%
^{47}Ti(n,p)	7.43	7.8%	8.4%	11.7%	23.6%	3.7%
^{46}Ti(n,p)	9.61	11.7%	12.2%	9.8%	4.8%	8.3%
^{59}Co(n,p)	10.05	3.2%	−7.1%	−5.5%	3.2%	4.1%
^{60}Ni(n,p)	10.25	18.1%	18.8%	20.9%	18.1%	6.9%
^{56}Fe(n,p)	10.30	−2.5%	−4.0%	0.2%	−2.5%	3.9%
^{24}Mg(n,p)	10.37	3.7%	8.4%	10.3%	7.7%	4.1%
^{59}Co(n, α)	10.43	−1.9%	−4.6%	1.0%	1.7%	4.0%
^{48}Ti(n,p)	10.45	−0.5%	0.1%	−1.9%	10.6%	4.1%
^{51}V(n, α)	10.57	−1.7%	−1.2%	8.4%	12.2%	5.3%
^{197}Au(n,2n)	10.60	−3.4%	−5.5%	22.6%	−6.1%	4.3%
^{58}Ni(n,x)^{57}Co	10.89	–	−20.9%	−10.6%	−18.1%	3.7%
^{59}Co(n,2n)	11.27	−2.7%	−2.7%	11.7%	14.0%	6.2%





^{58}Ni(n,x)^{57}Co validation in quasi monoenergetic field

$E_{protons}$	$E_{50\%}$ [MeV]	JEFF-3.3	JENDL-4	ENDF/B-VIII	Unc.
12.4 MeV	10.89	-20.9%	-10.6%	-18.1%	3.7%
14.4 MeV	12.57	-7.7%	2.5%	-10.2%	6.6%

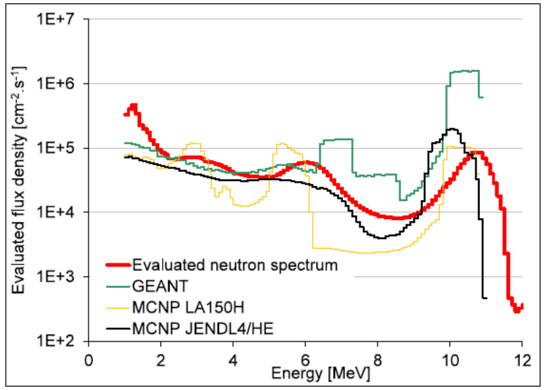
Matej et al., Rad. Phys. and Chem., 184 (2021) 109475

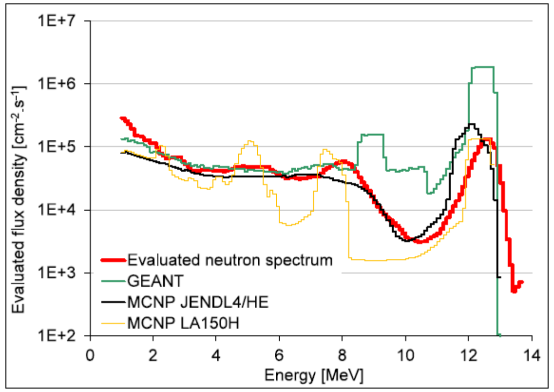
Quasi monoenergetic field

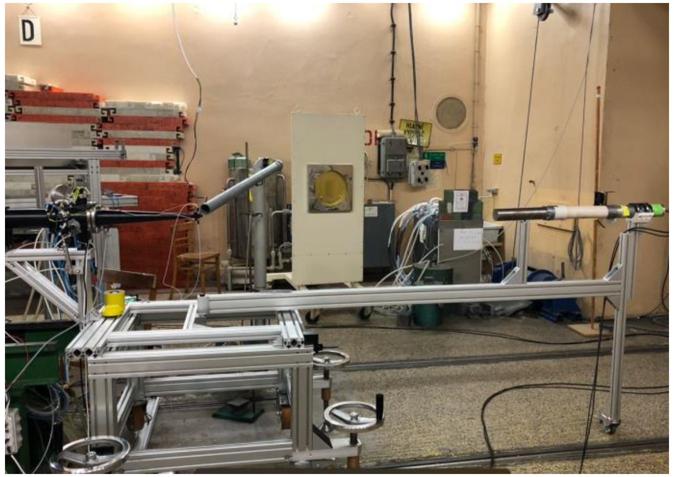
1

Need of experimental characterization

The calculation don't agree with measured spectra (while TOF and deconvolution)



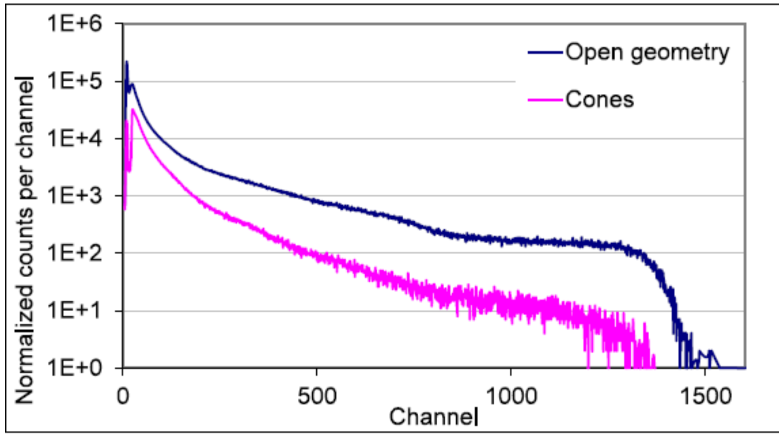


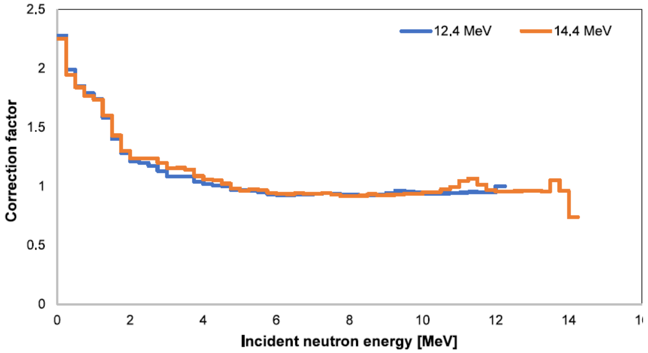


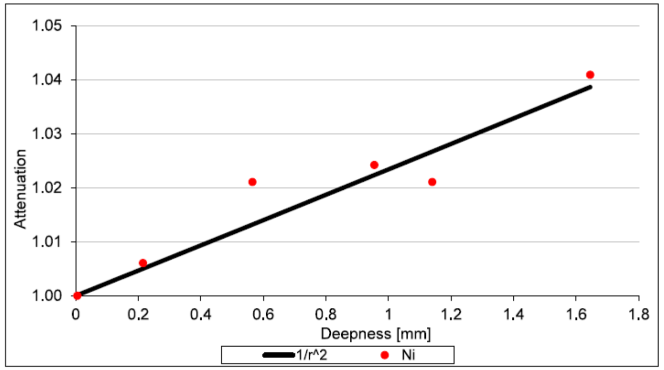
2

Background effect

Clasical estimation by room effect using cones







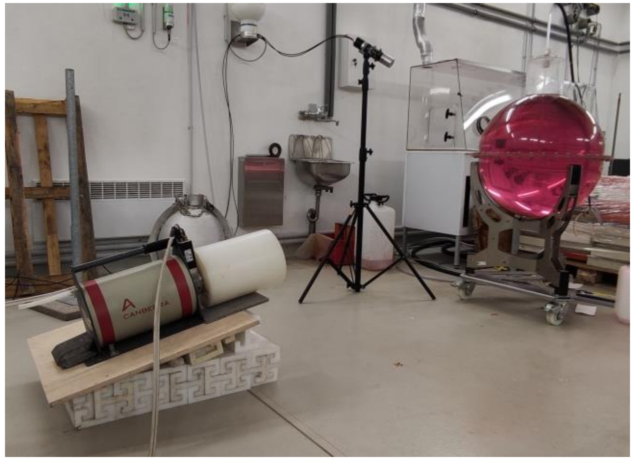
3

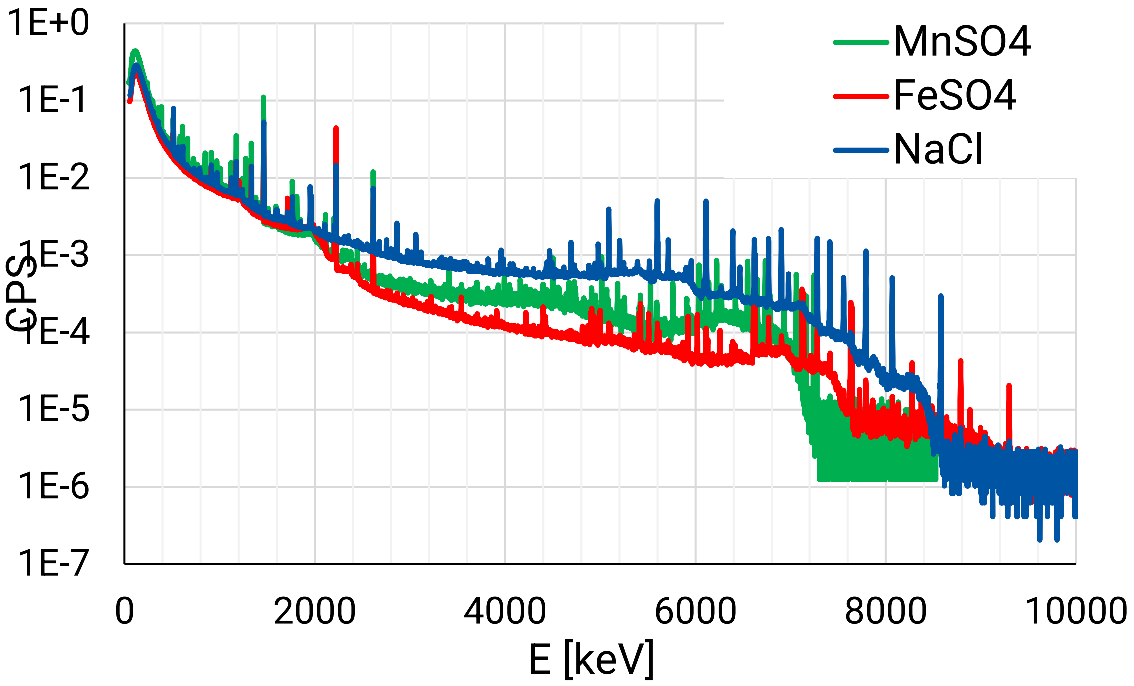
Material and geometrical correction

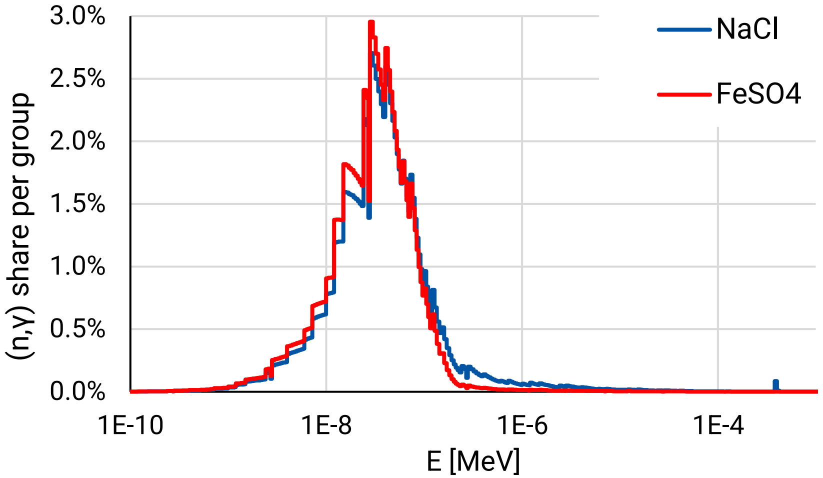
It is reflection of fact, that spectra is measured in position diffrerent from foils

Prompt gamma measurement

- Measurement of leakage gammas with HPGe and stilbene detectors
- Ideal geometry, because Cf inside is standart
- Due to water solvent – good moderation
- SINBAD benchmarking







Energy range	Cl	Fe
0 - 1 eV	97.738%	99.404%
1 eV - 0.1 keV	2.121%	0.503%
0.1 keV - 10 keV	0.134%	0.053%
10 keV - 20 MeV	0.007%	0.039%

Prompt gamma NaCl case

- Significant overprediction across libraries
- Cl is important in design of new reactors
- Importance in PGNAA issues
- Part of CRP (F40016 - Measurement of Prompt Capture Gamma Coming from Chlorine and Iron Neutron Capture)

E [MeV]	Measured flux [photon/cm²·s]	Measurement uncertainty	C/E-1		C/E-1 uncertainty
			ENDF/B-VIII.0	JEFF-3.3	
1.601	1.12E-02	3.2%	6.8%	2.5%	4.6%
2.876	1.90E-03	11.8%	94.2%	118.6%	12.3%
3.016	3.87E-03	12.1%	99.5%	127.8%	12.5%
3.116	5.49E-03	10.1%	34.3%	46.3%	10.6%
5.703	5.01E-03	9.1%	4.4%	23.7%	9.7%
5.715	6.42E-02	2.6%	23.4%	19.0%	4.2%
5.734	3.52E-03	12.6%	80.7%	108.9%	13.0%
5.903	1.28E-02	4.8%	28.6%	26.8%	5.8%
6.111	2.87E-01	2.6%	5.6%	8.3%	4.2%
6.620	1.08E-01	2.5%	13.5%	15.9%	4.1%
6.628	5.82E-02	2.7%	21.6%	28.9%	4.3%
6.978	3.08E-02	4.0%	20.9%	23.3%	5.2%
7.414	1.49E-01	2.5%	15.3%	21.7%	4.2%
7.790	1.26E-01	2.5%	14.1%	16.7%	4.2%
8.579	4.31E-02	2.8%	16.0%	19.0%	4.3%

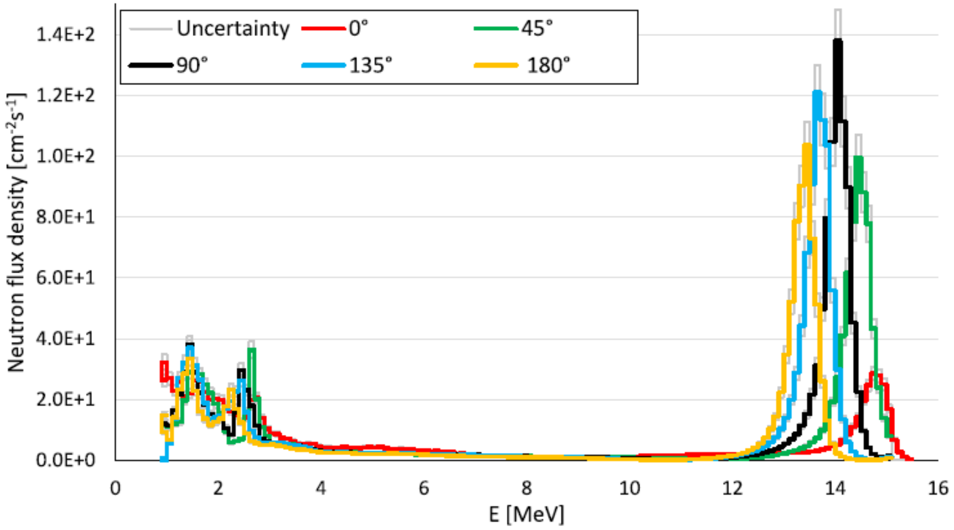
CVŘ Research Centre Řež

Czakoj et al., Ann. Of Nucl. En., will be published

UJV Group PEOPLE I INNOVATION I TECHNOLOGY

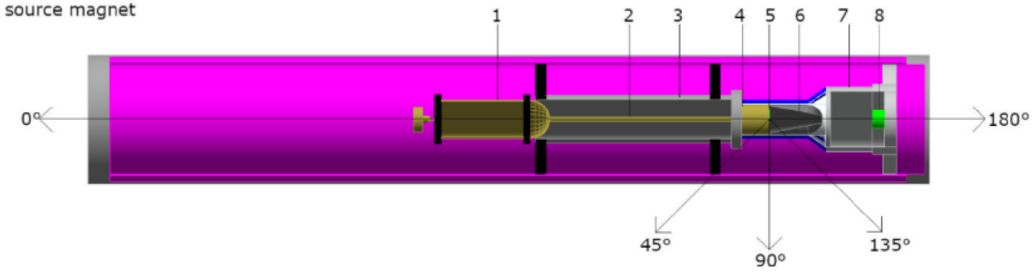
Characterization of compact generators

- Characterization of spectra (opposite geometry than assumed)
- Characterization of lower peaks flux by $^{115}In(n,n')$
- Used in measurement of dosimetry cross sections



	IRDFF-II	ENDF/B-VIII.0	JEFF-3.3.	JENDL-4	CENDL-3.2.
$^{nat.}Ti(n,x)^{47}Sc$	2.3	−11.0	−7.3	8.5	−19.9
$^{58}Ni(n,p)$	−1.2	−4.8	5.4	−11.5	3.2
$^{48}Ti(n,p)$	0.8	−4.4	0.7	−2.4	−1.7
$^{93}Nb(n,2n)^{92}Nb*$	−1.4	–	–	–	–
$^{89}Y(n,2n)$	6.2	6.3	6.3	7.5	9.6
$^{56}Fe(n,p)$	1.6	1.4	2.1	1.1	1.4
$^{197}Au(n,2n)$	6.7	6.3	6.3	8.5	−0.3
$^{24}Mg(n,p)$	3.9	6.1	6.1	6.1	8.3
$^{58}Ni(n,x)^{57}Co$	2.6	2.8	4.6	16.9	1.4
$^{90}Zr(n,2n)$	−7.5	−7.1	−6.4	−3.8	−3.8
$^{59}Co(n,\alpha)$	4.5	1.8	−0.1	7.7	0.5
$^{59}Co(n,2n)$	3.0	2.2	3.8	0.9	9.0
$^{59}Co(n,p)$	−4.8	−4.5	−5.0	0.0	0.8
$^{51}V(n,\alpha)$	0.4	–	–	–	–
$^{55}Mn(n,2n)$	7.1	−0.1	10.9	6.0	6.0
$^{169}Tm(n,2n)$	−3.0	−5.8	−4.8	−6.3	–
$^{46}Ti(n,p)$	−5.0	7.1	−5.5	−5.2	−8.1

1) Connection to Cockcroft-Walton high-voltage source
2) Electric connection to tritiated source plane
3) Aluminum cooling
4) Copper target cooling section
5) Target
6) Electron shroud
7) Deuteron Penning source
8) Ion source magnet



Czakoj et al., NIMA., 1034, (2022), p. 166837
Kostal et al, Ann. of Nucl. En., 191, (2023), p. 109904

Conclusions

Large portion of fission related research in fission field has large overlap into fusion

The Cf benchmark experiment is valuable tool for validation of FENDL, as it covers the lower energies – for example breeding blanket design

The neutron leakage during $^{18}O(p,n)^{18}F$ production is issue, and the characterization of leakage spectra is not satisfactory

High energy gamma is issue. The methodology developed in Rez (as companion of neutron spectra evaluation) is suitable for characterization of gamma fluxes

Thank you for attention

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Future plans