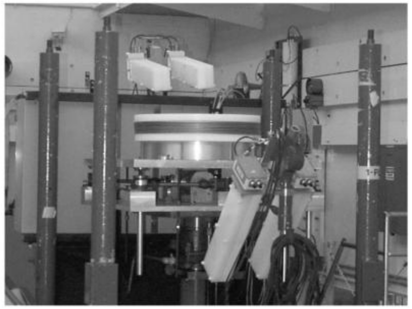
Measurement of the Ta(n,γ) cross-sections at EAR1

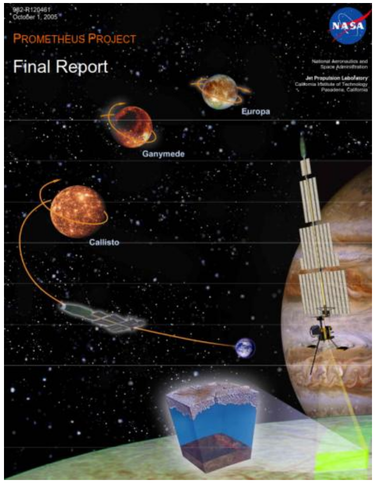
V. Alcayne[1], A. Pérez de Rada [1], D. Cano-Ott[1], E. González-Romero[1], T. Martínez[1], E. Mendoza[1], A. Sánchez-Caballero[1], J. Balibrea-Correa[2], F. Calviño[3], R. Capote[4], A. Casanovas[3], C. Domingo-Pardo[2], J. Lerendegui-Marco[2] and F. Garcia Infantes[5].

1- Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain.
2- Instituto de Fısica Corpuscular, CSIC - Universidad de Valencia, Spain.
3- Universitat Politècnica de Catalunya, Spain.
4- International Atomic Energy Agency, Vienna-A-1400, PO Box 100, Austria.
5- Universidad de Granada, Spain.

The Ta(n,γ) measurement at n_TOF

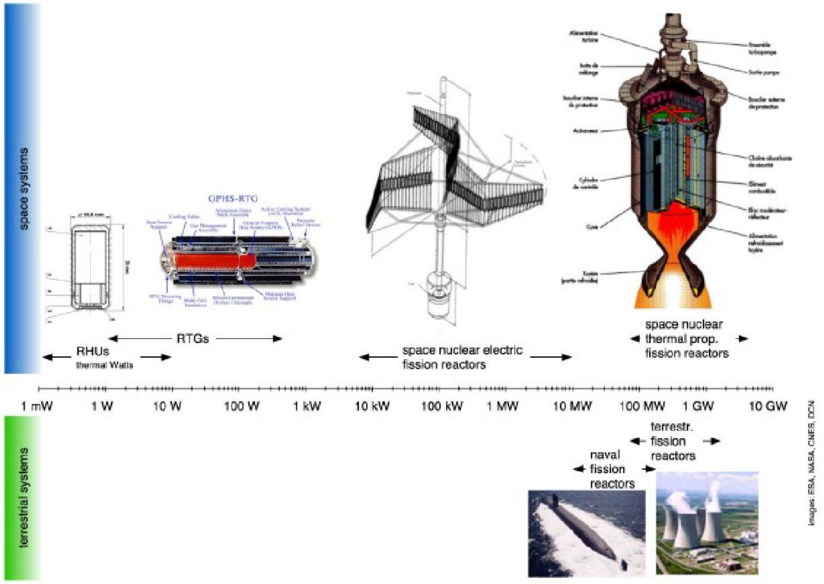
- The capture cross section of Ta is important for **nuclear reactors in space and fusion reactors**.





- **Recent critical experiments show discrepancies**, that may indicate issues with the cross section of Ta.

- The **previous data are discrepant and affected by important experimental corrections** like the self-shielding or angular correlations between γ-rays. There are considerable **difference between the recent evaluations.**

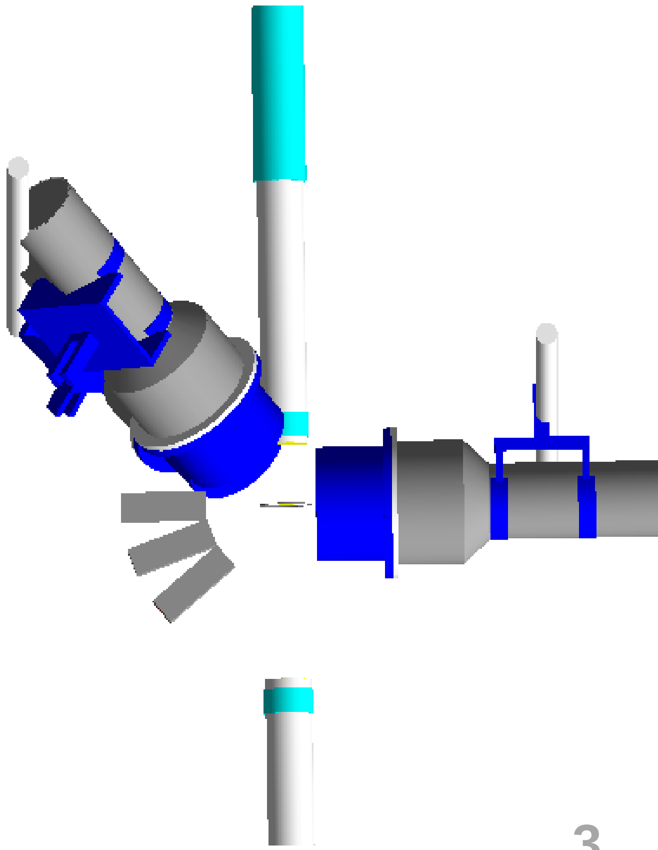


The n_TOF measurement at EAR1

Three samples of Ta (99.99% of ^{181}Ta and $1.2\cdot10^{-4}$ ^{180m}Ta) in the range **from 0.1 eV to 500 keV** with an aimed accuracy of 5%. The backgrounds and setup are share with the natural Er campaign:

- 1 BICRON at 3.7 cm at 90º with respect to the beam.
- 2 BICRON at 9.0 cm at 125º with respect to the beam.
- 3 sTED at 10 cm at 90º, 110º, 130º with respect to t

- S_n (^{182}Ta) = 6.062 MeV.
- **Three metallic high purity (99.999%) samples of 500, 100 and 10 μm of 4 cm diameter** for different energy regions and to verify the multiple corrections.



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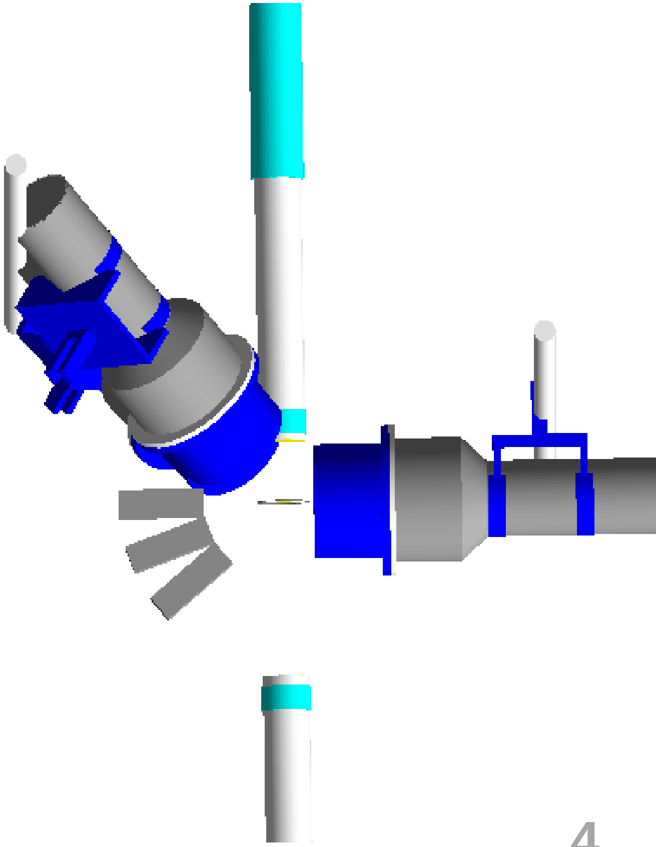

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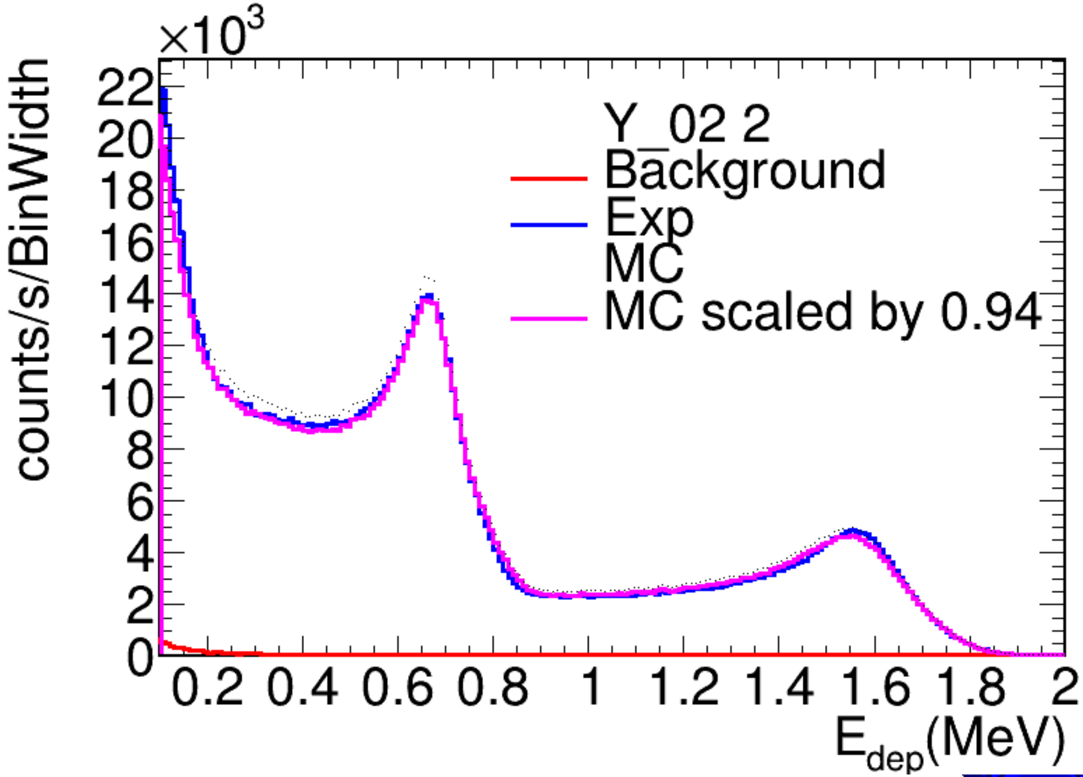
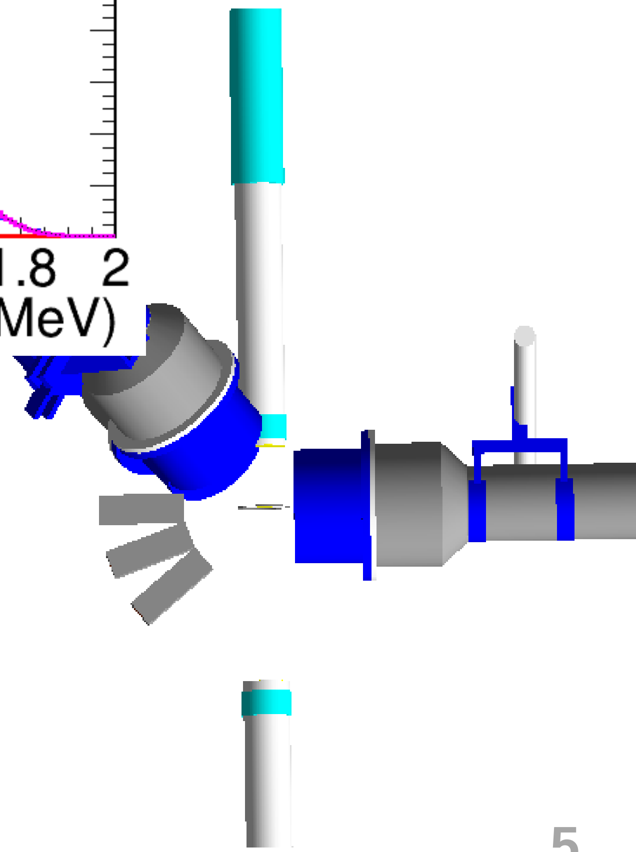
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

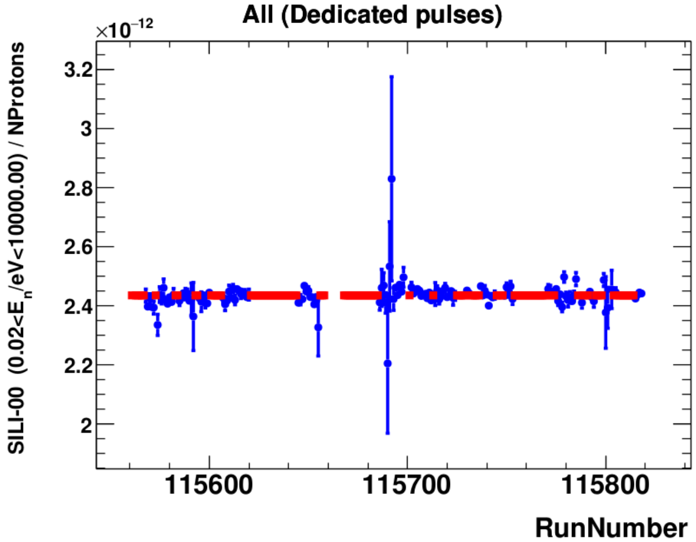
The n_TOF measurement at EAR1

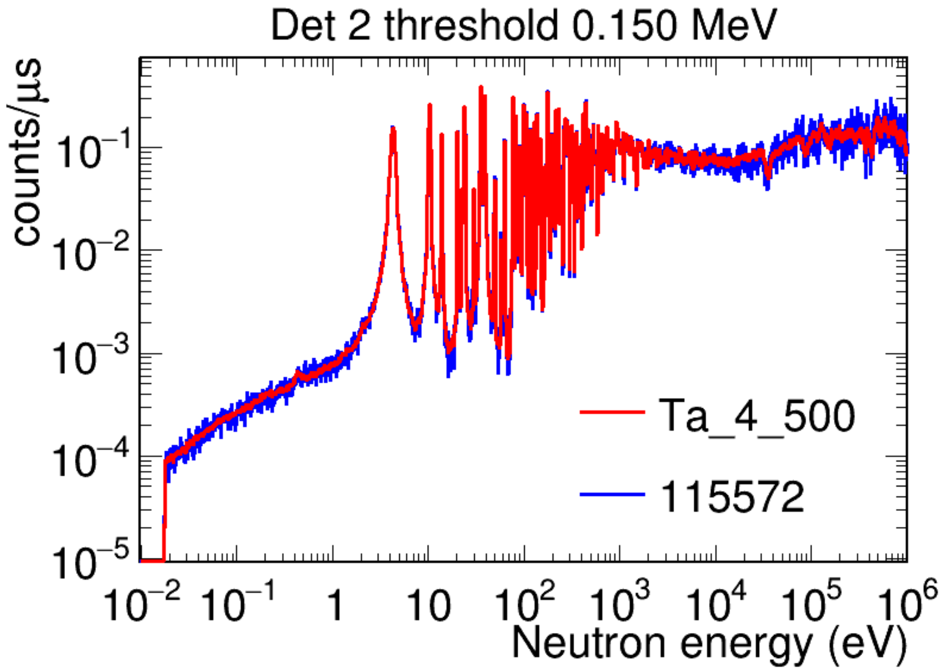


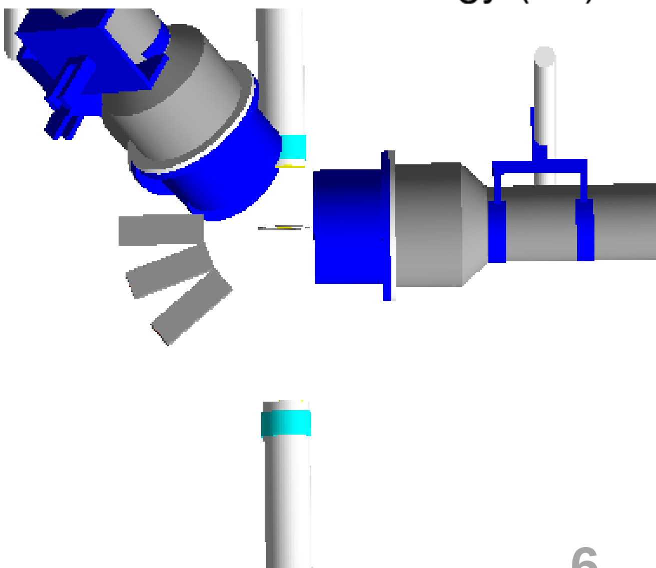


In the previous talk the following items were presented:
Calibration

The n_TOF measurement at EAR1



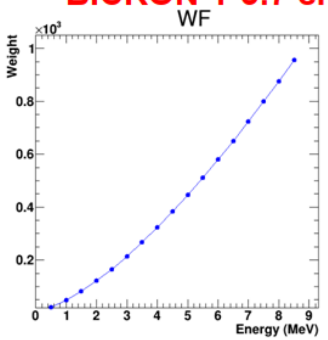




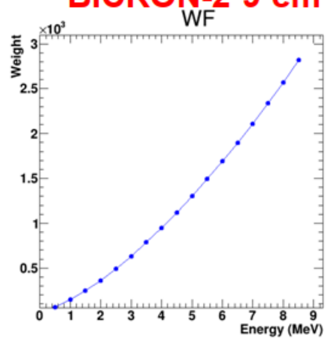
In the previous talk the following items were presented:
Calibration
Monitoring of the experiment

The n_TOF measurement at EAR1

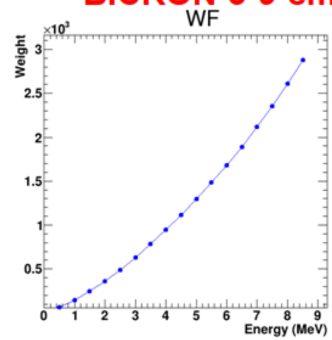
BICRON-1 3.7 cm



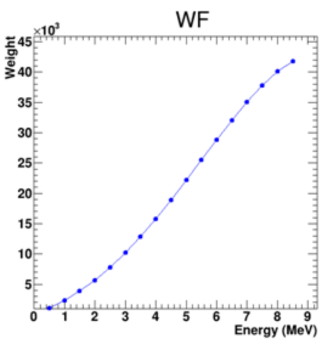
BICRON-2 9 cm



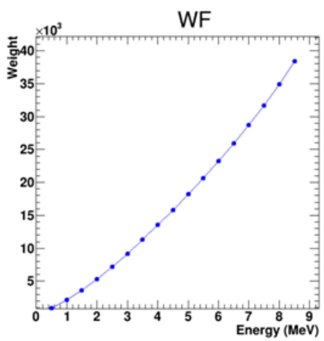
BICRON-3 9 cm



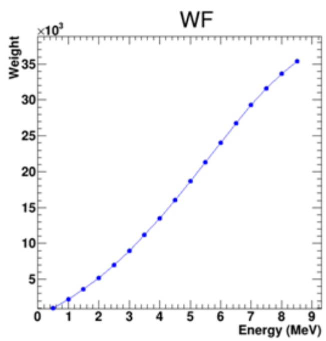
sTED 10 cm 90º



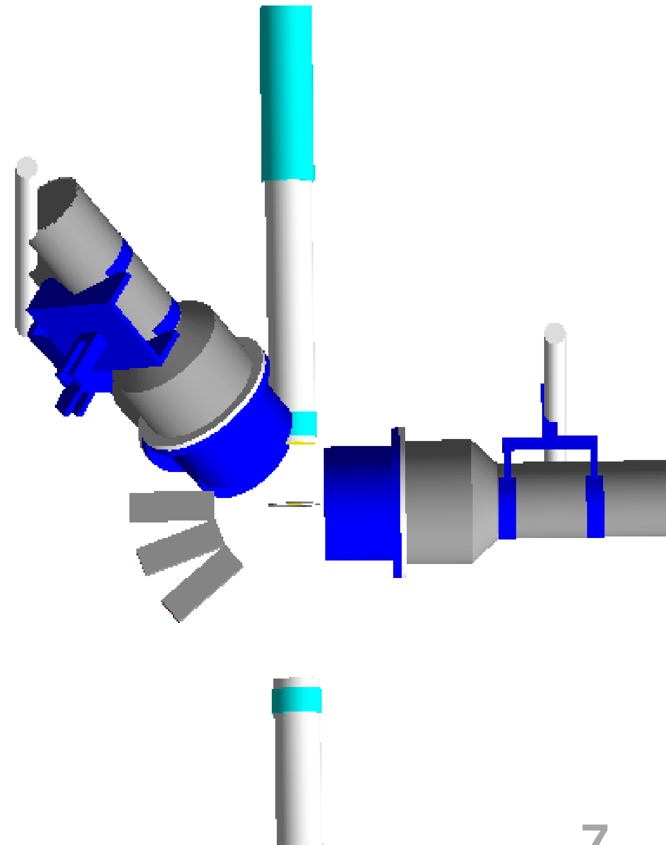
sTED 10 cm 110º



sTED 10 cm 130º



In the previous talk the following items were presented:
Calibration
Monitoring of the experiment
Preliminary WF
Preliminary Yield



The n_TOF measurement at EAR1

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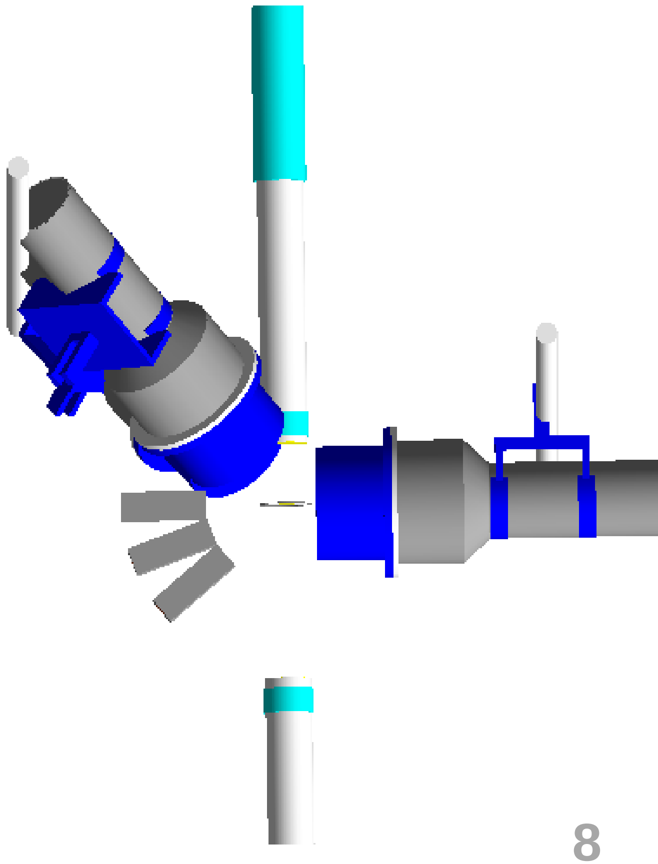
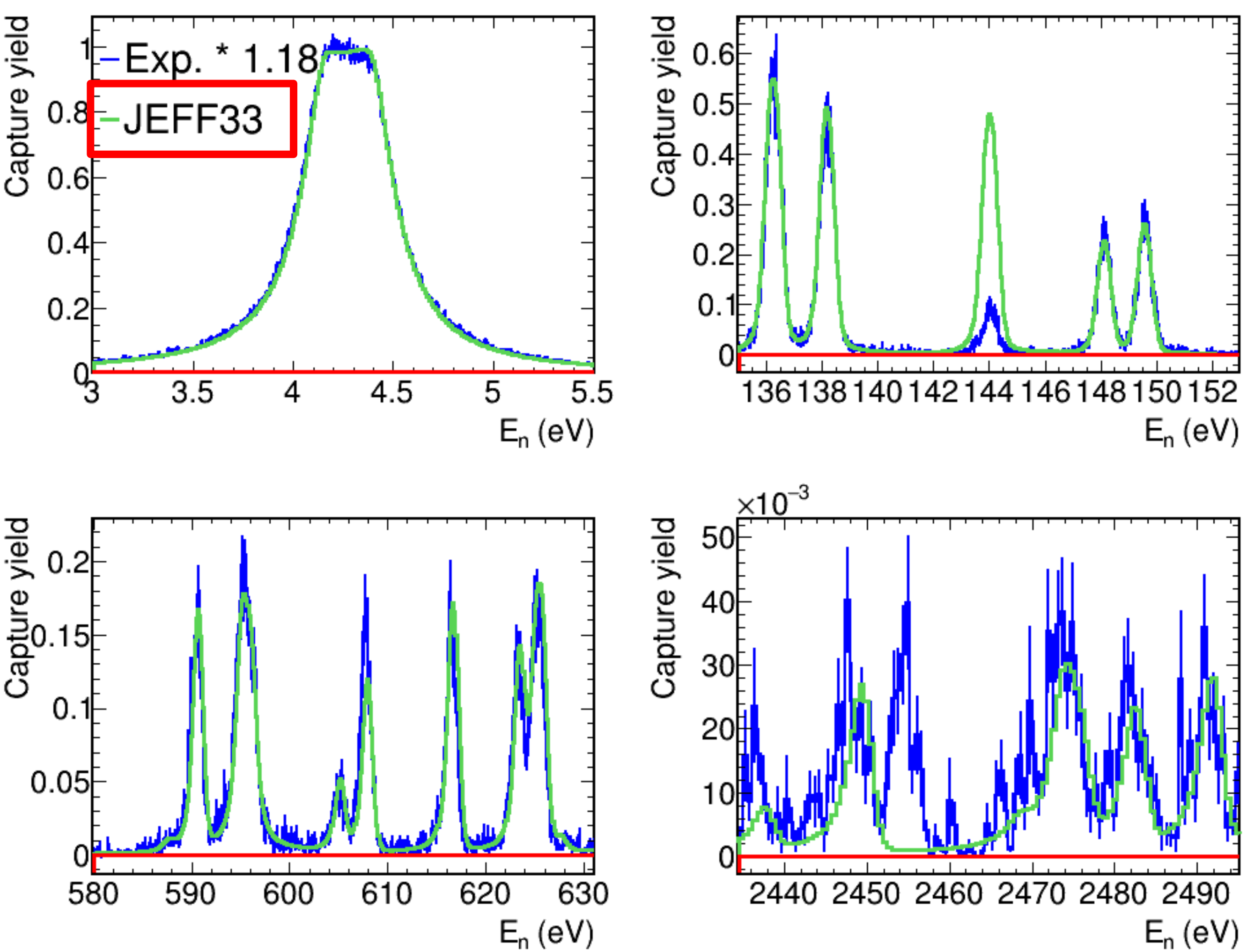
Preliminary WF

Preliminary Yield



Preliminary comparison for Ta-500 μm

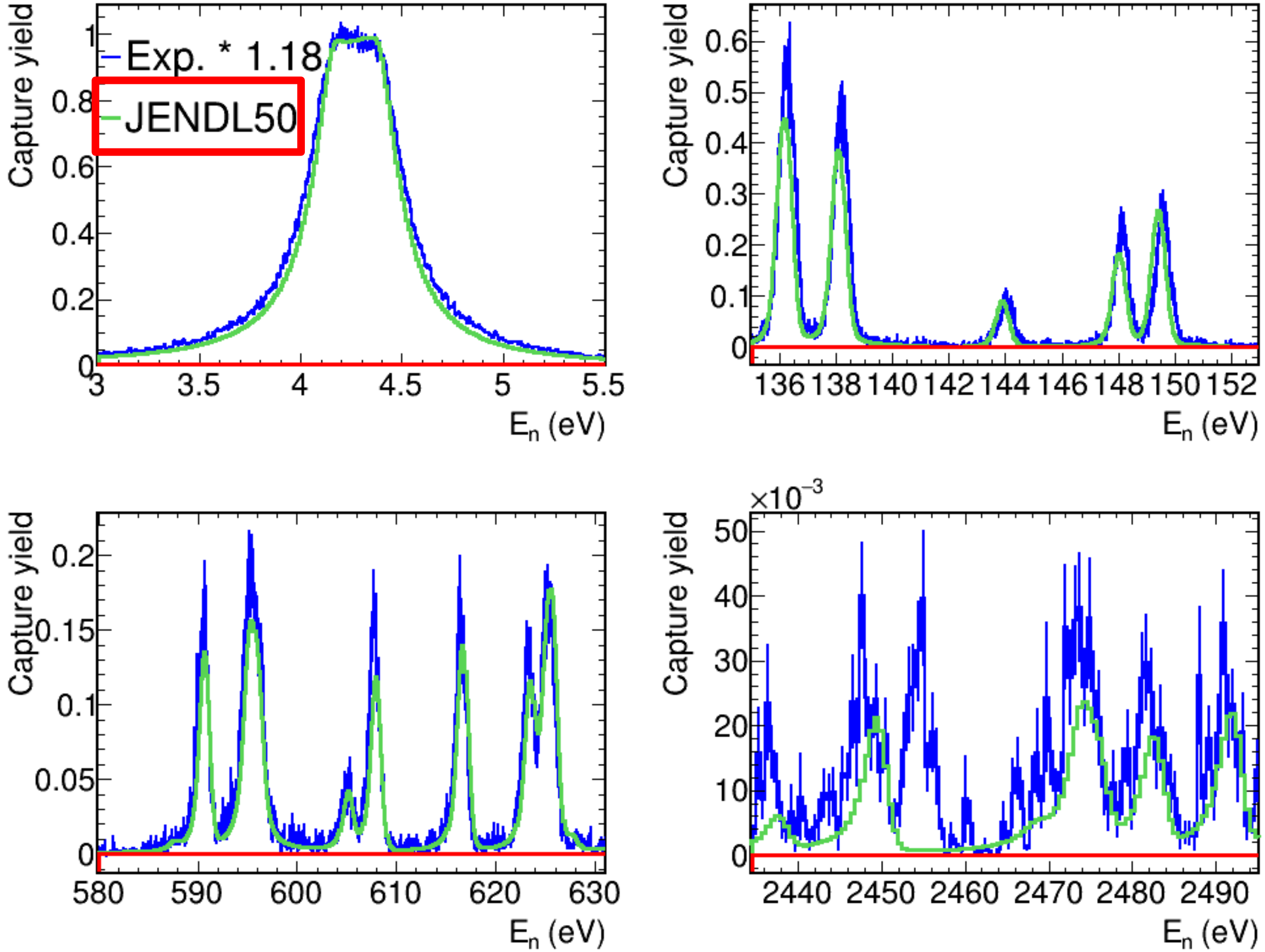
Yield of the Ta of 500 μm normalized to the first resonance



PRELIMINARY

Preliminary comparison for Ta-500 μm

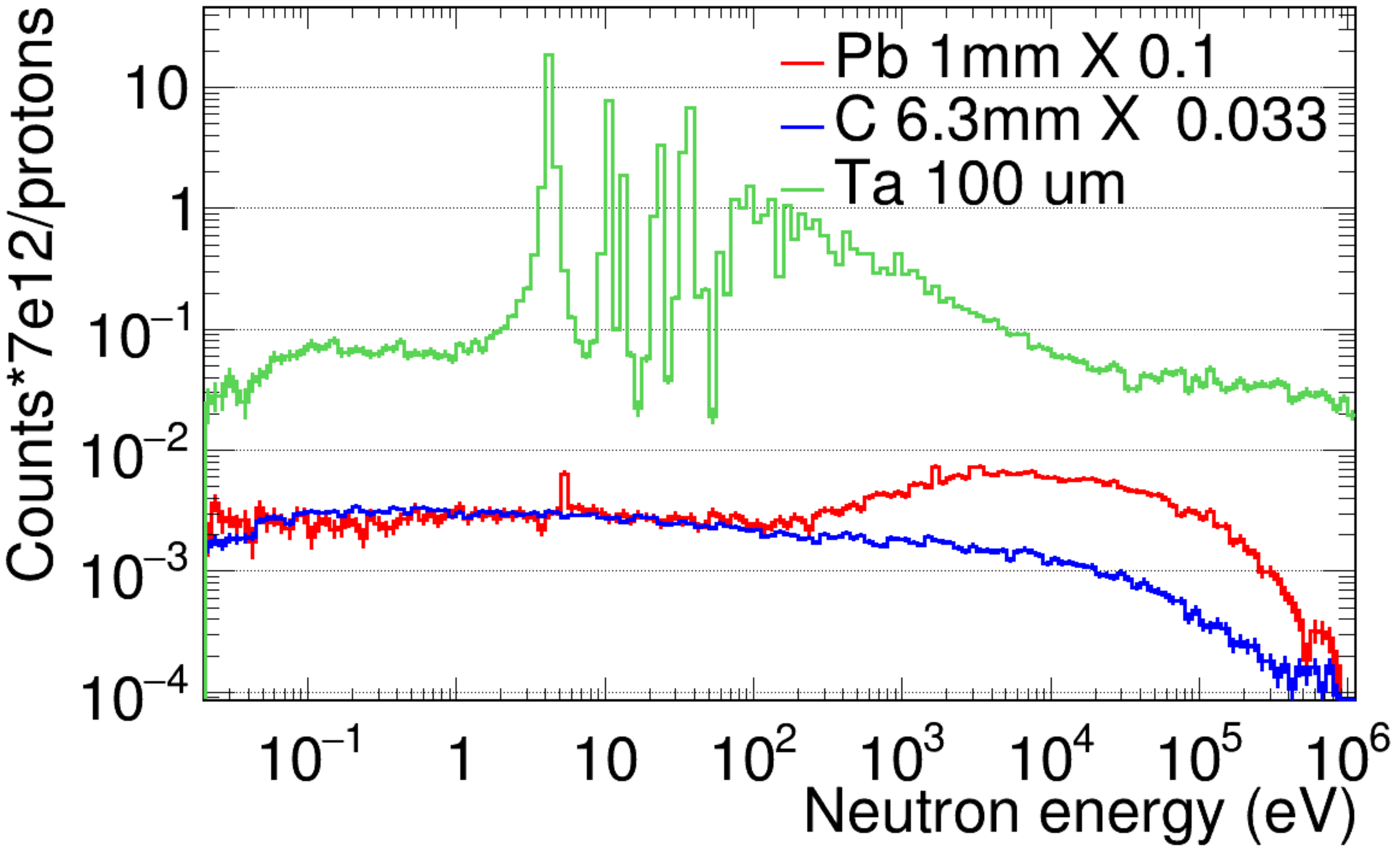
Yield of the Ta of 500 μm normalized to the first resonance



PRELIMINARY

Measurements with C and Lead

Measurements with Pb and C with background subtracted with a preliminary normalization to have an idea of the levels of background.

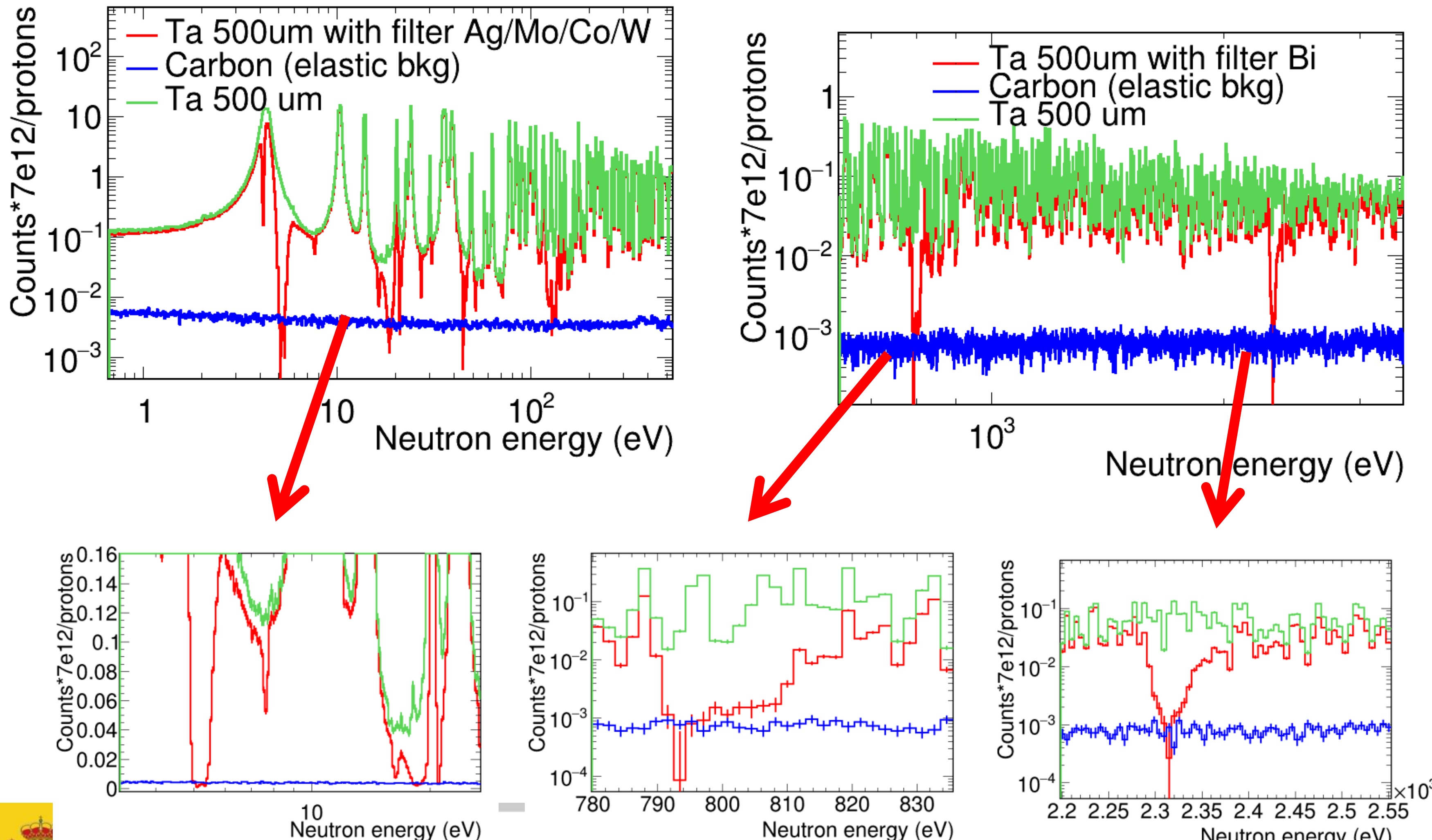


PRELIMINARY

Measurements with filters

PRELIMINARY

The measurements with filters are compared with the background estimated with the C sample. More corrections are needed.



Measurement of the $^{nat,166,167}Er(n,\gamma)$ cross-section at EAR1

V. Alcayne[1], S. Amaducci[2], J. Andrzejewski[3], D. Cano-Ott[1], A. Casanovas[4], D. M. Castelluccio[2,5], S. Cristallo[2,6], A. Gawlik-Ramiega[3], G. Gervino[2,7], G.Grasso[5], E. González-Romero[1], A. Guglielmelli[2,8], A. Manna[2,9], T. Martínez[1], C. Massimi[2,9], E. Mendoza[1], R. Mucciola[2,9], J. Perkowski[3], A. Sánchez-Caballero[1], P. Schillebeeckx[10] and D. Vescovi[11]

[1] Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain
[2] Nazionale di Fisica Nucleare, INFN, Italy
[3] University of Lodz, Poland
[4] Universitat Politècnica de Catalunya, Spain
[5] Agenzia per le Nuove Tecnologie, l'Energia e lo Sviluppo Economico Sostenibile, ENEA, Italy
[6] Istituto Nazionale di Astrofisica - Osservatorio Astronomico di Teramo, Italy
[7] Department of Physics, University of Torino, Italy
[8] European Commission, Joint Research Centre, Reactory Safey and Component Unit, Petten,Ispra, Italy
[9] Department of Physics and Astronomy, University of Bologna, Italy
[10] European Commission, Joint Research Centre, Geel, Belgium
[11] Goethe University Frankfurt, Germany

Motivations (Erbia vs Gadolinia)

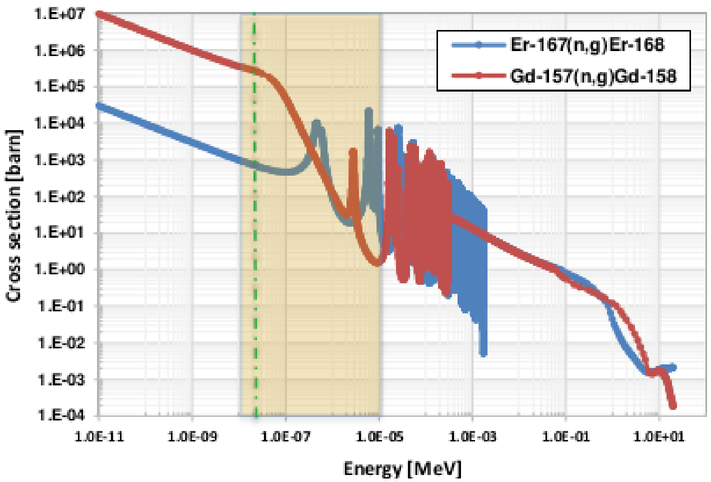
- Technical aspects:

– Lower thermal absorption cross sections (***Er: 162 b; Gd: 2.5E+05 b***) **not downgrade the power distribution**;

– More negative temperature feedback coefficient (***α=δk/δT***) **higher reactor core safety**;

– Higher and more energy extensive resonance integrals **better control of start-up and accidental transient phases**;

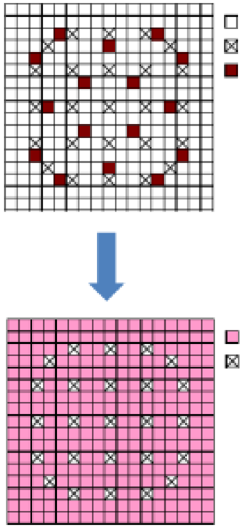
– Reduction of 239Pu in a EoL fuel core inventory **improvement of the non-proliferation actions.**

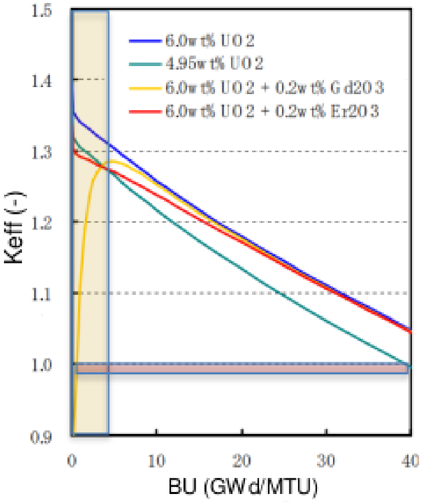


- Nuclear safety and economical aspects:

– Er-Super High Burnup fuel concept (BU>70 GWd/MTU, erbia>0.2 wt%, U-235> 5 wt%) was adopted in some exp. campaigns:

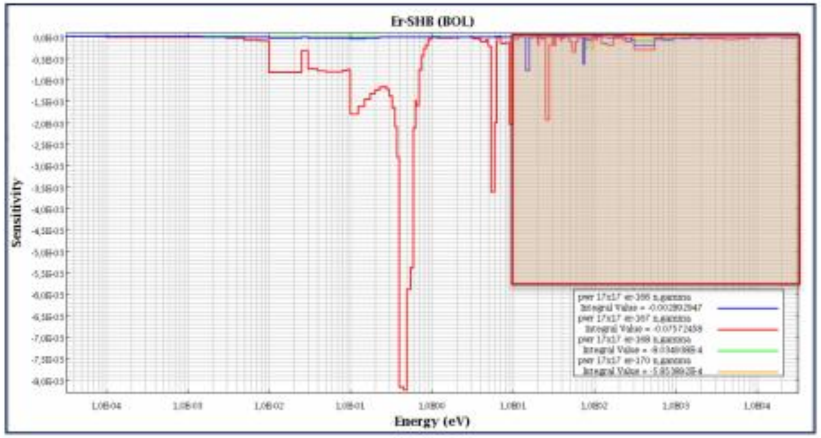
- Low content of Erbia is add into all UO2 (>5 wt%) powder just after the re-conversion process;
- Fuel enrichment is greater than 5 wt% but at BOL is equivalent to 5 wt%;
- Higher enriched fuel (HEU, enr > 5 wt%) can be handle within the existing fabrication facilities with **an improvement of the criticality safety** and a **global reduction of in-core the fuel cost**



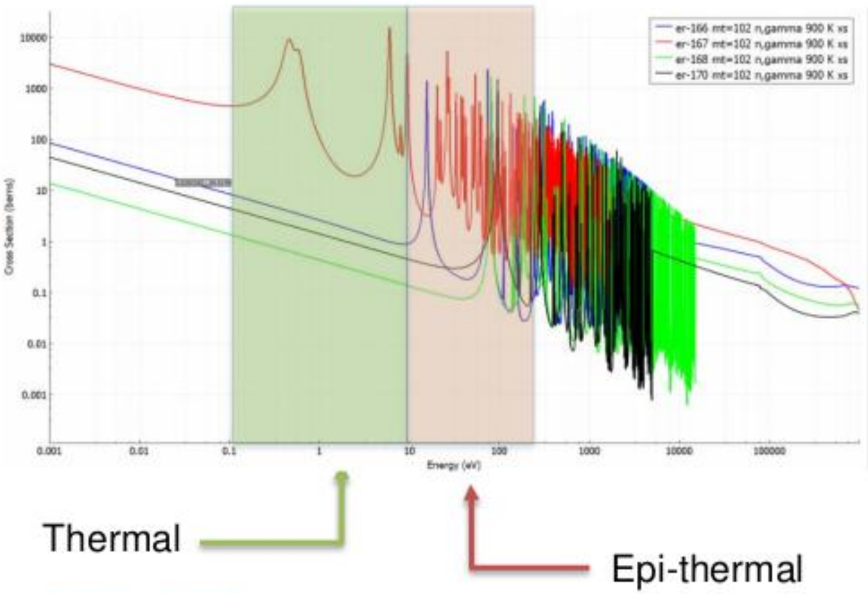


Slide by A. Guglielmelli

Er-SHB: S&U analysis – BOC



Isotope	Si (-)	Si/Si,tot (%)	Δk/k (-)	Δk (pcm)
(-)	E > 10 eV			
Er-166	-2.31E-03	80.0	1.38E-04	18
Er-167	-5.79E-03	7.0	7.08E-05	9
Er-168	-7.27E-04	90.5	7.67E-05	10
Er-170	-4.49E-04	76.7	5.37E-05	7

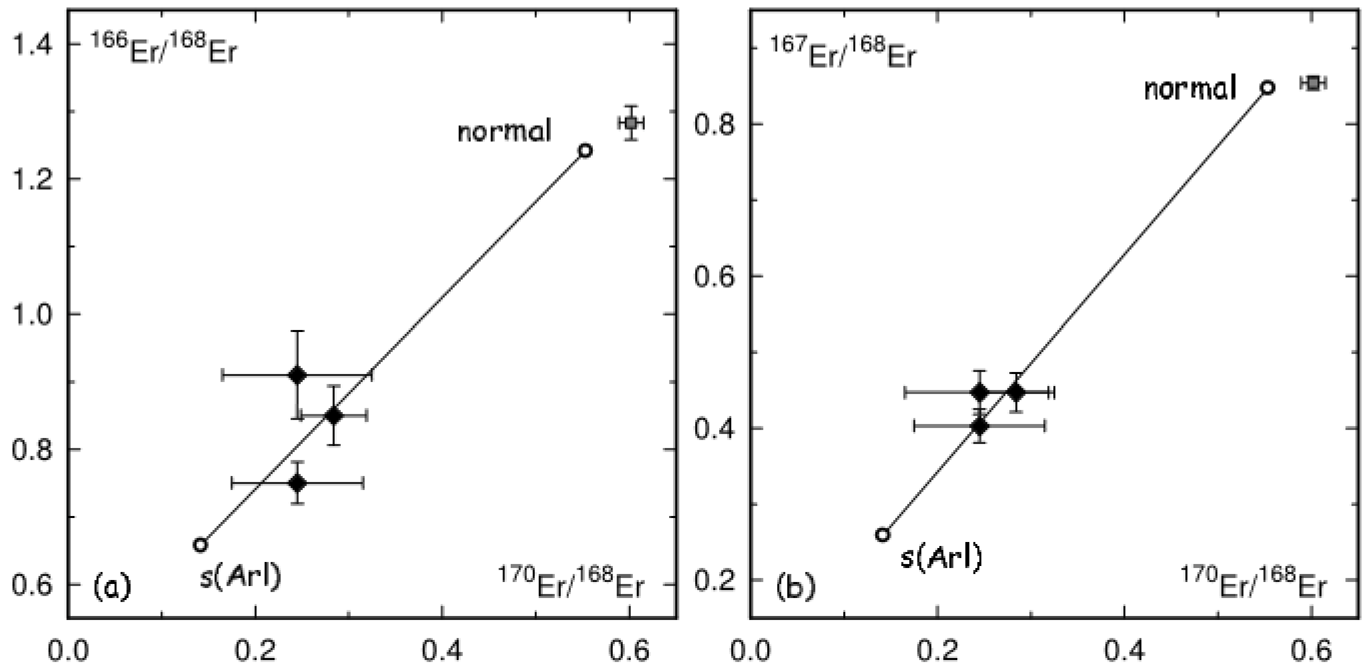


- Due to the overlapping of resonance of the Er-166,167,168,170 isotopes at energy higher than 10 eV, it's not possible to make a precise resonance shape analysis with natural erbium.
- Accurate contribution to criticality uncertainty of Er-166, Er-167, Er-168, Er-170 **for energy major than 10 eV** can be obtained only with Xs(n,g) measurements on single enriched isotopes.
- The sensitivity contribute to criticality uncertainty of Er-166, Er-168, Er-170 is equal to **45 pcm** (Cov. data: ENDF/B-VII.1).
- For core design purpose, any reduction of the criticality uncertainty is desirable.

Motivation astrophysics

Accurate cross section data on erbium isotopes could be of interest for the study of the s-process nucleosynthesis around the region of rare earth elements at A=160-170. For instance, the abundance of $^{166,167,168,170}Er$ isotopes in presolar silicon carbide grains was recently measured by Yin and collaborators.

The present overall disagreement between observed and calculated abundances clearly call for (n,γ) measurements of isotopes involved in this mass region



Slide by C. Massimi

https://iopscience.iop.org/article/10.1086/505188

Summary

- Erbia (Er_2O_3) can be considered as an **excellent alternative to burnable absorber** made of gadolinia (Gd_2O_3)

- There is a **new entry in the HPRL** to measure the capture C.S. of Er-167 between 0.01 and 100 eV with a 2% uncertainty.

Scientific motivations for a reassessment of the neutron capture cross sections of erbium isotopes in the high-sensitivity thermal energy range for LWR systems

A. Guglielmelli [a,c,*], F. Rocchi [a], C. Massimi [b,c], D.M. Castelluccio [a,c], A. Manna [b,c], R. Mucciola [d]

[a] ENEA, Italian National Agency for New Technologies, Energy and Sustainable Economic Development, Via Martiri di Monte Sole 4, 40129 Bologna, Italy
[b] Department of Physics and Astronomy, University Alma Mater Studiorum of Bologna, Via Irnerio 46, 40126 Bologna, Italy
[c] INFN, Italian National Institute of Nuclear Physics, Via Irnerio 46, 40126 Bologna, Italy
[d] INFN, Italian National Institute of Nuclear Physics, Via A. Pascoli 14, 06123 Perugia, Italy

https://doi.org/10.1016/j.anucene.2022.109337

Request ID	118		Type of the request	High Priority request	
Target	Reaction and process	Incident Energy	Secondary energy or angle	Target uncertainty	Covariance
68-ER-167	(n,g) SIG,RP	0.01 eV-100 eV		2	Y
Field	Subfield	Created date	Accepted date	Ongoing action	Archived Date
Fission	LWR, innovative fuel	09-JUL-21	30-AUG-21	Y	

https://www.oecd-nea.org/dbdata/hprl/hprlview.pl?ID=539

- It has been explored the criticality uncertainty contribute of **erbium isotopes at energy major than 10 eV for several reactor configuration.**

- The capture cross section of ^{166,167}Er are also important for astrophysics.

Previous measurements

The previous measurements used for the evaluations and the recent measurements are:

Enriched samples

Measurement	Energy range (eV)			
	^{166}Er	^{167}Er	^{168}Er	^{170}Er
Hopkins (1958)(Cap.)[9]	Thermal	Thermal	-	-
Møller (1960)(Tra.)[10]	-	0.4-0.6	-	-
Vertebnyi (1965)(Tra.)[11]	16	Thermal-30	-	95
Mughabghab (1967)(Tra.)[12]	Thermal-600	Thermal-150	Thermal-1.5e3	95
Liou (1972)(Cap./Tra.)[13]	15-1e4	0.4-1.7e3	80-1.5e4	95-2.4e4
Kahane (1984)(Cap.)[14]	-	5-600	-	-
Knopf (1996)(Tra.)[15]	Thermal	Thermal	Thermal	Thermal
Danon (1998)(Tra.)[16]	Thermal-15	Thermal-15	-	-
Harun (2000)(Tra.)[17]	-	1e4-9e4	-	-
Wang (2010)(Tra.)[18]	15-120	0.4-120	80	95
Li (2021)(Cap.)[19]	15-100	0.4-100	80	95

Natural samples

Evaluations

The uncertainty for ^{167}Er in the RRR is 2.3%, this value is questionable.

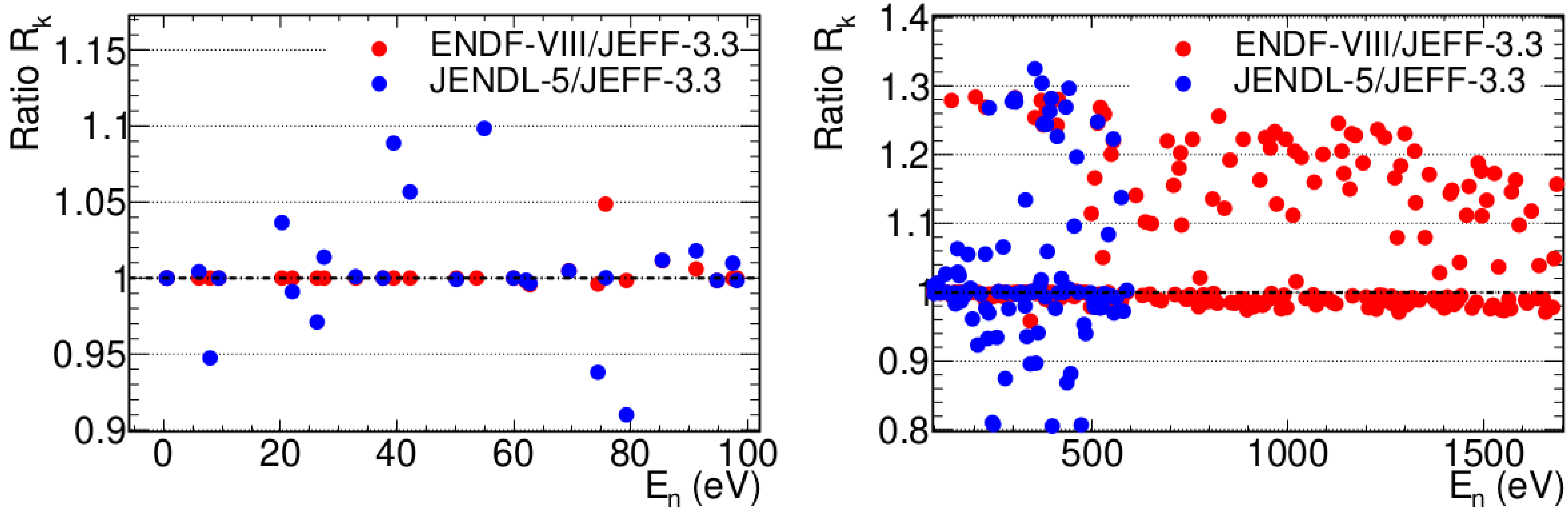


Figure 4: The ratios of the radiative kernels $(\Gamma_\gamma \cdot \Gamma_n/\Gamma)$ for the resonances of ^{167}Er for various libraries JEFF-3.3 [20], JENDL-5 [21] and ENDF-VIII [22].

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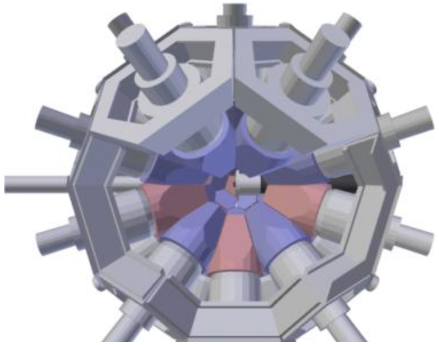
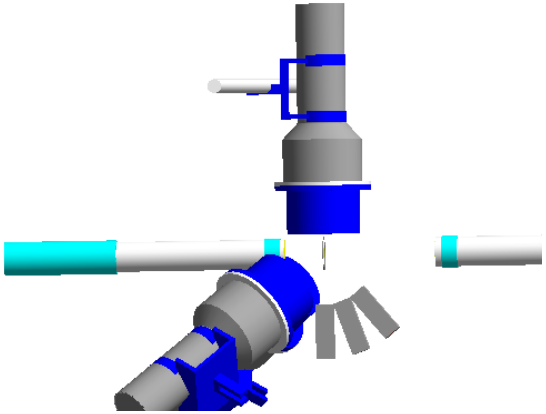
ENEA Agenzia nazionale per le nuove tecnologie, l'energia e lo sviluppo economico sostenibile

INFN

Summary of the Er campaign at n_TOF

- A measurement with a **natural Er sample using the C_6D_6 and the TAC** is proposed to fulfill the HPRL requirements between 0.01 and 50 eV.





Sample	Mass	Detector	Energy range	Number protons
Natural	30mg	TAC	0.01-50 eV	$1.0 \cdot 10^{18}$
Natural	30mg	C_6D_6	0.01-50 eV	$1.5 \cdot 10^{18}$
^{166}Er	200mg	C_6D_6	10 eV-100 keV	$1.0 \cdot 10^{18}$
^{167}Er	200mg	C_6D_6	50 eV-500 keV	$1.0 \cdot 10^{18}$
TAC auxiliary and normalization measurements				$0.5 \cdot 10^{18}$
C_6D_6 auxiliary and normalization measurements				$1.0 \cdot 10^{18}$
Total				$6.0 \cdot 10^{18}$

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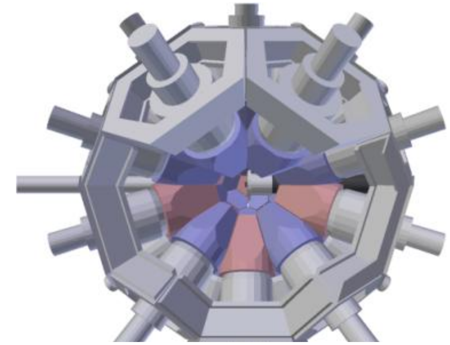

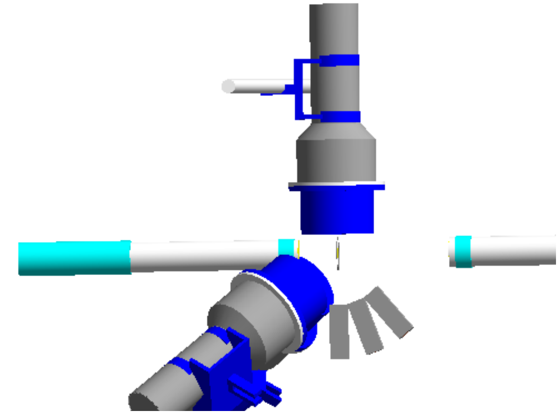

Measurement performed in 2023 →

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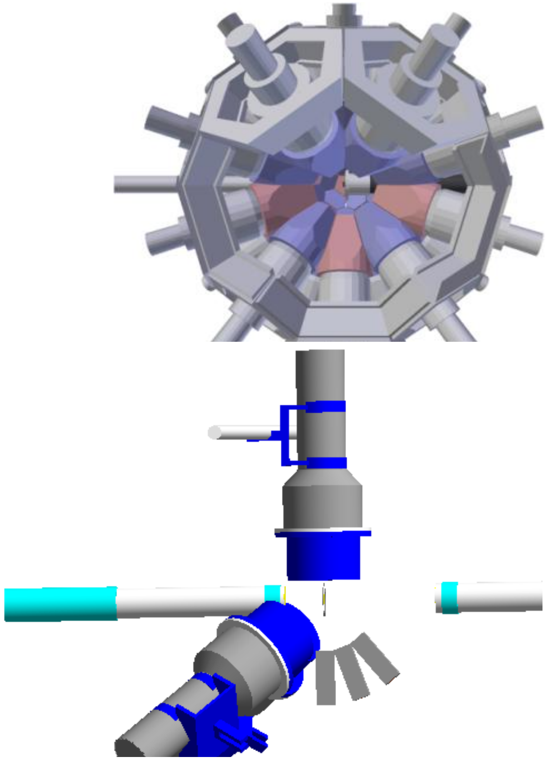
- A measurement with a **natural Er sample using the C_6D_6 and the TAC** is proposed to fulfill the HPRL requirements between 0.01 and 50 eV.

- **Measurements with ~200 mg enriched samples of ^{166,167}Er** with C_6D_6 are also proposed to extend the energy range and to perform the correct resonance assignment.



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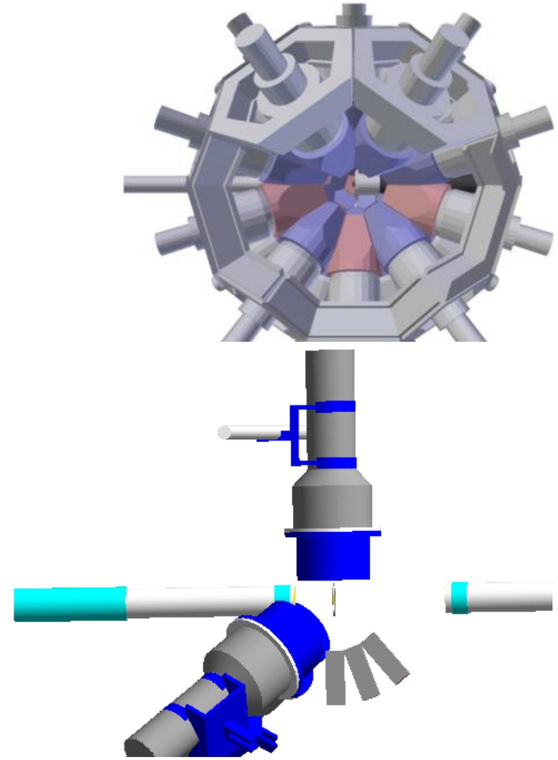

Measurement performed in 2023 →

Plan to perform the measurements in 2024 →

Sample	Mass	Detector	Energy range	Number protons
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Natural	30mg	C_6D_6	0.01-50 eV	$1.5 \cdot 10^{18}$
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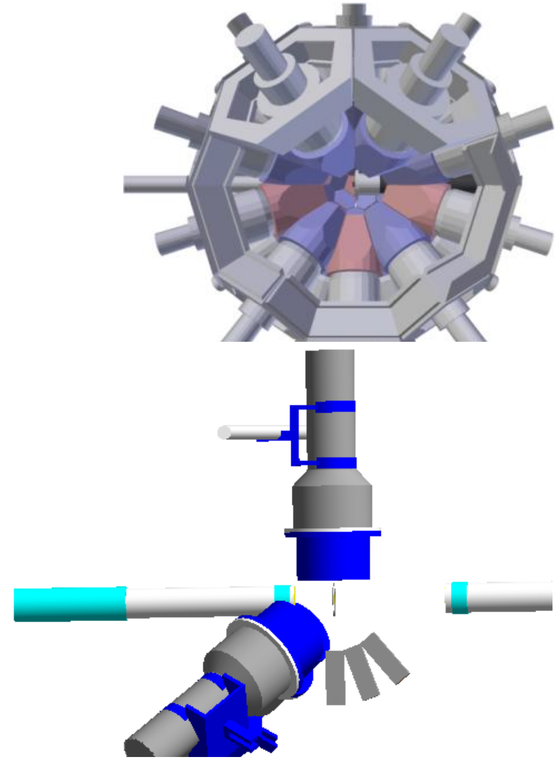
^{167}Er	200mg	C_6D_6	50 eV-500 keV	$1.0 \cdot 10^{18}$
TAC auxiliary and normalization measurements				$0.5 \cdot 10^{18}$
C_6D_6 auxiliary and normalization measurements				$1.0 \cdot 10^{18}$
Total				$6.0 \cdot 10^{18}$

Summary of the Er campaign at n_TOF

- A measurement with a **natural Er sample using the C_6D_6 and the TAC** is proposed to fulfill the HPRL requirements between 0.01 and 50 eV.

- **Measurements with ~200 mg enriched samples of ^{166,167}Er** with C_6D_6 are also proposed to extend the energy range and to perform the correct resonance assignment.

- The work of I. Knapova et al, would be considered for the PSF, spin assignment and the 109 ns isomer state.



Measurement performed in 2023 →

Plan to perform the measurements in 2024 →

Sample	Mass	Detector	Energy range	Number protons
Natural	30mg	TAC	0.01-50 eV	$1.0 \cdot 10^{18}$
Natural	30mg	C_6D_6	0.01-50 eV	$1.5 \cdot 10^{18}$
^{166}Er	200mg	C_6D_6	10 eV-100 keV	$1.0 \cdot 10^{18}$
^{167}Er	200mg	C_6D_6	50 eV-500 keV	$1.0 \cdot 10^{18}$
TAC auxiliary and normalization measurements				$0.5 \cdot 10^{18}$
C_6D_6 auxiliary and normalization measurements				$1.0 \cdot 10^{18}$
Total				$6.0 \cdot 10^{18}$

The natural Er measurement with C_6D_6

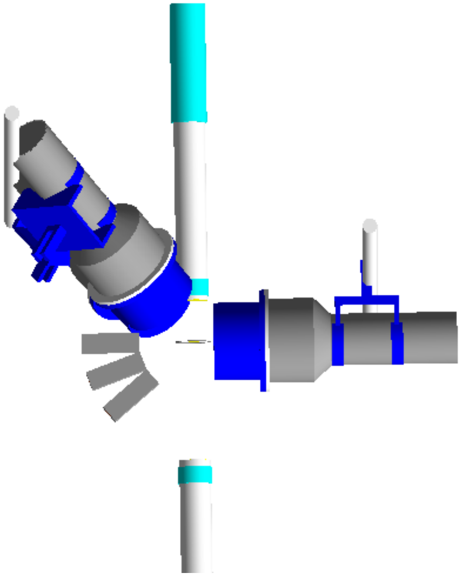
Two samples of Er (99% pure) of 2 cm diameter. One of 25 μm to obtain the capture cross section and another of 1000 μm to self-normalize the measurement.

The setup is the same as in the Ta campaign:

- 1 BICRON at 3.7 cm at 90º with respect to the beam.
- 2 BICRON at 9.0 cm at 125º with respect to the beam.
- 3 sTED at 10 cm at 90º, 110º, 130º with respect to the beam.

The same energy calibration, WF, Backgrounds, etc than in the Ta campaign would be used.

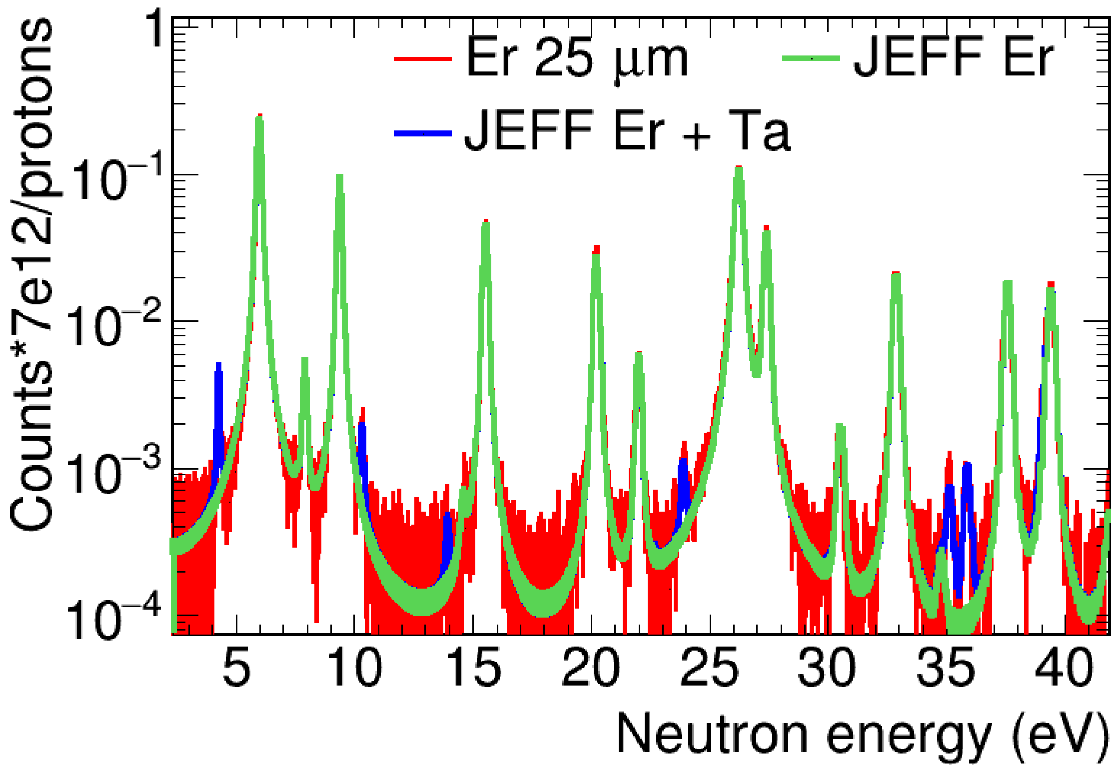
	Estimated protons(10^{17})	On target protons(10^{17})	Percentage
Empty	3.5	3.6	102
Carbon-2cm-6350um	1	1.1	108
Au-2 cm - 200 um	3	2.7	91
Lead-2cm-1000um	1	1.1	105
Au-1 cm	1	0.8	76
Carbon-2cm-6350um	1	1.1	108
Er-2 cm-25 um	10	9.6	96
Er-2 cm-1000um	2	2.5	125
Total protons used	22.5	22.4	108



Preliminary results of natural Er

It has been found in the samples a contaminant of Tantalum of ~0.5%, it is not a problem for the analysis of the capture cross section of Er-167. Already the producer mention that it was possible to have Ta in the Er samples.

In **Blue** the resonances associated to Tantalum are presented



Preliminary results of natural Er

It has been found in the samples a contaminant of Tantalum of ~0.5%, it is not a problem for the analysis of the capture cross section of Er-167. Already the producer mention that it was possible to have Ta in the Er samples.

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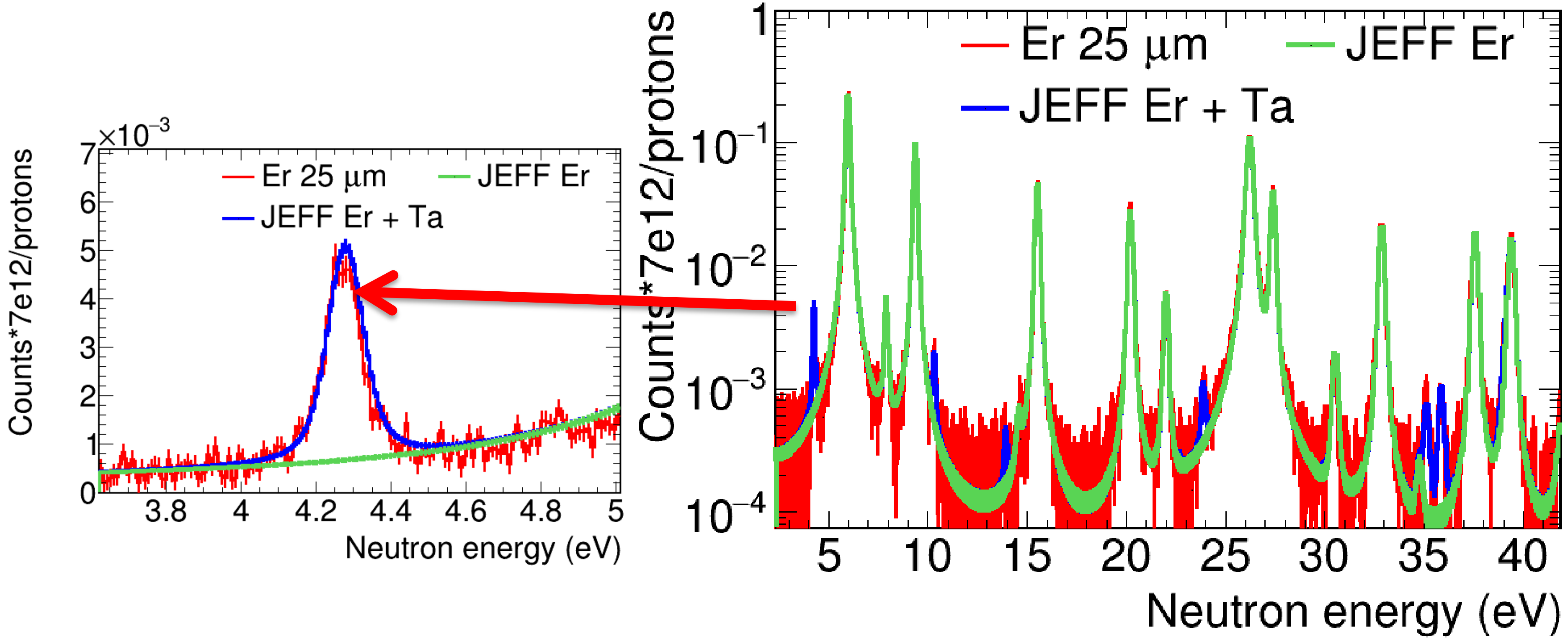
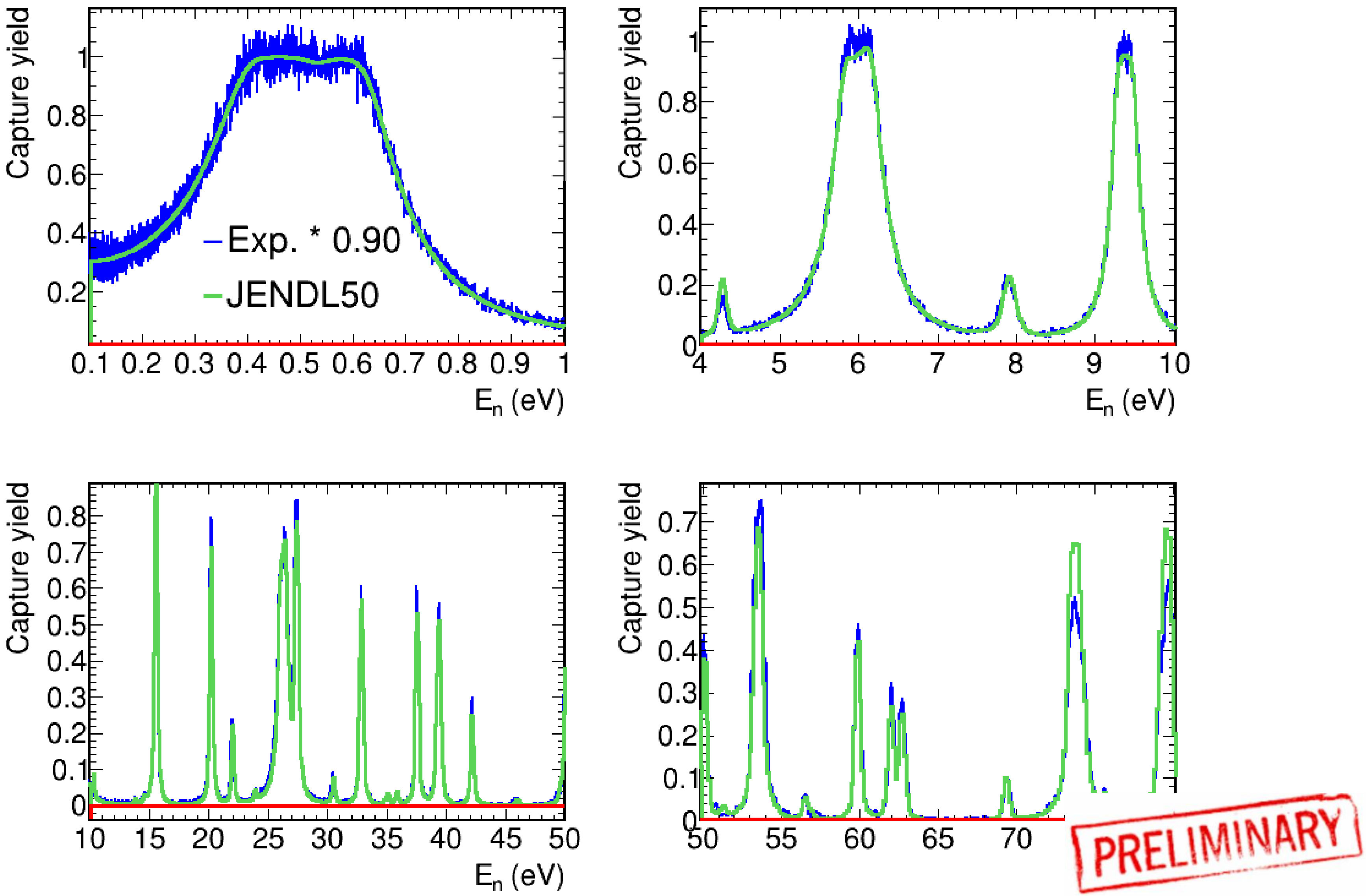


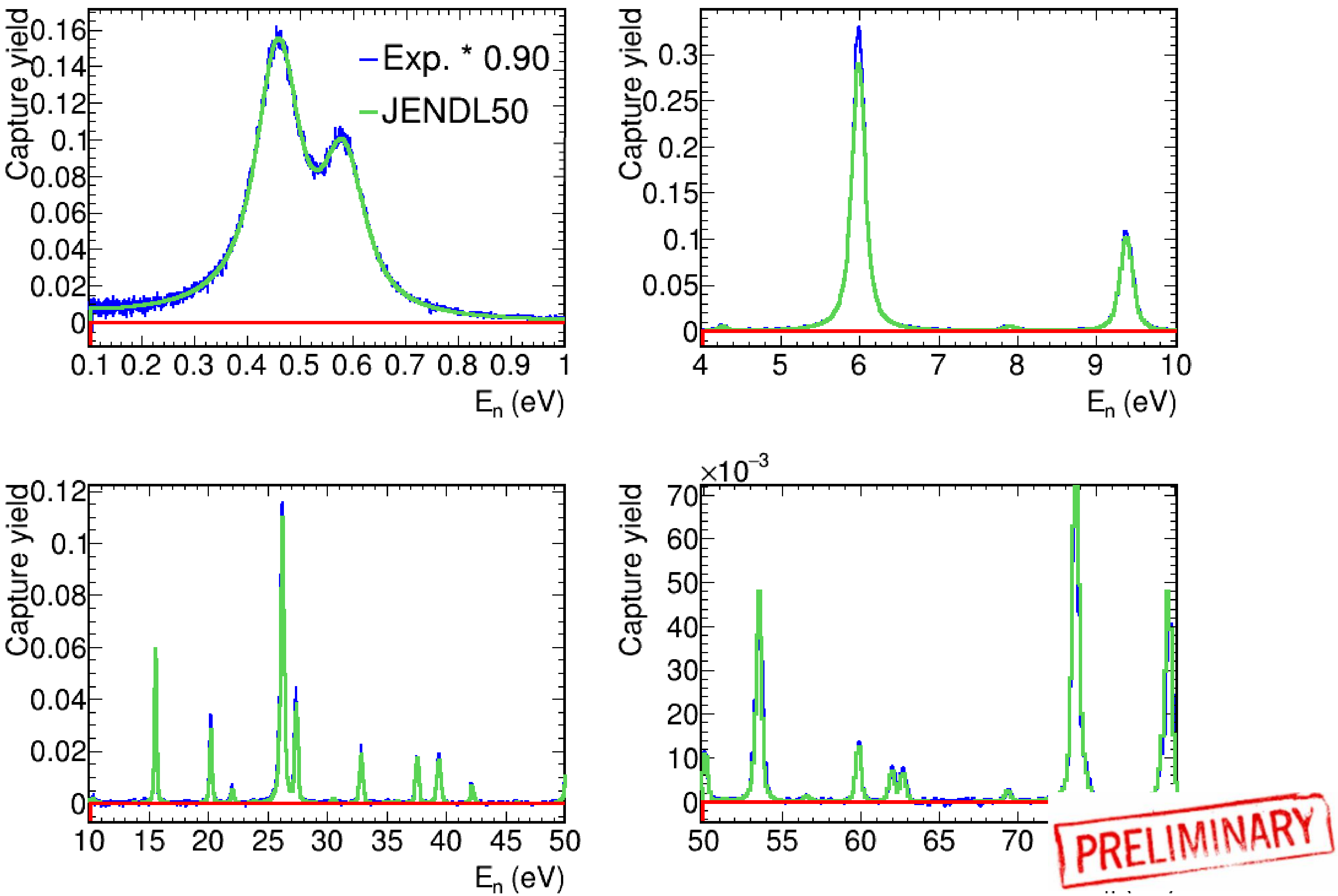
Natural Er sample 1 mm

The experimental compared with the yield obtained with SAMMY and JENDL-5.0 normalized to the first resonances.

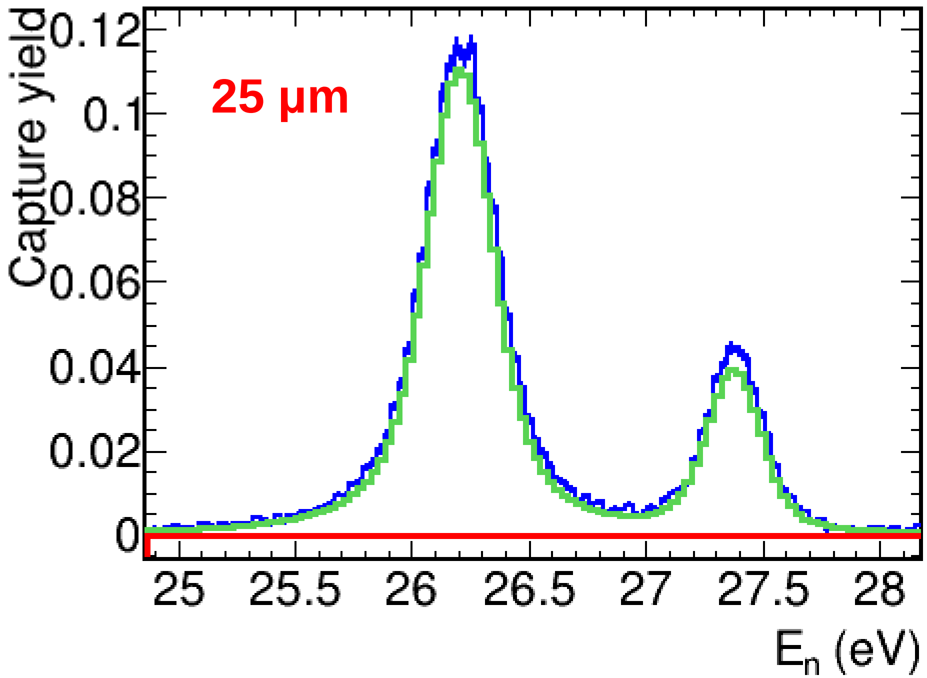


Natural Er sample 25 μm

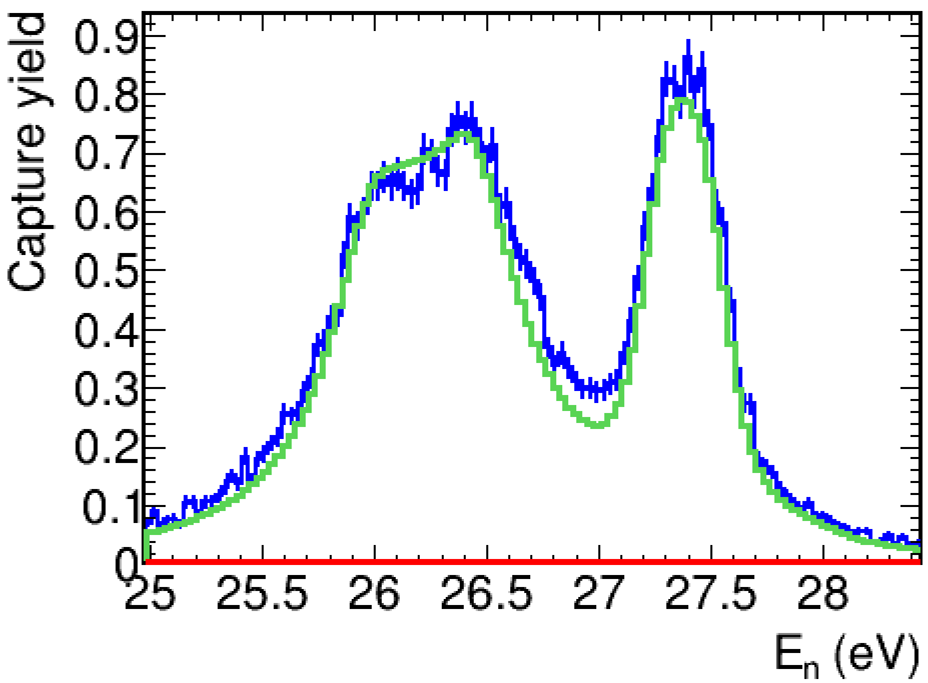
The experimental compared with the yield obtained with SAMMY and JENDL-5.0 normalized to the first resonances.



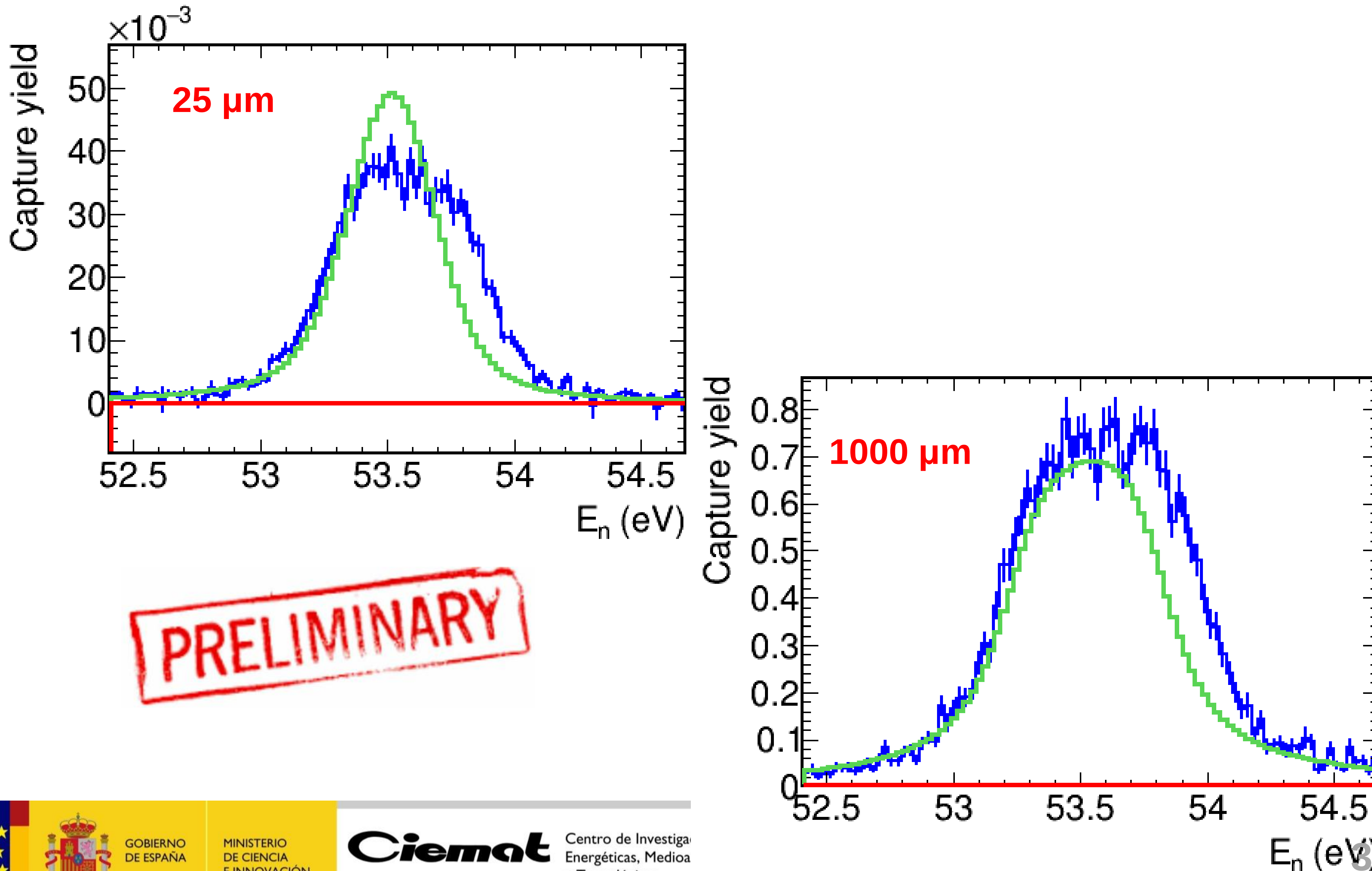
Resonances at 25 eV



PRELIMINARY



Differences in the resonance at 50 eV



The measurement with enriched samples

The idea is to do the measurement with enriched samples of ^{166,167}Er in 2024.

We already have the final quotation for the sample and we would start the purchase process this week.

ISOFLEX USA
Isotopes for Science, Medicine and Industry

P.O. Box 29475
San Francisco CA 94129 USA
Tel: 415-440-4433 Fax: 415-563-4433
Email: info@isoflex.com.ru
iusa@isoflex.com
FEIN: 20-8066748

QUOTATION

Confidential Business Matter
DATE: November 14, 2023
QUOTE NUMBER: 231114-I
SELLER CONTACT: Allan Pashkovski

BUYER:
Att: Dr. Victor Alcayne Aicua
victor.alcayne.aicua@cern.ch
CERN
Espl. des Particules 1
Meyren GENEVA 1211
Switzerland

CONSIGNEE / SHIP TO:
TBD

QUOTATION SUMMARY

DESCRIPTION	PROPOSED DELIVERY	QUANTITY	UNIT PRICE	SUBTOTAL
Er-166 in oxide form with I.E. 98,1atom%	6-8 weeks ARO	200 mg	US$5.60/ mg	US$1,120.00
Er-167 in oxide form with I.E. 96,3atom%	1-2 weeks ARO	200 mg	US$5.90/ mg	US$1,180.00

Bank details: Bank Name: Comerica Bank, Bank Address: 2001 Union Street, San Francisco, CA 94123, USA
SWIFT Code: MNBDUS33 For credit to Acct. # 1895755195 For benefit of: ISOFLEX USA

Subtotal: US$2,300.00
Shipping, Handling and Insurance: US$250.00

Notes: ARO = After Receipt of Order
We Accept VISA
TOTAL (USD) at CIP terms: US$2,550.00

Isotopic Distribution

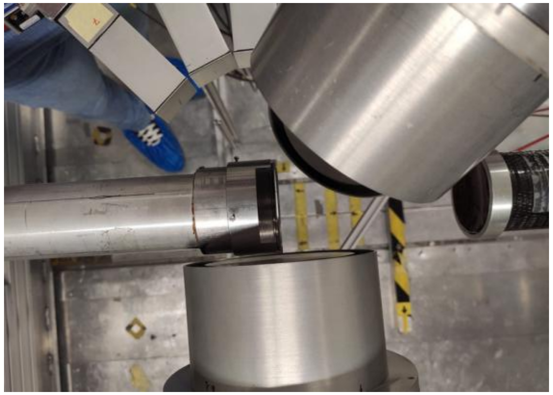
ISOTOPE	Er-162	Er-164	Er-166	Er-167	Er-168	Er-170
CONTENT (%)	<0.01	0.02	98.10(±0.10	1.33	0.45	0.10

Isotopic Distribution

ISOTOPE	Er-162	Er-164	Er-166	Er-167	Er-168	Er-170
CONTENT (%)	<0.01	0.01	0.96	96.30(±0.10)	2.57	0.16

The money to purchase the samples is already transfer to CERN from INFN-Bologna.

Similar setup to the Natural Er one.



Proposal number: 101164596

Proposal acronym: APRENDE

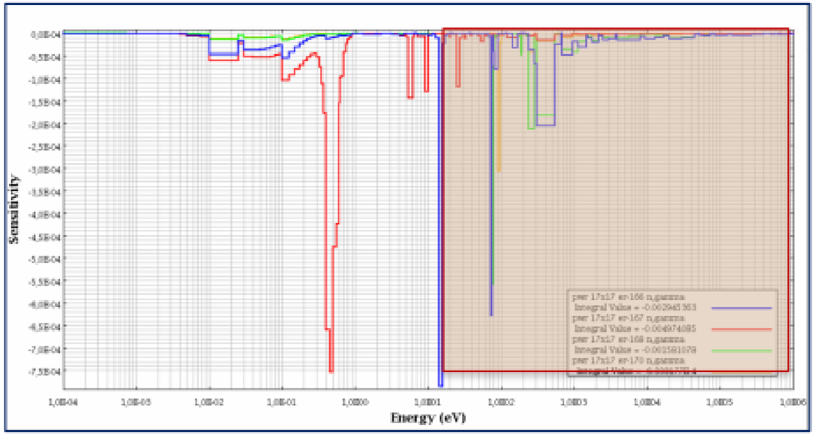
This work is part of APRENDE:

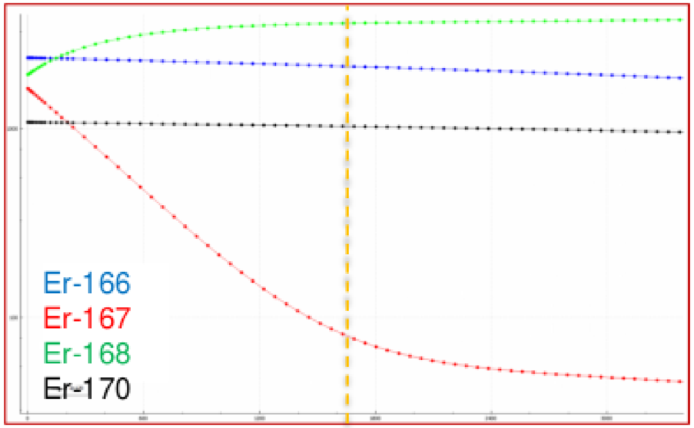
- 1 postdoc for ^{166}Er from Bologna
- 1 postdoc for ^{167}Er from CIEMAT

Back-up slides

Er-SHB: S&U analysis – EOC

- S&U analysis of the Er Xs(n,g) at high burnup (i.e., 60 GWd/MTU) on a Er-SHB FA system:
  1. The nuclide BU-related inventory was evaluated with the T-DEPL module of SCALE 6.2.3;
  2. The inventory of the most important isotopes for criticality (i.e., Ag, Am, Cm, Cs, Er, Eu, Gd, Mo, Nd, O, Pu, Rh, Ru, Sm, Tc, U) was imported in TSUNAMI-2D to perform a S&U analysis.





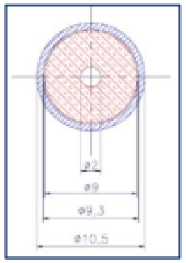
Isotope	Si (-)	Si/Si,tot (%)	Δk/k (-)	Δk (pcm)
(-)	E > 10 eV			
Er-166	-2.28E-03	77.5	1.38E-04	15
Er-167	-3,13E-04	6.3	7.08E-05	0
Er-168	-1.40E-03	88.4	7.67E-05	17
Er-170	-4.68E-04	73.9	5.37E-05	6

- Due to the spectrum hardening the relative weight of the erbium 166,168,170 isotopes sensitivity increase at higher energy;
- Due to the low content of Er-167 **the major contributor to uncertainty are Er-166 and Er-168**;
- The overall contribute to criticality uncertainty of Er-166, Er-168, Er-170 at E > 10 eV is equal to **38 pcm** (Cov. data: ENDF/B-VII.1).
- In order to have a precise assessment of the IBA reactivity penalty, any reduction of the criticality uncertainty at EOC is desirable

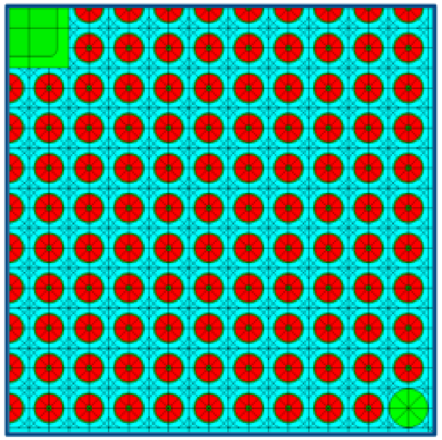
Slide by A. Guglielmelli

LFR-MOX: Design

- Research on the field of GEN IV LFR Reactor involves the use of MOX fuel in order to **[1]**:



  1. convert the uranium stored in Spent Nuclear Fuel (SNF) into fissile fuel;
  2. Burn the minor actinides (i.e, Np, Am, Cm, Cf) in SNF of LWR;

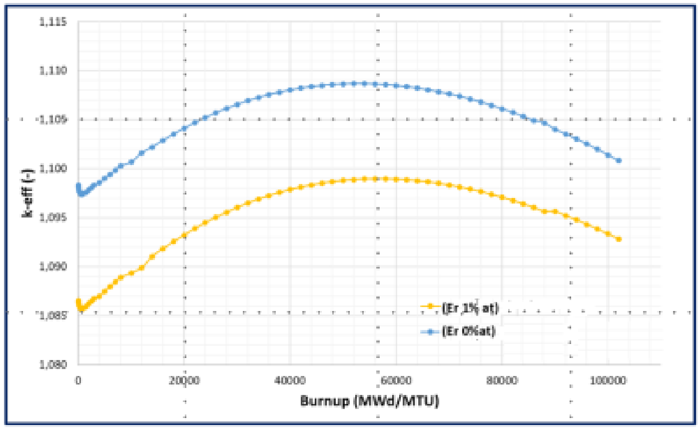


- S&U analysis on the LFR European conceptual design (**ELSY**):
  1. The ELSY open square design (ENEA) was chosen;
  2. S&U at BOC with and without Erbia as IBA was performed with TSUNAMI-2D.

0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,01
0,01	0,01	0,00	0,00	0,00	0,00	0,00	0,00	0,01
0,00	0,00	0,01	0,01	0,00	0,00	0,00	-0,01	0,00
0,00	0,00	0,01	0,00	0,00	0,00	0,00	0,00	0,00
0,00	0,00	0,00	0,00	0,00	-0,01	0,00	0,00	0,00
0,00	0,00	0,00	0,00	-0,01	0,00	-0,01	0,00	0,00
0,00	0,00	0,00	0,00	0,00	-0,01	0,00	-0,01	-0,01
0,00	0,00	-0,01	0,00	0,00	0,00	-0,01	0,00	0,00
0,01	0,01	0,00	0,00	0,00	0,00	-0,01	0,00	0,02

Very slight erbia content reduction during the fuel cycle

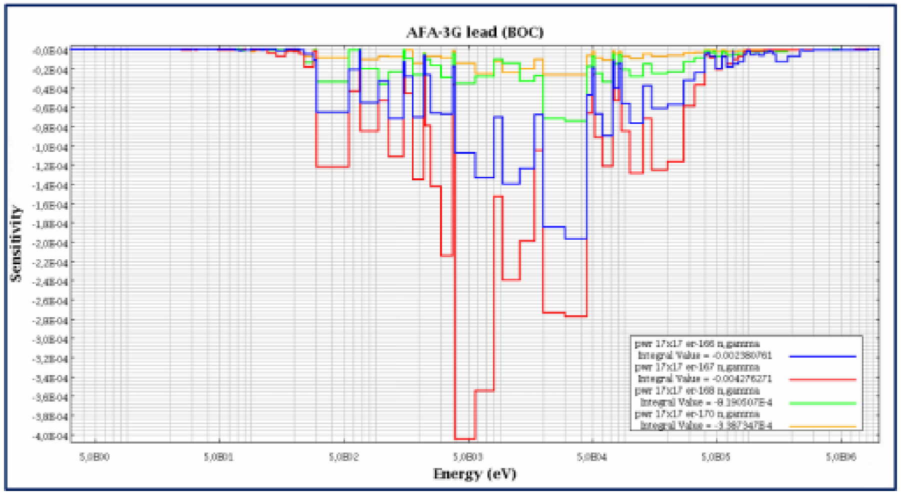
Very slight relative power distribution impact

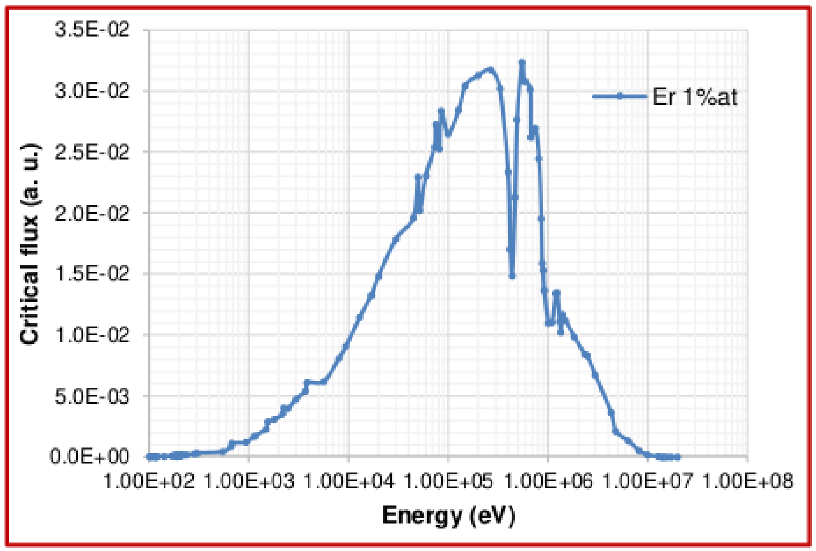


[1] M. Ibrahim et al, Neutronic performance analysis of MOX fuel with different candidate austenitic stainless-steel cladding in ALFRED reactor

Slide by A. Guglielmelli

LFR-MOX FA: S&U analysis – BOC





Covariance matrix				
nuclide-reaction with nuclide-reaction (-)				delta-k/k (%)
u-238	n,n'	u-238	n,n'	1,01E+00
u-238	n,gamma	u-238	n,gamma	4,02E-01
pu-239	n,gamma	pu-239	n,gamma	3,25E-01
pu-239	fission	pu-239	fission	2,16E-01
o-16	elastic	o-16	elastic	1,99E-01
pb-207	n,n'	pb-207	n,n'	1,87E-01
pu-239	chi	pu-239	chi	1,69E-01
pb-206	n,n'	pb-206	n,n'	1,47E-01
pu-241	chi	pu-241	chi	1,43E-01
u-238	nubar	u-238	nubar	1,37E-01
pu-239	n,n'	pu-239	n,n'	1,11E-01
u-238	chi	u-238	chi	1,07E-01
u-238	n,n'	u-238	elastic	-9,83E-02
pb-208	n,n'	pb-208	n,n'	8,90E-02
pu-239	nubar	pu-239	nubar	6,71E-02
pu-241	n,gamma	pu-241	n,gamma	6,49E-02
pu-241	fission	pu-241	fission	6,02E-02
zr-90	n,gamma	zr-90	n,gamma	5,91E-02
pu-240	n,gamma	pu-240	n,gamma	5,32E-02
pu-239	fission	u-238	fission	5,14E-02
pu-240	chi	pu-240	chi	4,88E-02
pb-208	elastic	pb-208	elastic	4,77E-02
zr-91	n,gamma	zr-91	n,gamma	4,68E-02
zr-92	n,gamma	zr-92	n,gamma	4,66E-02
pb-207	n,gamma	pb-207	n,gamma	4,53E-02
pb-208	n,gamma	pb-208	n,gamma	4,44E-02
er-167	n,gamma	er-167	n,gamma	4,34E-02
pu-240	n,n'	pu-240	n,n'	3,99E-02
zr-94	n,n'	zr-94	n,n'	3,88E-02
pu-240	fission	pu-240	fission	3,61E-02
zr-92	n,n'	zr-92	n,n'	3,50E-02
pb-204	n,gamma	pb-204	n,gamma	3,46E-02
u-238	fission	u-238	fission	3,43E-02
pu-240	nubar	pu-240	nubar	3,43E-02
pu-241	n,n'	pu-241	n,n'	3,32E-02
u-235	n,gamma	u-235	n,gamma	3,26E-02

zr-90	elastic	zr-90	elastic	2,95E-02
pu-241	nubar	pu-241	nubar	2,80E-02
u-235	fission	pu-239	fission	2,62E-02
zr-90	n,n'	zr-90	n,n'	2,37E-02
pb-206	n,gamma	pb-206	n,gamma	2,31E-02
pb-207	elastic	pb-207	elastic	2,29E-02
pb-206	elastic	pb-206	elastic	2,26E-02
pu-239	n,n'	pu-239	elastic	-2,19E-02
u-238	elastic	u-238	n,gamma	-2,14E-02
zr-94	n,gamma	zr-94	n,gamma	1,89E-02
nb-93	n,gamma	nb-93	n,gamma	1,65E-02
u-238	elastic	u-238	elastic	1,49E-02
er-166	n,gamma	er-166	n,gamma	1,45E-02
zr-91	n,n'	zr-91	n,n'	1,41E-02
pu-239	fission	pu-239	n,gamma	-1,36E-02
zr-94	elastic	zr-94	elastic	1,30E-02
pu-239	elastic	pu-239	n,gamma	-1,22E-02
u-235	fission	u-238	n,gamma	-1,18E-02
pu-238	chi	pu-238	chi	1,12E-02
pb-204	n,n'	pb-204	n,n'	1,10E-02
zr-92	elastic	zr-92	elastic	1,06E-02
pu-242	n,gamma	pu-242	n,gamma	7,84E-03
am-241	n,gamma	am-241	n,gamma	7,77E-03
u-238	fission	u-238	n,gamma	7,41E-03
zr-91	elastic	zr-91	elastic	7,38E-03
er-168	n,gamma	er-168	n,gamma	7,23E-03
u-235	fission	u-238	fission	6,98E-03
u-235	chi	u-235	chi	6,81E-03
er-164	n,gamma	er-164	n,gamma	6,58E-03
pu-240	n,n'	pu-240	elastic	-5,83E-03
pu-238	n,gamma	pu-238	n,gamma	5,77E-03
u-235	fission	u-235	fission	5,71E-03
o-16	n,gamma	o-16	n,gamma	5,31E-03
er-170	n,gamma	er-170	n,gamma	5,24E-03
er-167	n,n'	er-167	n,n'	5,18E-03
pu-242	fission	pu-242	fission	5,15E-03

- Sensitivity: erbium sensitivity range between $10^2 - 10^6$ eV.
- Uncertainty: Er-167 (**46 pcm**), Er-166 (**15 pcm**), Er-168 (**8 pcm**), Er-170 (**6 pcm**).

Slide by A. Guglielmelli

The measurement with enriched samples

C6D6	162	164	166	167	168	170	Cost per mg
Er-166	0,002	0,02	98,1	1,33	0,45	0,1	5,6$
Er-167	<0,01	<0,01	0,96	96,3	2,6	0,2	5,9$
Total cost							2300$ + 250€ (shipment)

ISOFLEX USA
Isotopes for Science, Medicine and Industry

P.O. Box 29475
San Francisco CA 94129 USA
Tel: 415-440-4433 Fax: 415-563-4433
Email: info@isoflex.com.ru
iusa@isoflex.com
FEIN: 20-8066748

QUOTATION

Confidential Business Matter

DATE: November 14, 2023
QUOTE NUMBER: 231114-I
SELLER CONTACT: Allan Pashkovski

BUYER:
Att: Dr. Victor Alcayne Aicua
victor.alcayne.aicua@cern.ch
CERN
Espl. des Particules 1
Meyren GENEVA 1211
Switzerland

CONSIGNEE / SHIP TO:
TBD

QUOTATION SUMMARY

DESCRIPTION	PROPOSED DELIVERY	QUANTITY	UNIT PRICE	SUBTOTAL
Er-166 in oxide form with I.E. 98,1atom%	6-8 weeks ARO	200 mg	US$5.60/ mg	US$1,120.00
Er-167 in oxide form with I.E. 96,3atom%	1-2 weeks ARO	200 mg	US$5.90/ mg	US$1,180.00

Bank details: Bank Name: Comerica Bank, Bank Address: 2001 Union Street, San Francisco, CA 94123, USA
SWIFT Code: MNBDUS33 For credit to Acct. # 1895755195 For benefit of: ISOFLEX USA

Subtotal: US$2,300.00
Shipping, Handling and Insurance: US$250.00

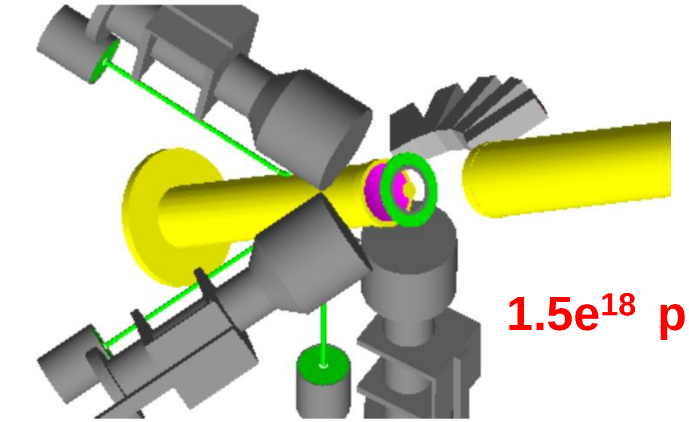
Notes: ARO = After Receipt of Order
We Accept VISA MasterCard
TOTAL (USD) at CIP terms: US$2,550.00

GOBIERNO DE ESPAÑA | MINISTERIO DE CIENCIA E INNOVACIÓN

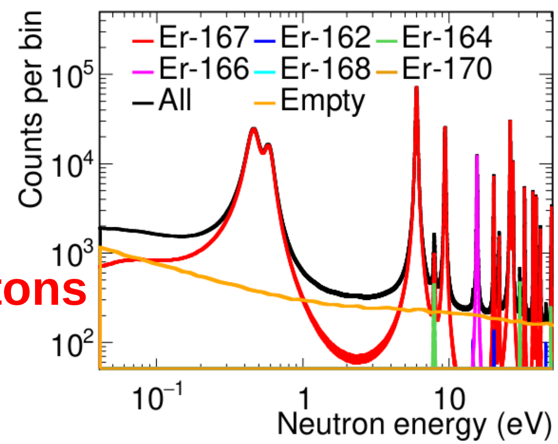
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

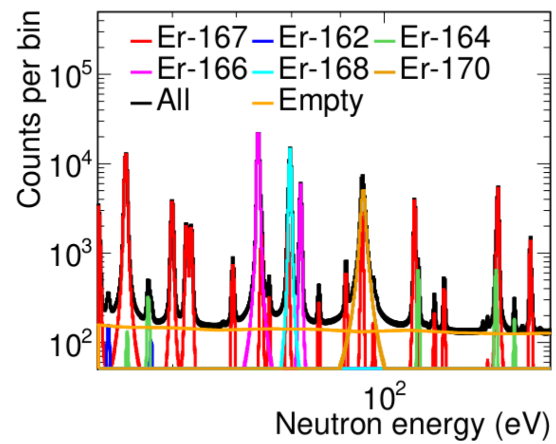
The measurement at EAR1 with natural Er

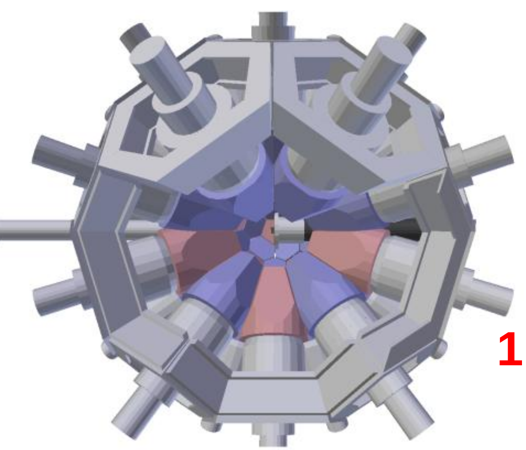
Measurement of a Natural sample of Er in the range **from 0.02 eV to 50 eV** with an aimed accuracy of 2%. The idea is to use a very well characterized metallic sample of ~30 mg. Samples of higher mass would need considerable self-shielding and multiple scattering corrections. It is not possible to obtain precisely the RP for ^{167}Er at energies higher than 50 eV.



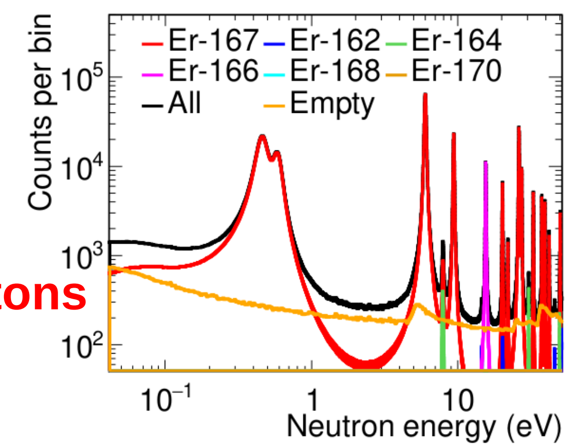
1.5e^{18} protons

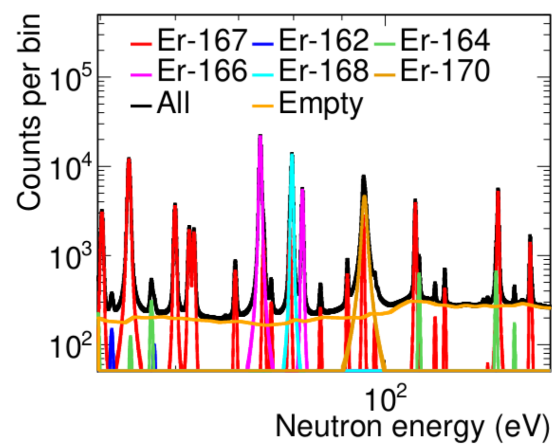






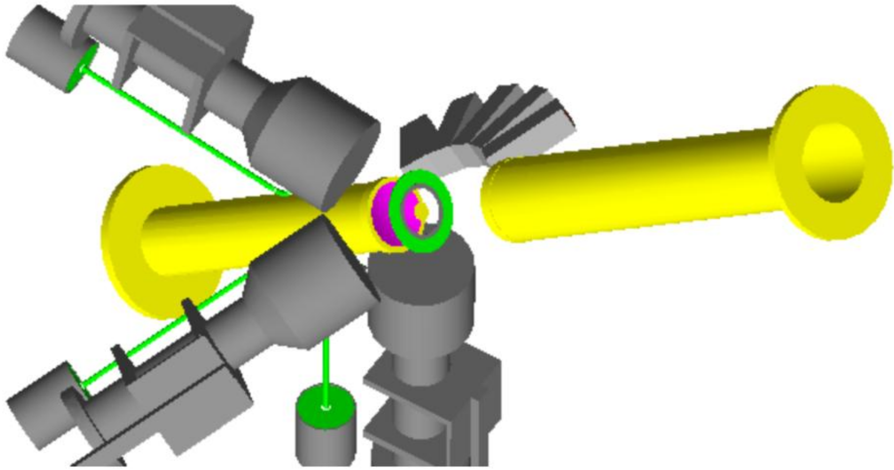
1.0e^{18} protons





The measurement at EAR1 with enriched Er

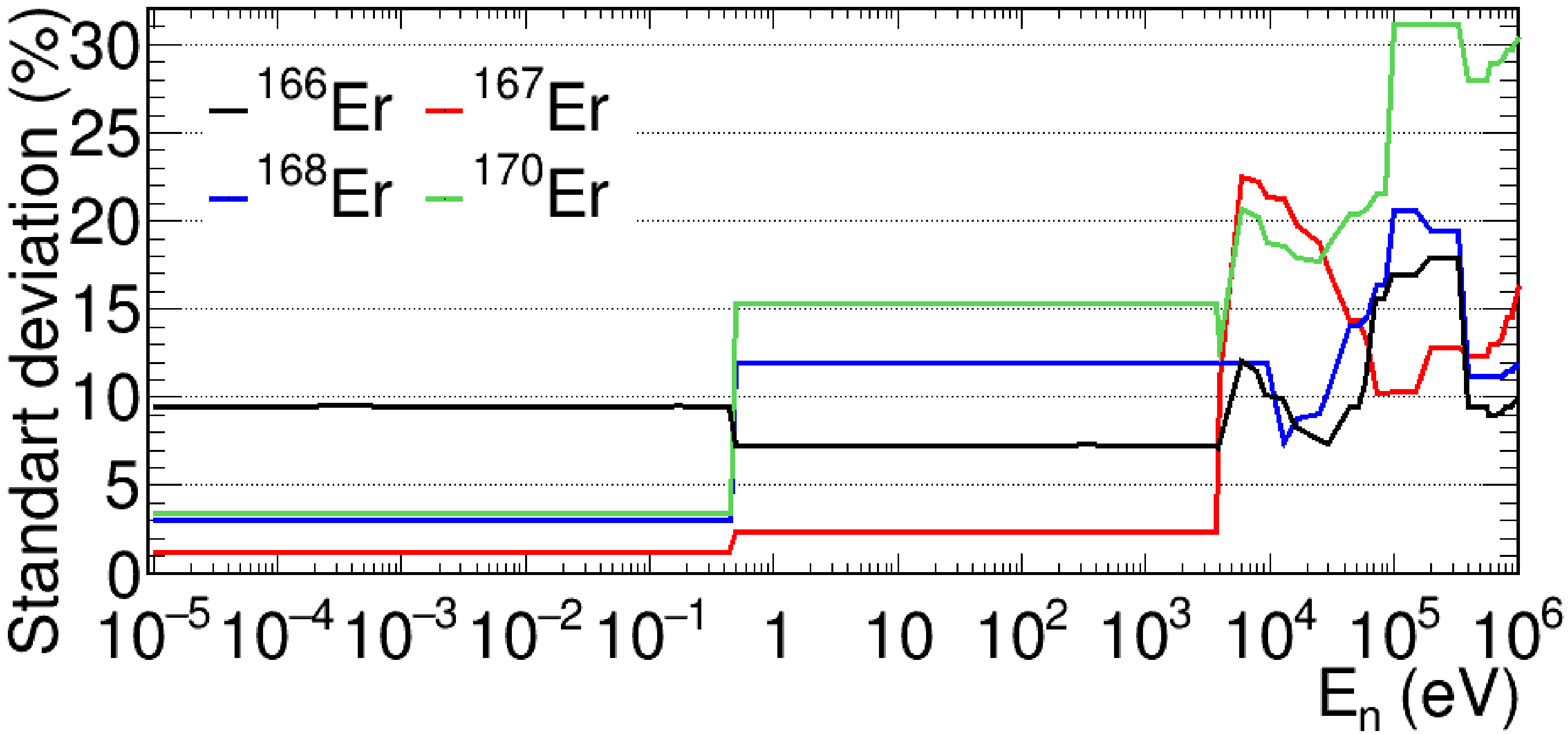
The cross sections of $^{166,167,168,170}Er$ would be measured with enriched samples of ~200 mg using 3 L6D6 and 5 sTED at different angles. The detectors at different angles are to observe the possible angle effects in the p-waves and s-waves of Er.



Sample	Mass	Detector	Energy range	Number protons
^{166}Er	200mg	C_6D_6	10 eV-100 keV	$1.0\cdot10^{18}$
^{167}Er	200mg	C_6D_6	50 eV-500 keV	$1.0\cdot10^{18}$
^{168}Er	200mg	C_6D_6	50 eV-100 keV	$1.5\cdot10^{18}$
^{170}Er	200mg	C_6D_6	50 eV-50 keV	$1.5\cdot10^{18}$

Evaluations

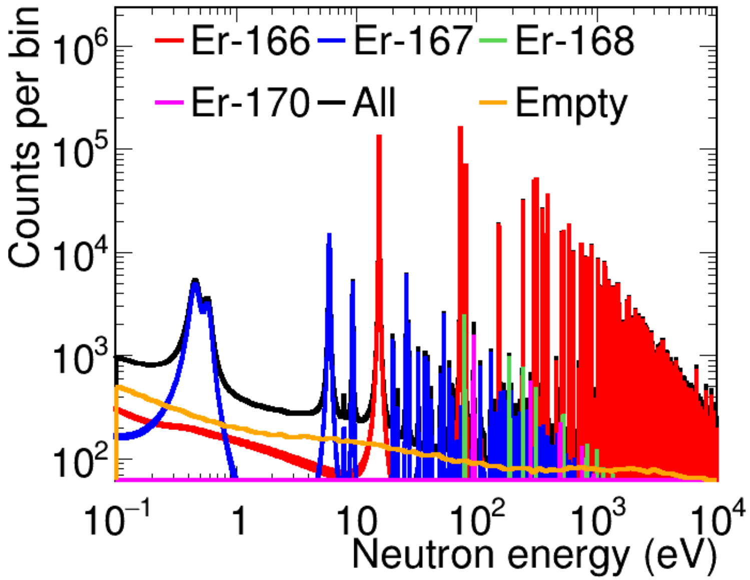
For ^{166,168,170}Er the evaluations of JENDL-5, JEFF-3.3 and ENDF-VIII and the uncertainties are between 7-15% in the RRR.
The uncertainty for ^{167}Er in the RRR is 2.3%, this value is questionable.

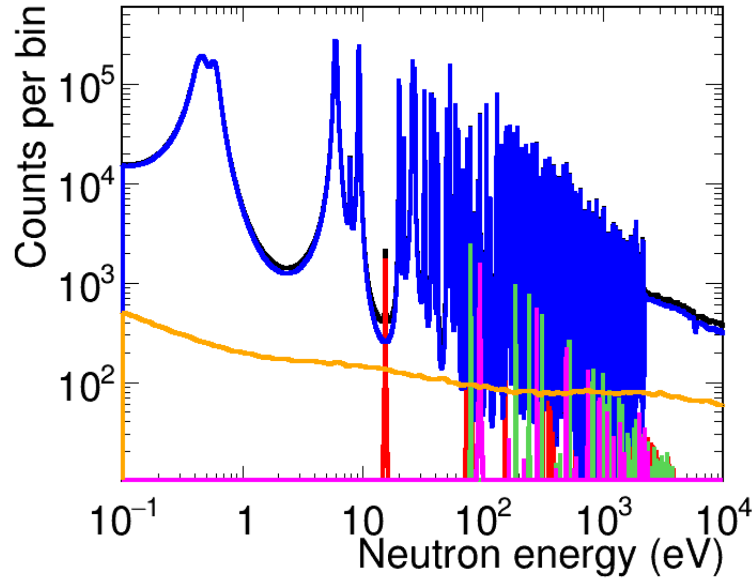


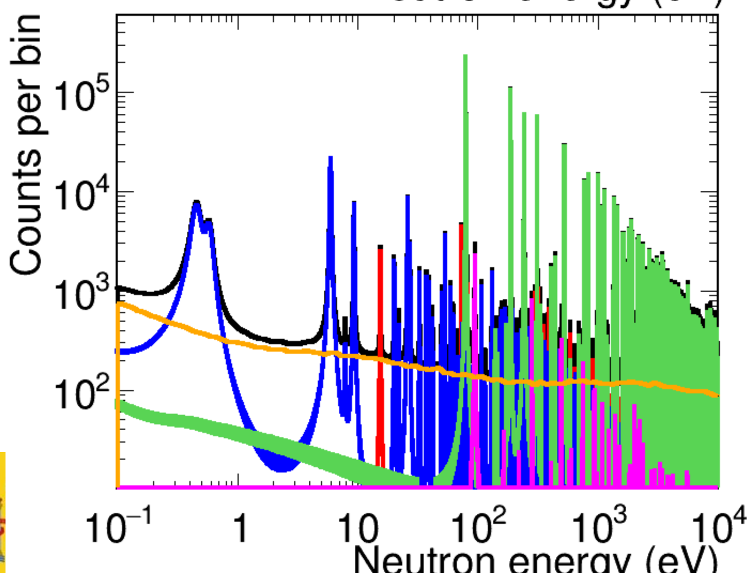
https://doi.org/10.1016/j.anucene.2022.109337

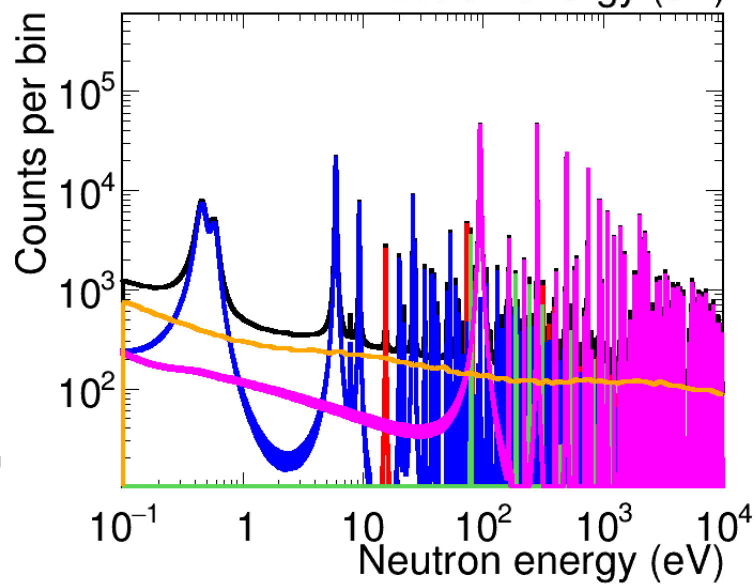
The measurement at EAR1 with enriched Er

The cross sections of $^{166,167,168,170}Er$ would be measured with enriched samples of ~200 mg using 3 L6D6 and 5 sTED at different angles.









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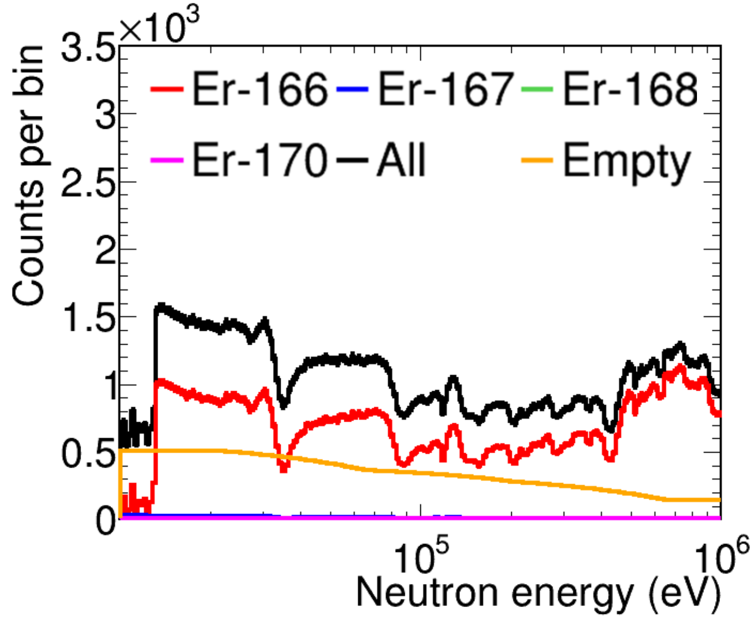
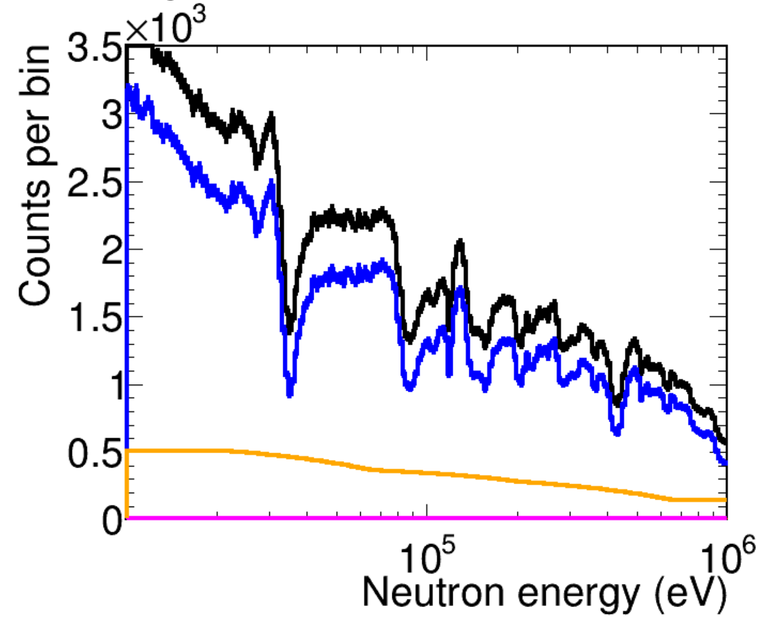
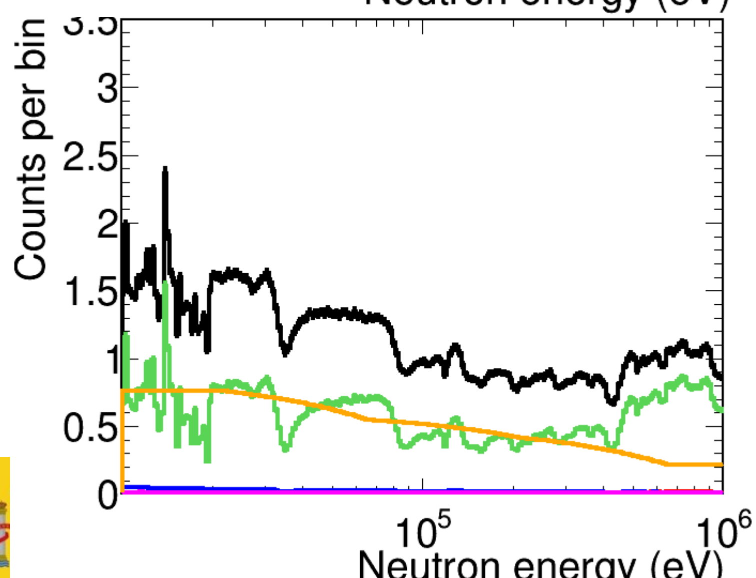
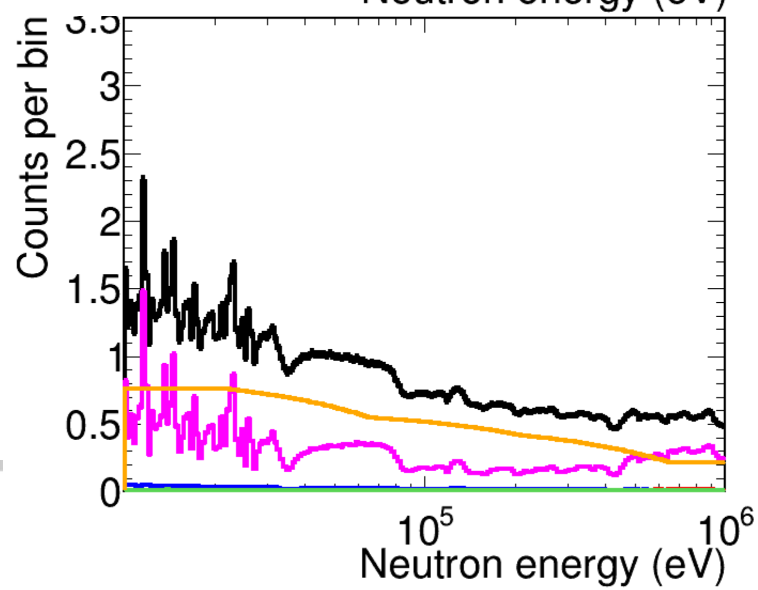






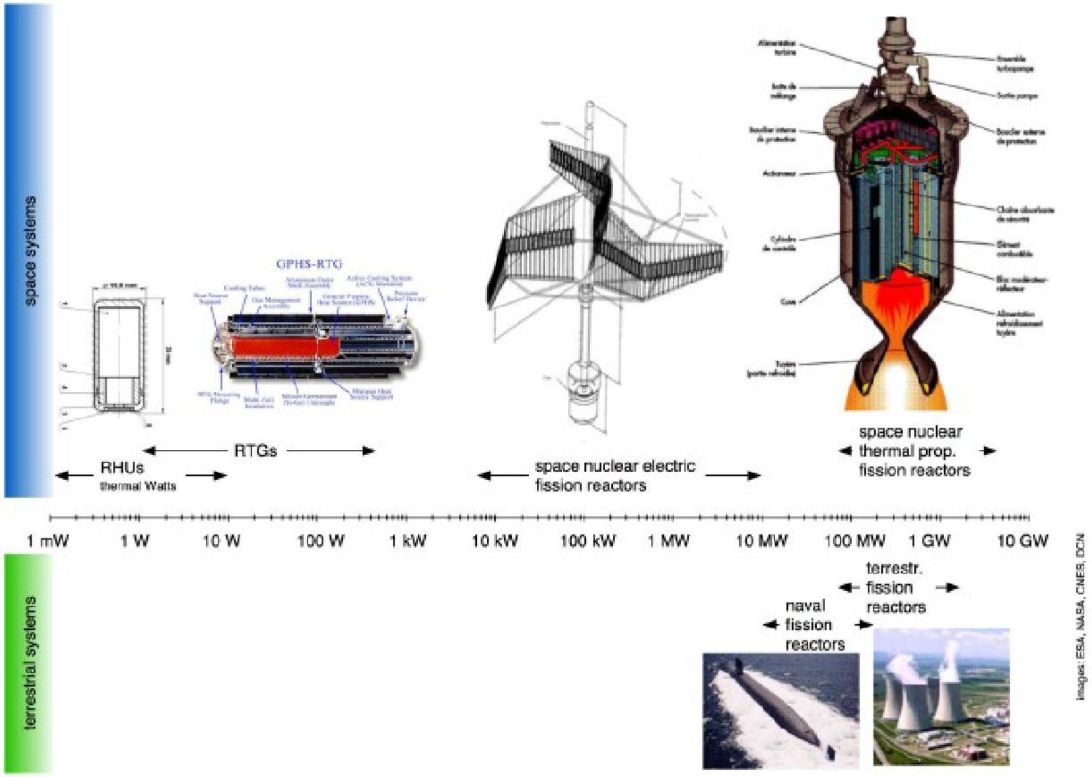


Outline of the presentation

- Introduction and motivation
- Previous measurements and evaluations of Ta
- Ta measurement at n_TOF EAR1
- Monitoring of the experiment

Reactors for space

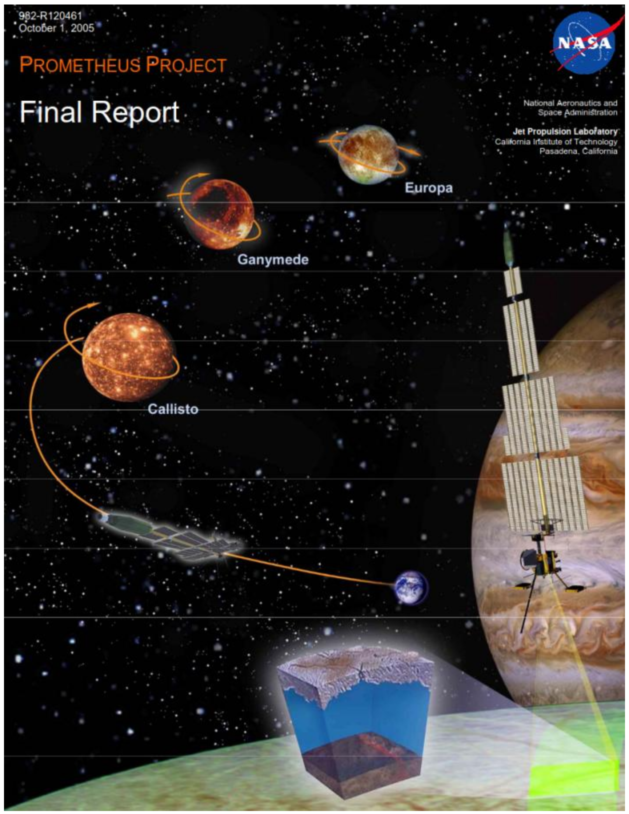
The absence of hydrocarbon power sources in space and the limitations of batteries have led to the development of photovoltaic and nuclear devices.



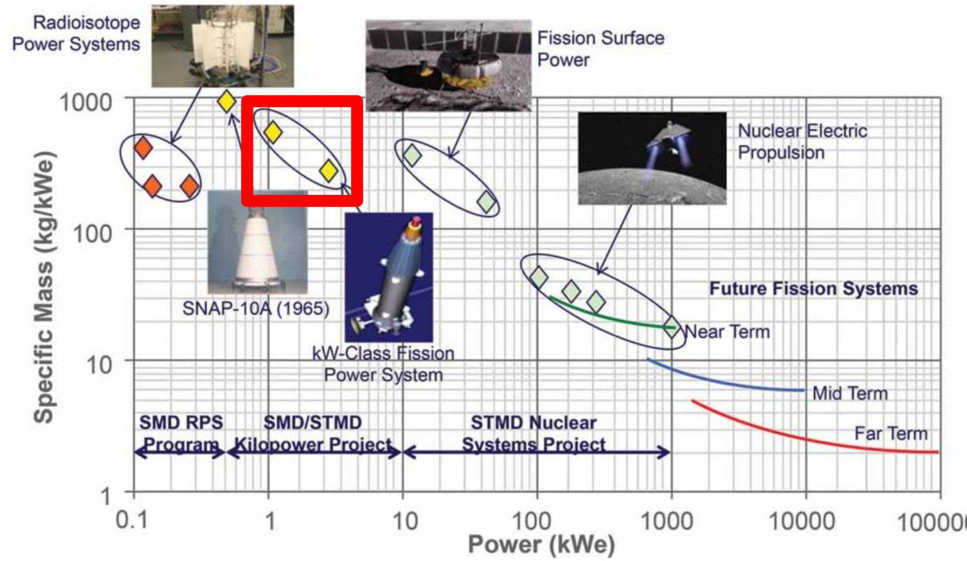
For space missions to Jupiter and beyond and surface missions on Mars nuclear devices are the most suitable option. When spacecrafts require more than 100 kW for power, nuclear reactors are much more cost-effective than RPS.

The NASA projects

The Prometheus project



The Kilopower project



nance map.[1] SMD is the NASA Science Mission Directorate; STMD is the NASA Space Technology Mission Directorate.

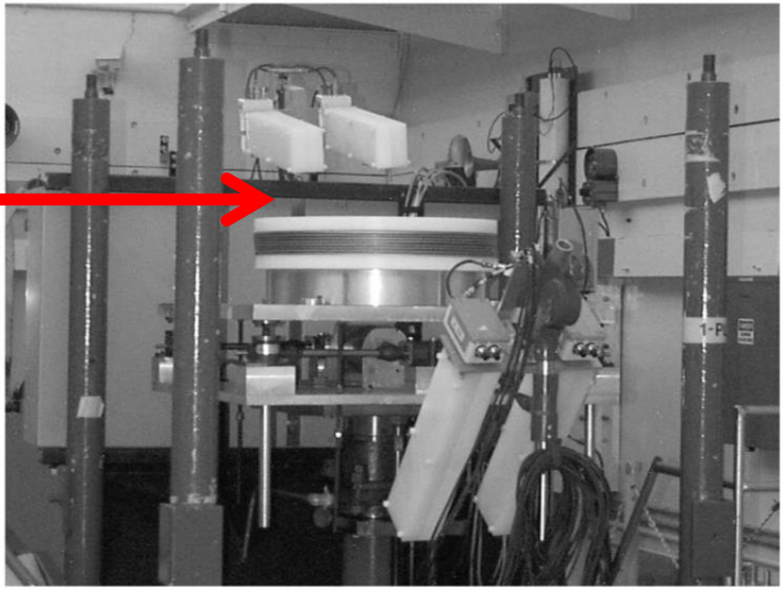
Fig. 9. LANL and NASA engineers lowering the top of the vacuum chamber over the Stirling engines.

The Krusty experiment has already test a 1kW fission power system on earth.

Refractory metals and critical experiments

Refractory metals are needed for the space nuclear reactors that operate at high temperatures. The available materials are Mo, W, Rh, and **Ta**.

Critical experiments in refractory materials were done as part of the Prometheus Project.



Uncertainty	Energy spectrum in the experiment			Mass differences in percentage
	<0.625 eV	0.625 eV-100 keV	<100 keV	
Ta-2.5W-1	0.0%	14.0%	86.0%	0.17
Ta-2.5W-2	0.0%	20.7%	79.3%	9.25
Ta-2.5W-3	0.0%	31.1%	68.9%	7.67
Ta-2.5W-4	3.7%	43.4%	52.9%	7.48

Considerable differences for experiments with Ta in the keV region.
There are also differences in the experiments with moderators.

Tantalum CS for fusion and ADS

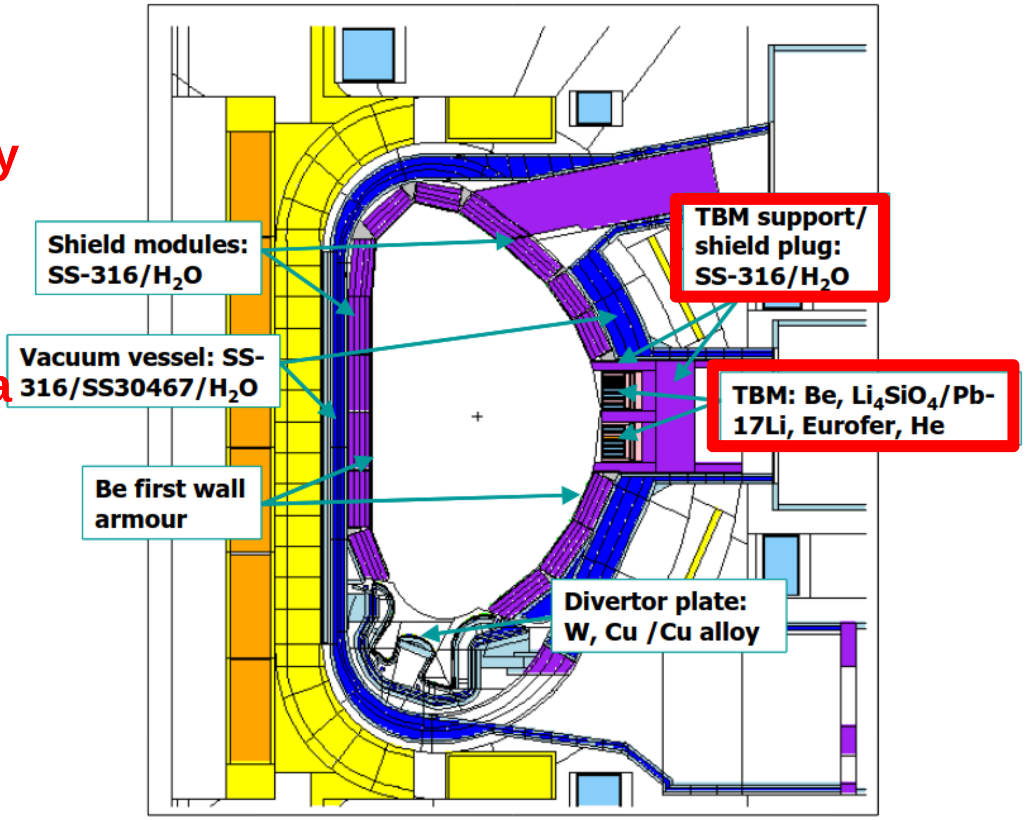
Tantalum is considered one of the high-priority elements for which well-qualified evaluated data sets are required for the ITER and IFMIF fusion projects.

Test Blanket Module (TBM) includes Eurofer, that contains Tantalum.
Ta is also present in the super-conducting magnets of the reactor.

Previous works claim an uncertainty lower than 10% is needed in the Ta capture cross section from thermal to 1keV. This energy region is important due to the activation of Ta by thermalized neutrons.

Tantalum have been also considered as the target for producing neutrons in Accelerator Driven Systems (ADS).

The ITER reactor



Previous measurements

The previous measurements used for the evaluations and the recent measurements are:

	Type	Range
Harvey (1953)	Transmission	1-700 eV
Belanova (1973)	Transmission	2-70 eV
Mughabghab (1975)	Compilation	4-200 eV
Yamamuro (1980)	Capture	3-100 keV
Mackin (1984)	Capture	2.6-1900 keV
Tsubone (1987)	Transmission	100-4000 eV
Meaze (2005)	Transmission	1-100 eV
McDermott (2017)	Capture	0.1 eV-1 MeV
Brown (2018)	Cap/Trans	0.3-500 keV

Limitations of previous measurements

	Type	Range
Harvey (1953)	Transmission	1-700 eV
Belanova (1975)	Transmission	2-70 eV
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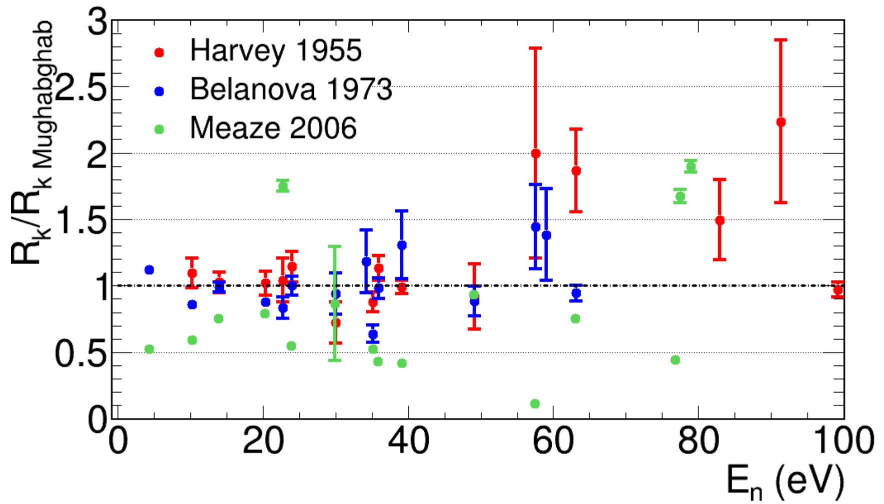
Brown (2018)	Capture	0.3-500 keV

Meaze reports very different RP. The Γ_γ parameters are four times larger



The Brown and McDemortt measurement have considerable limitations:

- **All the detectors are at the same angle.**
- **The samples have more than 1 mm thickness**, so considerable multiple scattering and photon attenuation corrections are needed (>30%).
- The measurements **of Macklin, Tsobune and Yamamuro also use samples thicker** than 1 mm.

The RP or the yield of **the McDemortt measurement are not available.**

Evaluations

The JENDL-4 and JEFF-3.3 libraries take the values from JENDL-3.3

	Based in	Range RP
ENDF/B-VIII.0	Mughabghab and Macklin	4-300 eV
JENDL-3.3	Mughabghab, Macklin, Tsubone and Yamamuro	4-2400 eV
JENDL-5.0	Mughabghab, Macklin, Tsubone, Yamamuro and **Endo** (**new measurement at J-PARC** not published yet between 1 and 200 eV)	4-2400 eV

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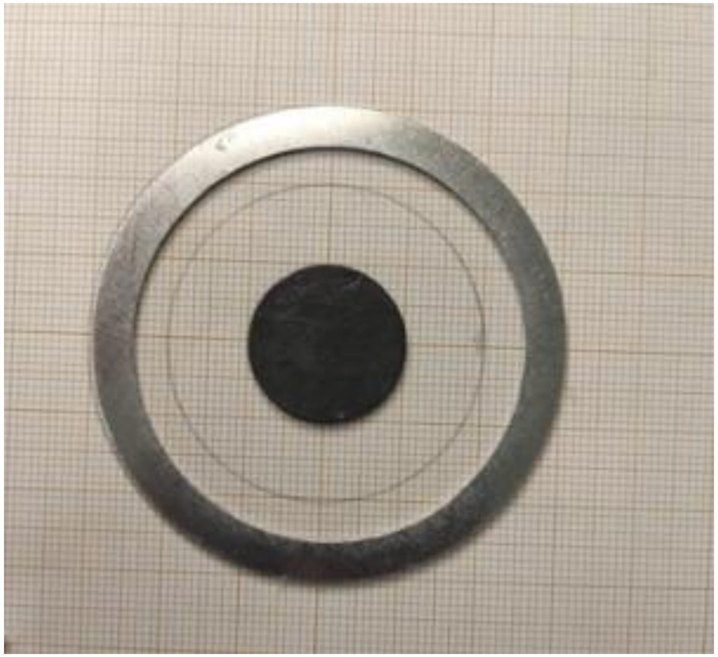
Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

Ta experiment at n_TOF

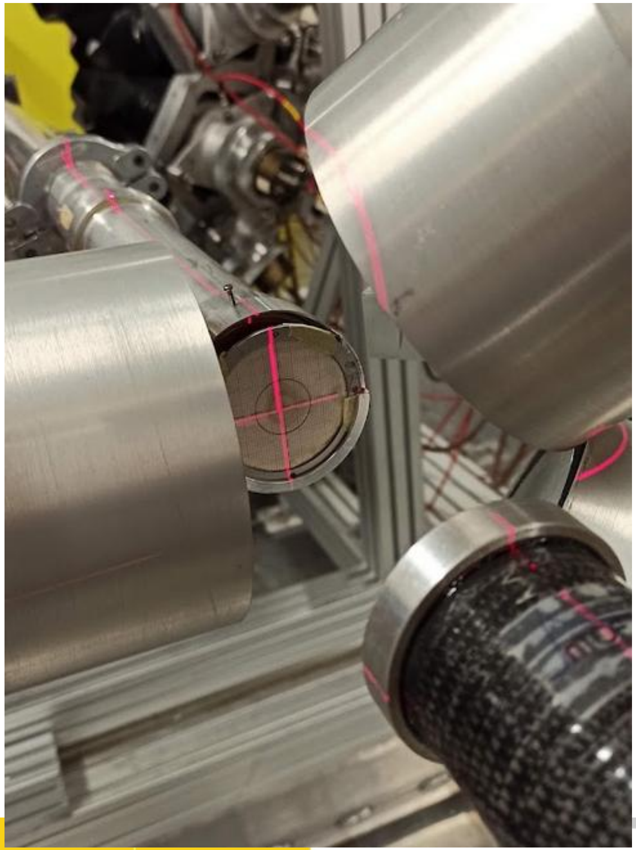
The experiment start the 3 of May and it is still running.
We decided to measure samples of 4 cm diameter (BIF= ~95%) in order to avoid problems with the sample alignment.
We also decided to measure samples of 2 cm to check the various corrections.

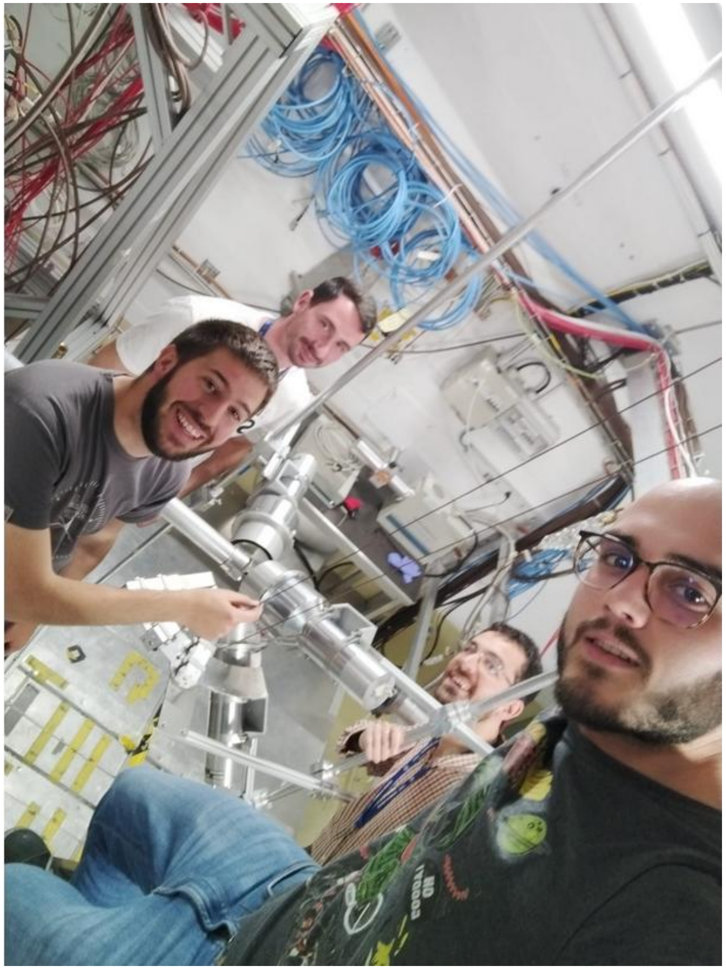
Ta -4 cm- 500 um	4	4.0	99
Ta-4 cm - 100 um	3	3.3	111
Ta -2 cm- 100 um	0.5	0.6	114
Ta-4 cm - 10 um	5	2.9	58
Ta-2 cm - 10 um	0.5	0.5	100
Empty	3	3.0	99
Au-4 cm-200 um	4	4.4	109
Au-2 cm - 200 um	3	1.8	60
Lead-4 cm	1	0.0	0
Lead-2 cm	1	0	0
Carbon- 2 cm	1	0.0	0



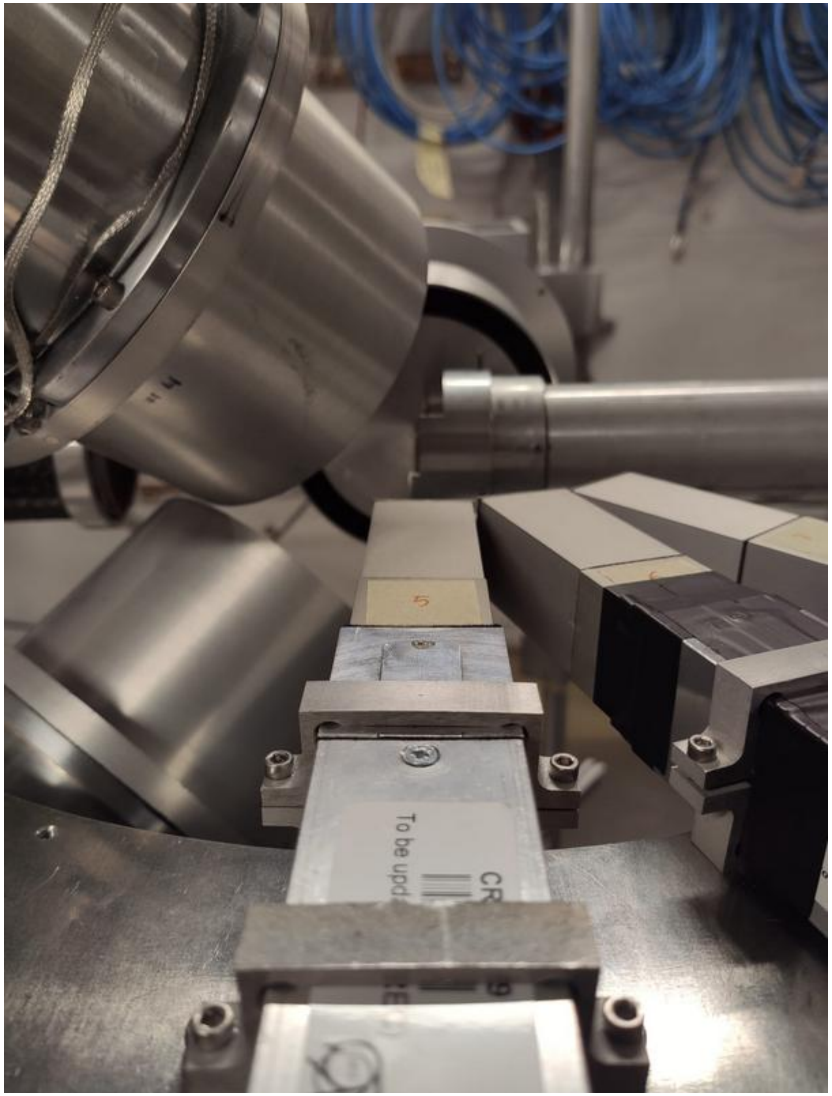
Setup

- 1 BICRON at 3.7 cm at 90º with respect to the beam
- 2 BICRON at 9.2 cm at 125º with respect to the beam
- 3 sTED at 10 cm at 90º, 110º, 130º with respect to the beam



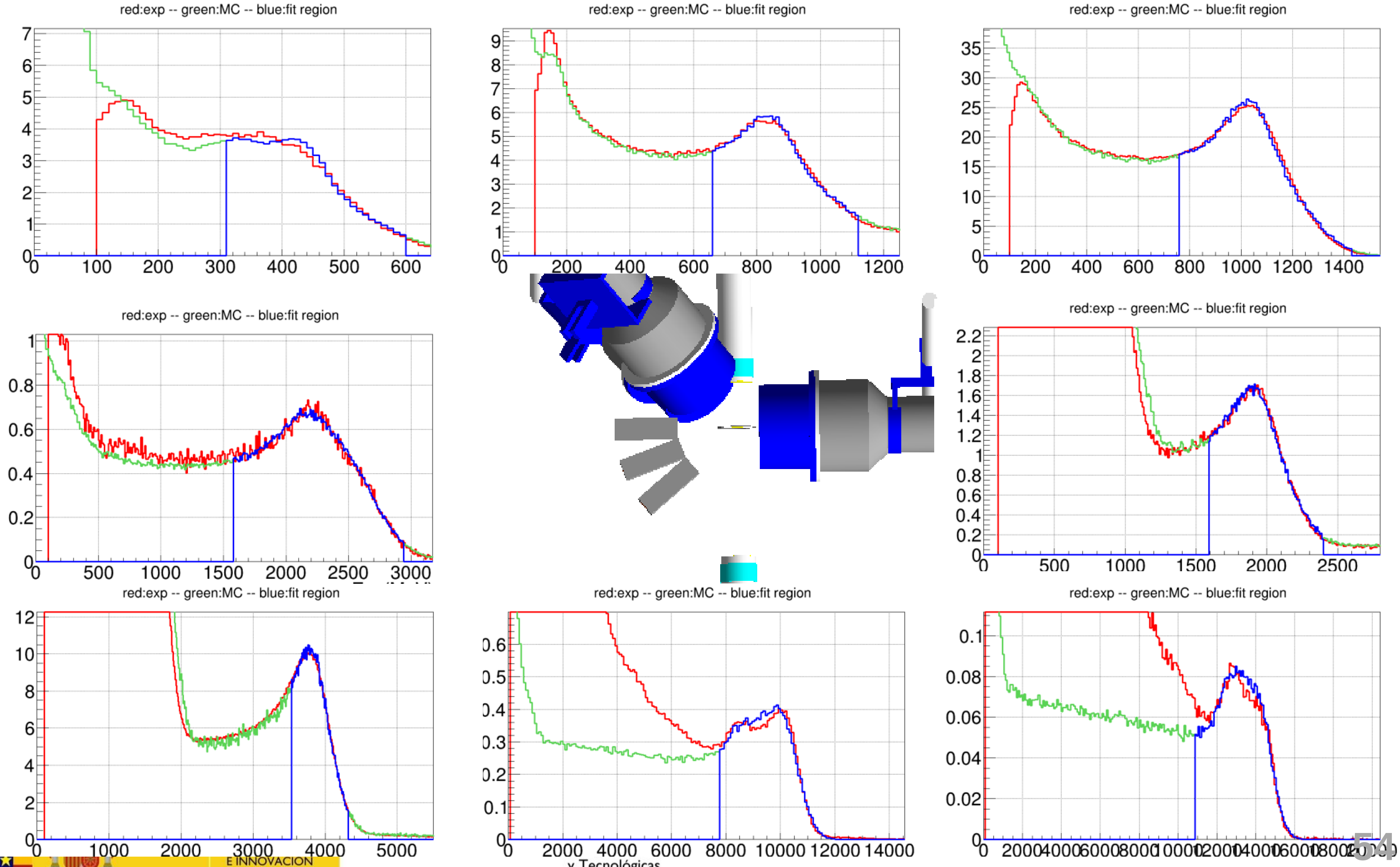


Setup



Energy calibrations

Calibrations were performed with 8 sources (^{133}Ba, ^{137}Cs, ^{54}Mn, ^{60}Co, ^{209}Bi, ^{88}Y, AmBe, CmC) from 200 keV to 6 MeV.



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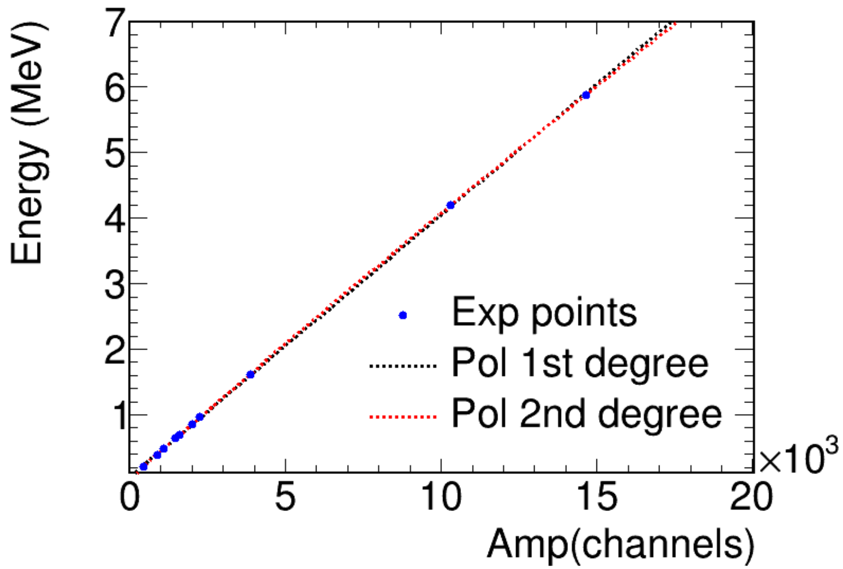
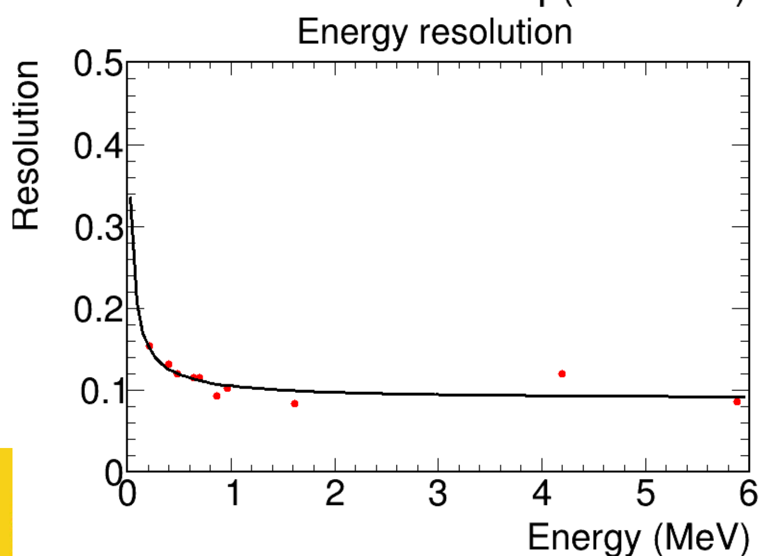
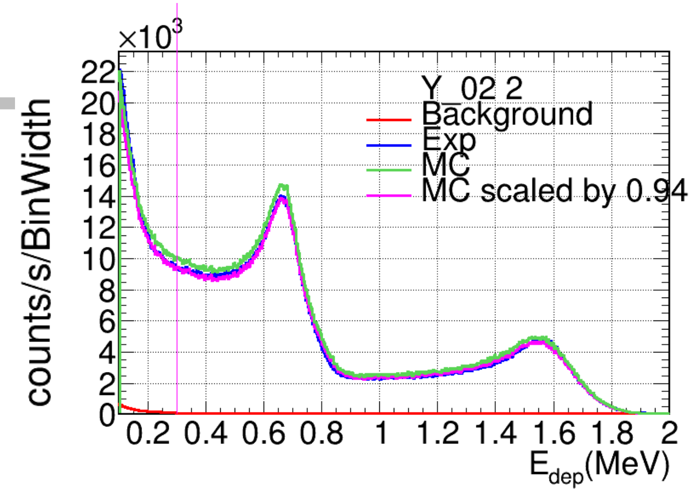
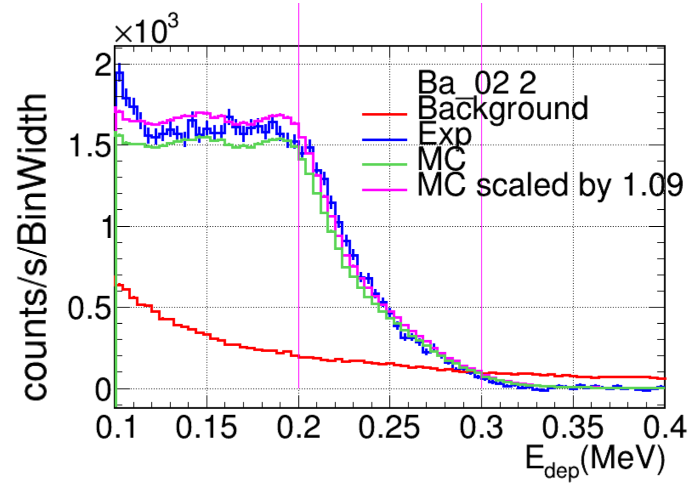
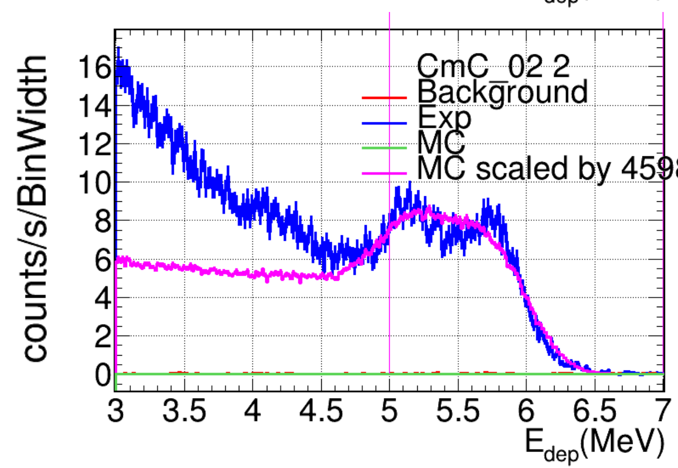






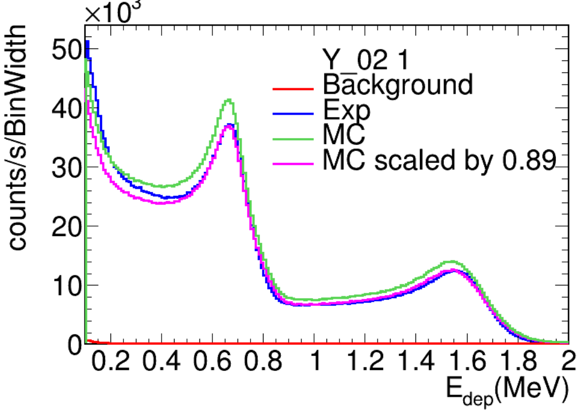




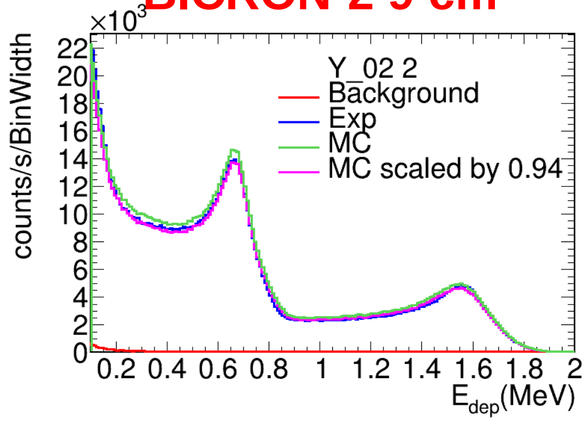
Energy calibrations

All the sources were placed in the same place as the Ta samples.
The differences between the calculated and the obtained efficiencies are below 10%.
This differences are compatible with the uncertainties in the position of the detectors.

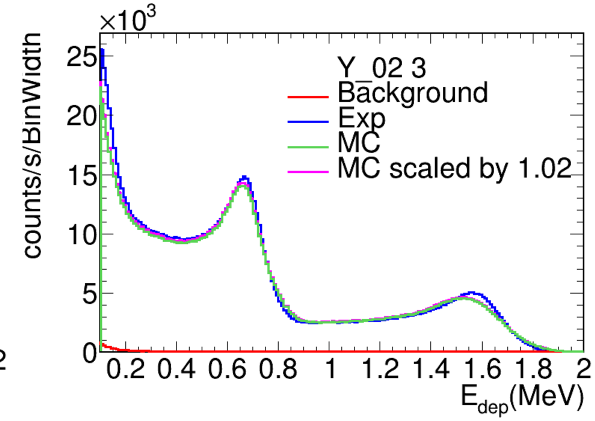
BICRON-1 3.7 cm



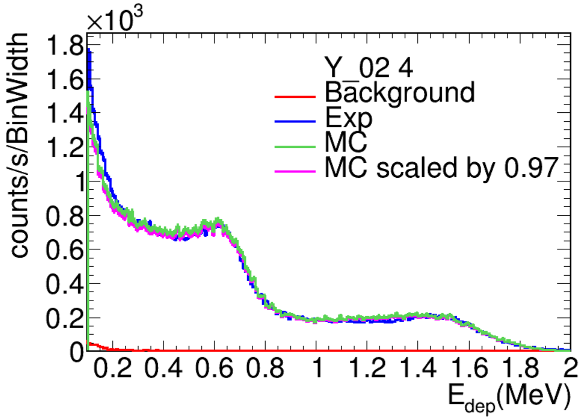
BICRON-2 9 cm



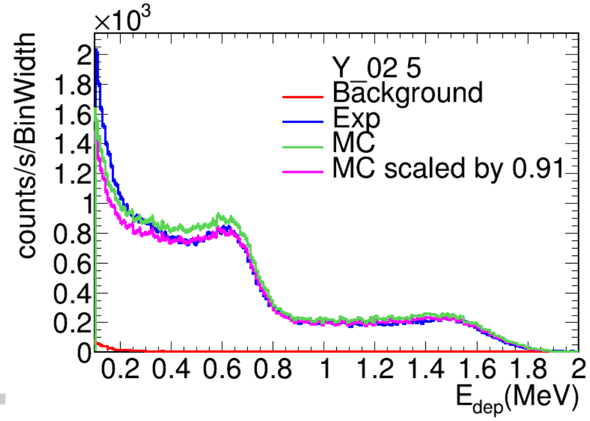
BICRON-4 9 cm



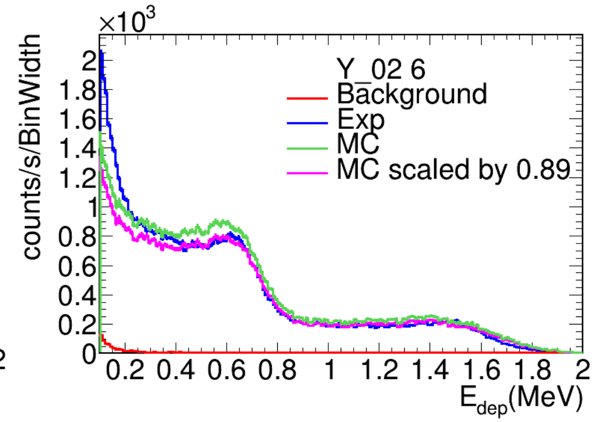
sTED 10 cm 90º



sTED 10 cm 110º



sTED 10 cm 130º



Energy calibrations

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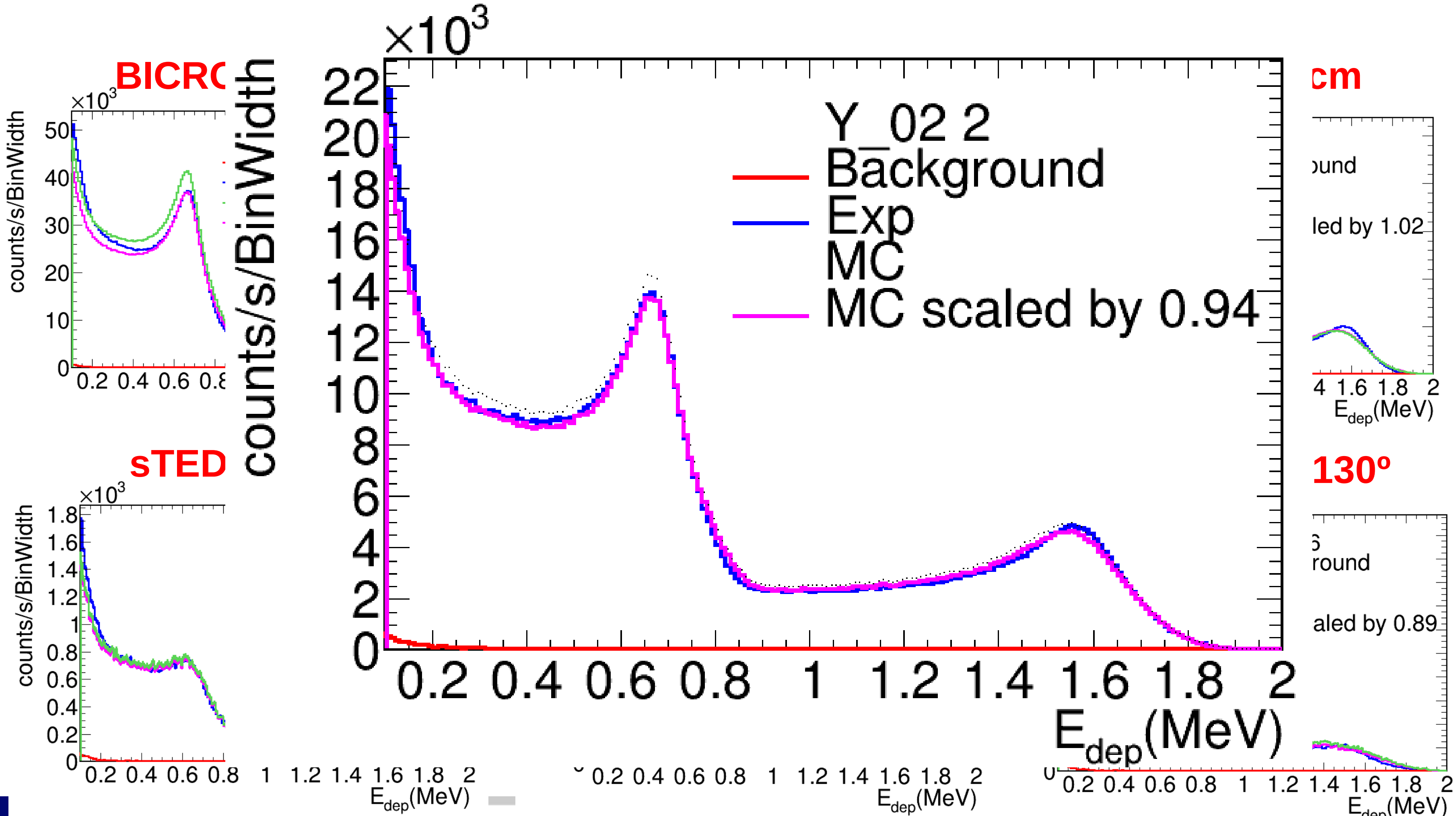

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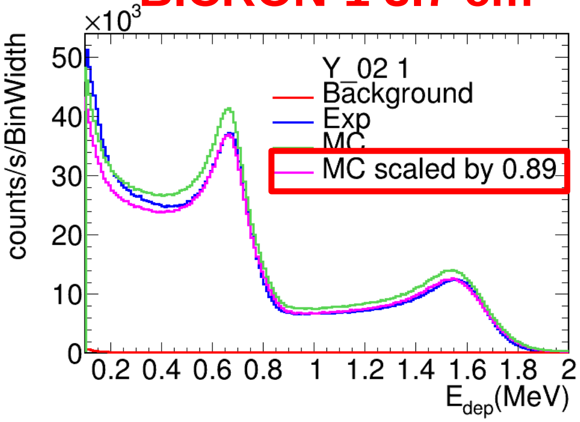
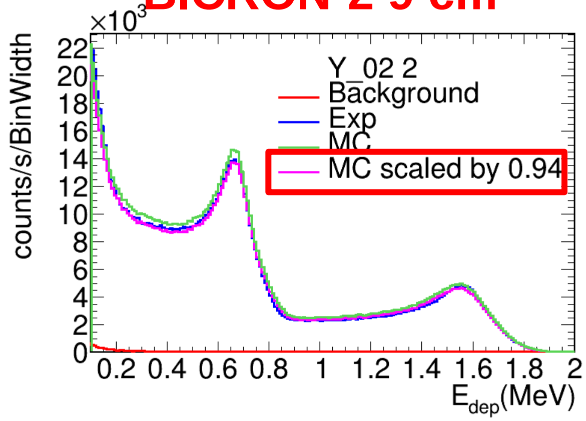
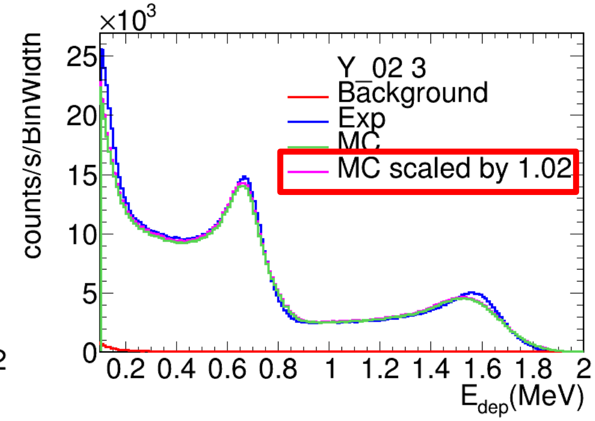


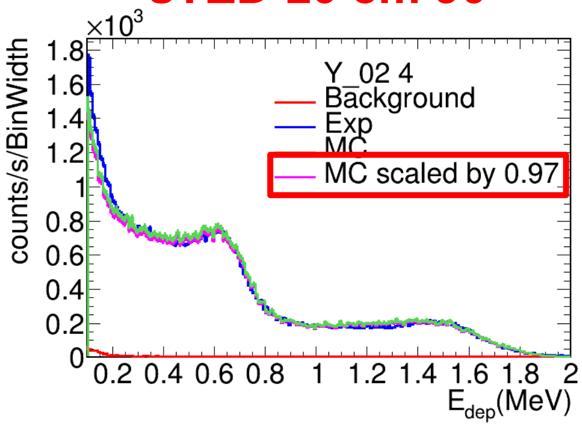
BICRON-2 9 cm



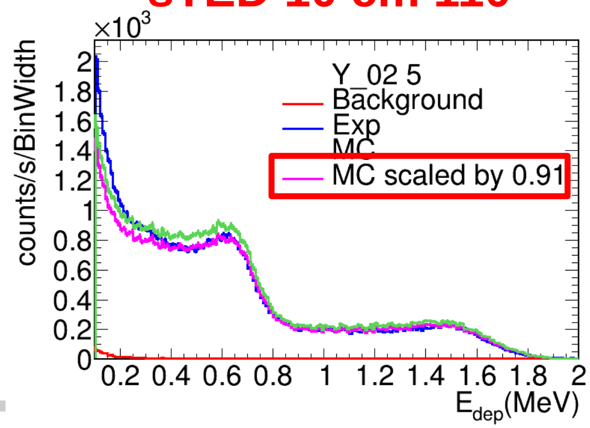
BICRON-4 9 cm



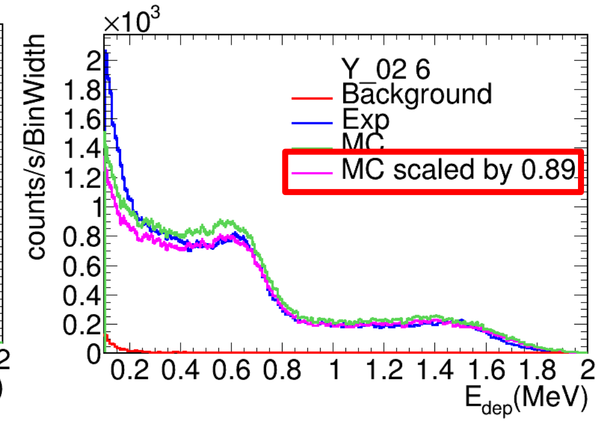
sTED 10 cm 90º



sTED 10 cm 110º

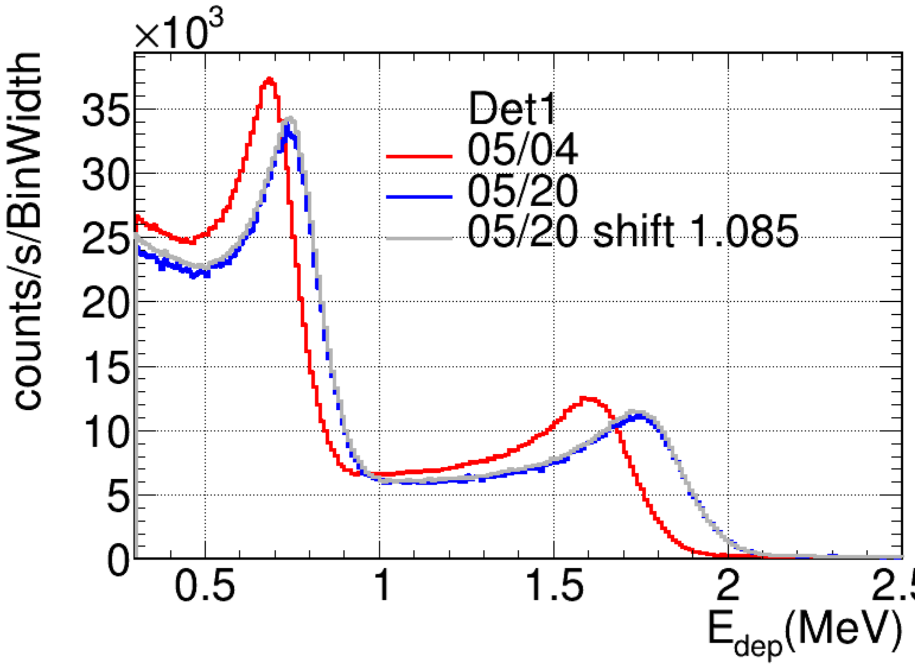


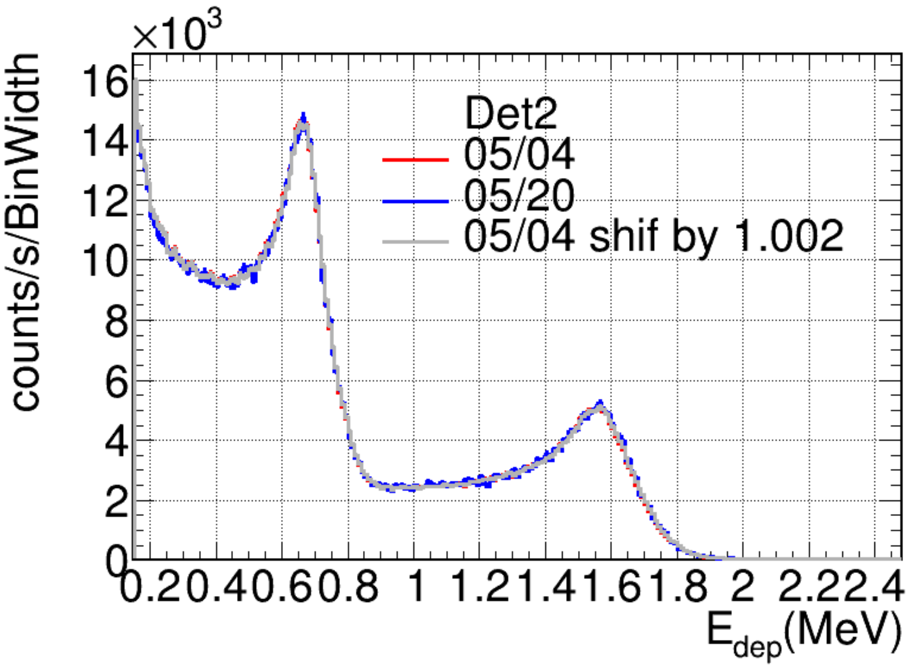
sTED 10 cm 130º



Gain shifts during the experiment

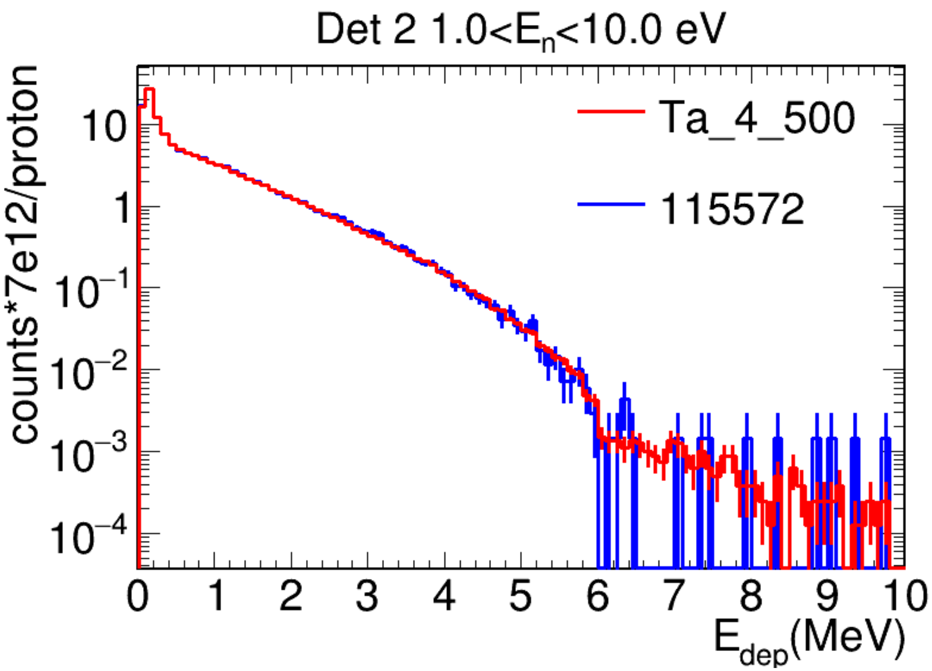
The gain of the detectors is check every few days with calibration sources.

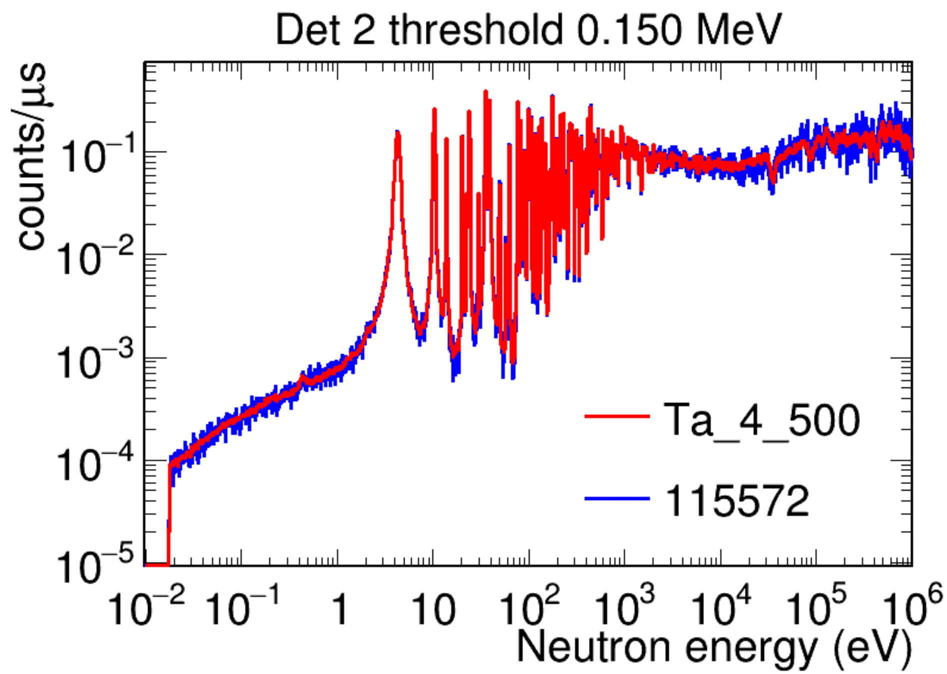


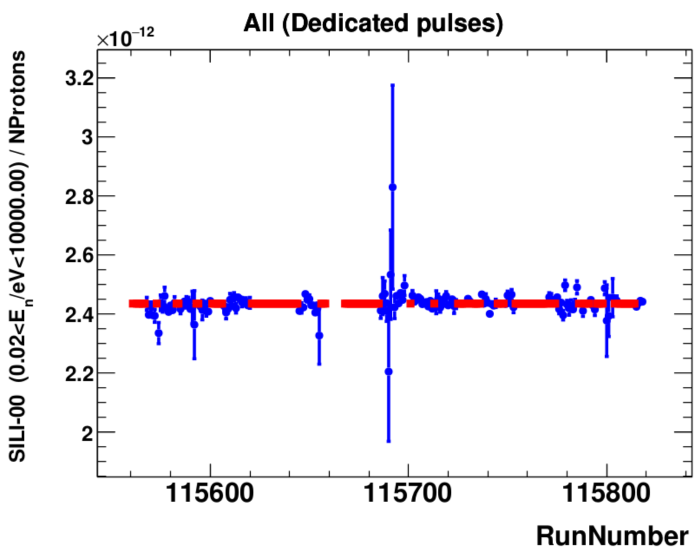


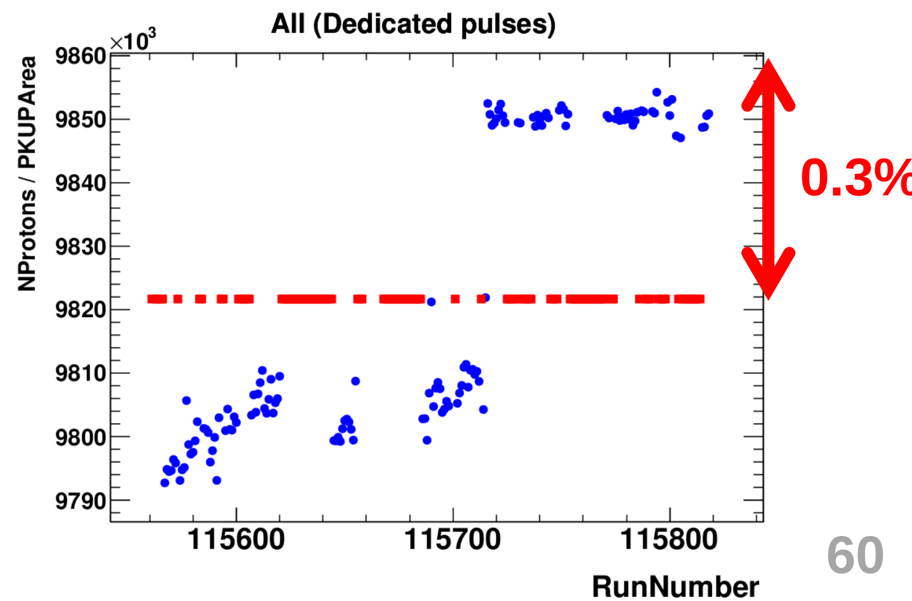
The gain of BICRON 1 (3.7 cm) suffers considerable shifts and also this detectors has shifts with the light. The gain shifts in the rest of detectors are smaller than 1%.

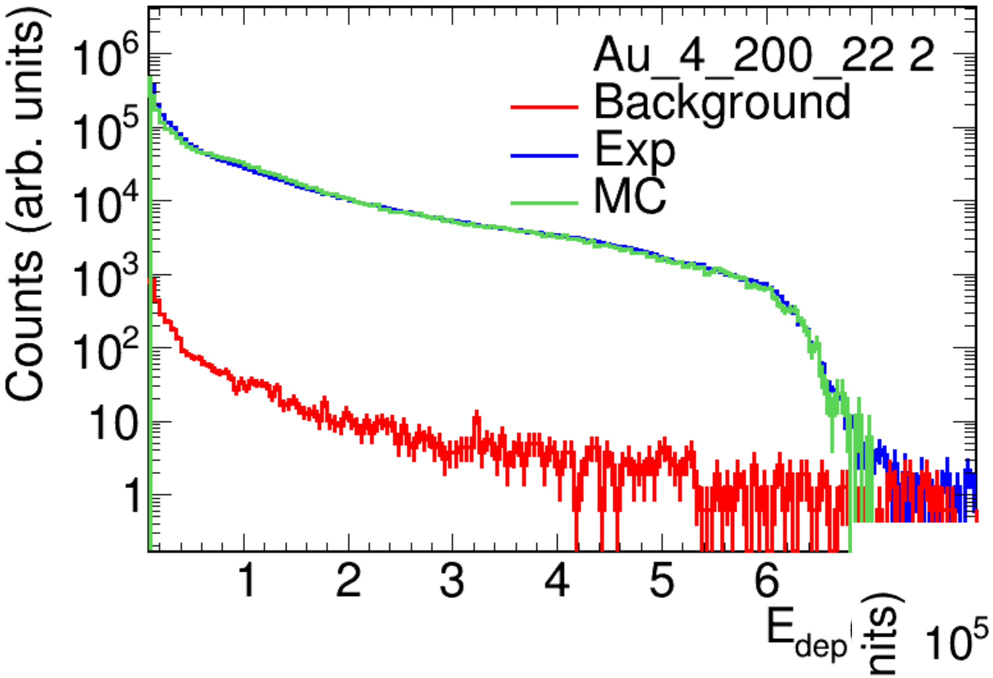
Monitoring of the experiment





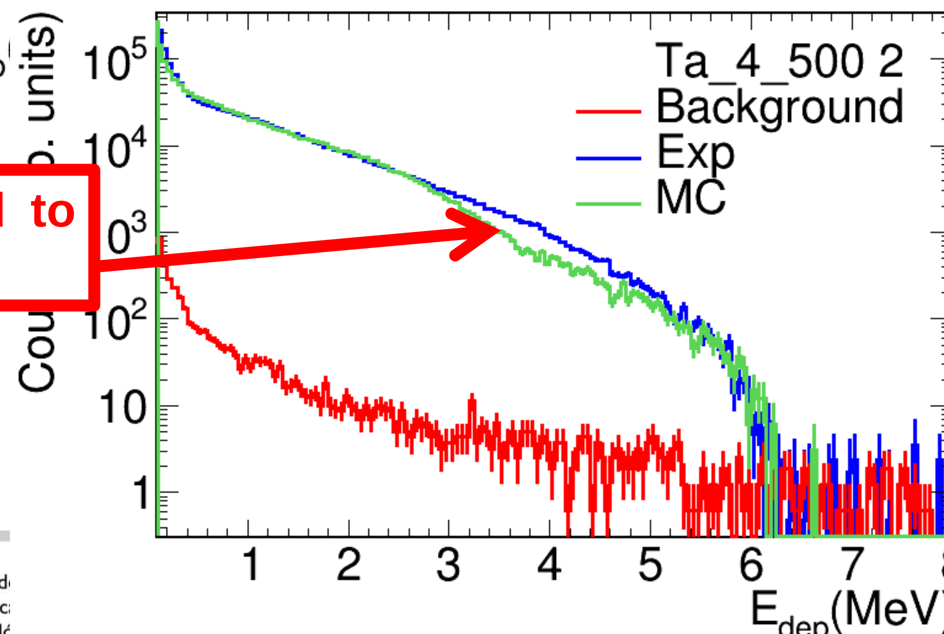






The capture cascades of ^{181}Ta and ^{197}Au have been simulated with **NuDEX.**

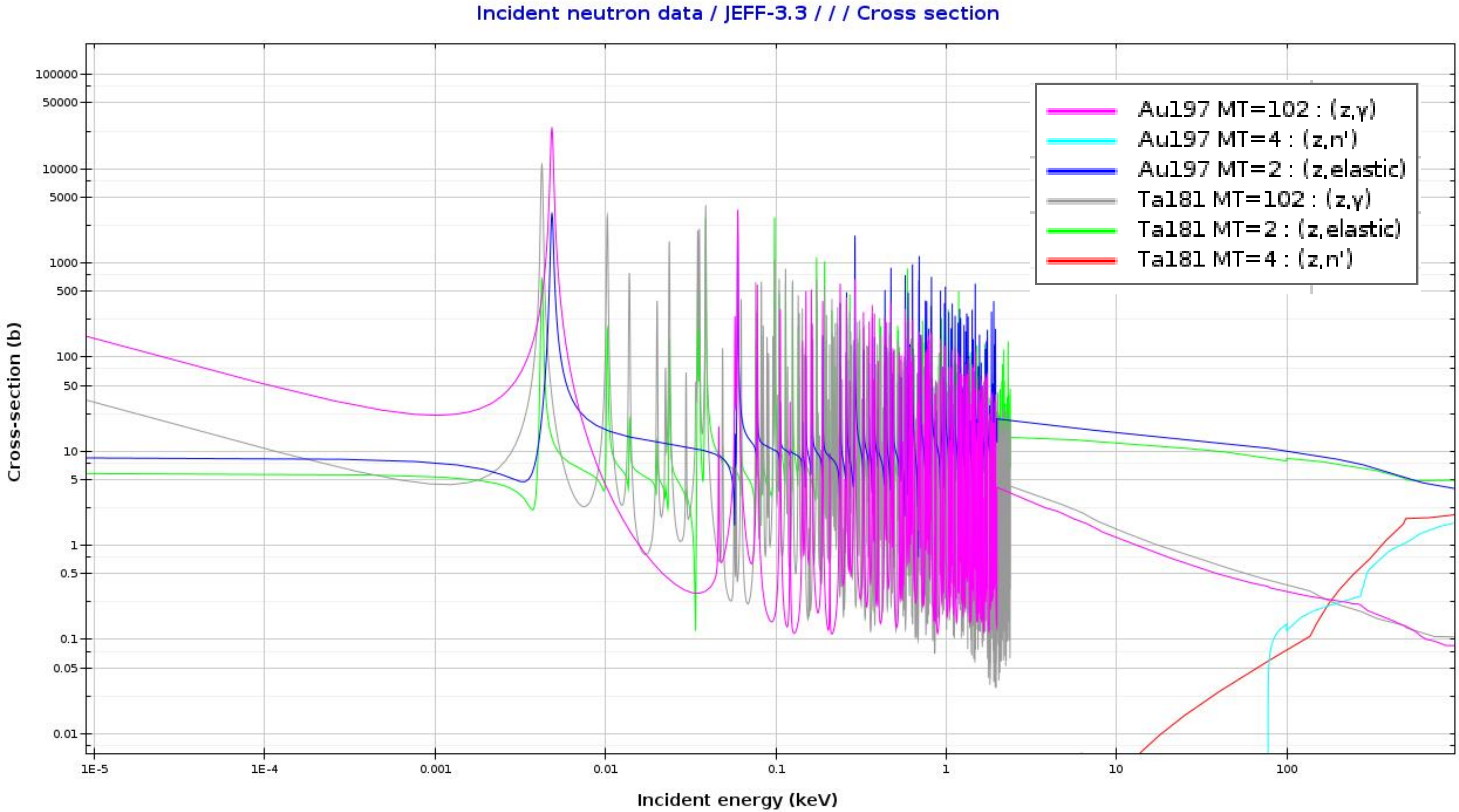
https://doi.org/10.1051/epjconf/202023917006



The PSF of ^{181}Ta can be adjusted to improve the fit

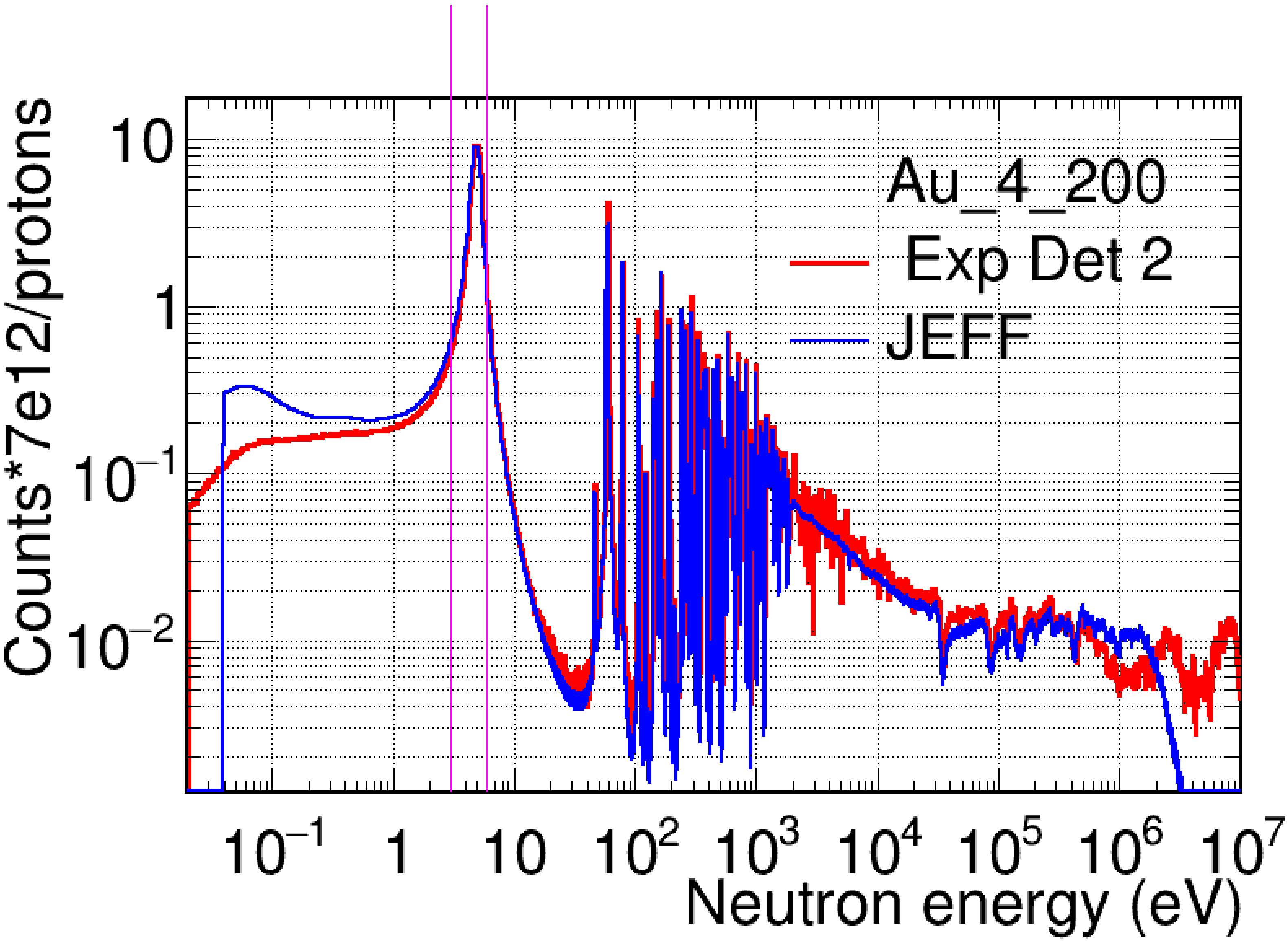
CS of Ta and Au

The CS of ^{197}Au is very similar to the one of Ta, so we would extract the yield of Au to validate the one of Ta.



Comparison of number of counts with JEFF-3.3

The Au sample compared with JEFF-3.3



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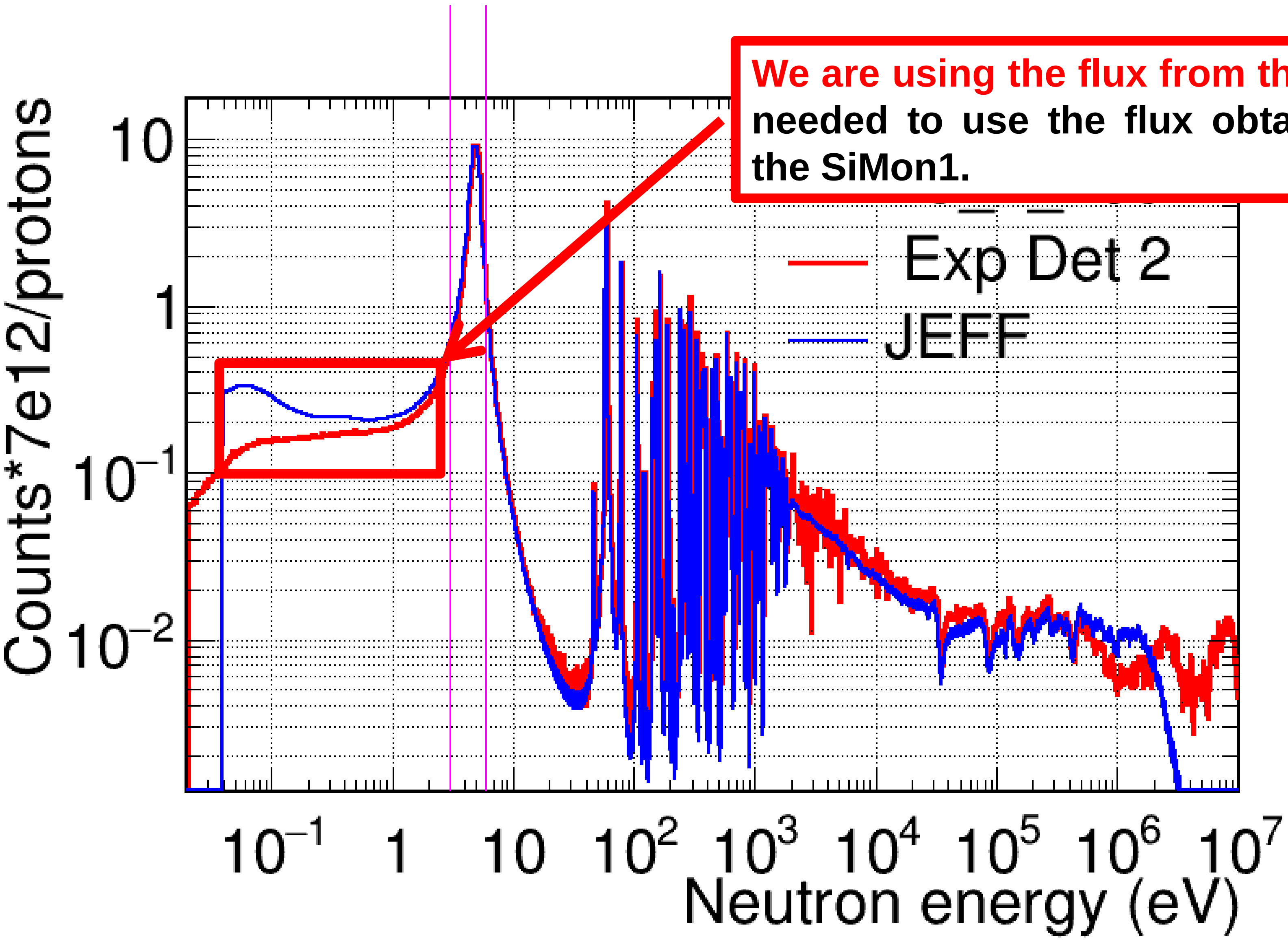
Comparison of number of counts with JEFF-3.3

The Au sample compared with JEFF-3.3



We are using the flux from the TC, it is needed to use the flux obtained with the SiMon1.

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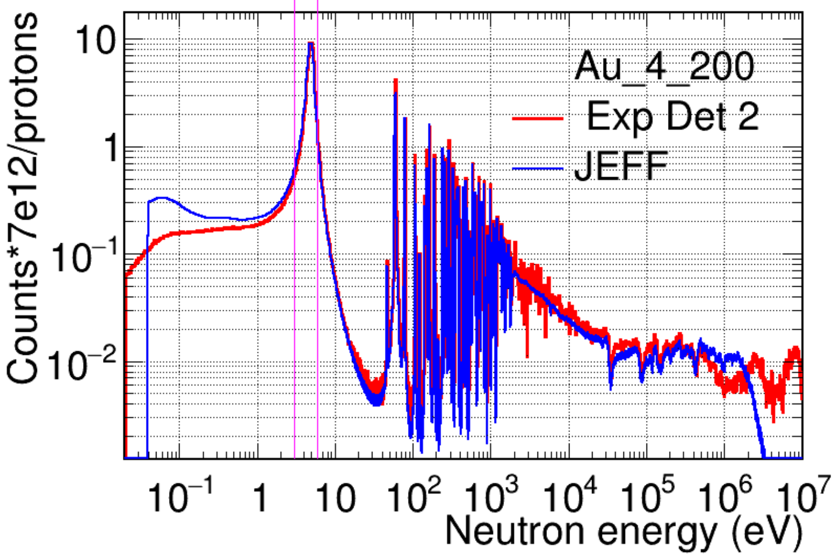
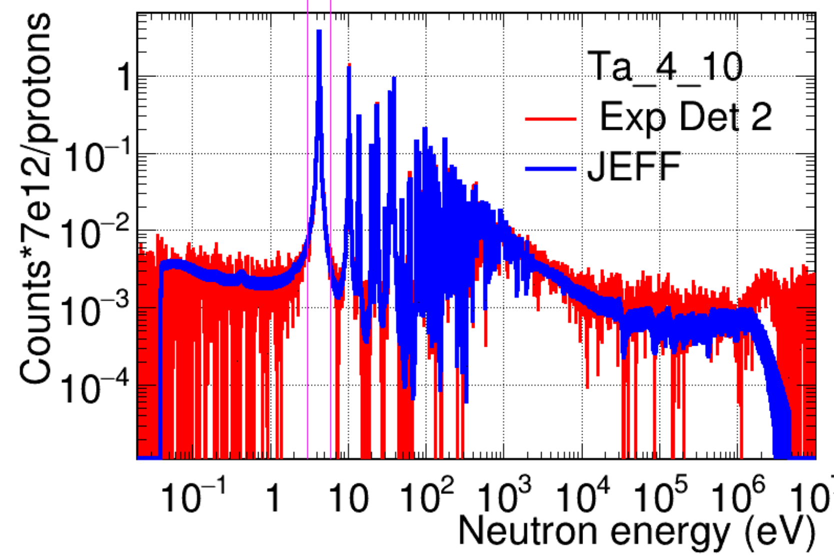
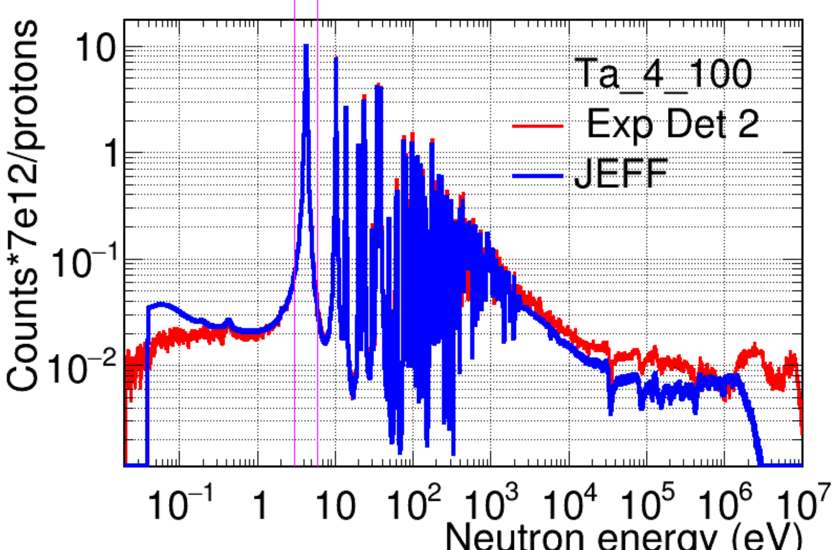
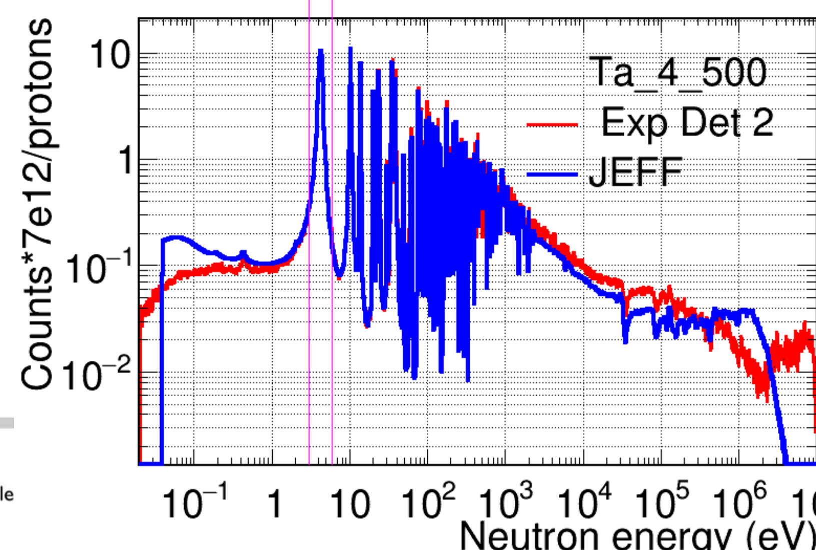
Comparison of number of counts with JEFF-3.3

The different Ta and Au samples are compared with JEFF-3.3



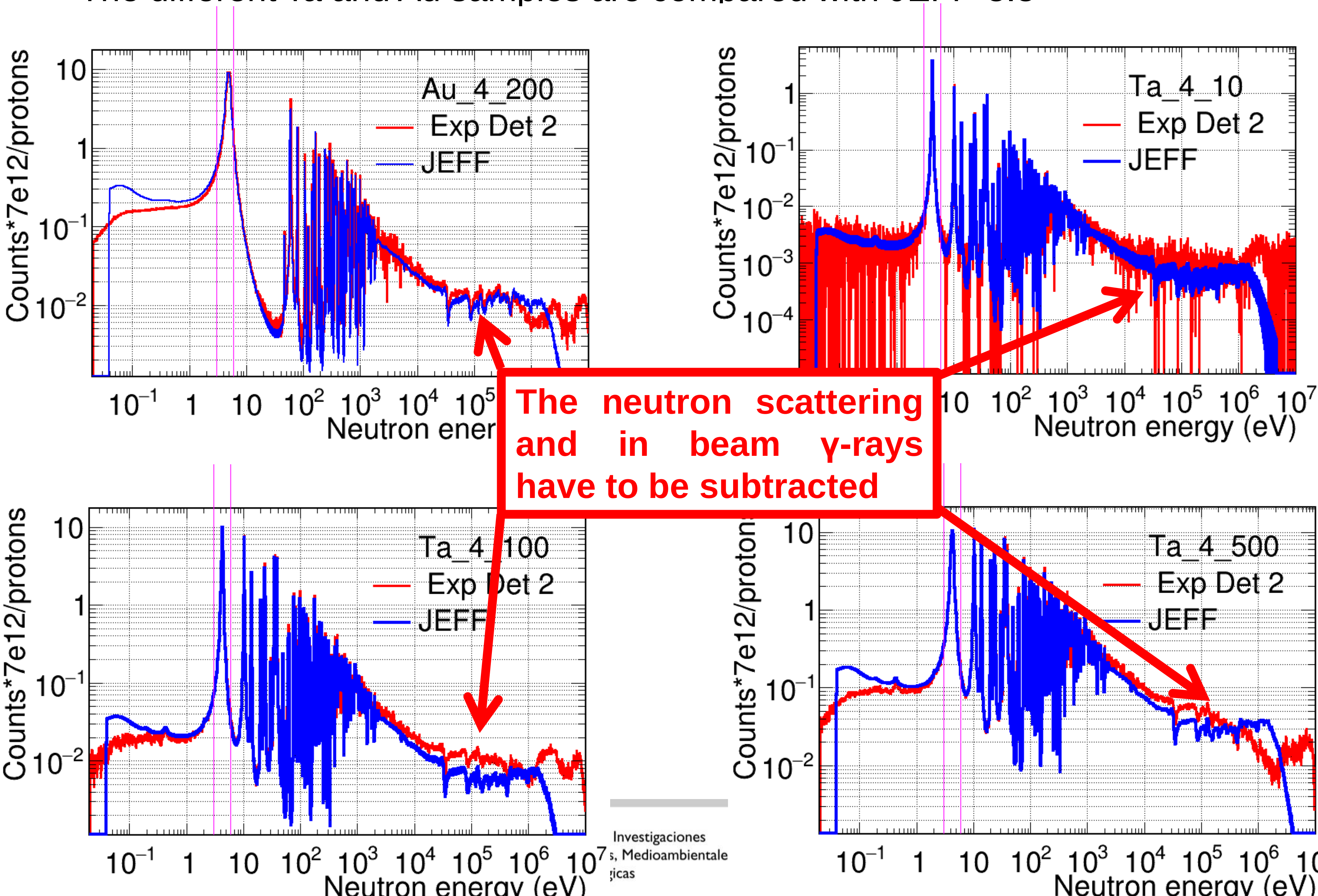






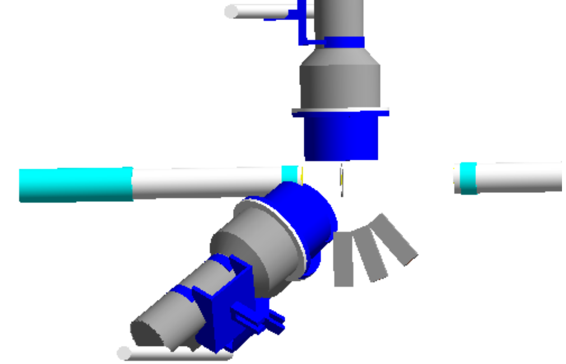
Comparison of number of counts with JEFF-3.3

The different Ta and Au samples are compared with JEFF-3.3



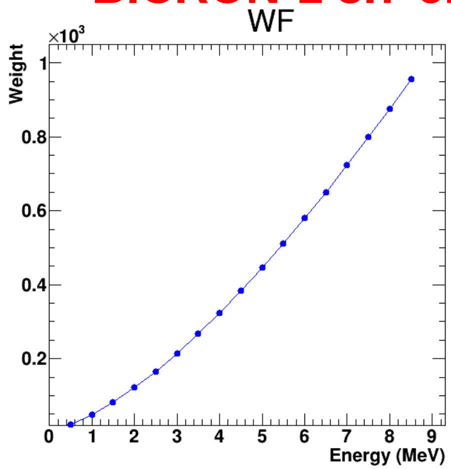
The neutron scattering and in beam γ-rays have to be subtracted

Preliminary calculation of the WF

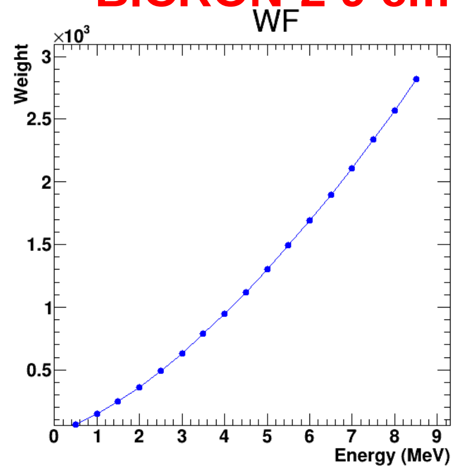


Preliminary determination of the WF with Geant4 without considering the effects of the sample (γ-ray attenuation)

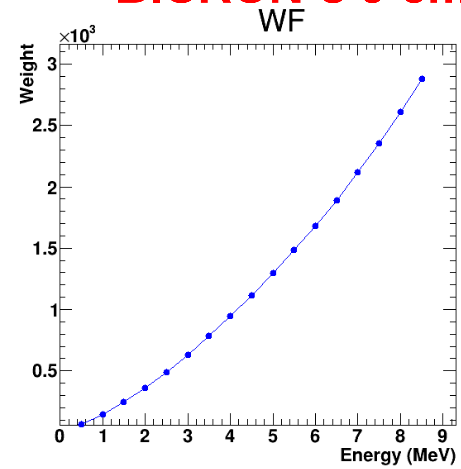
BICRON-1 3.7 cm



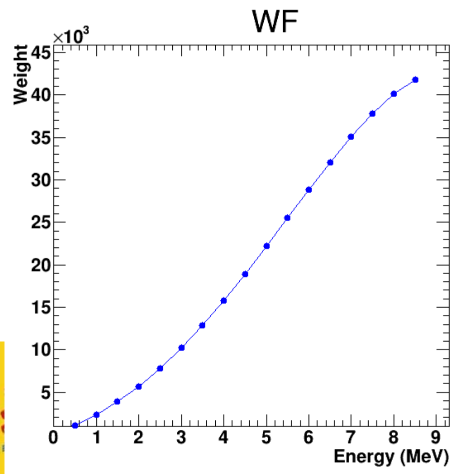
BICRON-2 9 cm



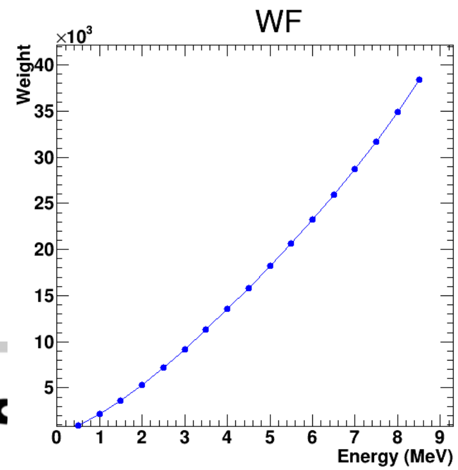
BICRON-3 9 cm



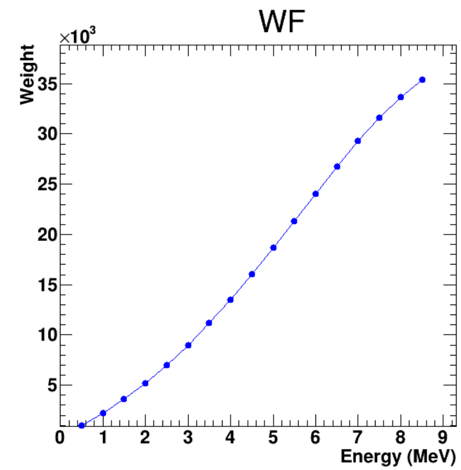
sTED 10 cm 90º



sTED 10 cm 110º



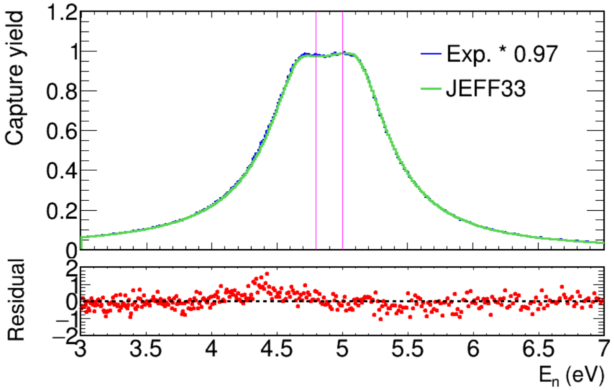
sTED 10 cm 130º



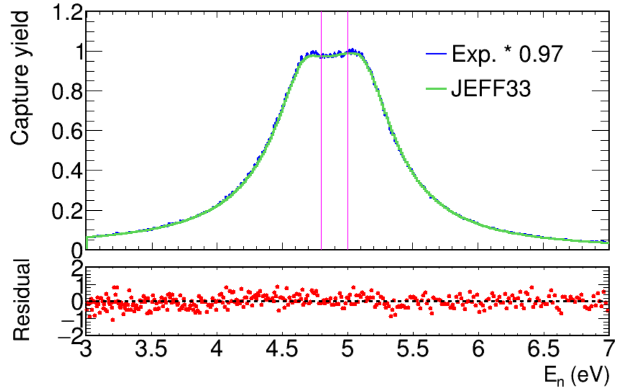
Preliminary calculation of the WF

The values to normalize to the saturated resonances of gold are close to one. We are missing the threshold and other corrections. Using RF RF_EAR1_test_18447_rEn1_rL1.txt provided by Adria.

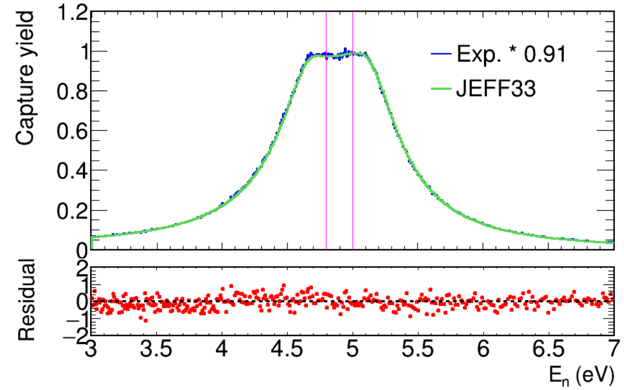
BICRON-1 3.7 cm



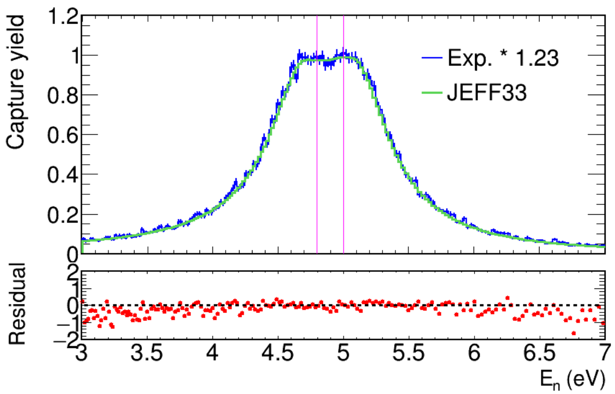
BICRON-2 9 cm



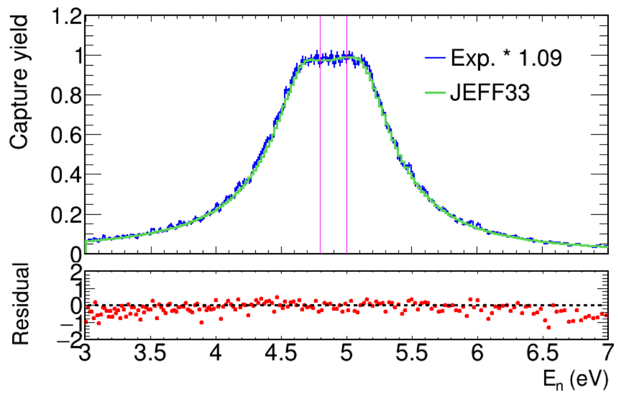
BICRON-3 9 cm



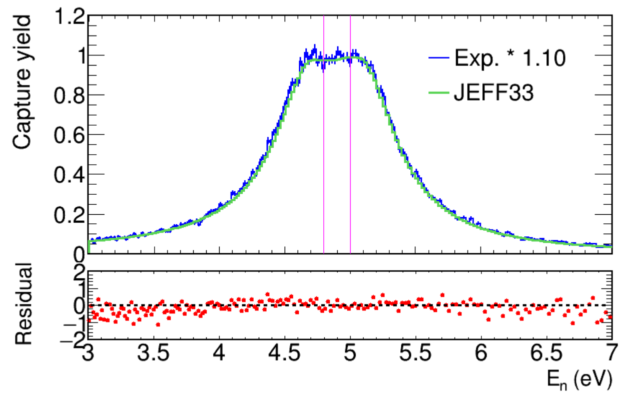
sTED-5 10 cm 90º



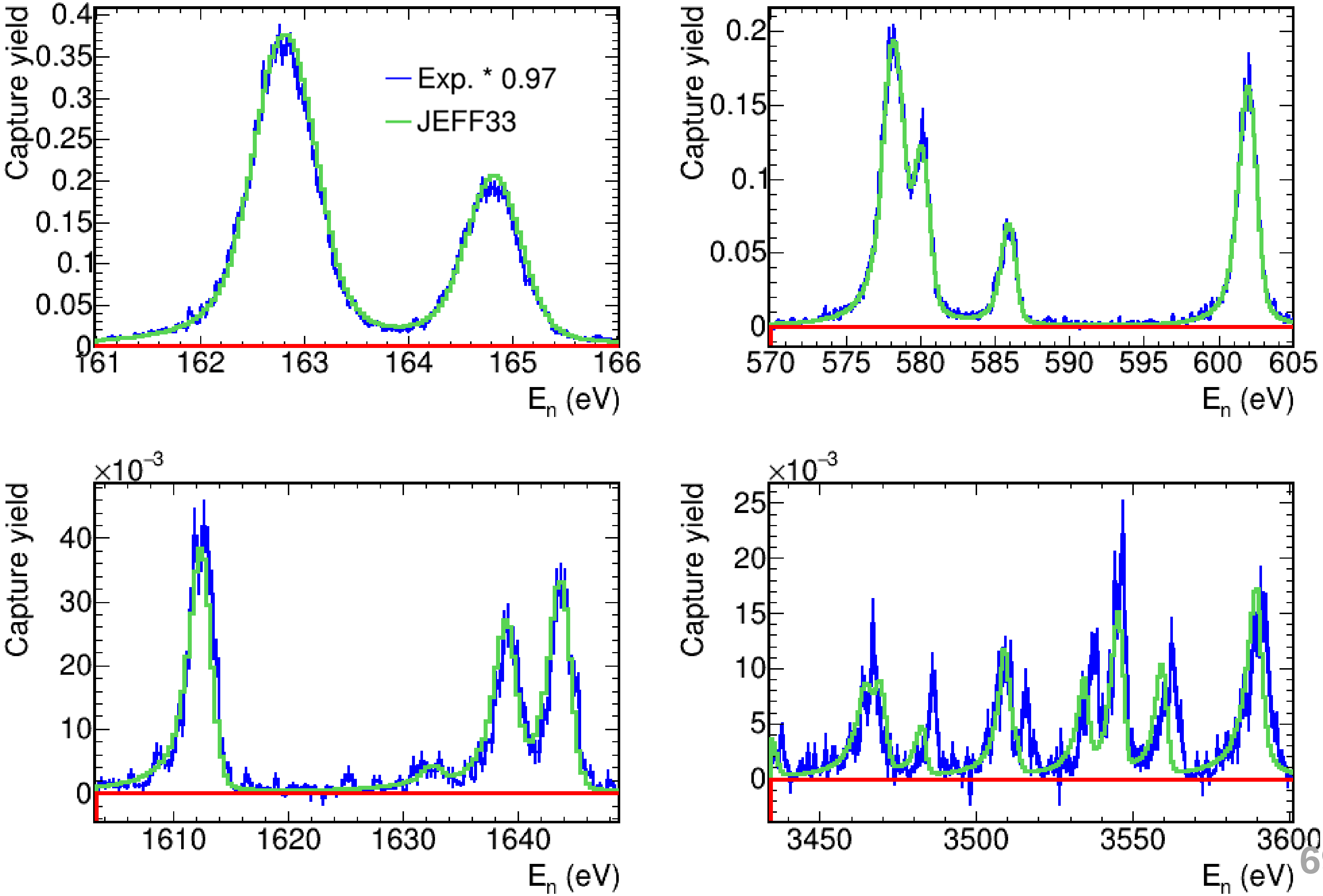
sTED-6 10 cm 110º



sTED-7 10 cm 130º

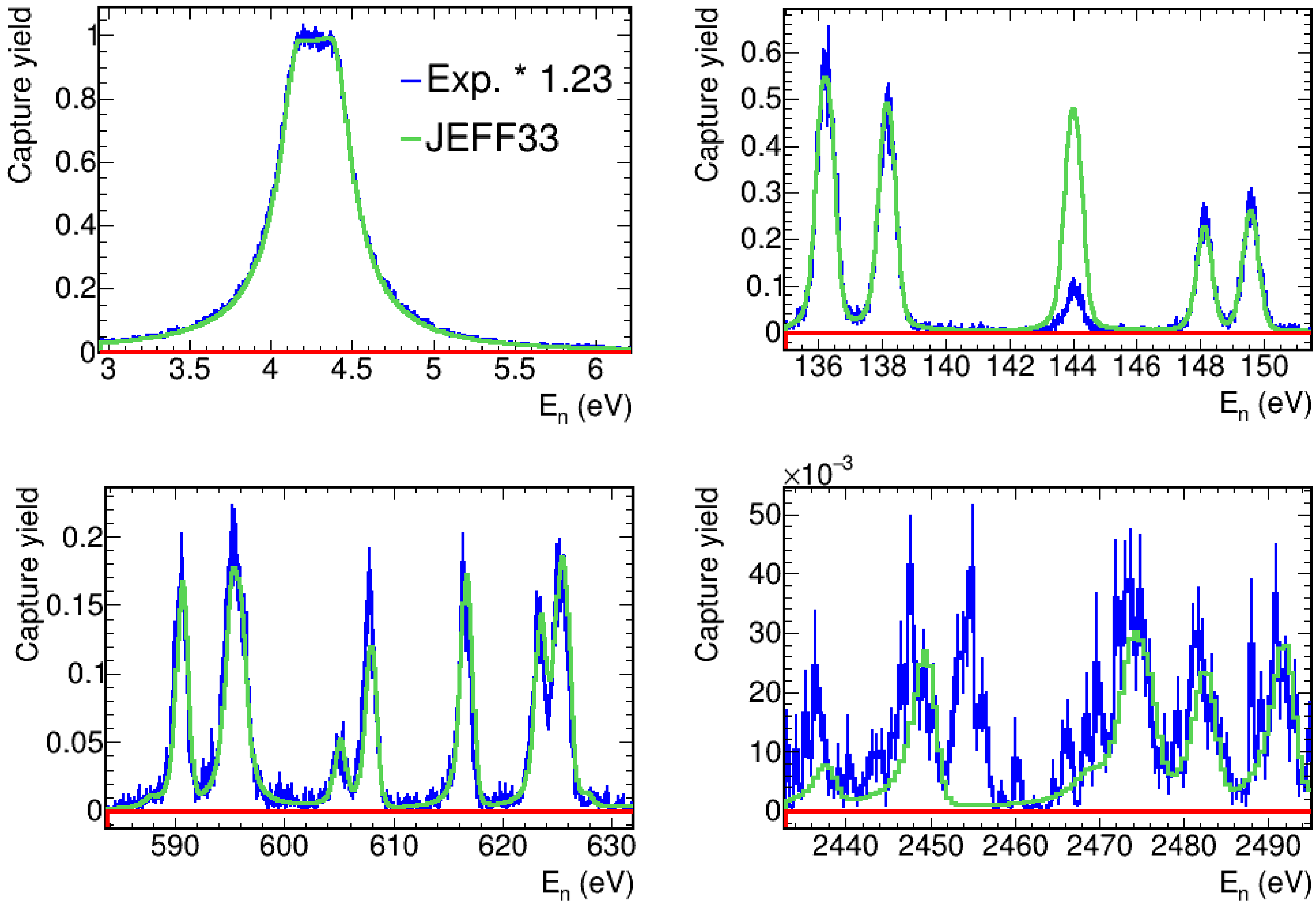


Compare Au with JEFF-3.3



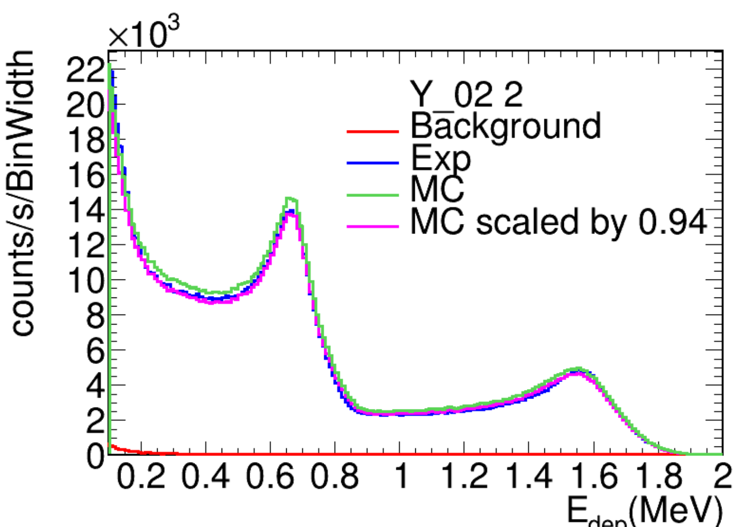
Preliminary comparison for Ta-500 µm

Yield of the Ta of 500 µm normalized to the first resonance



Summary and conclusions

- **The experiment is still on going** but the data looks promising.
- The preliminary calibrations with 8 γ-rays sources looks very nice in **all the range of the measurement**.
- The monitoring of the experiment shows that there are not major problems.
- **Different samples and detectors** would allow to check all the corrections and to reduce the uncertainties.



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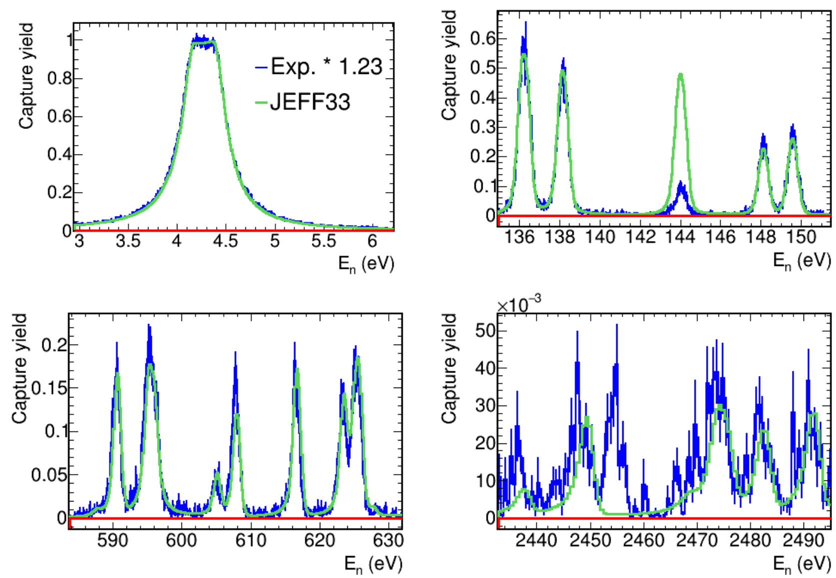


Summary, conclusions and requested protons

- Erbium has been proposed to be used as **burnable absorber** in commercial nuclear reactors, instead of gadolinium.

- The uncertainty CS of ^{167}Er in the RRR in ENDF-VIII is ~2.3%, it has been shown that this value is underestimate. There is a **new entrance in the HPRL of NEA for new measurements with uncertainties close to 2%.**

- The cross sections of ^{166,168,170}Er also play a important role for reactors and the uncertainties are from 7 to 15% in the RRR. New precise measurements are needed

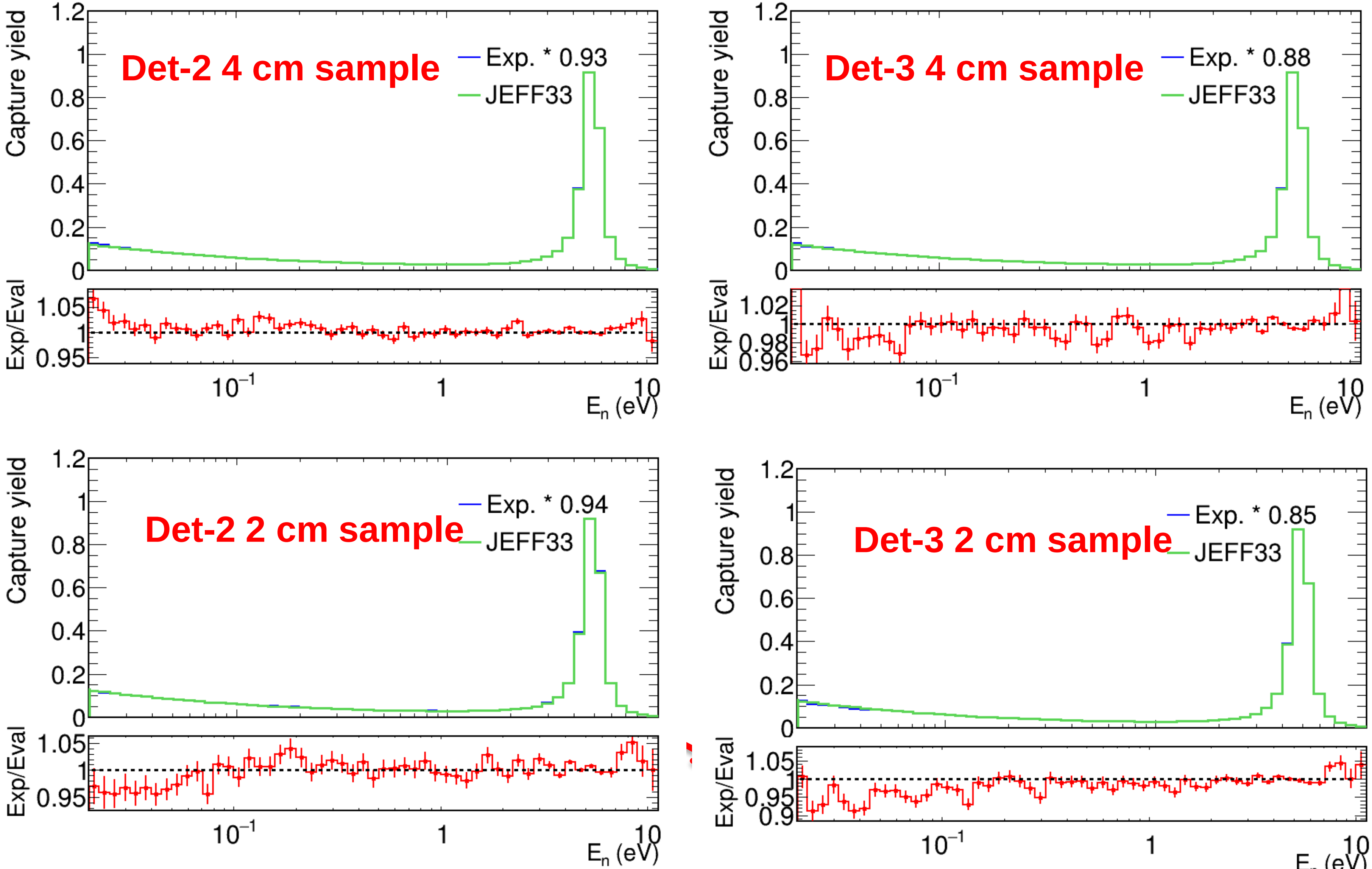
- A measurement with a **natural Er sample using the C6D6 and the TAC** is proposed to fulfill the HPRL requirements between 0.01 and 50 eV.

- **Four measurements with ~200 mg enriched samples of ^{166,167,168,170}Er** with C6D6 are also proposed.

Sample	Mass	Detector	Energy range	Number protons
Natural	30mg	TAC	0.01-50 eV	$1.0 \cdot 10^{18}$
Natural	30mg	C_6D_6	0.01-50 eV	$1.5 \cdot 10^{18}$
^{166}Er	200mg	C_6D_6	10 eV-100 keV	$1.0 \cdot 10^{18}$
^{167}Er	200mg	C_6D_6	50 eV-500 keV	$1.0 \cdot 10^{18}$
^{168}Er	200mg	C_6D_6	50 eV-100 keV	$1.5 \cdot 10^{18}$
^{170}Er	200mg	C_6D_6	50 eV-50 keV	$1.5 \cdot 10^{18}$
TAC auxiliary and normalization measurements				$0.5 \cdot 10^{18}$
C_6D_6 auxiliary and normalization measurements				$1.0 \cdot 10^{18}$
Total				$9.0 \cdot 10^{18}$

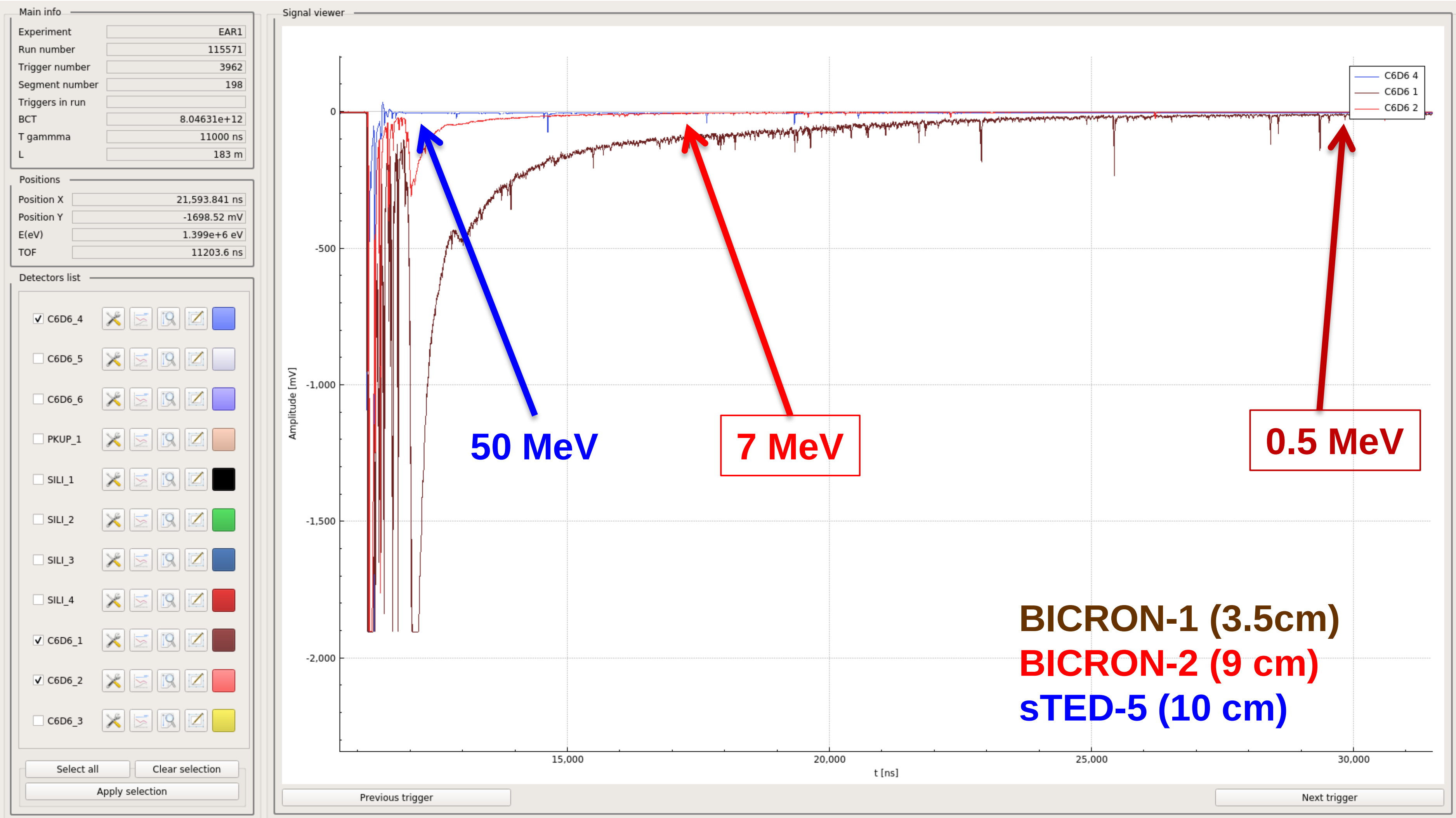
Comparison of the Au results with evaluations

The new flux reproduce the shape of Au in the thermal region very accurate



Measurements with beam

In general terms the response of the detectors are reliable:



Thermal Epithermal eXperiments (TEX)

TEX is a project to perform critical experiments that span a wide range of fission energy. The ^{239}Pu experiments of TEX were performed with Ta as a diluent.

Preliminary results with ZPPR

Adding tantalum worsened the calculated results, with **intermediate and fast systems calculating approximately 0.5-1.5% differences** pointing to issues with the tantalum cross sections.

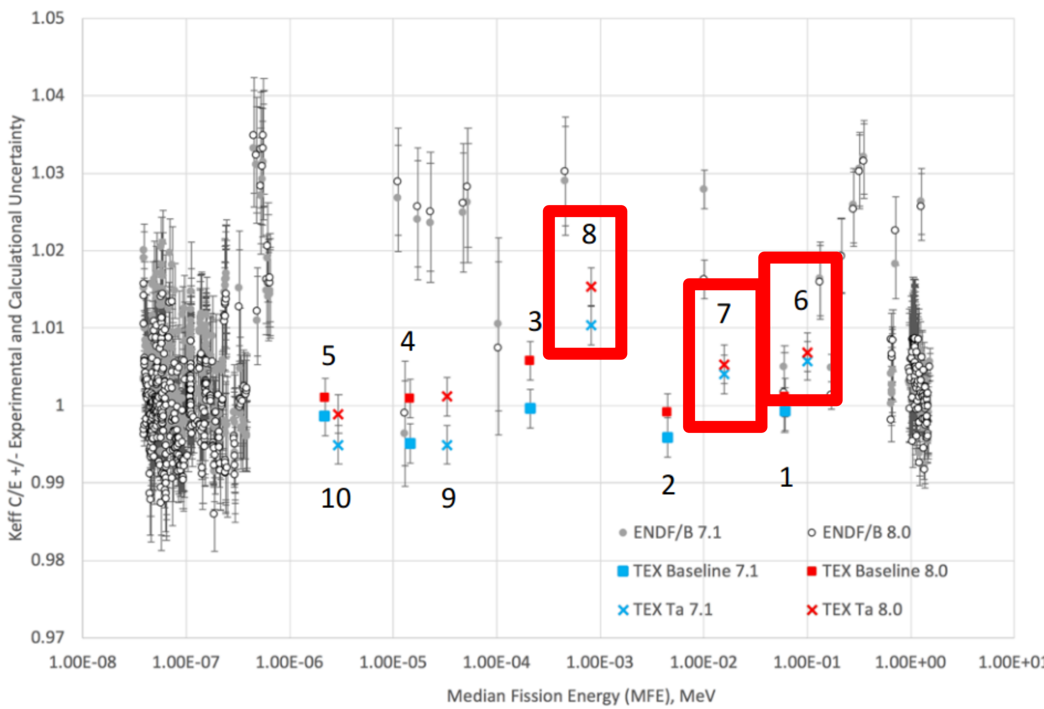
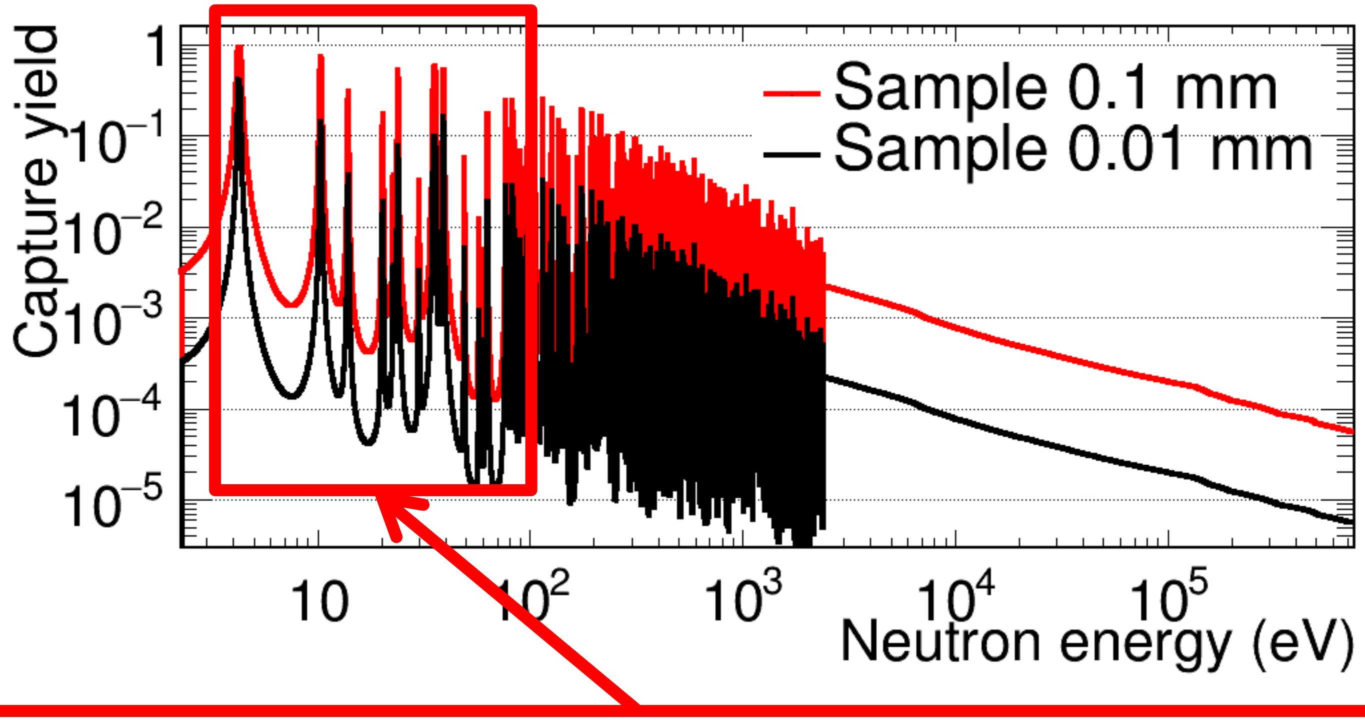


Fig. 2. Plutonium TEX Calculational over Experimental (C/E) Results (colored markers), Overlaid with Plutonium Benchmark Configurations (gray markers) as a Function of Medium Fission Energy.

The measurement with the Thick sample (0.1 mm)

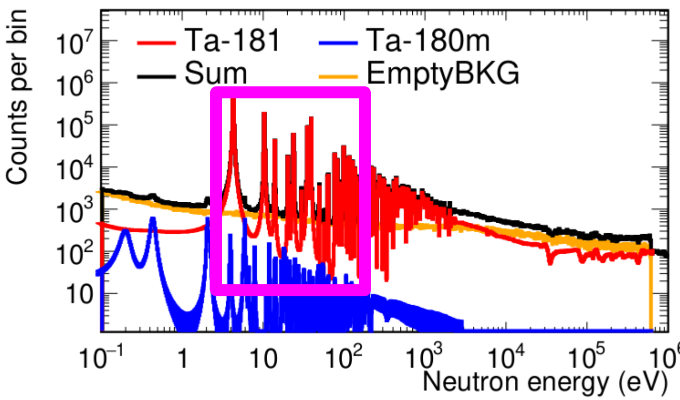
A *Thick* sample of 0.1 mm would be measured, this samples is thinner than the ones used in previous measurements, so no strong shelf-shielding, photon attenuation or multiple corrections would be needed.



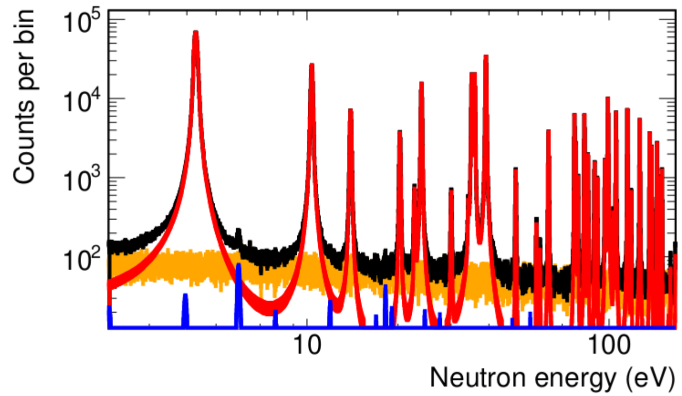
The yield for the *Thick* sample at energies below 200 is close to 1, in order to avoid the considerable corrections a *Thin* sample of 0.01 mm would be used.

The counting rates estimations

Two samples to measure two different energy regions, the counts estimates with $7x10^{17}$ protons.

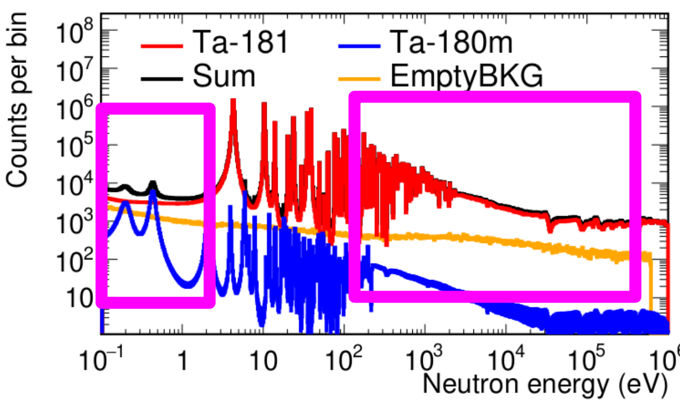


(a) *Thin* sample (0.01 mm), 100 bins per decade

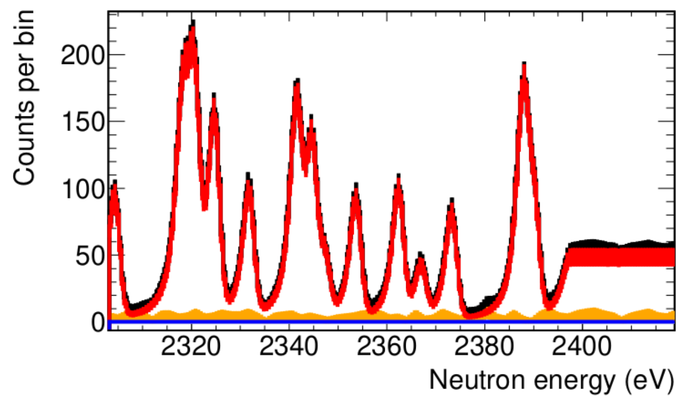


(b) *Thin* sample (0.01 mm), 1000 bins per decade

At least 2000 counts per resonance to fit the RP



(c) *Thick* sample (0.1 mm), 100 bins per decade



(d) *Thick* sample (0.1 mm), 10000 bins per decade

~3% statistical uncertainty in the URR 100 bins decade

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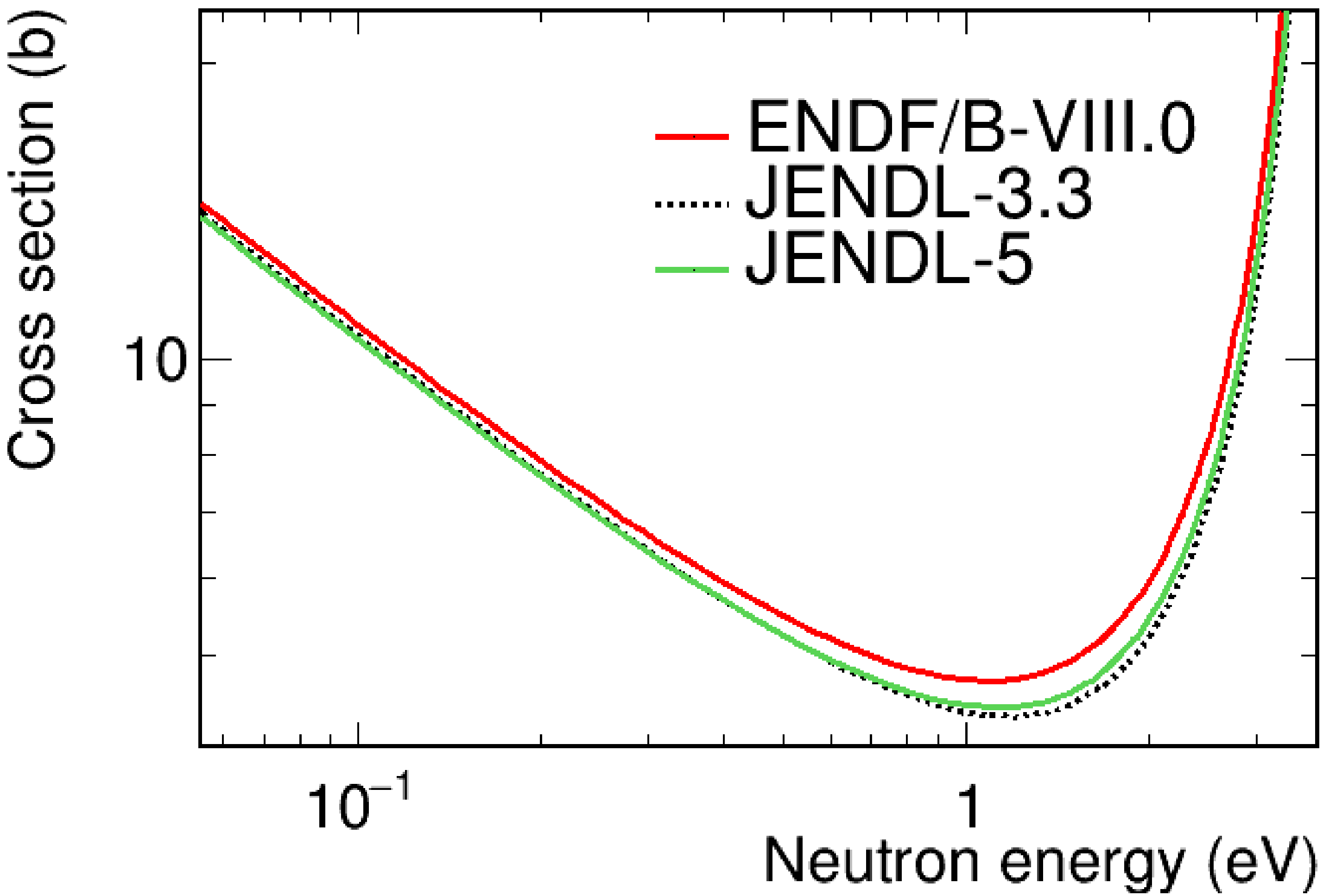
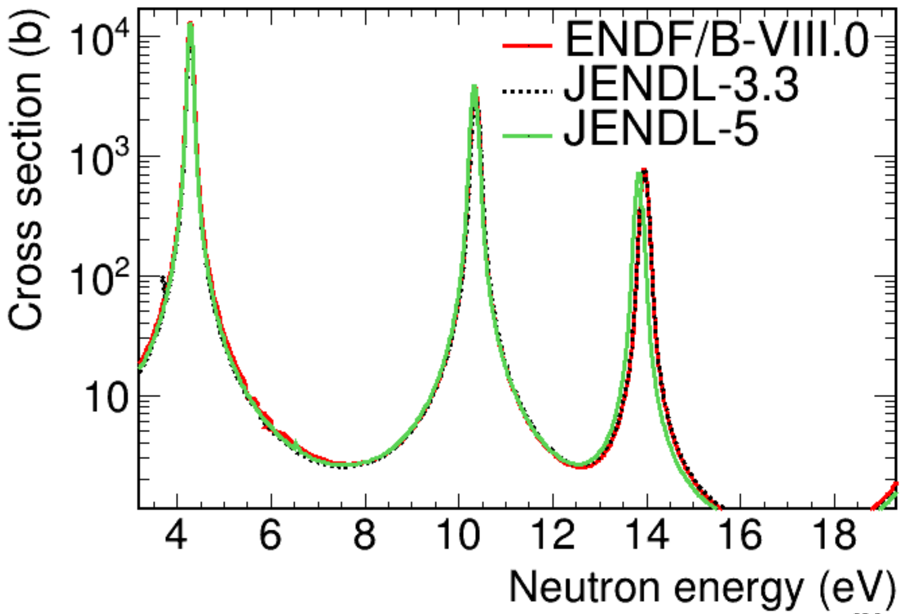
Differences between evaluations

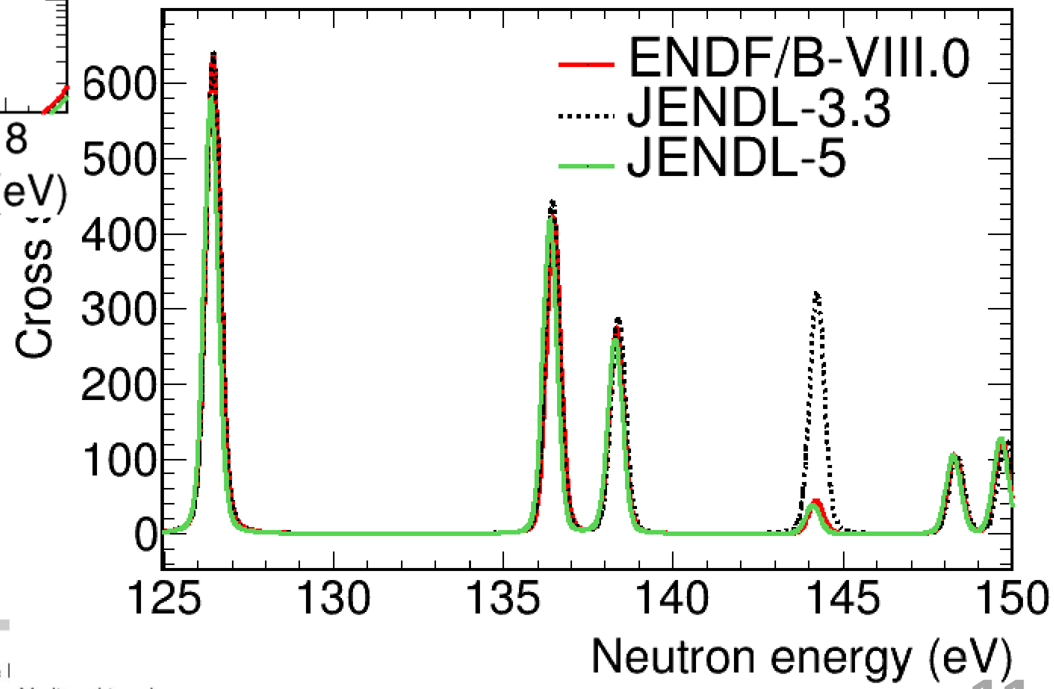
At energies below 4 eV ENDF/B-VIII.0 is ~5% higher than JENDL-5



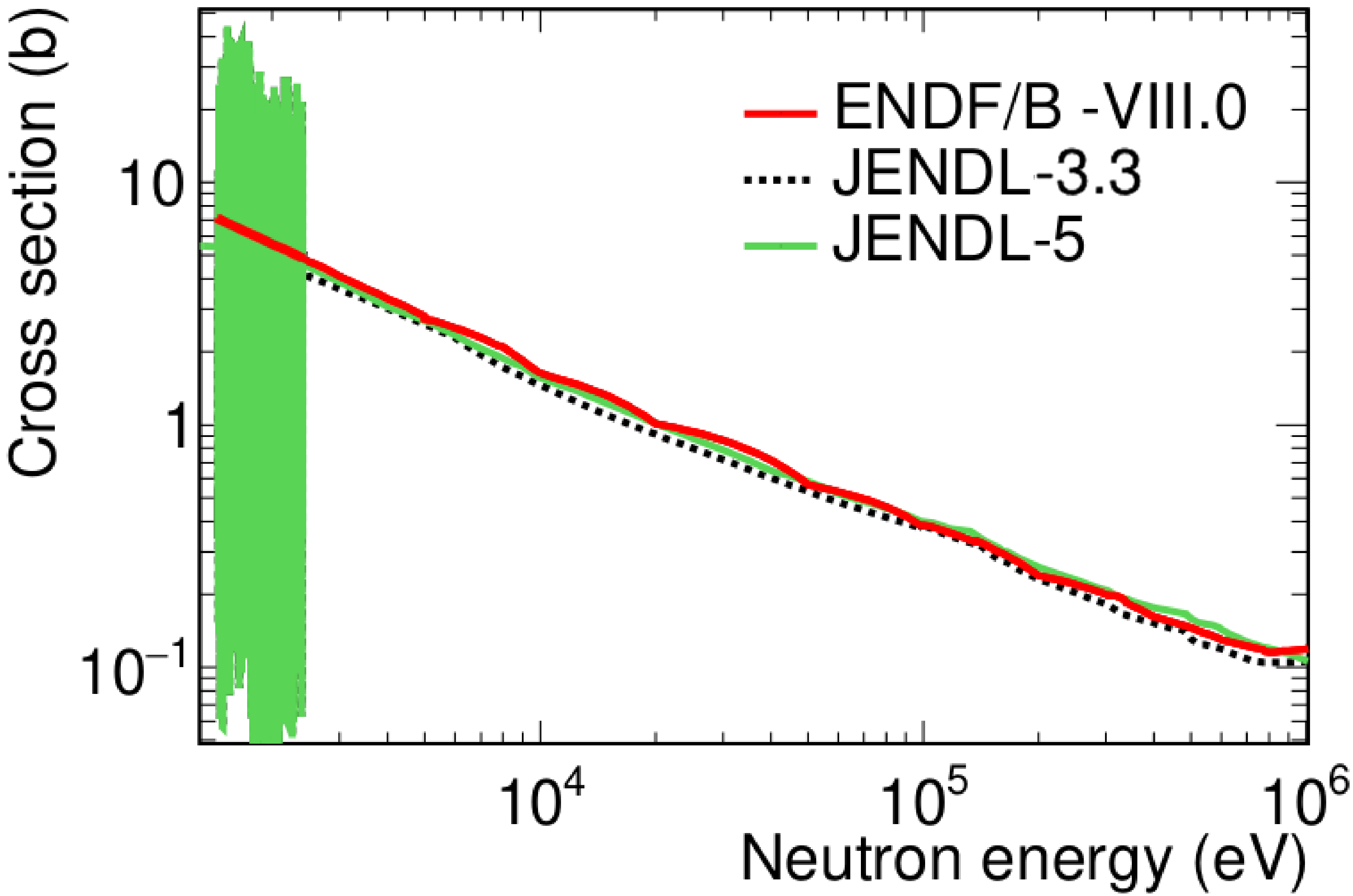
Differences between evaluations

Differences in the RRR between ENDF-8, JENDL-3.3 and JENDL-5

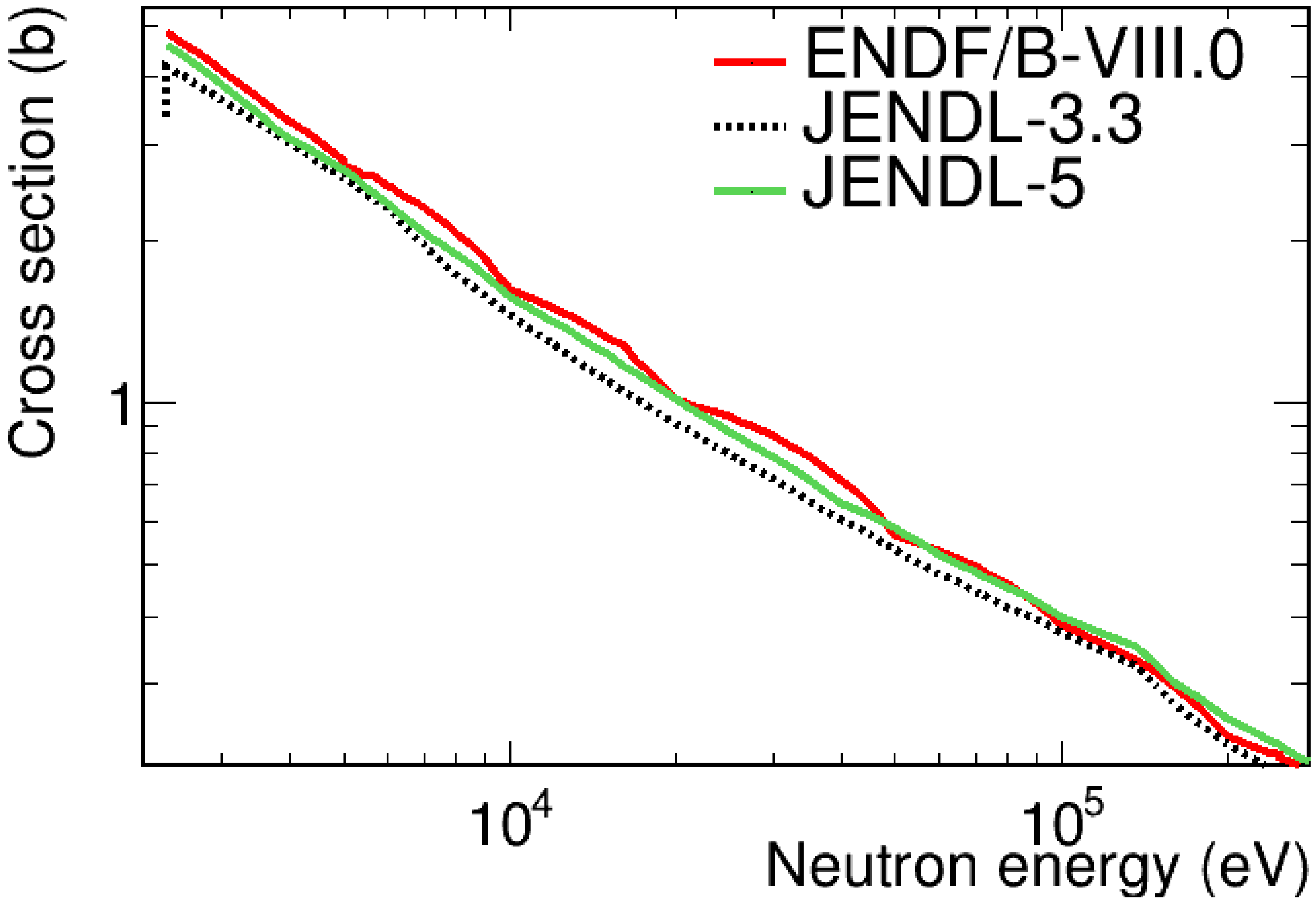




Differences between evaluations

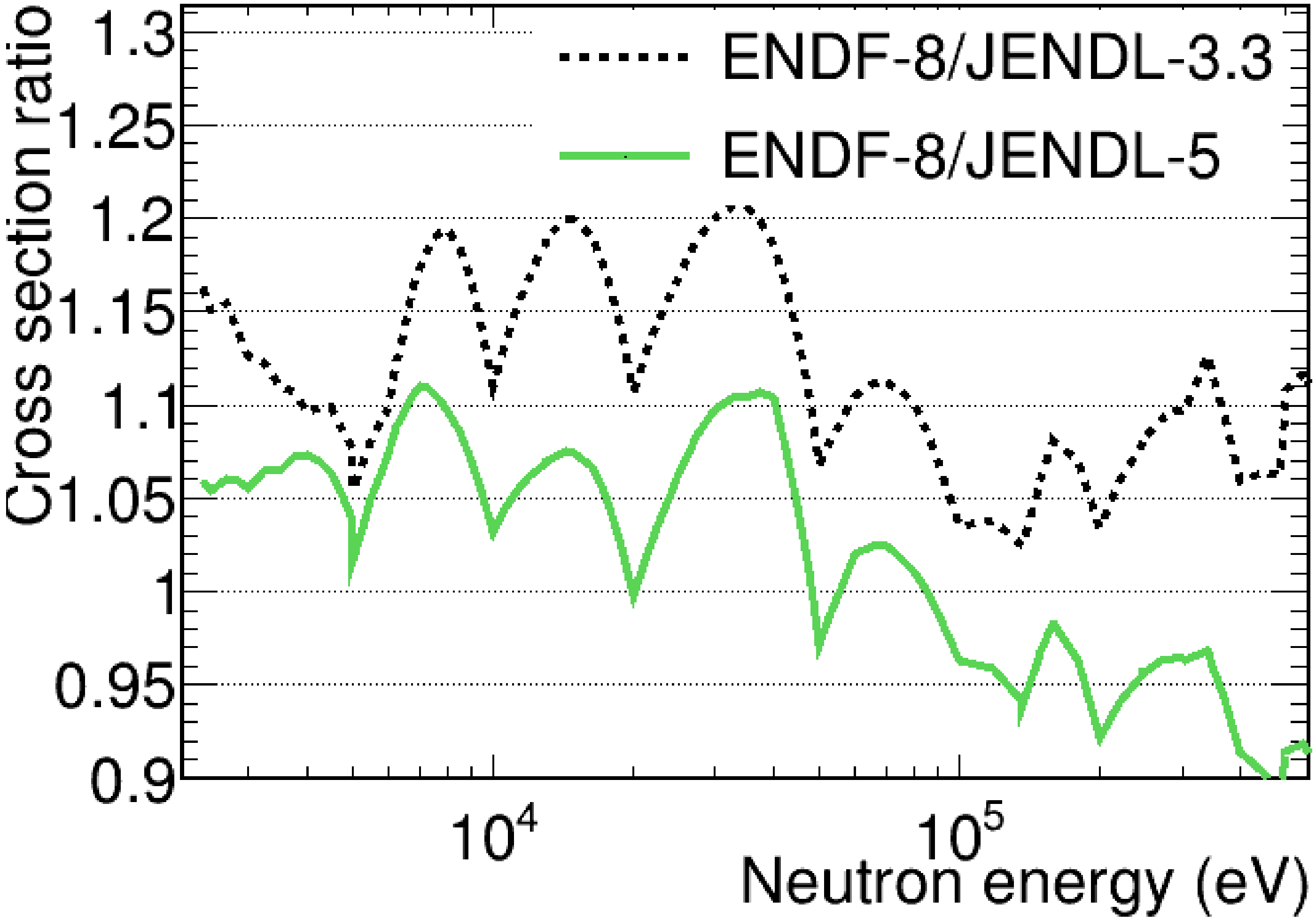


Differences between evaluations

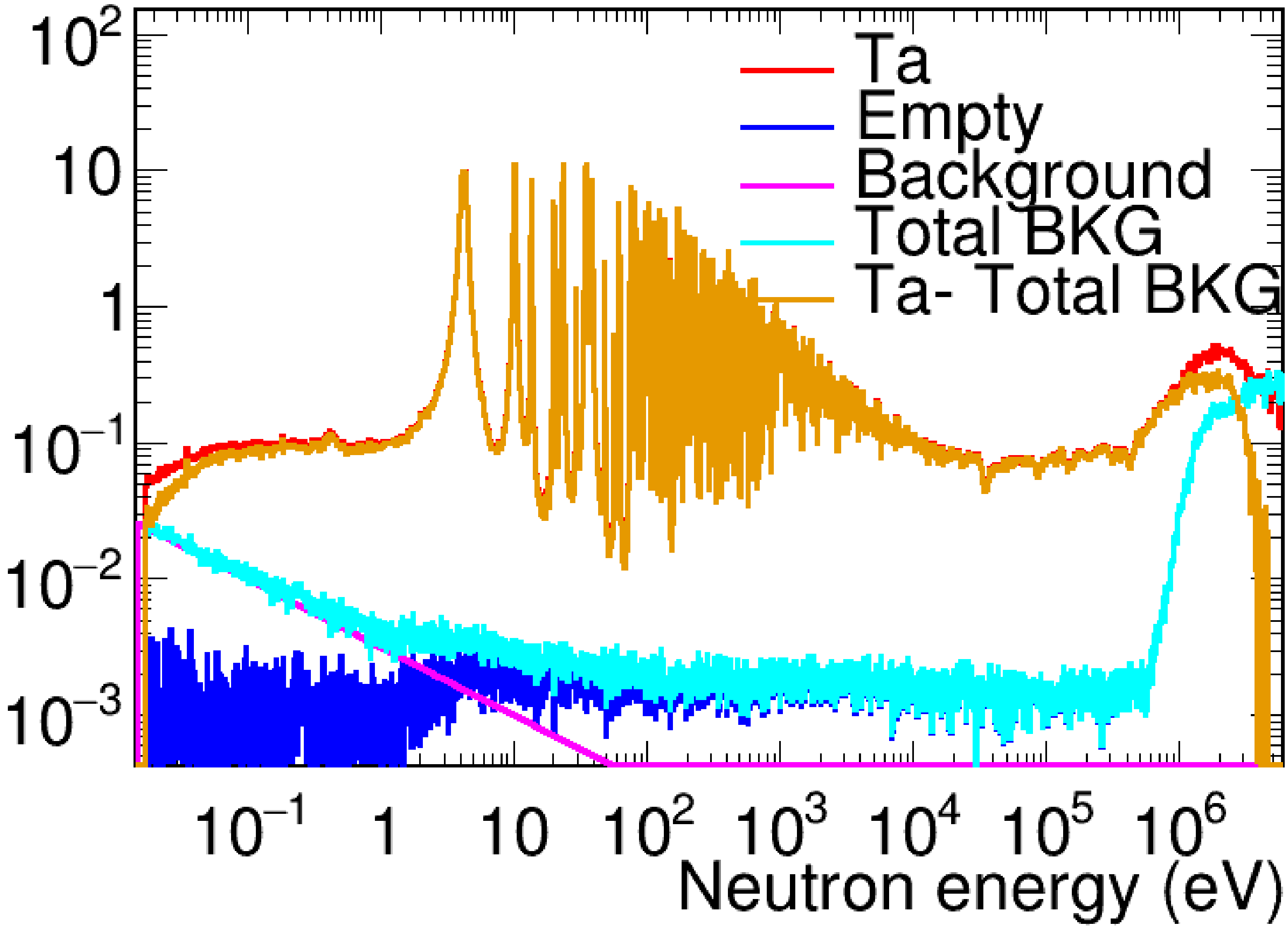


Differences between evaluations

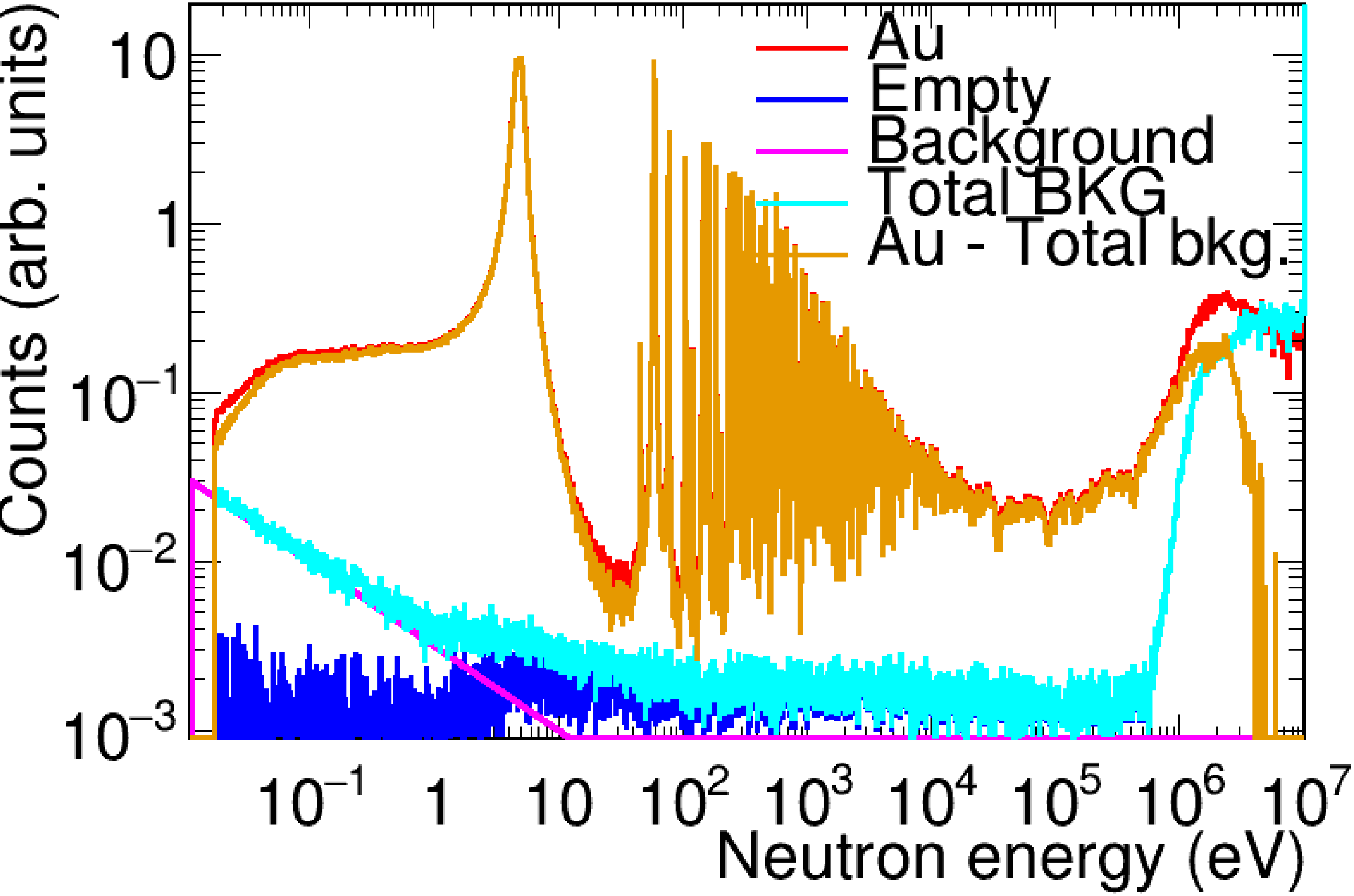
Differences in the URR are as high as 10% between ENDF-8 and JENDL-5



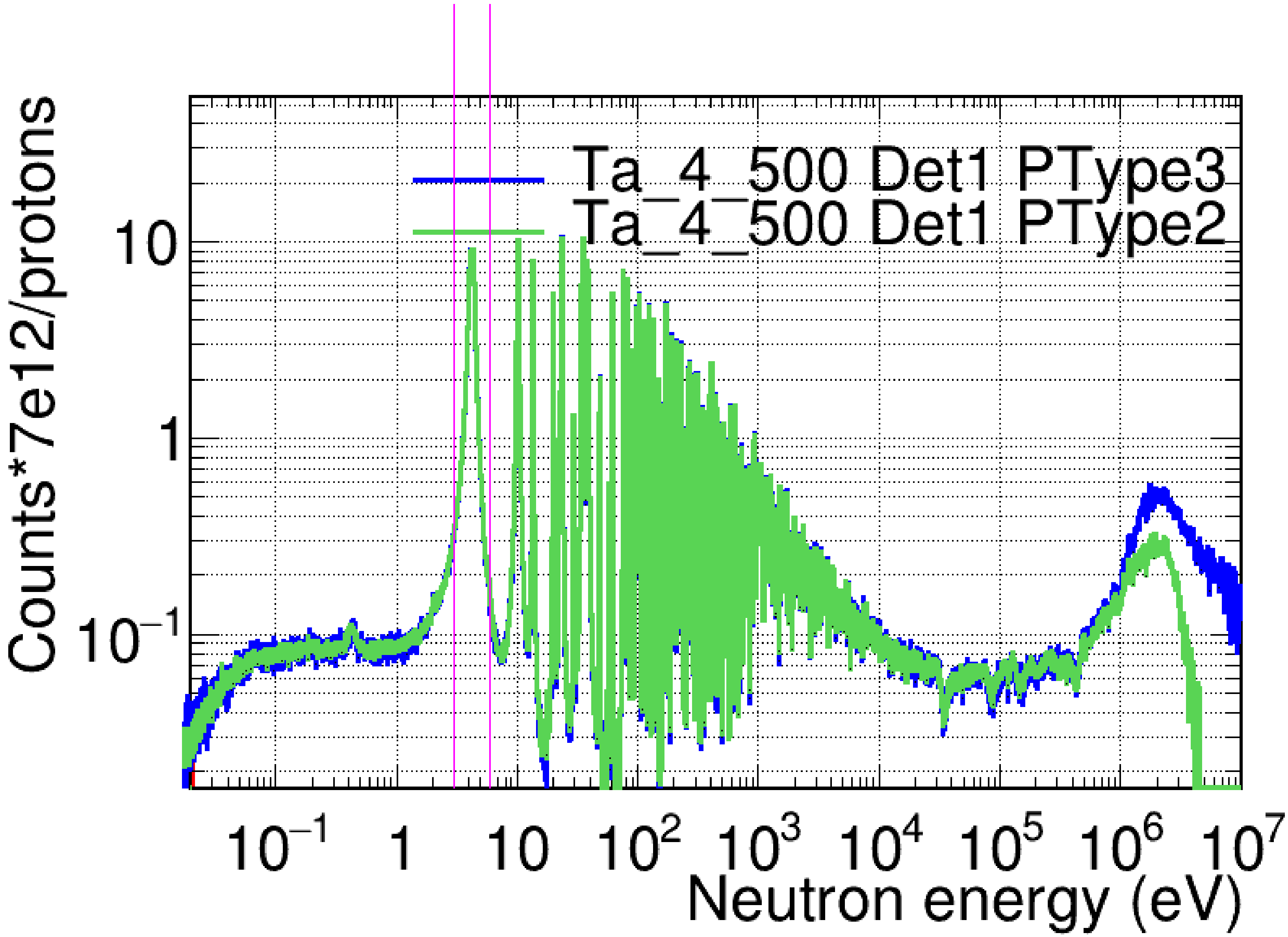
Background subtraction Ta-4cm-500um



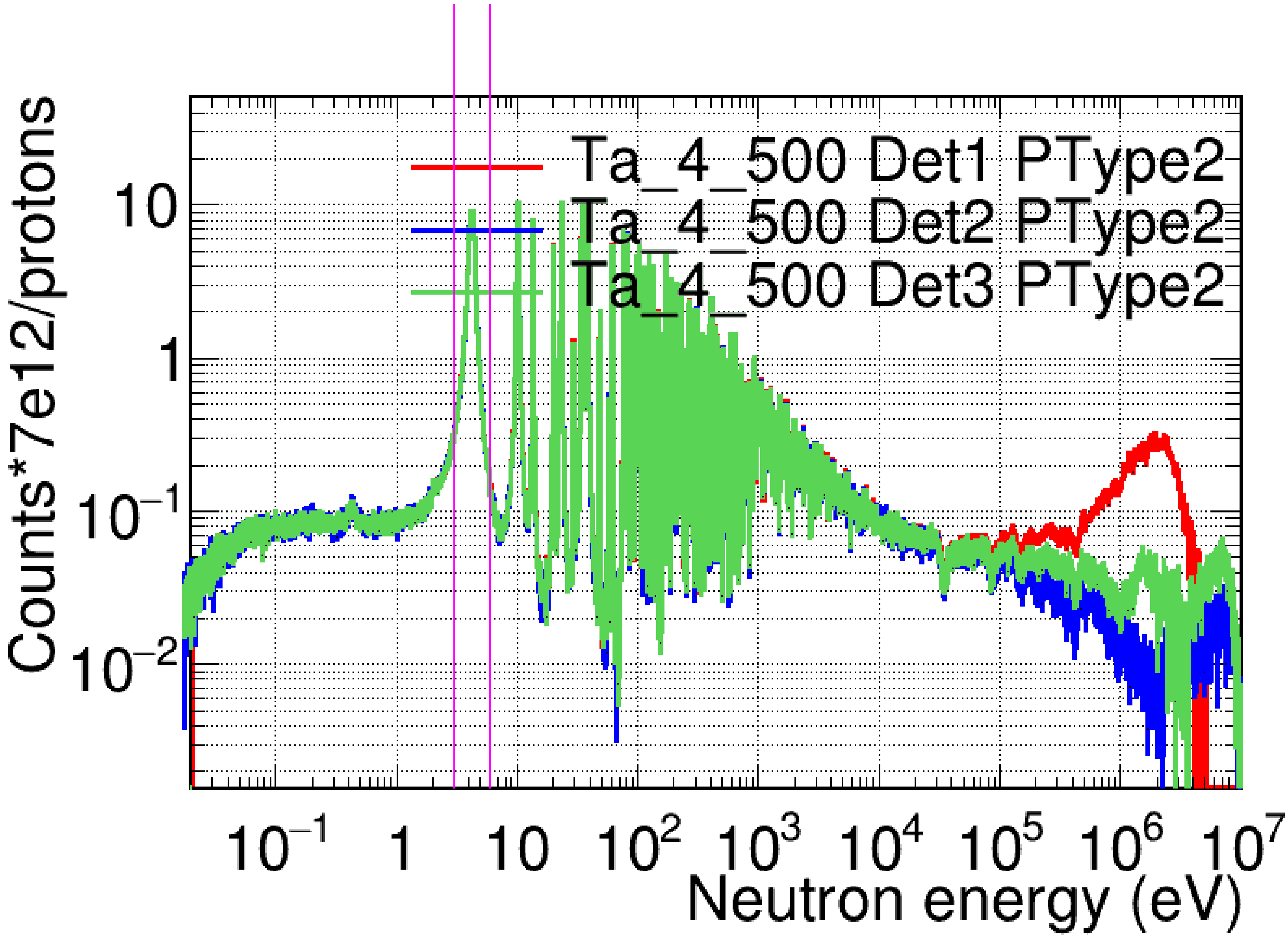
Background subtraction Au-4cm-200um



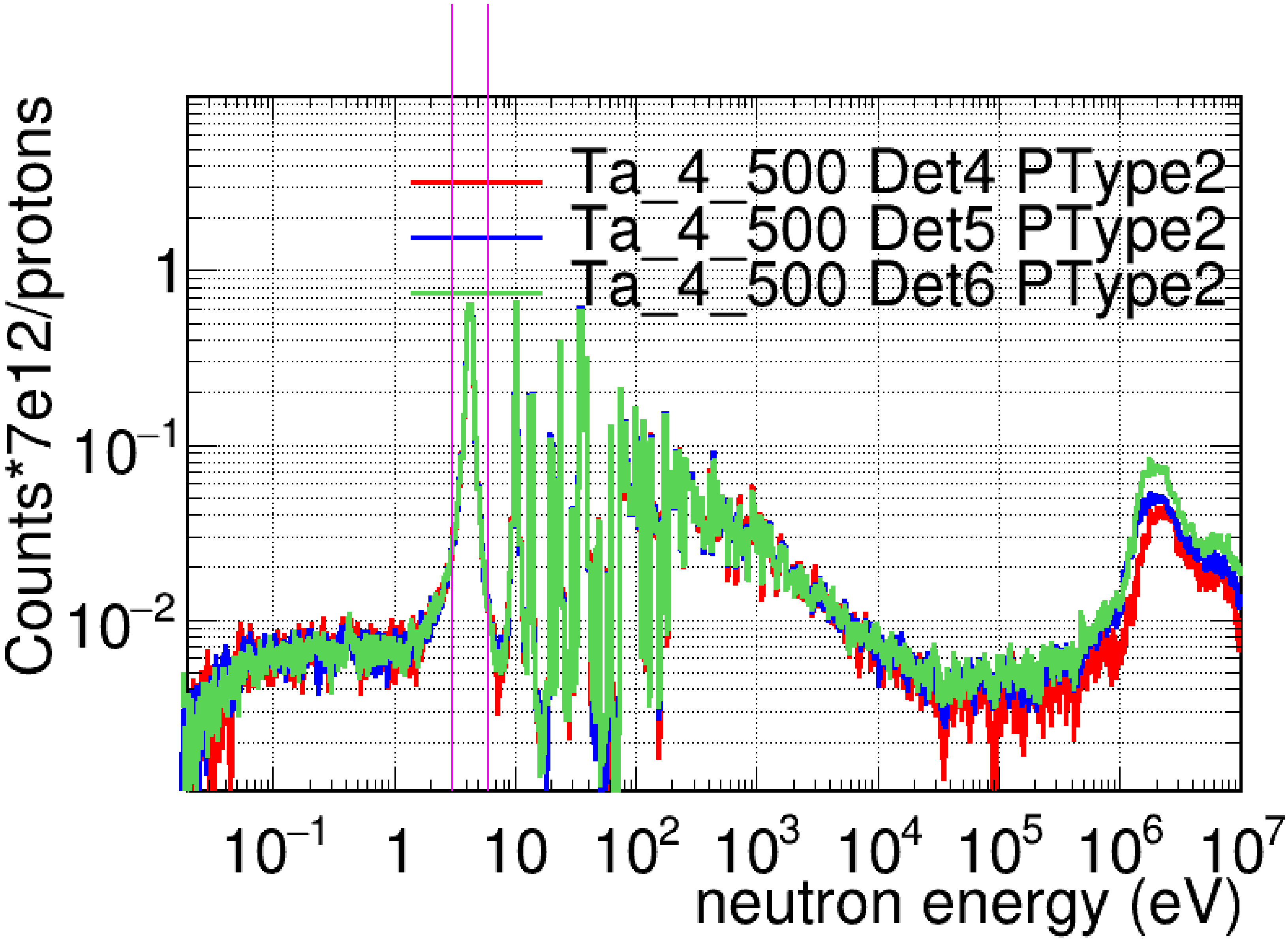
Compare Primary and parasitic



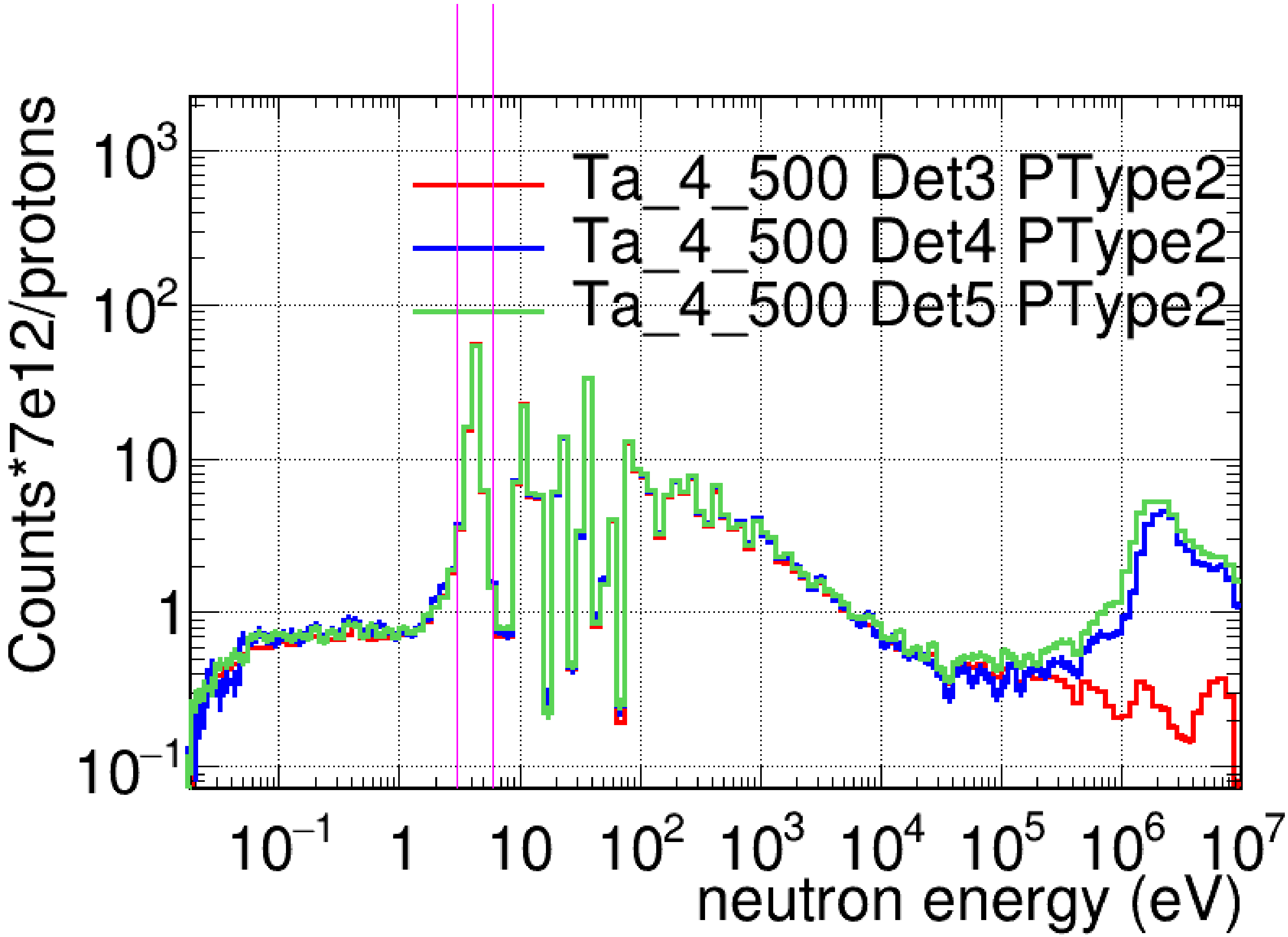
Compare 3 BICRON



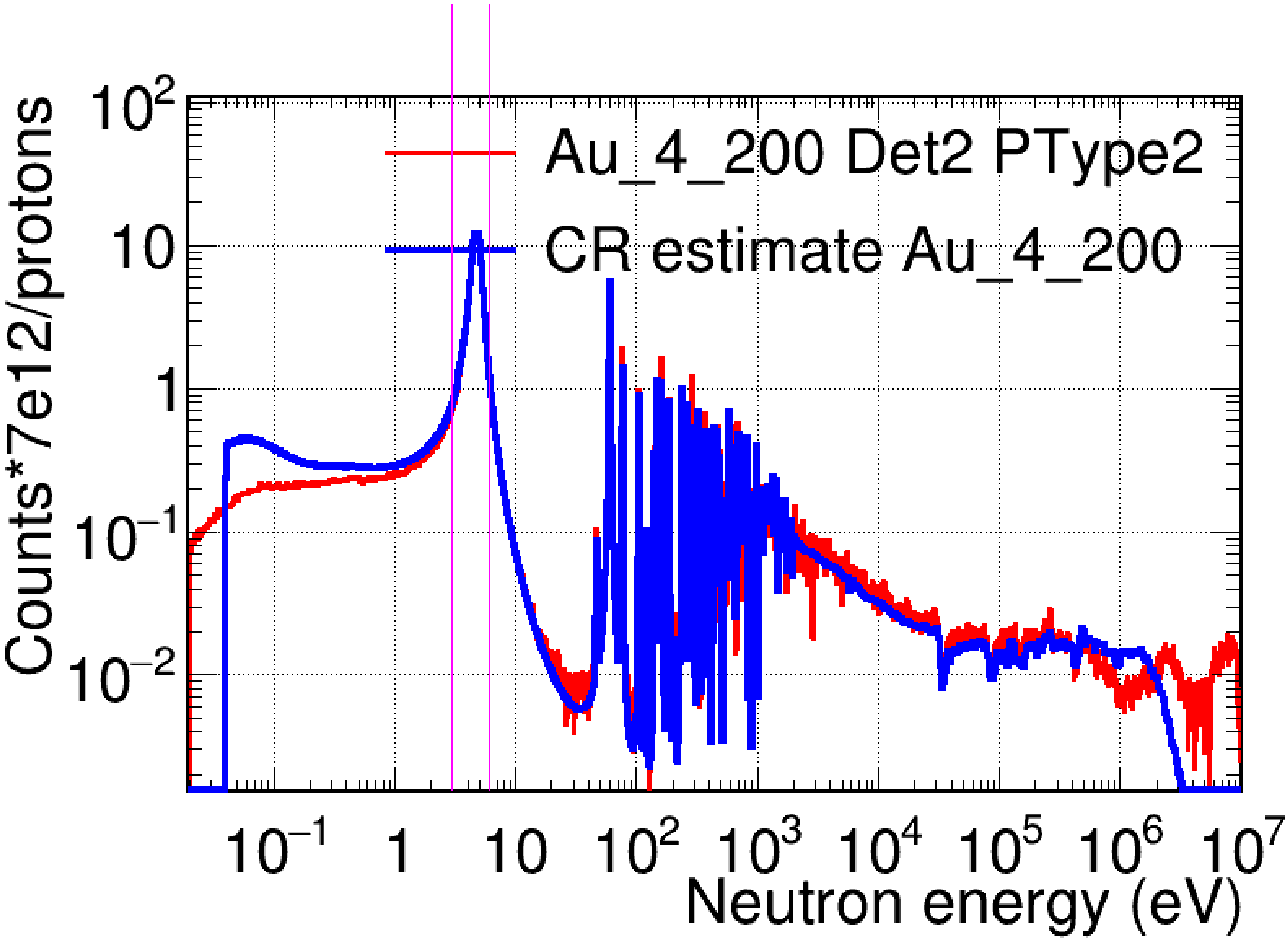
Compare 3 sTED



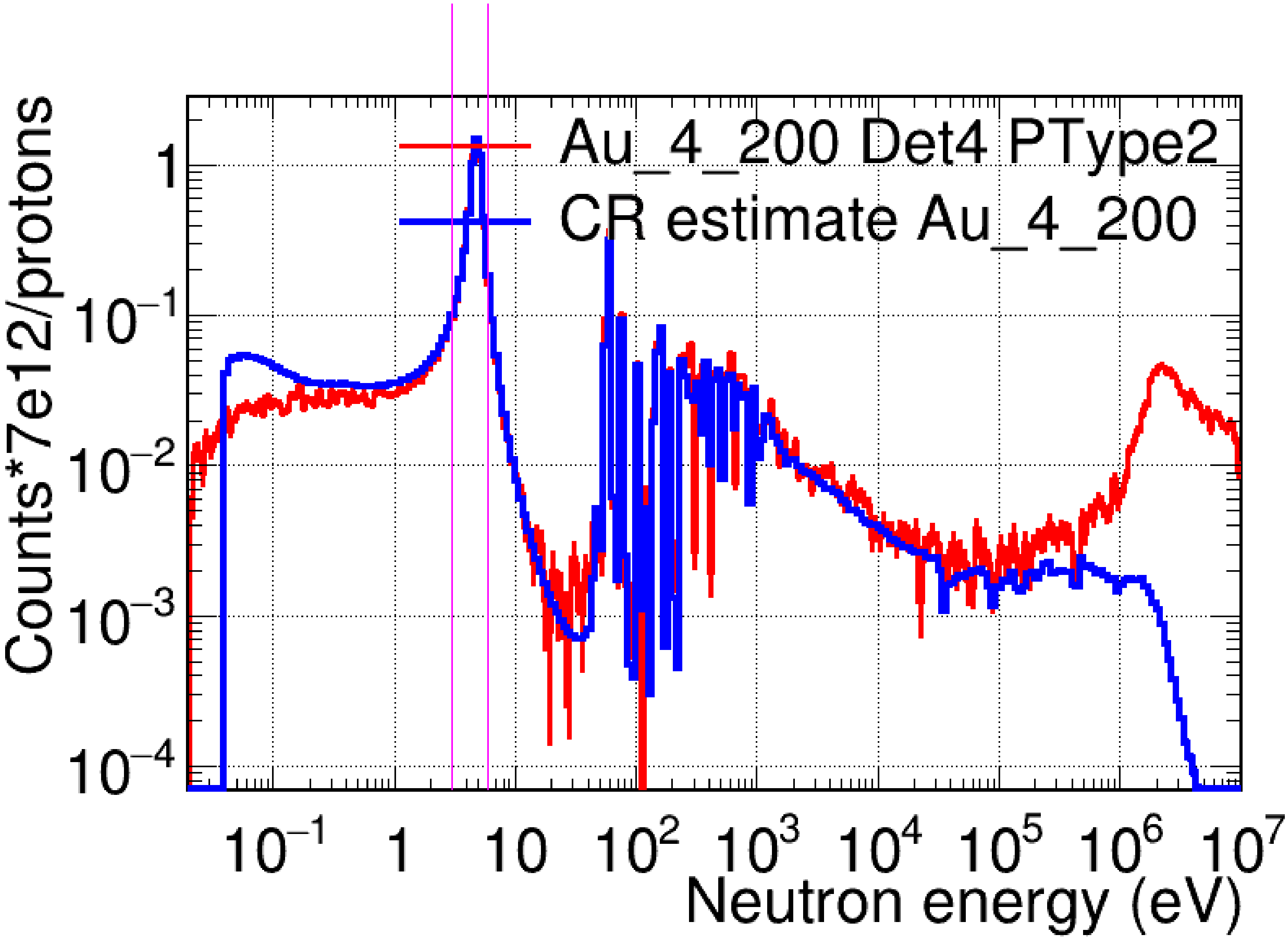
Compare sTED and BICRON



Compare CR of Au-4cm-200um-BICRON



Compare CR of Au-4cm-200um-sTED



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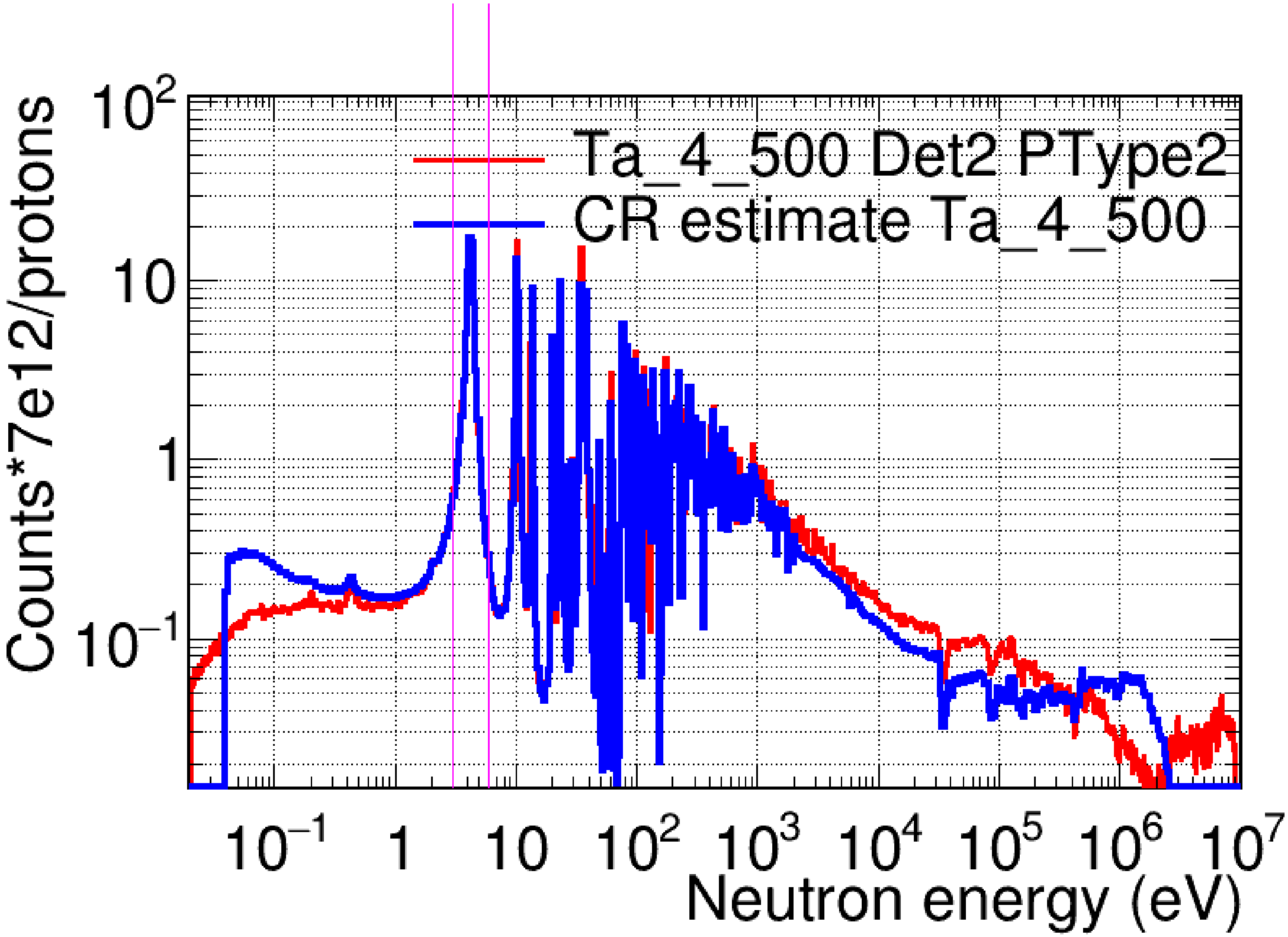
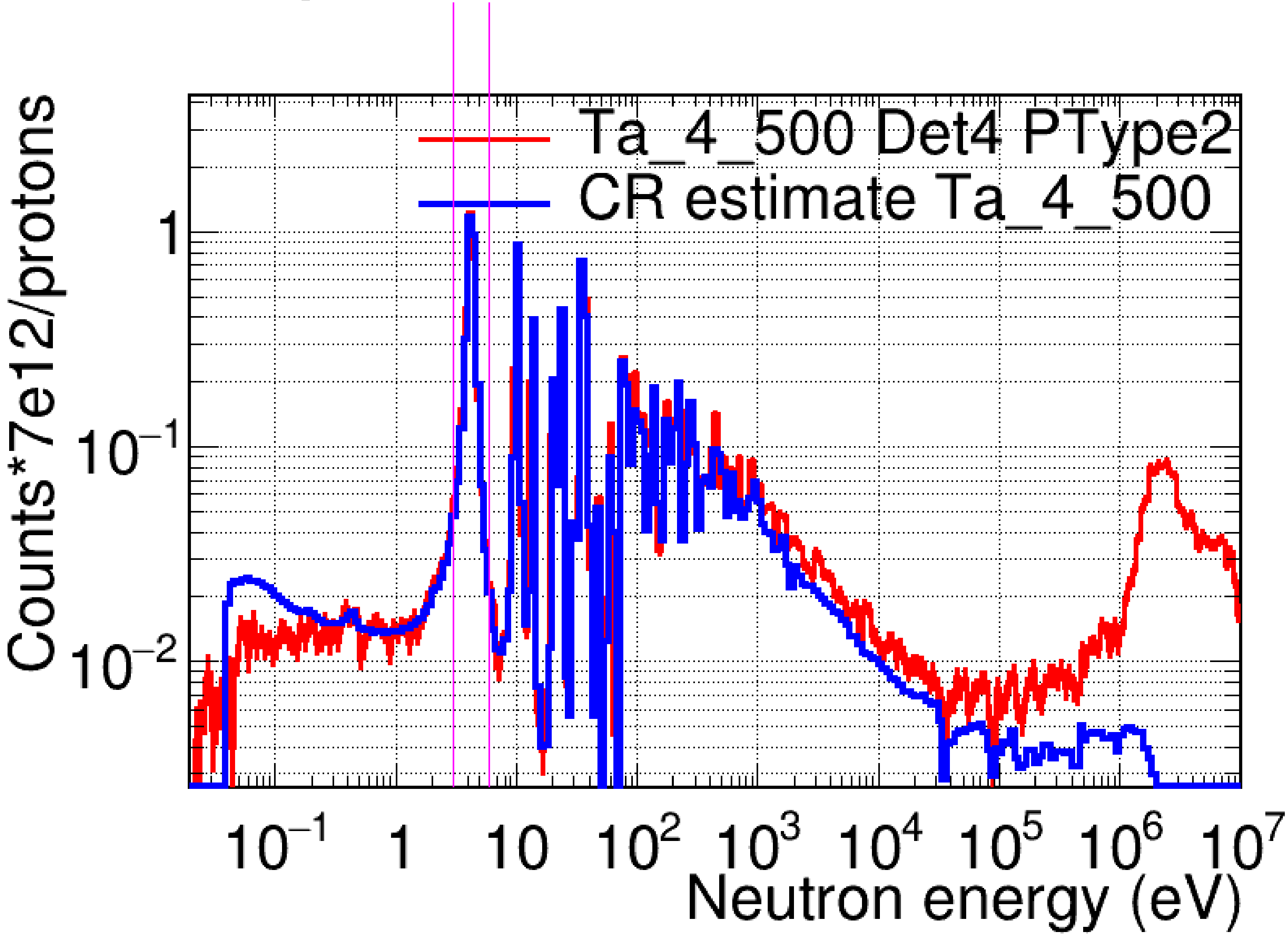
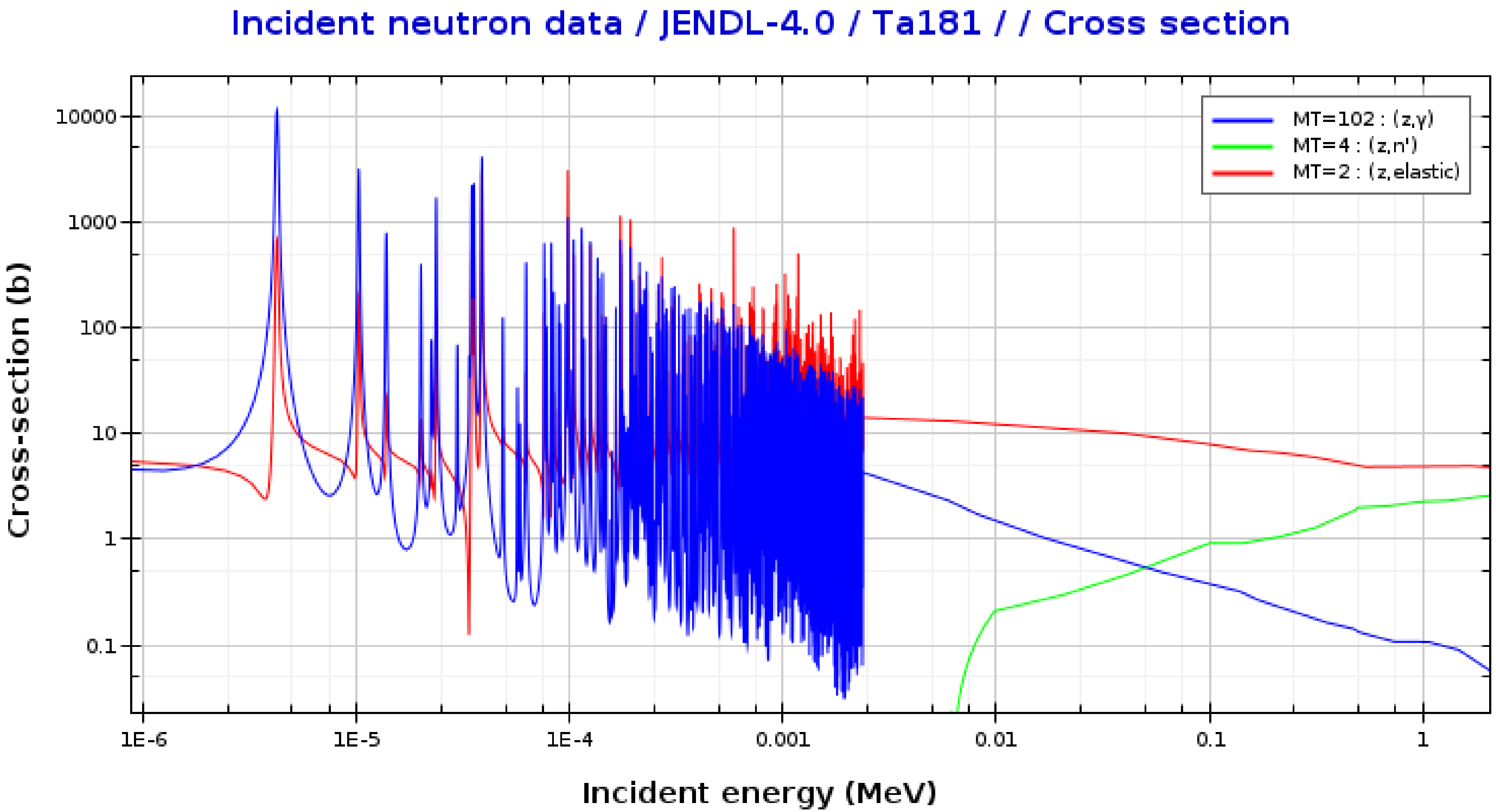
Compare CR of Ta-4cm-500um-BICRON



Compare CR of Ta-4cm-500um-sTED

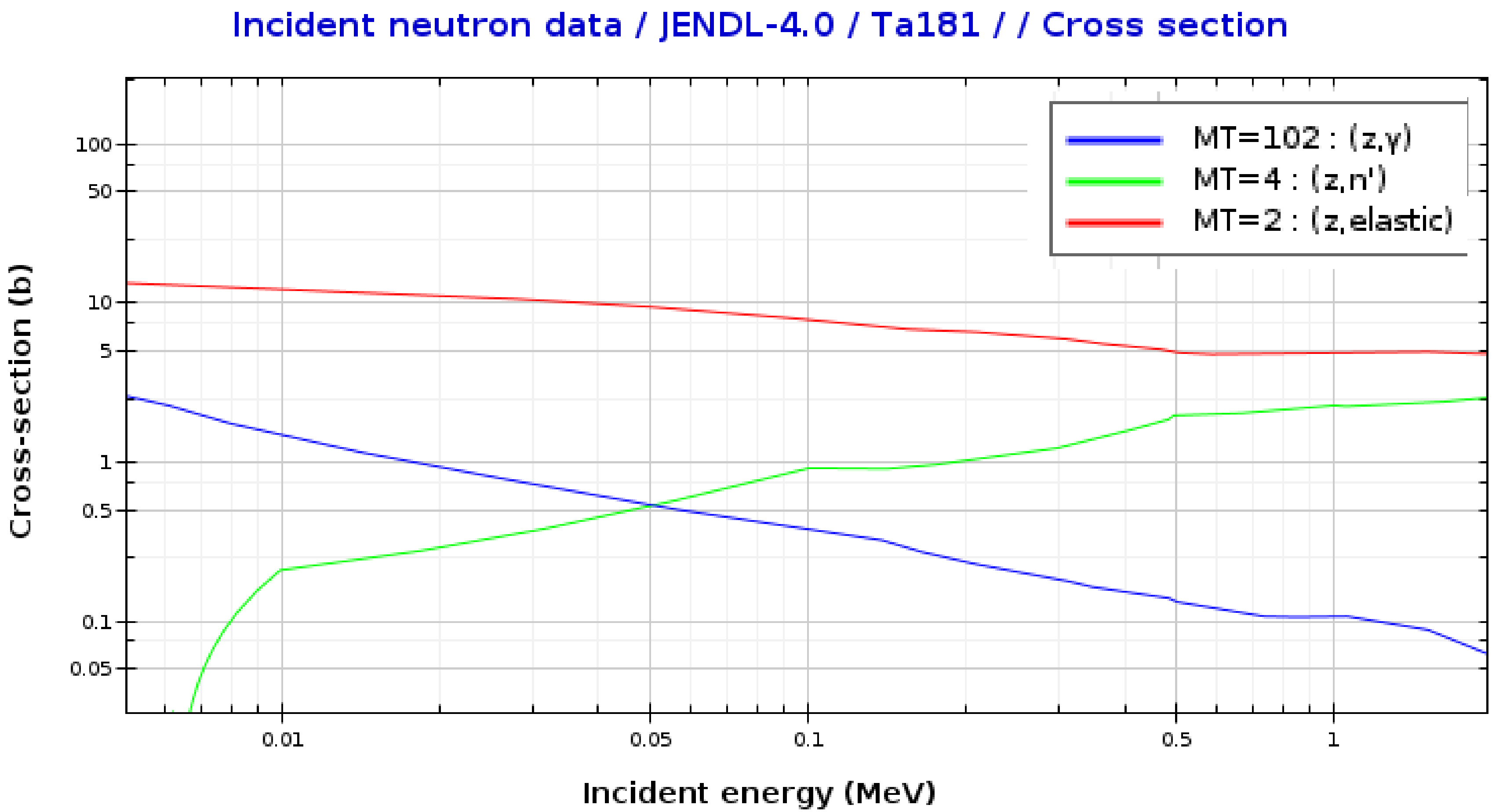


CS Ta-181



Incident neutron data / JENDL-4.0 / Ta181 / / Cross section
MT=102 : (z,γ)
MT=4 : (z,n')
MT=2 : (z,elastic)
10000
1000
100
10
1
0.1
Cross-section (b)
1E-6
1E-5
1E-4
0.001
0.01
0.1
1
Incident energy (MeV)

CS Ta-181


Incident neutron data / JENDL-4.0 / Ta181 / / Cross section
MT=102 : (z,γ)
MT=4 : (z,n')
MT=2 : (z,elastic)
Cross-section (b)
100
50
10
5
1
0.5
0.1
0.05
0.01
0.05
0.1
0.5
1
Incident energy (MeV)

Capture C.S. of 181 and 180m