^{50,53}Cr (n,γ) cross section measurement at EAR1

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& THE N_TOF COLLABORATION

N_TOF COLLABORATION GENERAL MEETING, VALENCIA. 22/11/2023

Motivation: nuclear data for criticality safety

NEA Nuclear Data High Priority Request List, HPRL

HPRL Main	High Priority Requests (HPR)	General Requests (GR)	Special Purpose Quantities (SPQ)		New Request	EG-HPRL (SG-C)
			Standard	Dosimetry		

Request ID	98		**Type of the request**	High Priority request	
Target	**Reaction and process**	**Incident Energy**	**Secondary energy or angle**	**Target uncertainty**	**Covariance**
24-CR-53	(n,g) SIG	1 keV-100 keV		8-10	Y
Field	**Subfield**	**Created date**	**Accepted date**	**Ongoing action**	**Archived Date**
Fission		20-JAN-18	05-FEB-18	Y	

Send a comment on this request to NEA.

Requester: Dr Roberto CAPOTE NOY at IAEA, AUT
Email: roberto.capotenoy@iaea.org

Project (context):

Impact:

Neutron absorption in the Cr isotopes of structural materials affects the criticality of fast reactor assemblies [Koscheev2017]. These cross sections are also of interest for stellar nucleosynthesis [Kadonis10].

Accuracy:

8-10% in average cross-sections and calculated MACS at 10, 30, 100 keV.

Selected criticality benchmarks with large amounts of Cr (e.g., PU-MET-INTER-002, and HEU-COMP-INTER-005/4=KBR-15/Cr) show large criticality changes of the order of 1000 pcm due to 30% change in Cr-53 capture in the region from 1 keV up to 100 keV [Trkov2018]. On the other side different evaluations (e.g., BROND-3.1, ENDF/B-VII.1, ENDF/B-VIII.0 and JEFF-3.3) for Cr-53(n,g) are discrepant by 30% in the same energy region. For Cr-50, evaluated files show better agreement at those energies but they are lower than Mughabghab evaluation of the resonance integral by 35%. These discrepancies are not reflected in estimated uncertainty of the evaluated files (e.g., JEFF-3.3 uncertainty is around 10% which is inconsistent with the observed spread in evaluations). Due to these differences we request new capture data with 8-10% uncertainty to discriminate between different evaluations and improve the C/E for benchmarks containing Chromium and/or SS.

Justification document:

Criticality benchmarks can test different components of stainless steel (SS), including Cr which is a large component of some SS. Currently, a large part of the uncertainty in SS capture seems to be driven by uncertainty in Cr capture [Koscheev2017]. Indeed, some benchmarks highly sensitive to Cr (as a component of SS) indicate a need for much higher capture in Cr for both Pu and U fueled critical assemblies (e.g., HEU-COMP-INTER-005/4=KBR-15/Cr and PU-MET-INTER-002=ZPR-6/10).

- Stainless Steel is often used as a **structural material in nuclear reactors** and contains between **11-26% of chromium.**

- There are **serious discrepancies** (~30%) between the different evaluated data of **^{50}Cr and ^{53}Cr capture cross section**, which is not present in the corresponding estimated uncertainties.

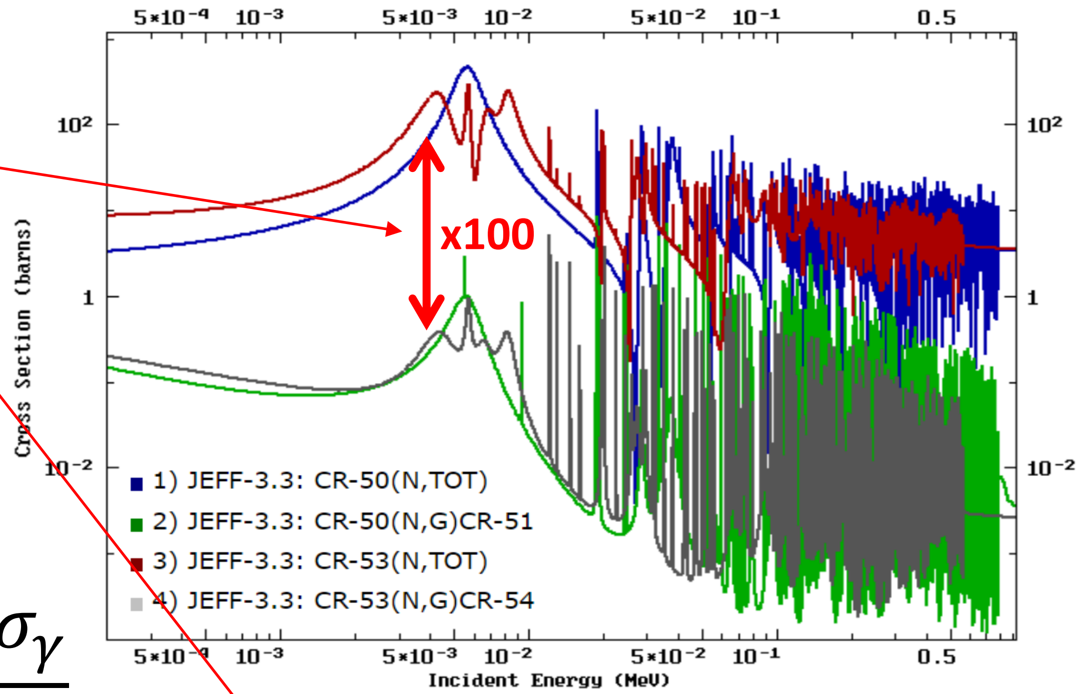
- **OECD NEA-HPRL** (High Priority Request List) → **^{50,53}Cr(n,γ) within 8-10% at 1 to 100 keV.**

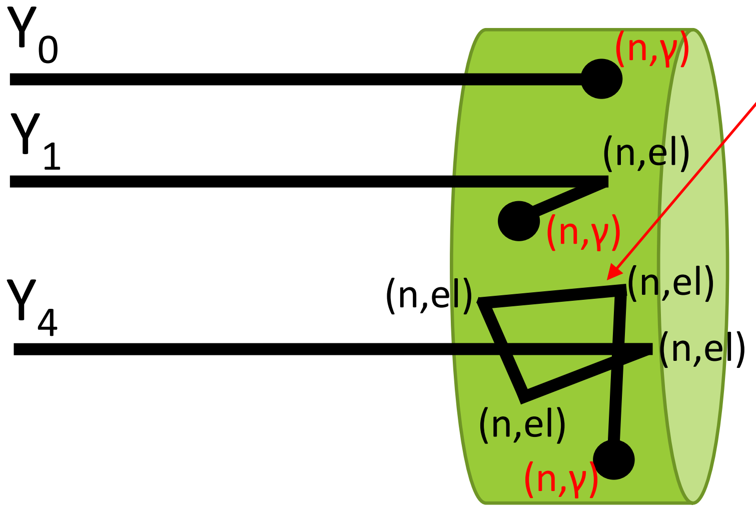
- New evaluation available: IAEA-INDEN (August'23)

Previous talk link: Geneva'23

Why the discrepancies?

- The main problem for measuring Cr(n,γ) is the large **neutron multiple-scattering effects**
- In the previous measurements thick samples were used, aiming for good statistics in a very wide energy range





$$Y_0 = (1 - e^{n\sigma_t})\frac{\sigma_\gamma}{\sigma_t}$$

Capture yield (captures/neutron) $\rightarrow Y = Y_0 + Y_1 + Y_2 + Y_3 \ldots$

$Y_0 + Y_1$: Analytical (accurate)

$Y_2 + Y_3 \ldots$: Numerical (aproximate)

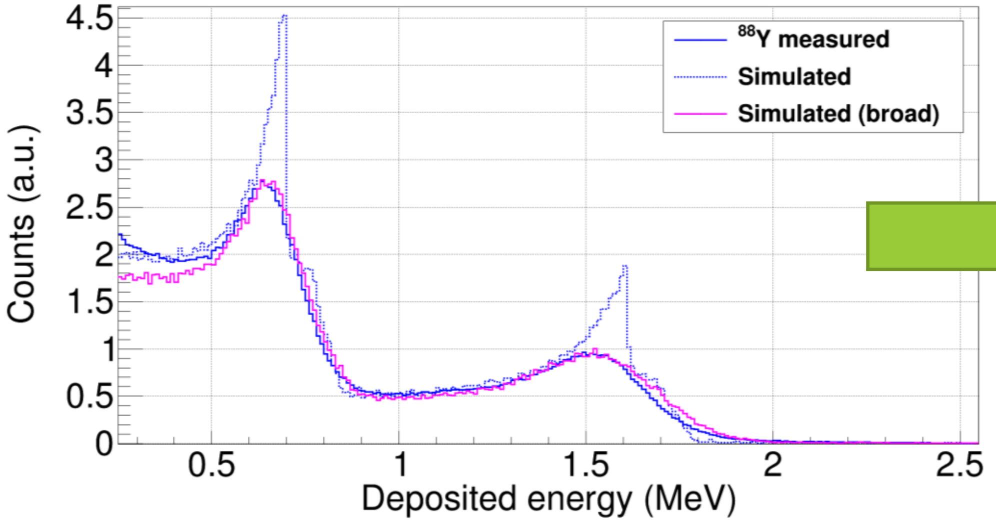
How to improve σ(n,γ) down to a few %?

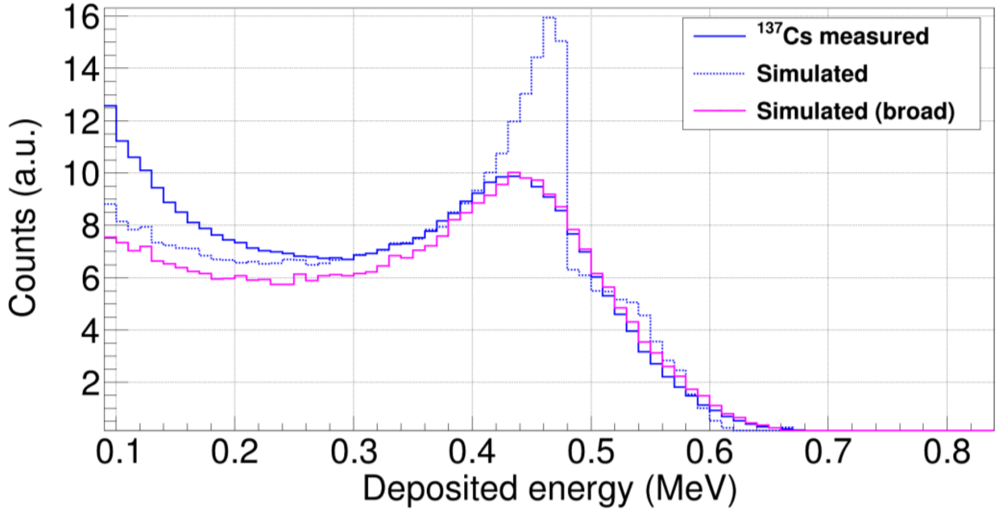
- Enriched (expensive and scarce) material with high purity → 94,6% ^{50}Cr & 97,7% ^{53}Cr
- Controlling multiple-scattering effects:
  - Very thin/thin sample approach
  - C_6D_6 detectors (low sensitivity to scattered neutrons)
- Complementing with ^{50}Cr activation measurement → HiSPANoS@CNA

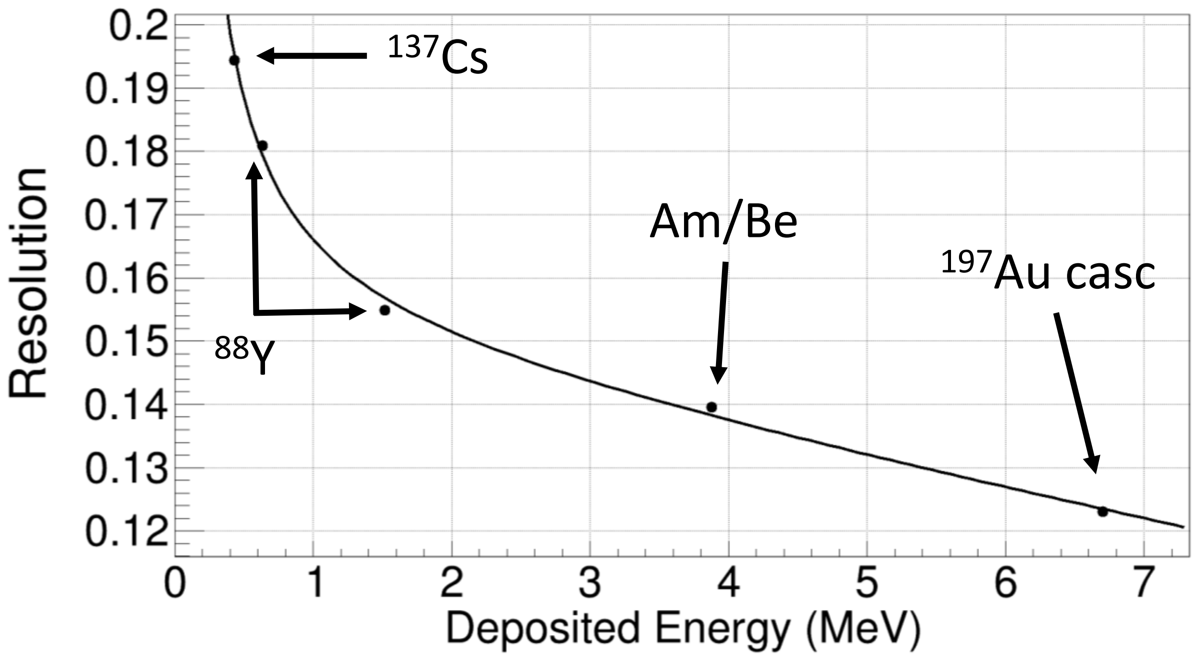
Experiment	Beer (1975)	Stieglitz (1971)	Brusegan (1986)	Kenny (1977)	Guber (2011)	**This work (2022)**
Facility	FZK	RPI	GELINA	ORELA	ORELA	**n_TOF**
L (m)	0,7	27	60	40	40	**185**
Energy (keV)	1-300	1-200	1-200	1-200	0,01-600	**1-100**
Density ^{50}Cr (10^{-3} at/barns)	18	8	7	5/8	-	**0,6/1,9**
Density ^{53}Cr (10^{-3} at/barns)	14	14	12/60	8/12	14	**1,2/6**

Our "thicks" are thinner than all previous → lower multiple interaction corrections

C_6D_6 calibrations

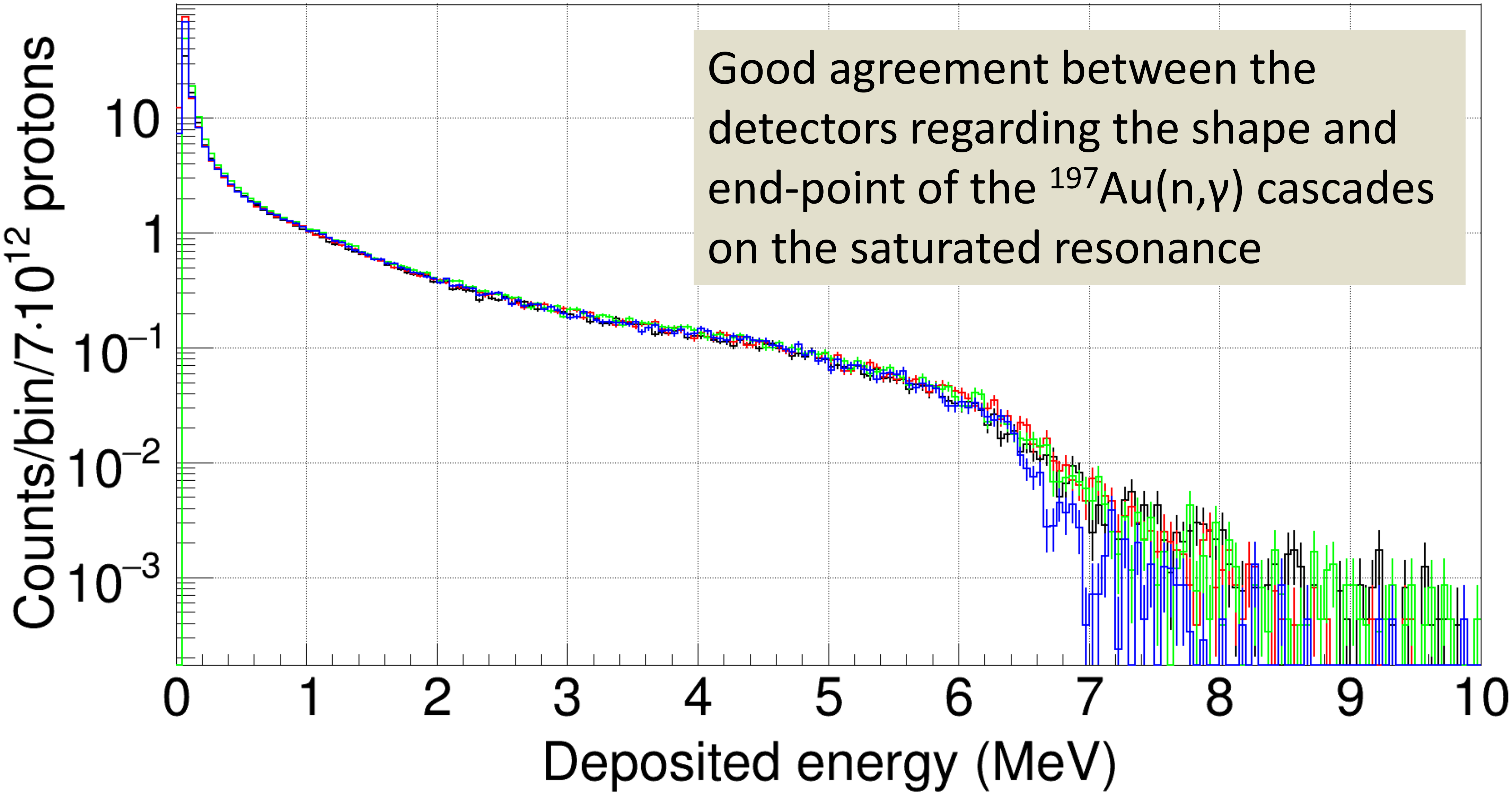






We calibrate the C_6D_6 detectors in energy and in resolution using a combination of radioactive source measurements + GEANT4 simulations

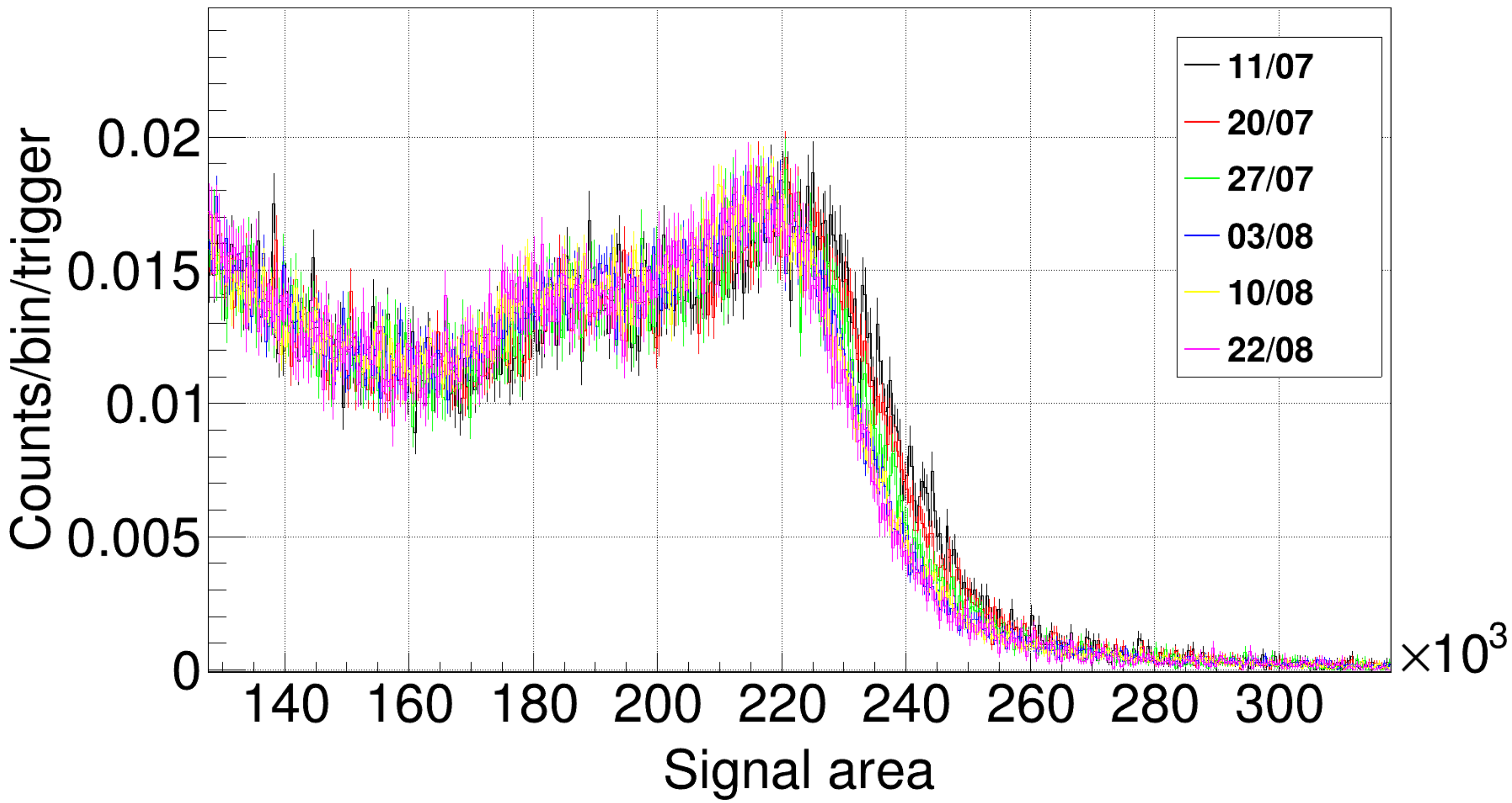
C_6D_6 calibrations with $^{197}Au(n,\gamma)$ cascades



Good agreement between the detectors regarding the shape and end-point of the $^{197}Au(n,\gamma)$ cascades on the saturated resonance

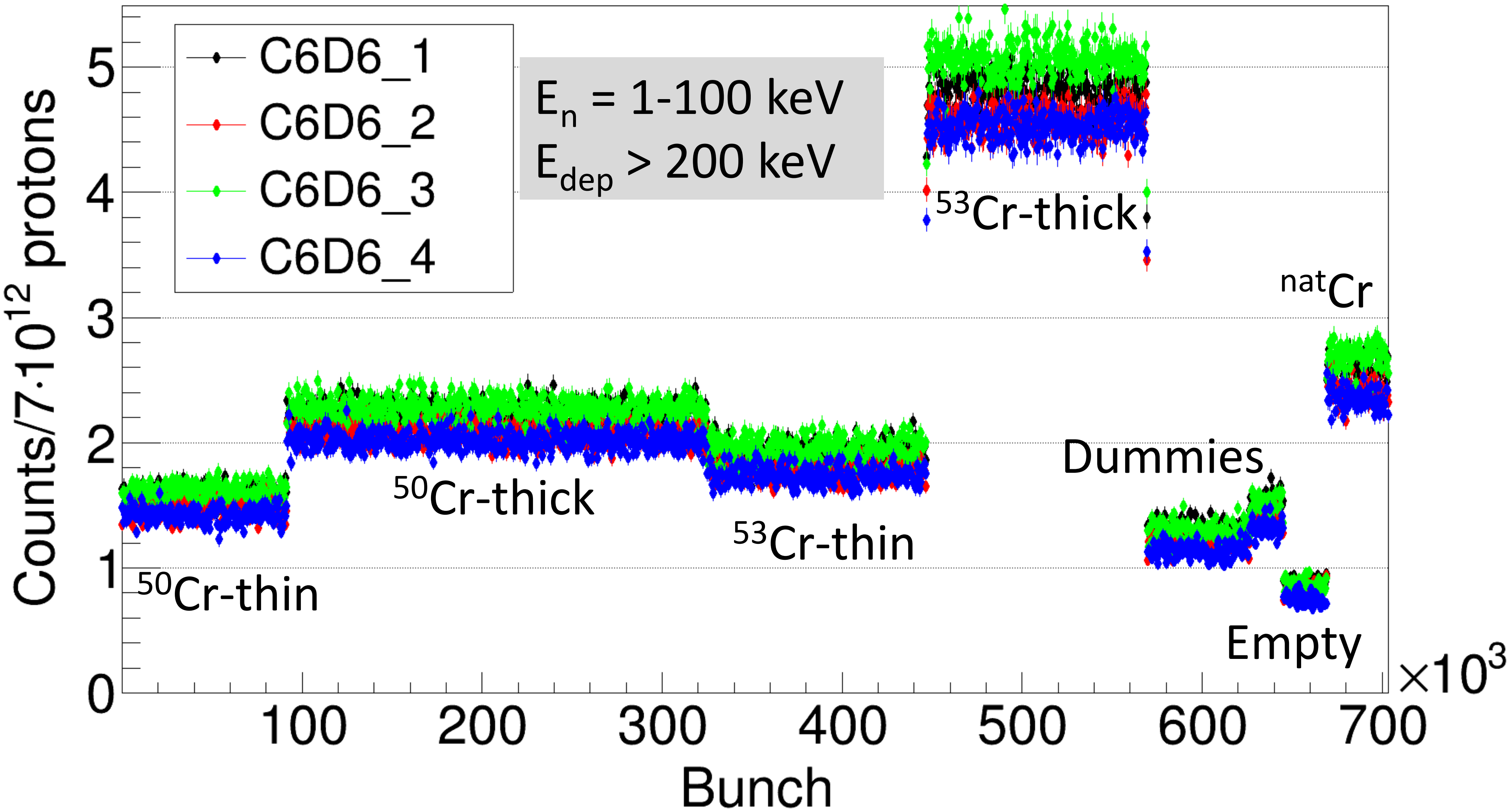
C_6D_6 gain shift

Am/Be on C6D6_4

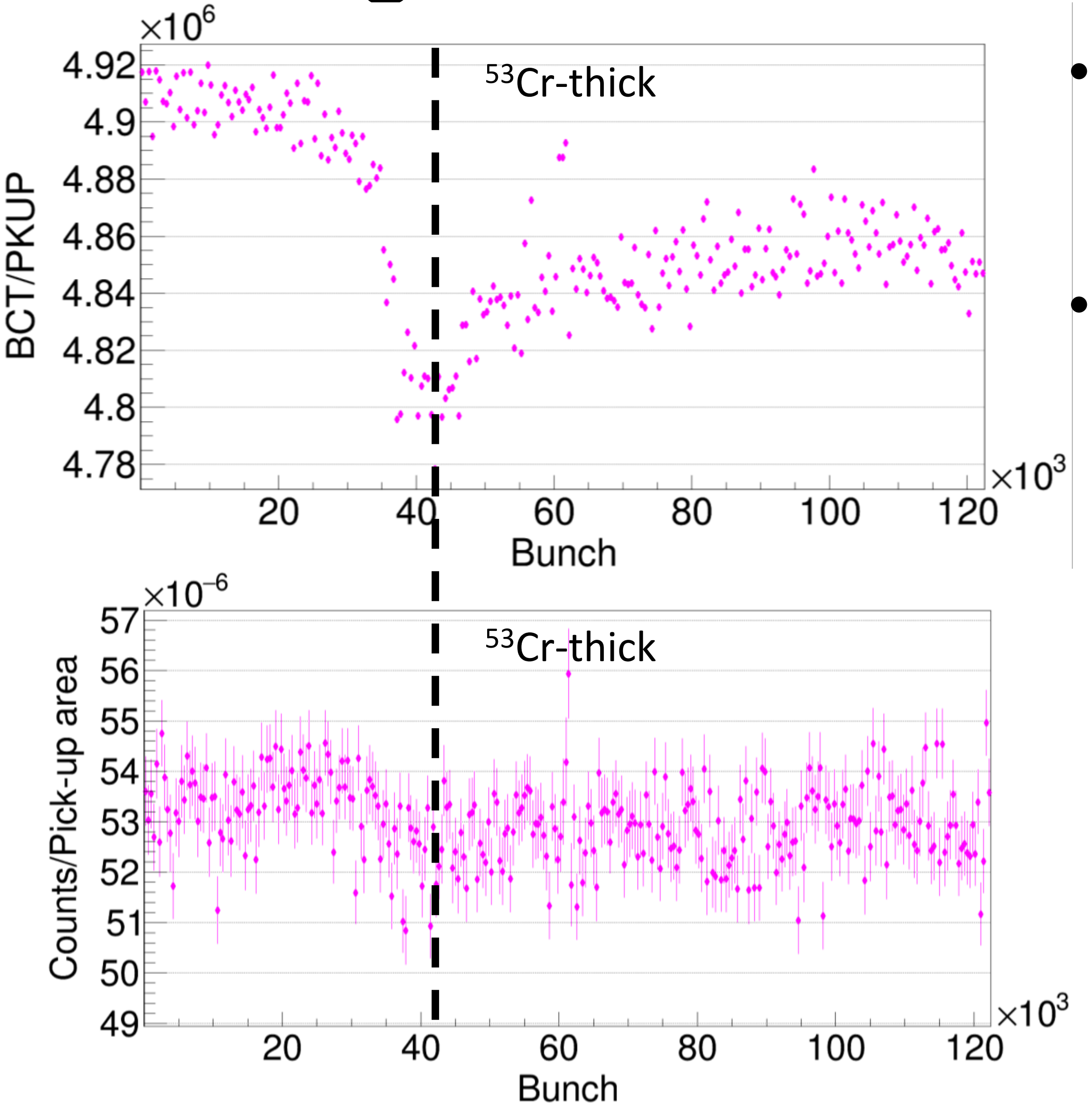


- Very small gain shift during the 42 days of experimental campaign; seems more significant in detector 4 than in the others.
- Each run-set has its own calibration to take the shift into account.

Counting rates and monitors (E_n = 1-100 keV)

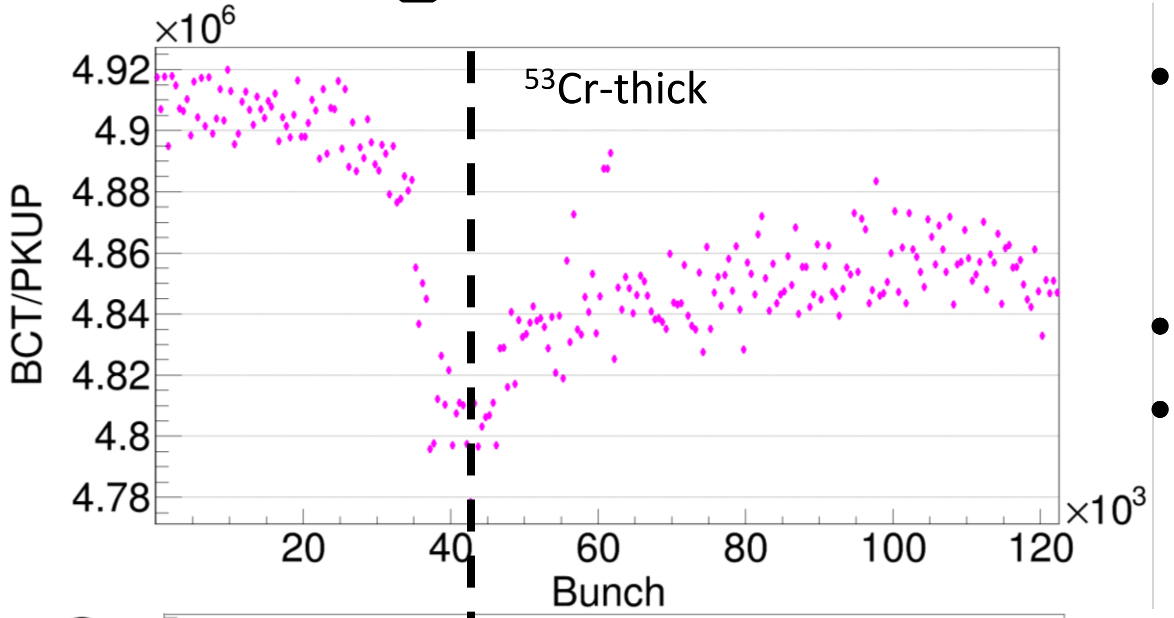


Counting rates and monitors (E_n = 1-100 keV)

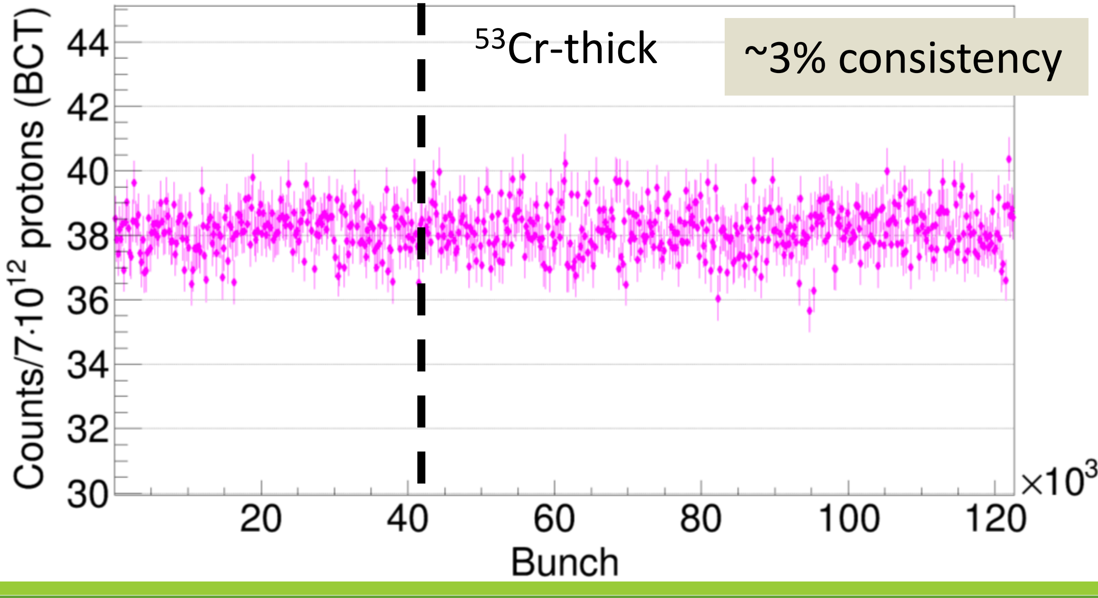


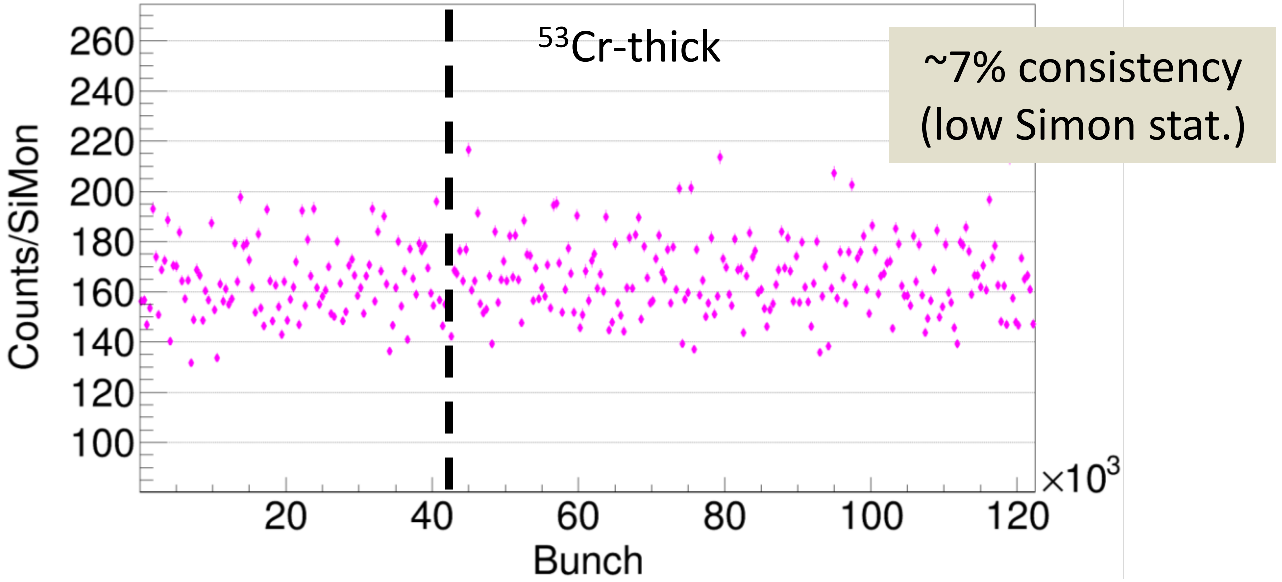
- On 23/07 something happened that affected the Pick-up (not visible on BCT/SiMon ratio).
- Anyway, the BCT/PKUP ratio change is 1%.

Counting rates and monitors (E_n = 1-100 keV)

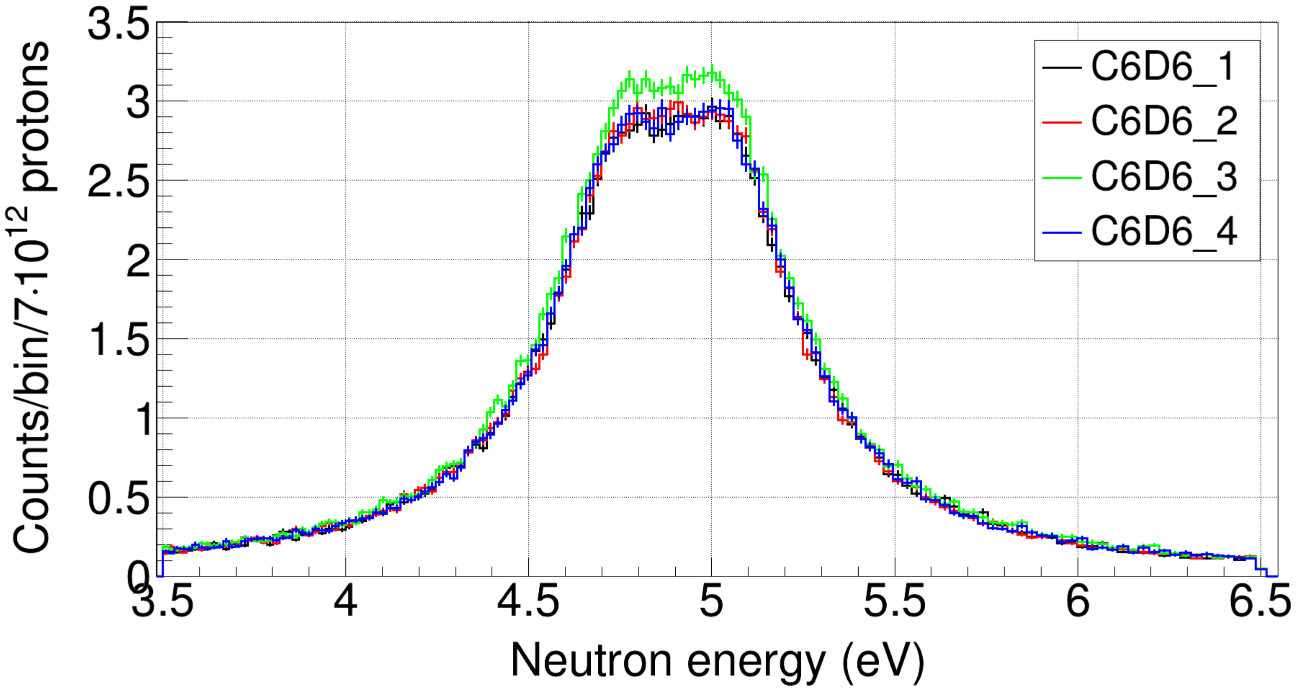


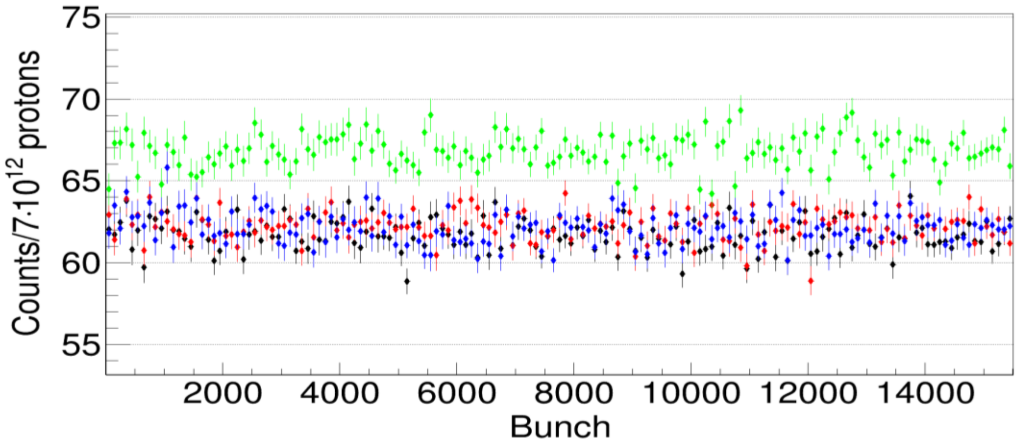
- On 23/07 something happened that affected the Pick-up (not visible on BCT/SiMon ratio).
- Anyway, the BCT/PKUP ratio change is 1%.
- Not visible on C_6D_6 Counting rate vs BCT & SiMon → best options for monitoring.





Counting rates and monitors

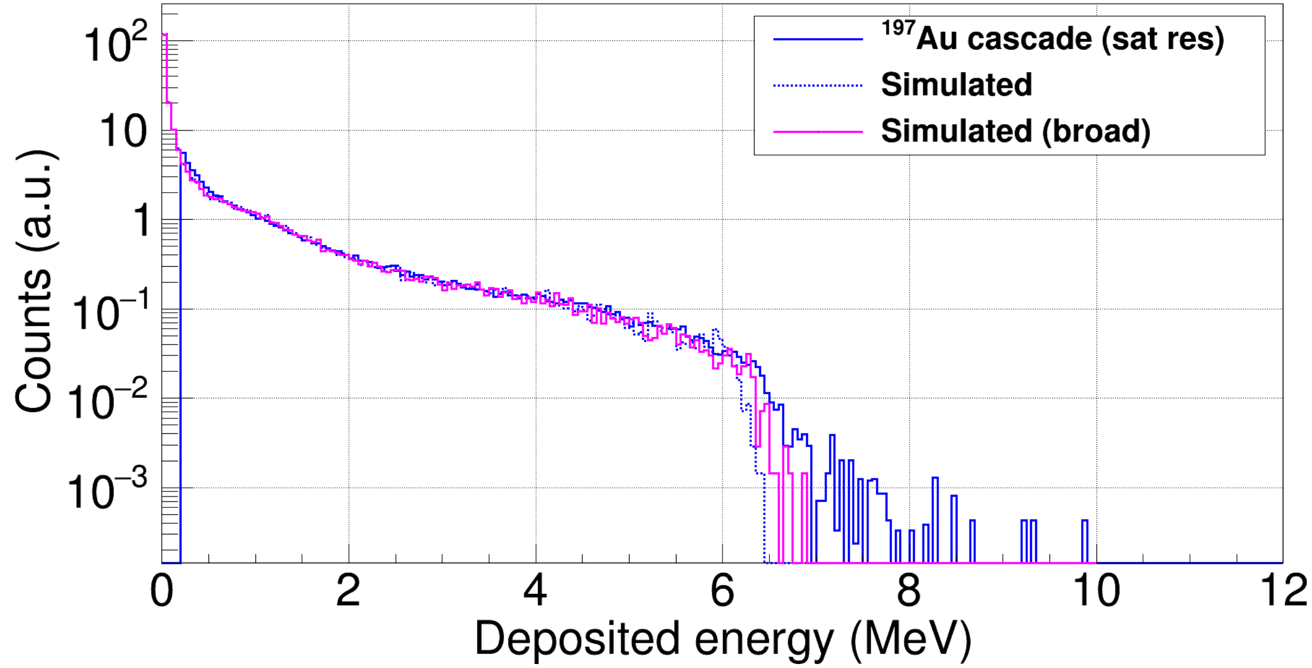


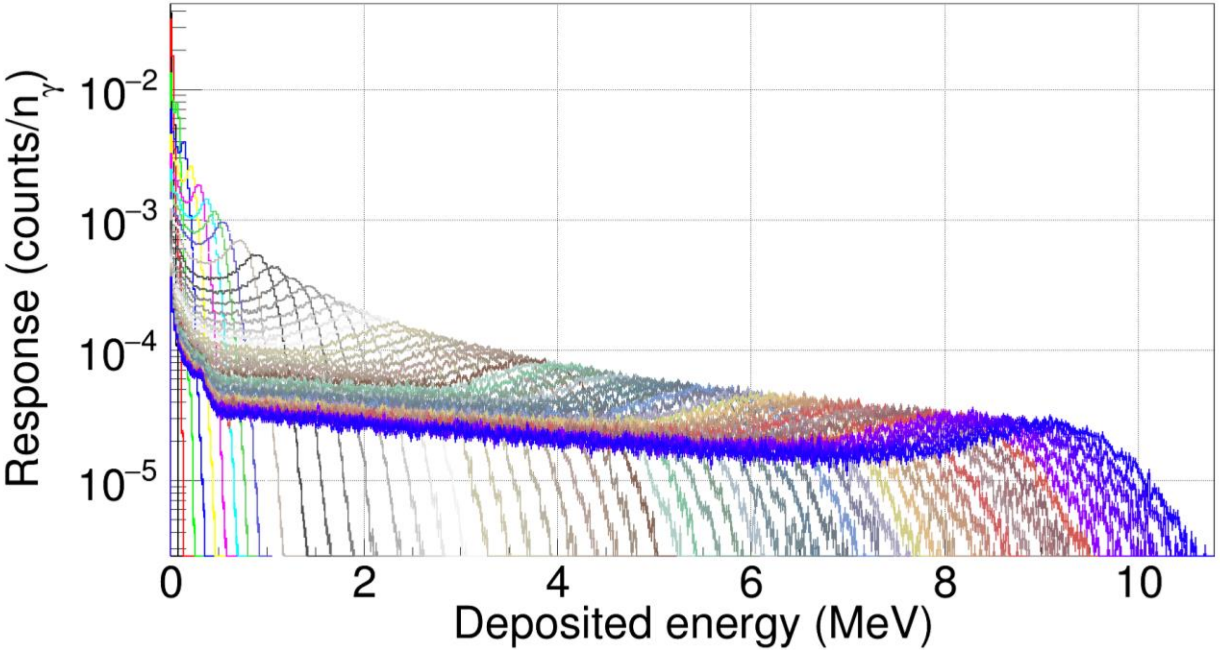


- During the Mo-campaign, it was detected that detector 3 was ~5 mm closer to the sample than the others.
- In the Cr data the same is observed.
- Needs to be taken into account when simulating the response for the Weighting Function.
- Less than 0.5% difference between the other three.

^{197}Au Weighting Function

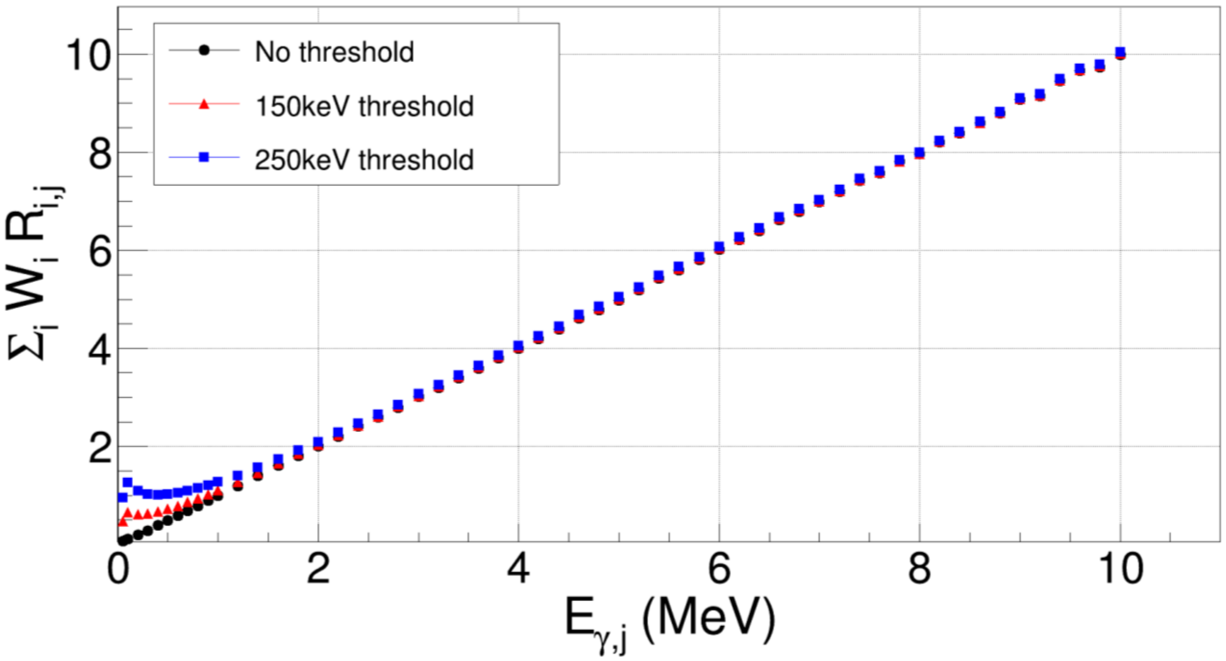
- We are going to normalize the Cr data to ^{197}Au saturated resonance
- Two methods to obtain the Weighting Function:
  - With E_{min} = 0 MeV + full capture cascade
  - With E_{min} = $E_{threshold}$
- High quality simulated ^{197}Au cascades are available (thanks Emilio & CIEMAT!)

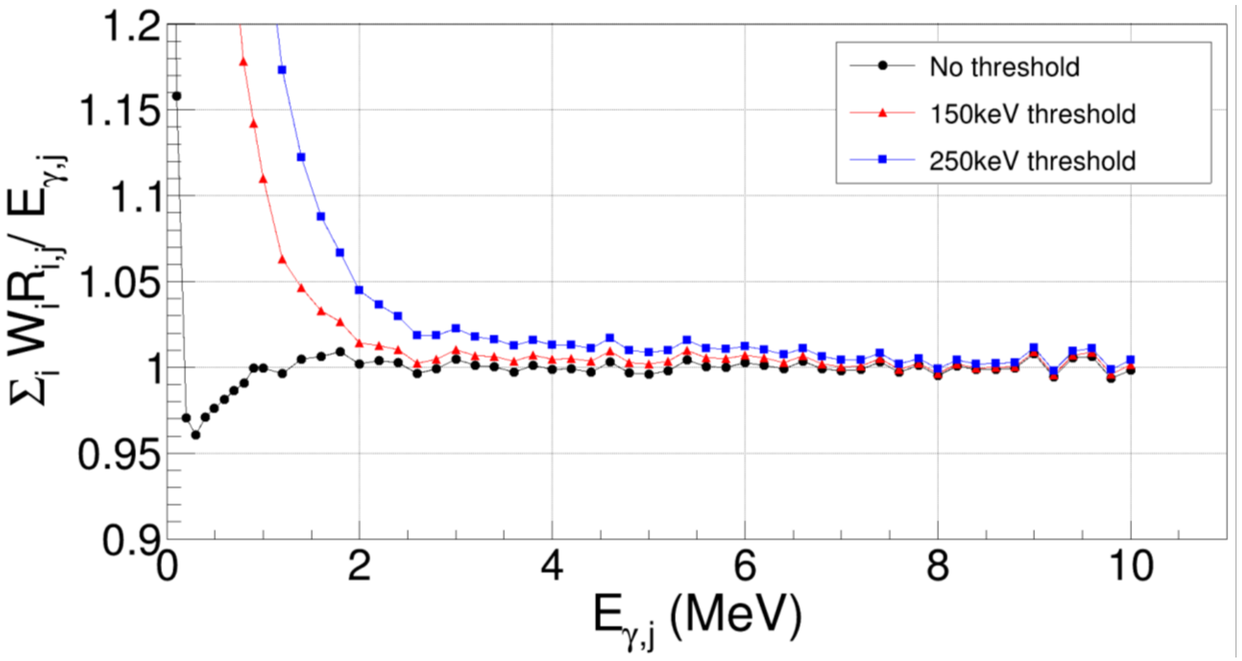




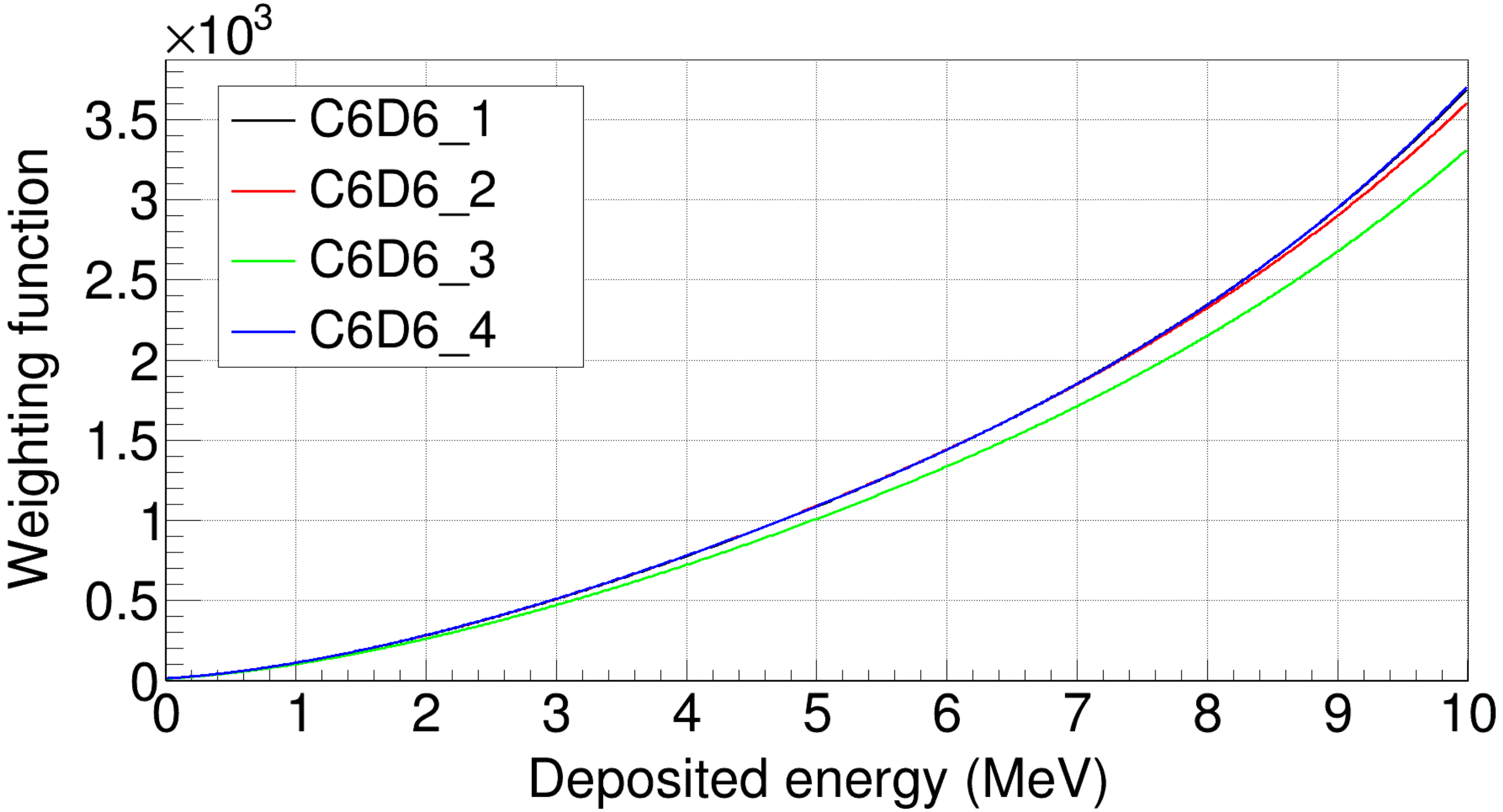
^{197}Au Weighting Function

- With a perfectly calculated Weighting Function, the weighted efficiency should be $\varepsilon_W(E_j) = \sum_i W_i R_{i,j}$
- It's not true when applying a "threshold" to get the WF.





^{197}Au Weighting Function

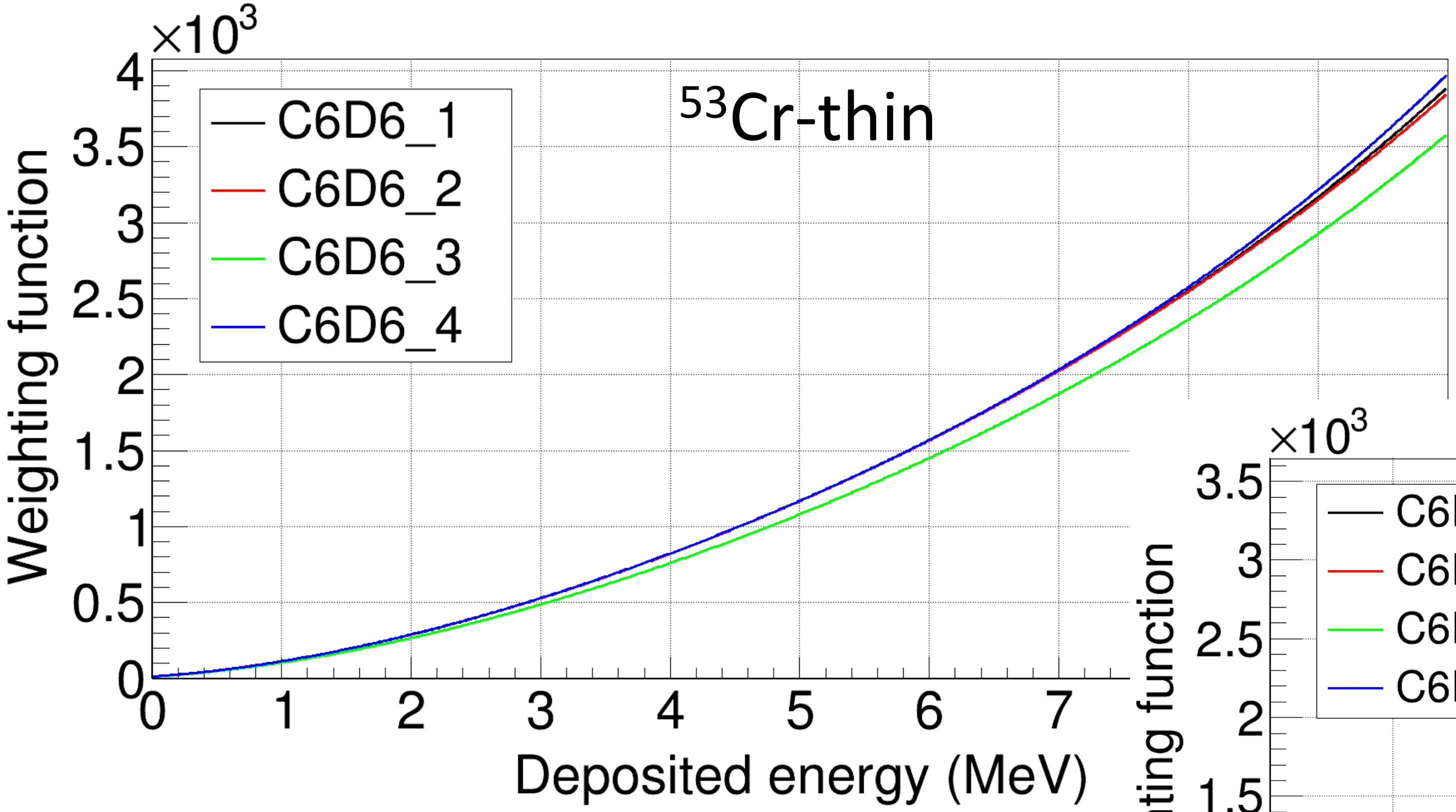


- Realistic ^{197}Au cascades are available → our desired option to apply the WF.
- For the moment we don't have the Cr cascades (we will soon!).
- For now: we calculate the WF considering E_{min} = 200 keV.

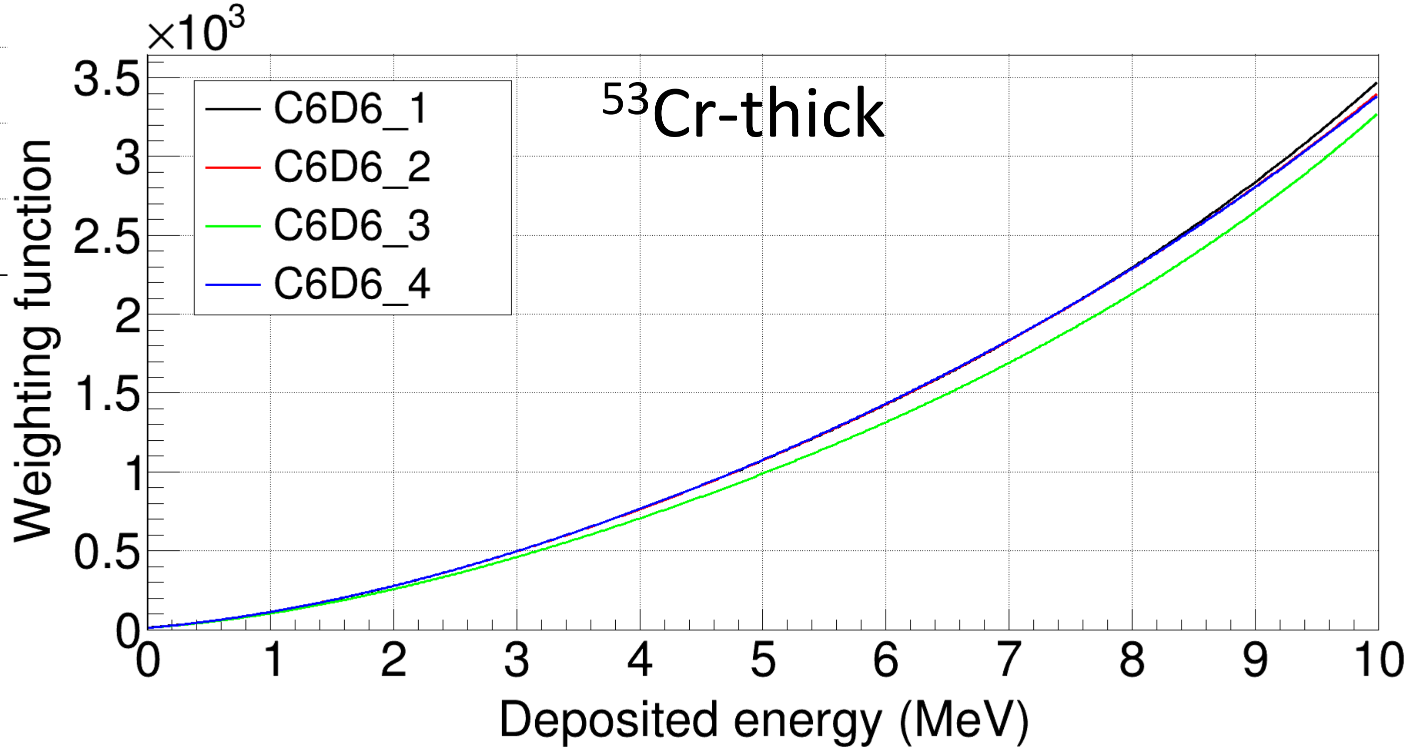
$$F_{thr} = \frac{\sum_{k=1}^{N_C} \sum_i W_i R_{i,j}^C}{N_c E_C}$$

	C6D6_1	C6D6_2	C6D6_3	C6D6_4
F_{thr}	0.950	0.973	0.968	0.976

^{53}Cr Weighting Function

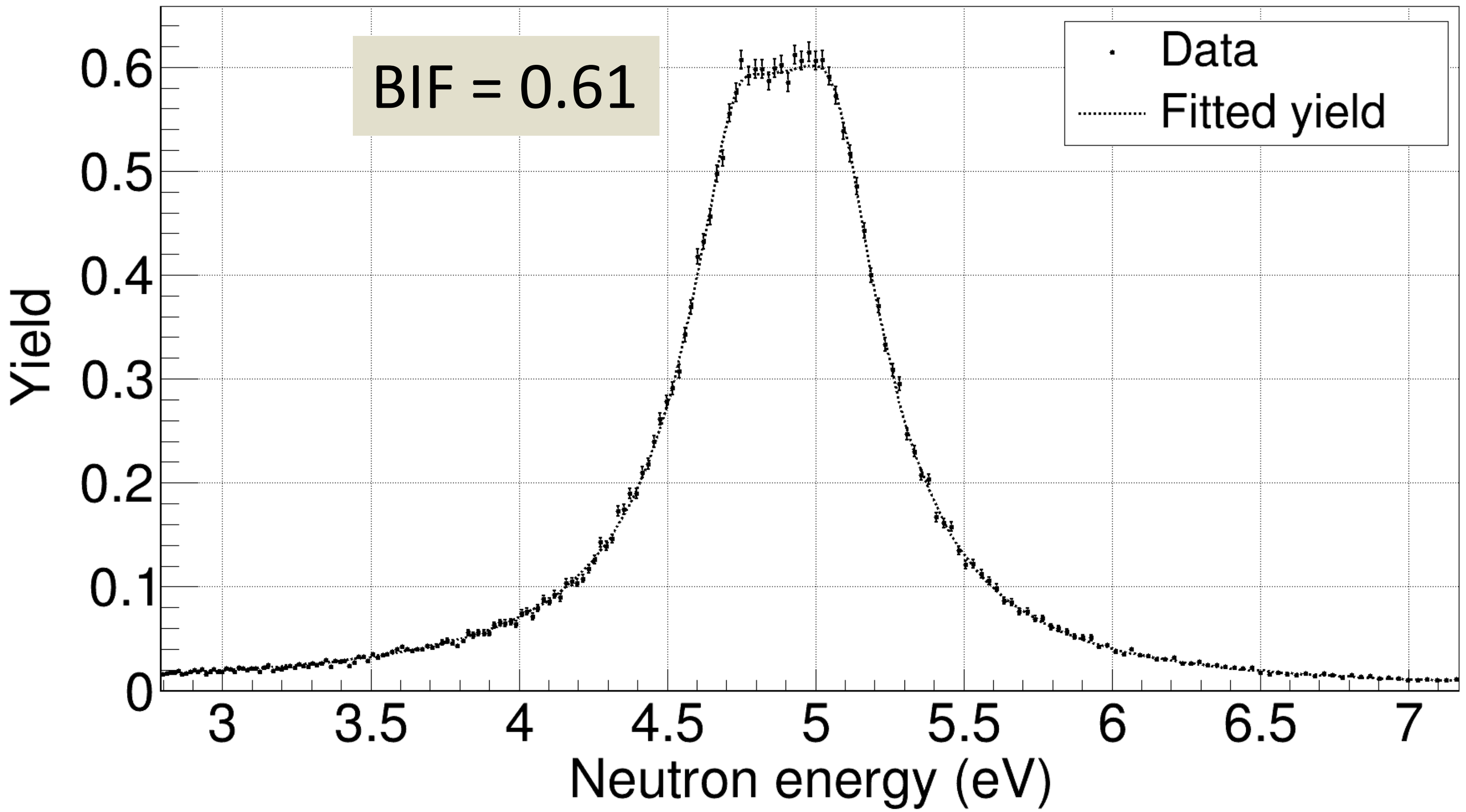


Each sample's geometry is different → 4x4 different WFs (^{50,53}Cr, thin and thick)



200 keV threshold, no correction applied

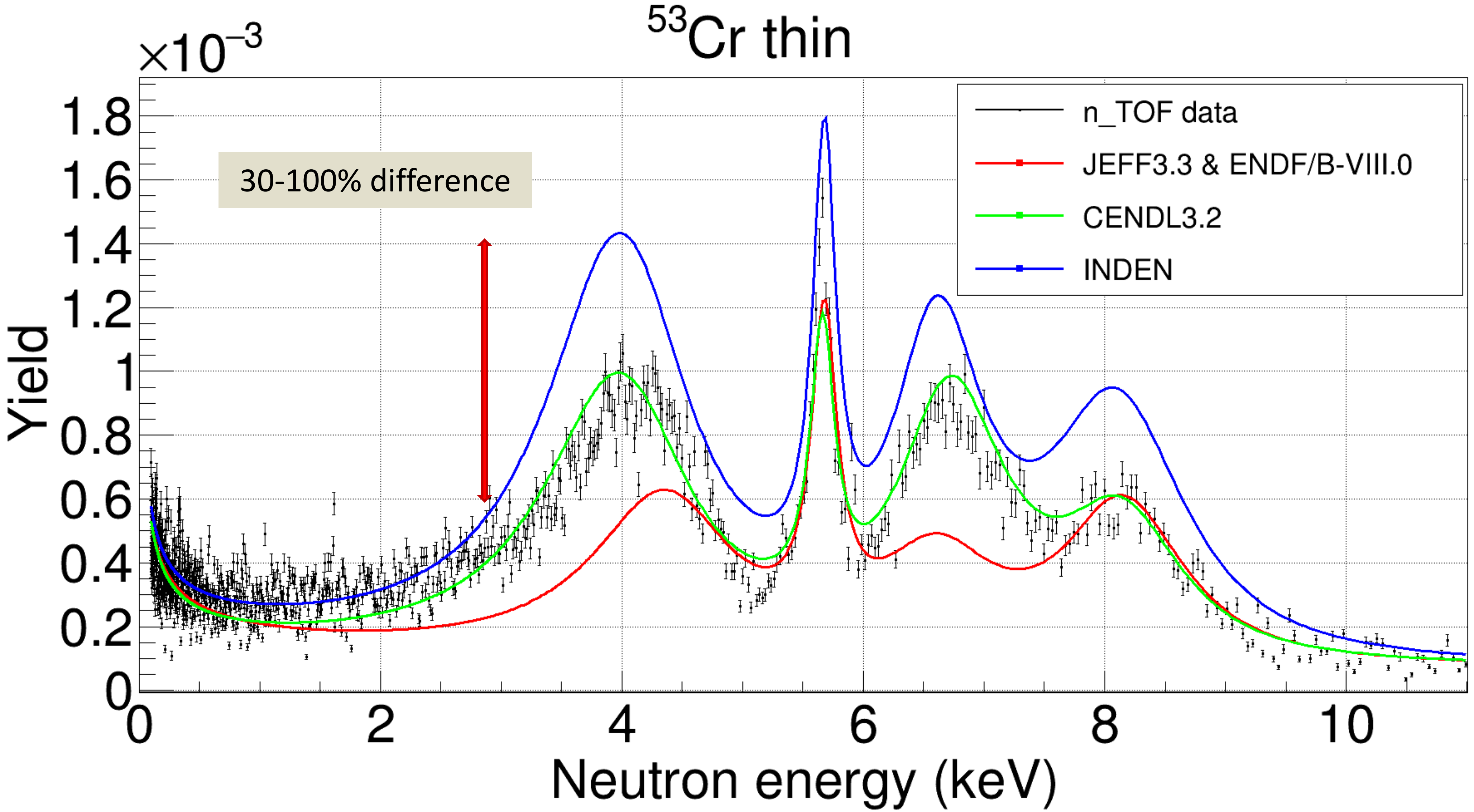
Preliminary ^{197}Au yield



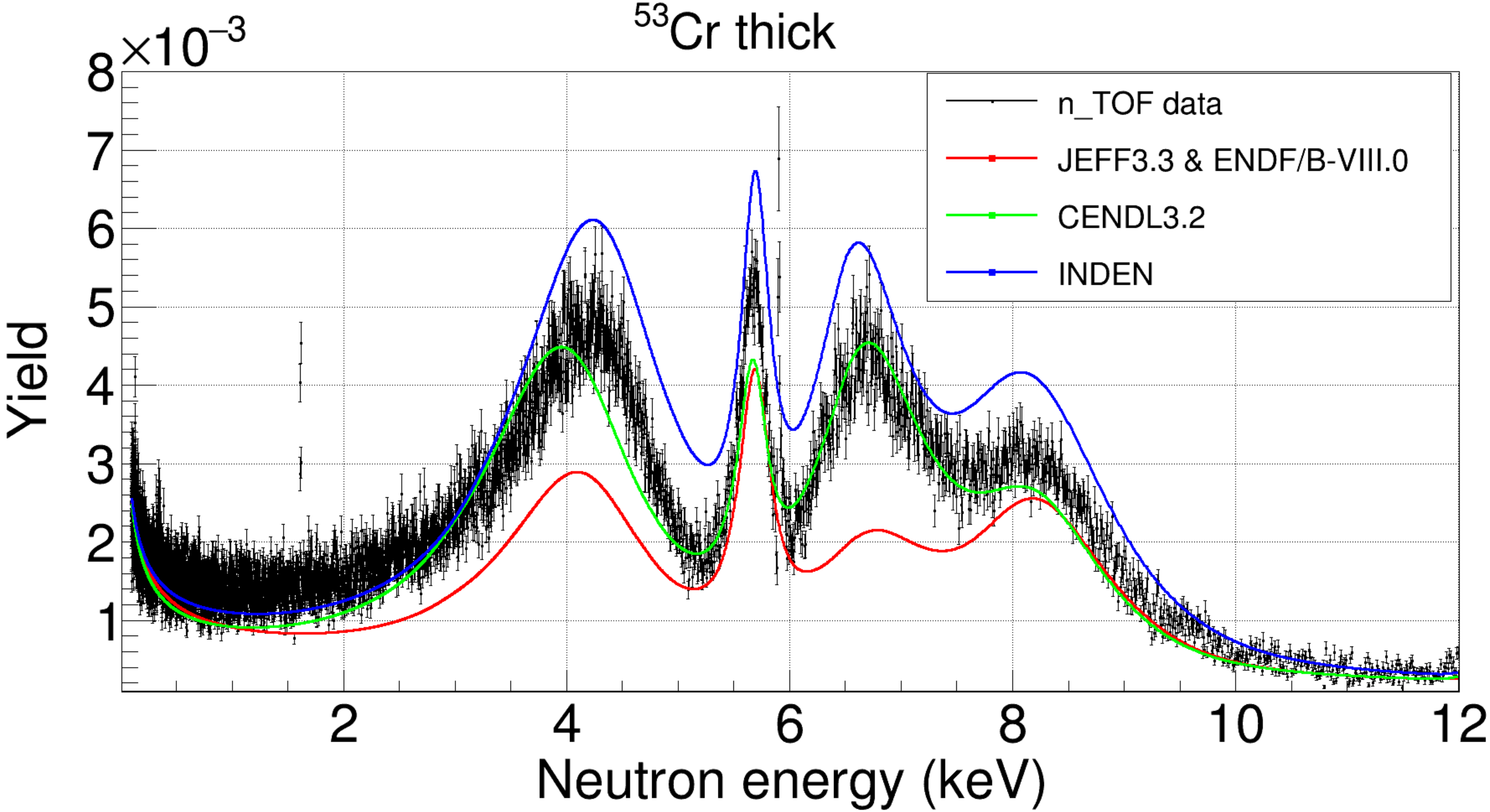
- Expected BIF ≈ 0.66 [1]
- Not the final version of the Weighting Function, in the future we will use the full cascades.
- Also missing the rest of correction factors like multiple γ-ray counting and internal conversion e^-.

[1] Guerrero, C. et al, *"Performance of the neutron time-of-flight facility n_TOF at CERN"*. The European Physical Journal A, 49(2), 27 (2013)

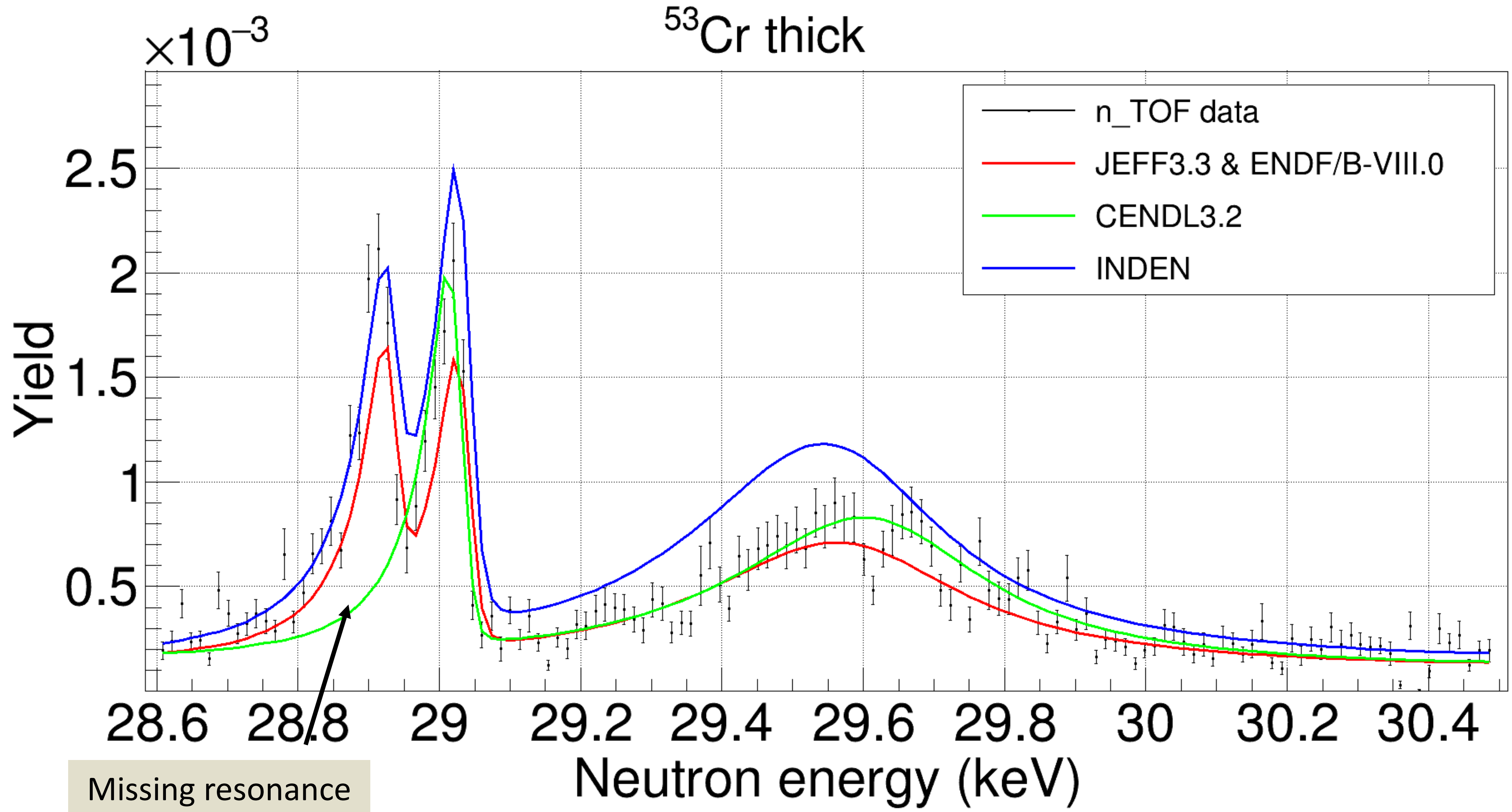
Preliminary ^{53}Cr yield (1-10 keV, thin target)



Preliminary ^{53}Cr yield (1-10 keV, thick target)

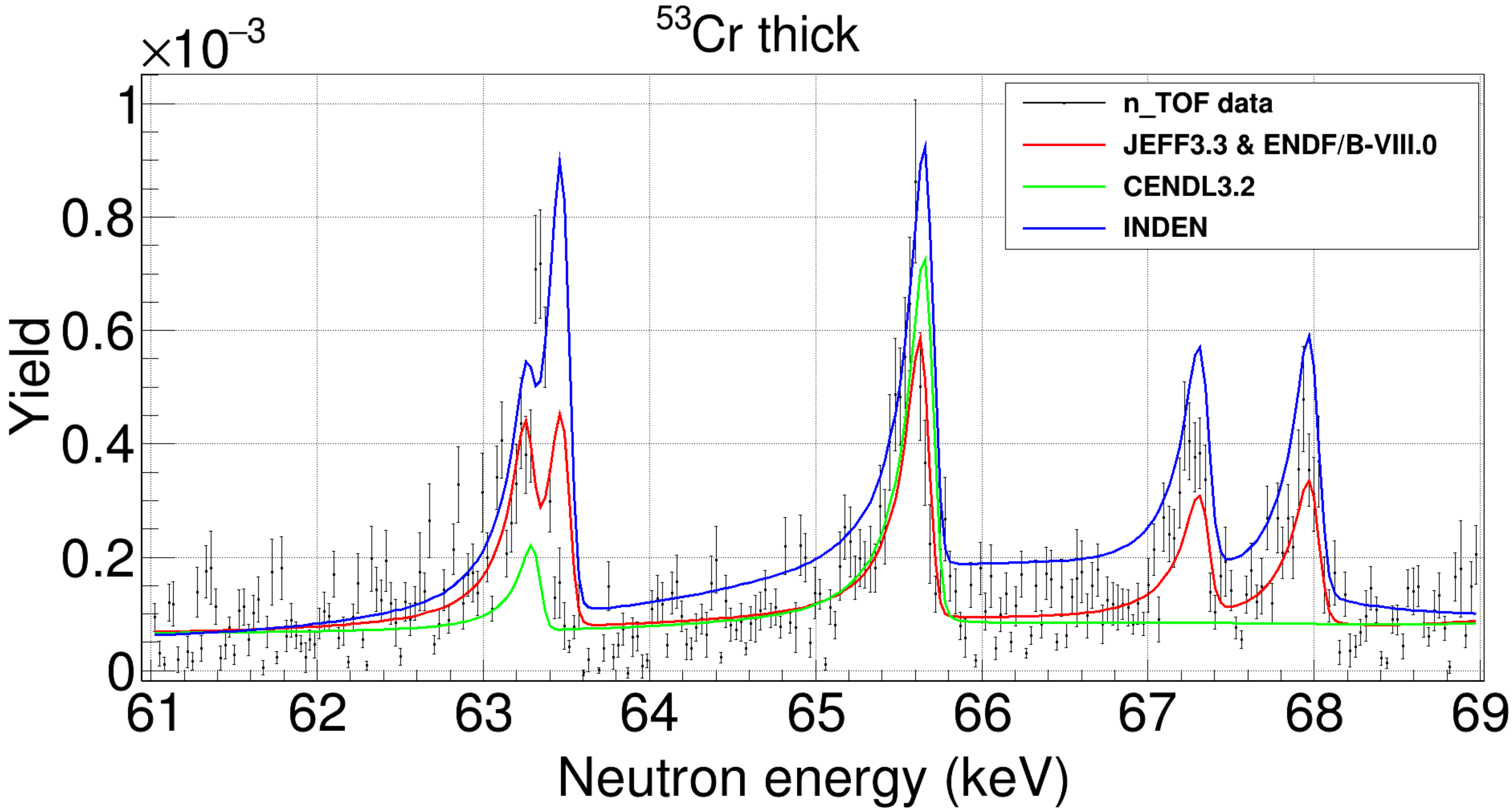


Preliminary ^{53}Cr yield (~30 keV, thick target)

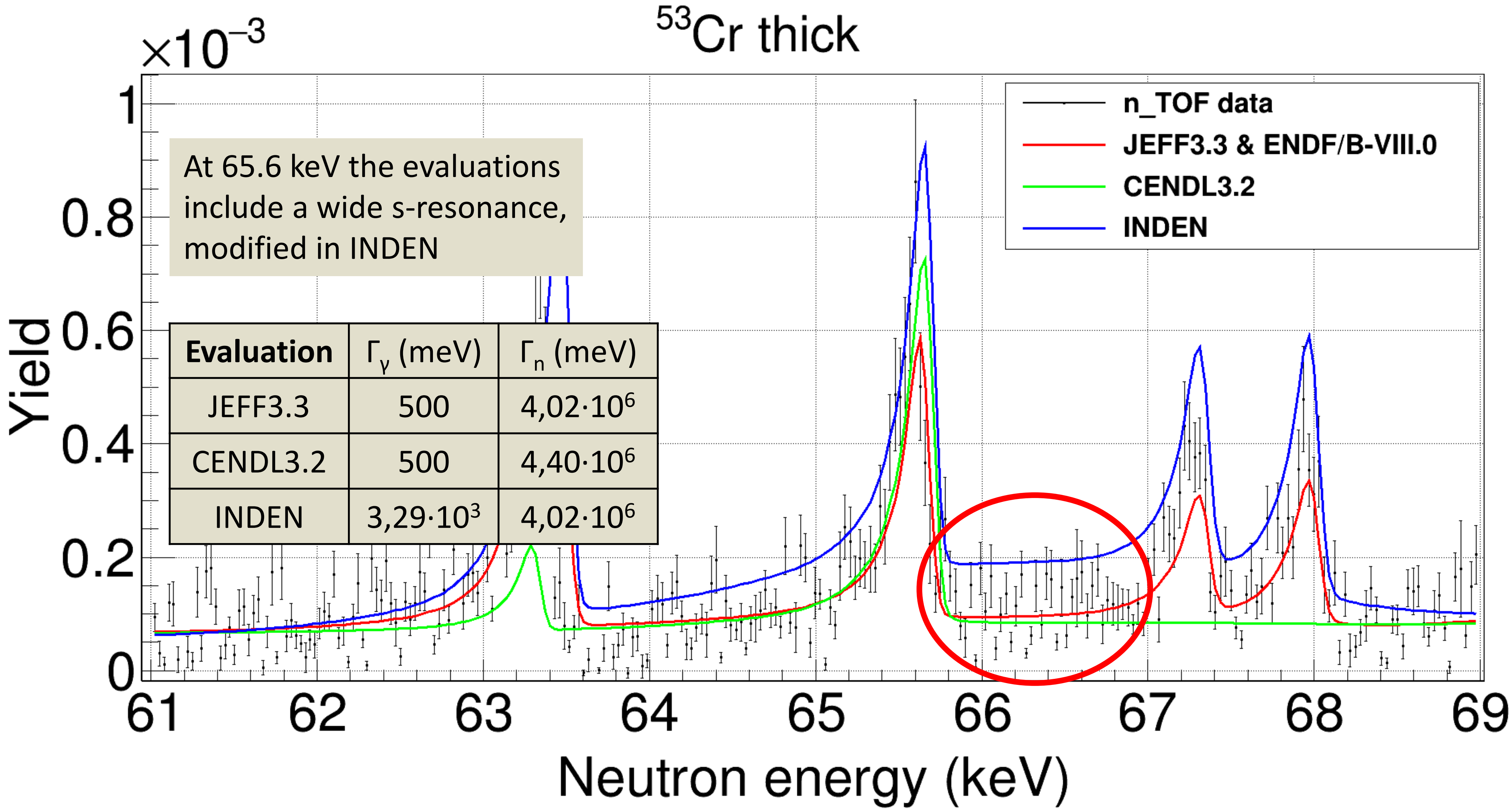


Missing resonance

Preliminary ^{53}Cr yield (~65 keV, thick target)



Preliminary ^{53}Cr yield (~65 keV, thick target)

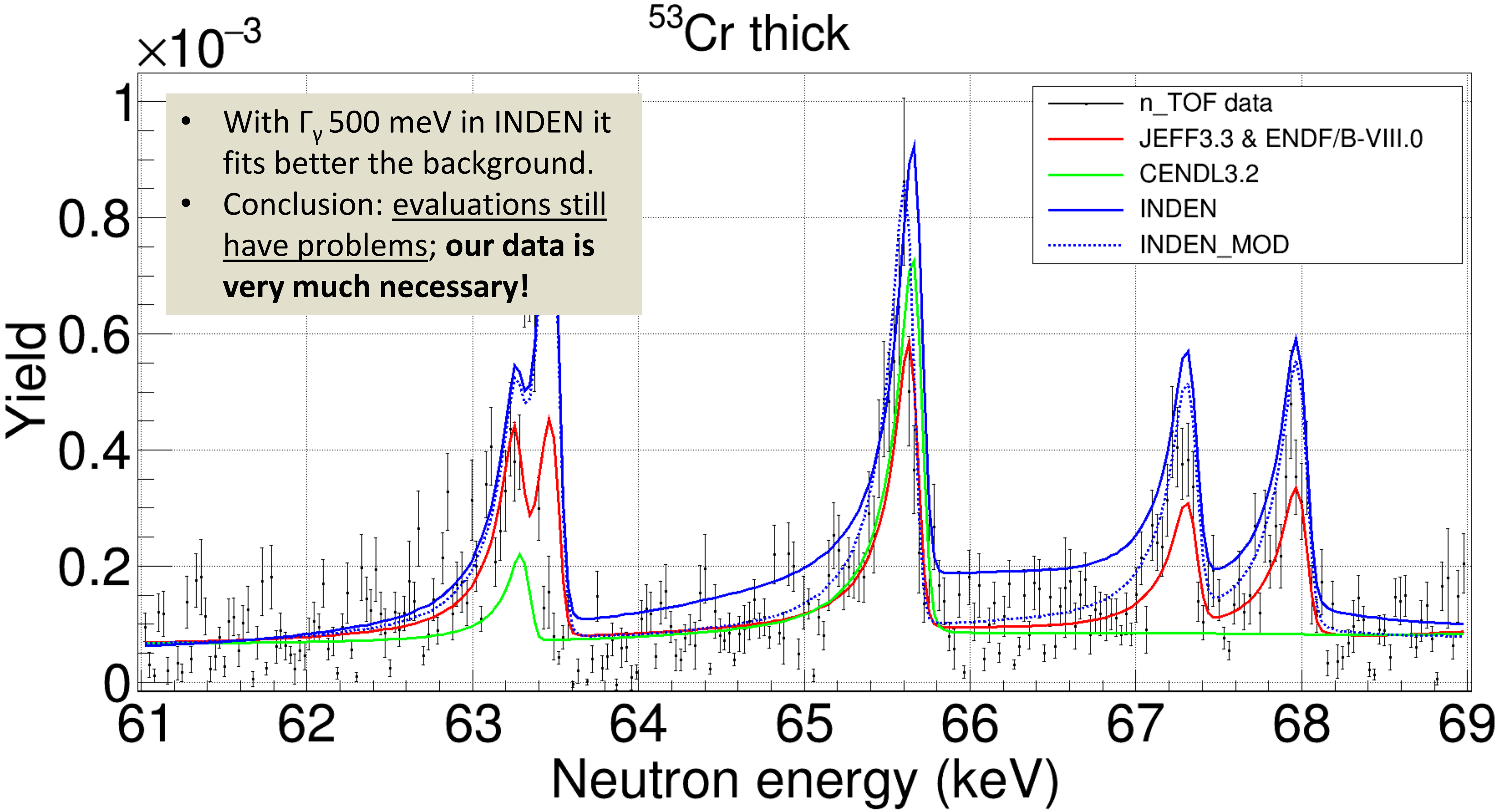


At 65.6 keV the evaluations include a wide s-resonance, modified in INDEN

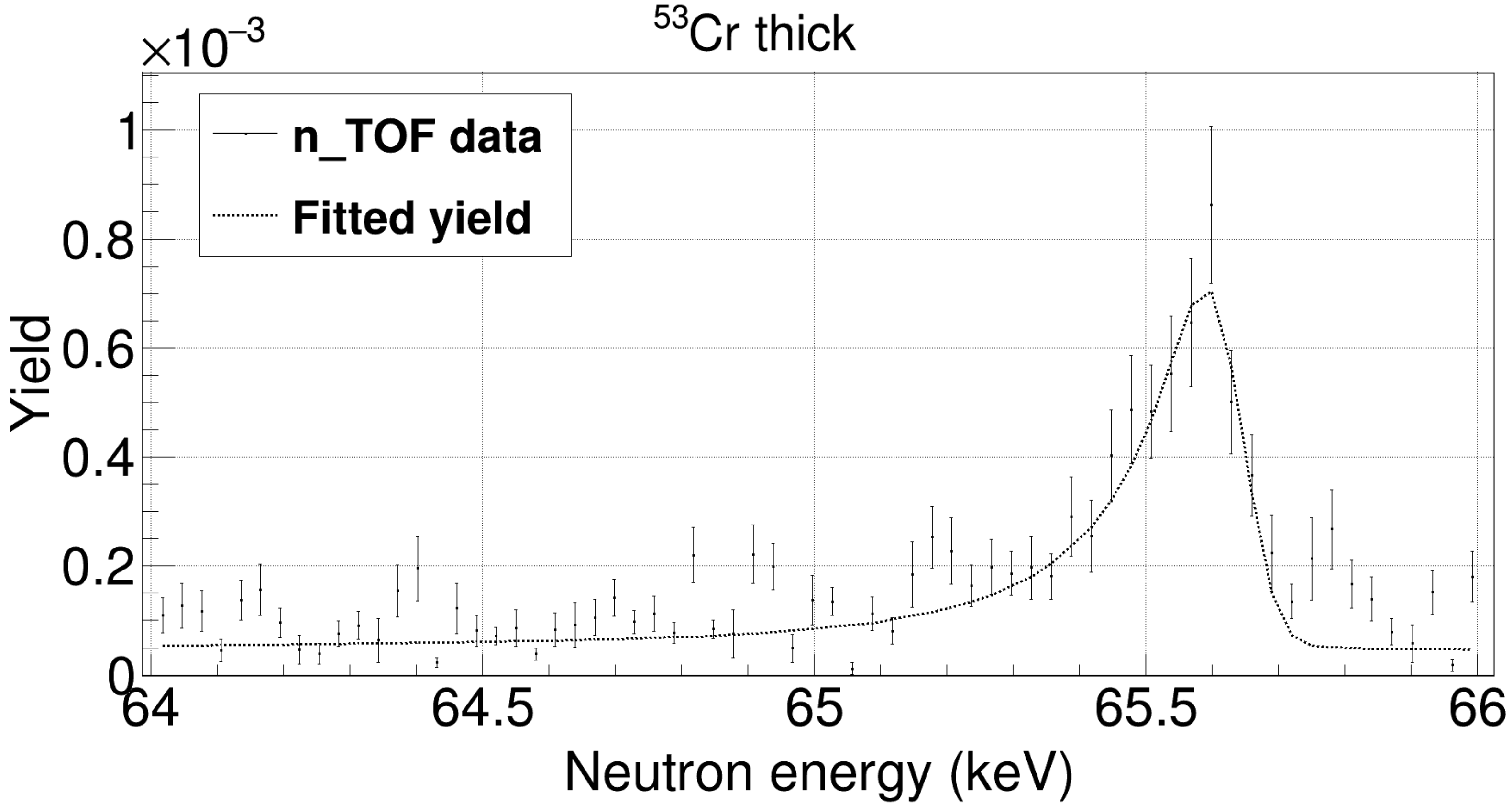
Evaluation	Γ_γ (meV)	Γ_n (meV)
JEFF3.3	500	$4{,}02 \cdot 10^6$
CENDL3.2	500	$4{,}40 \cdot 10^6$
INDEN	$3{,}29 \cdot 10^3$	$4{,}02 \cdot 10^6$

Preliminary ^{53}Cr yield (~65 keV, thick target)

- With Γ_γ 500 meV in INDEN it fits better the background.
- Conclusion: evaluations still have problems; **our data is very much necessary!**



How good does the RF fit our tails?



- We are using a May'23 version of the RF.
- Fit → only E_n free.
- The "tail" of the resonances are well reproduced, but we observe a shift in energy from ~ 40 keV onwards.
- Final version of the RF also needed for our analysis.

Summary & Outlook

- The goal is to improve the ^{50,53}Cr(n,γ) cross section to 8-10% accuracy at 1-100 keV
- Two experiments:
  - n_TOF@CERN, Summer’22 (H2020-Ariel Scientific Visit).
  - HiSPANoS@CNA, March’23 (H2020-Ariel Transnational Access).
- Preliminary results show high quality data.

- Next steps:
  - Obtain ^{50,53}Cr capture cascades (known?)
  - Apply corrected WF → Yield
  - Estimate systematic uncertainties
  - Resonance analysis with SAMMY
  - Activation @CNA data analysis (2023/24)
  - PhD defense in Fall 2024, one year from now

} n_TOF experiment data analysis (2023/24)

Thank you!

Pablo Pérez Maroto
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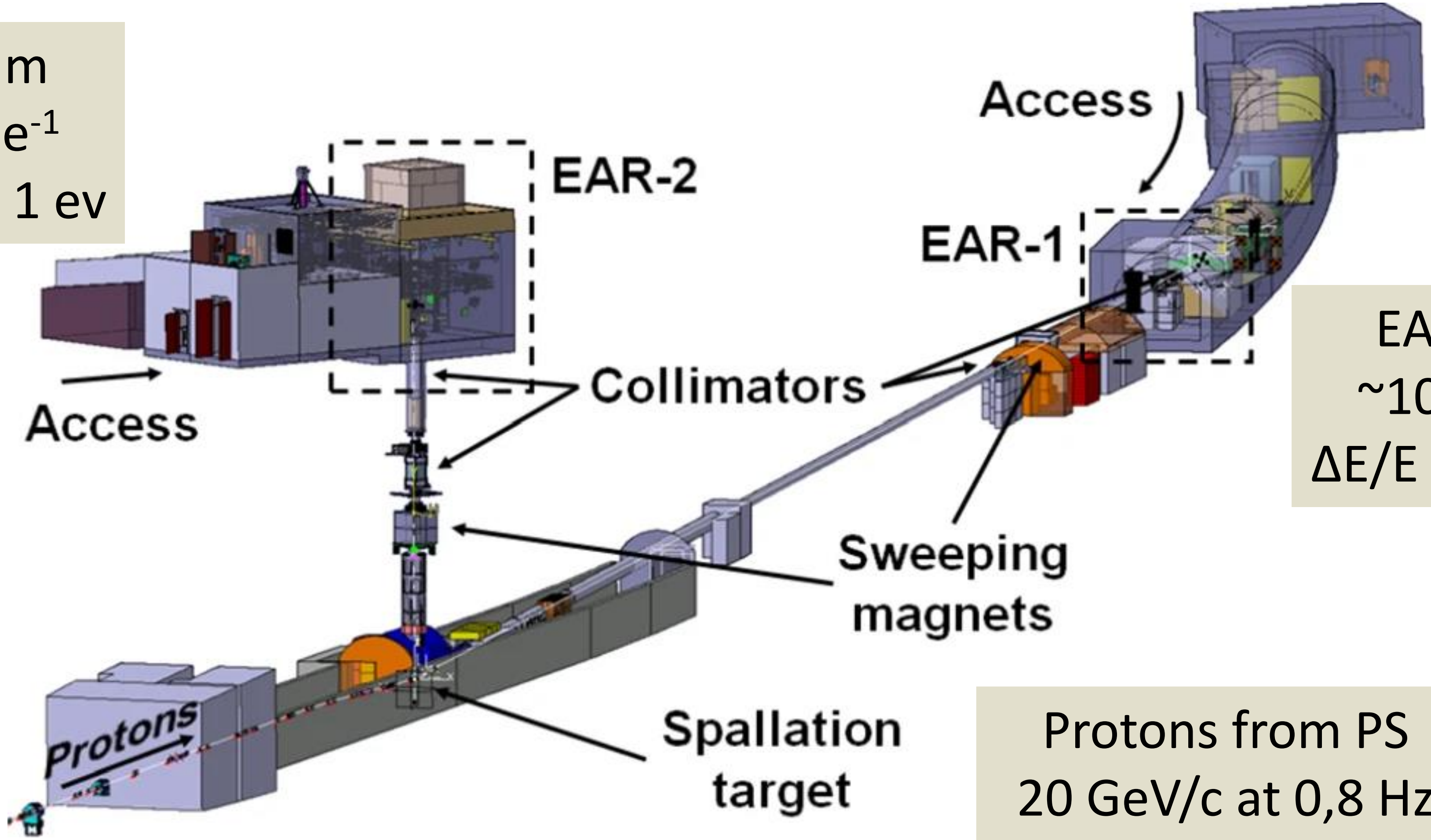
Backup. The neutron_TOF facility at CERN

EAR2 -> 18,5 m
~10^6 $cm^{-2}pulse^{-1}$
$\Delta E/E \sim 4\cdot10^{-3}$ @ 1 ev

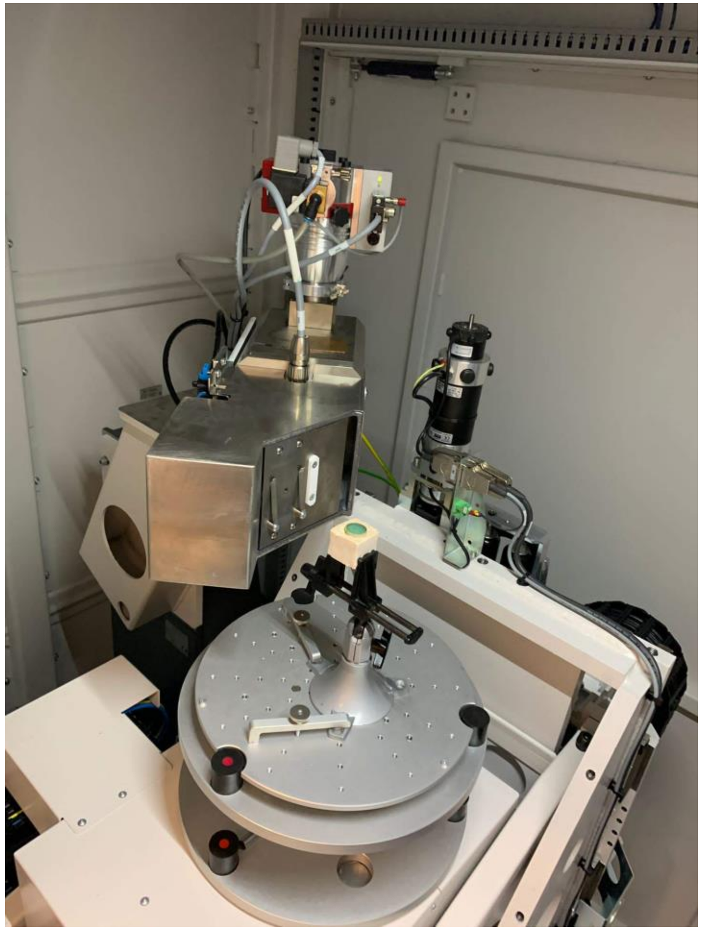


EAR1 -> 185 m
~10^4 $cm^{-2}pulse^{-1}$
$\Delta E/E \sim 5\cdot10^{-4}$ @ 1 ev

Protons from PS
20 GeV/c at 0,8 Hz
~$850\cdot10^{10}$ ppp

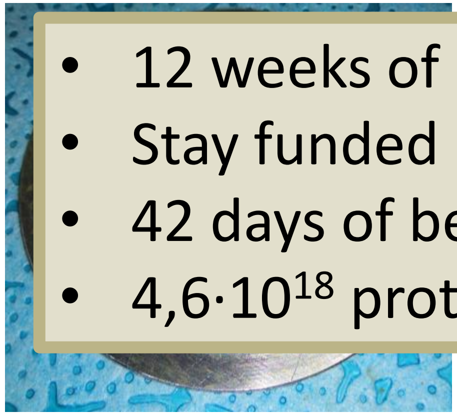
N. Colonna

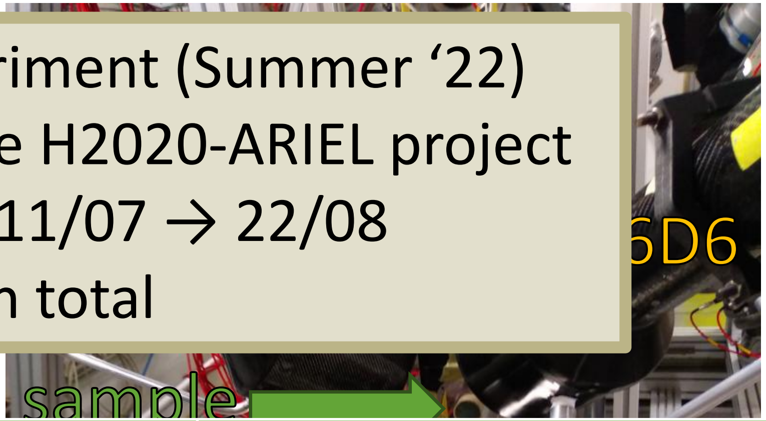
Backup. Tomography for homogeneity check



- Tomography of the samples → **MME Group (CERN)**
- Very helpful for determining the density and thickness of the samples
- With the thinnest sample (^{50}Cr thin, ~240 mg) serious imperfections were observed → we were able to redo this sample
- With simulations we will estimate **self-shielding** and **multiple scattering effects** and the cross section **uncertainty**

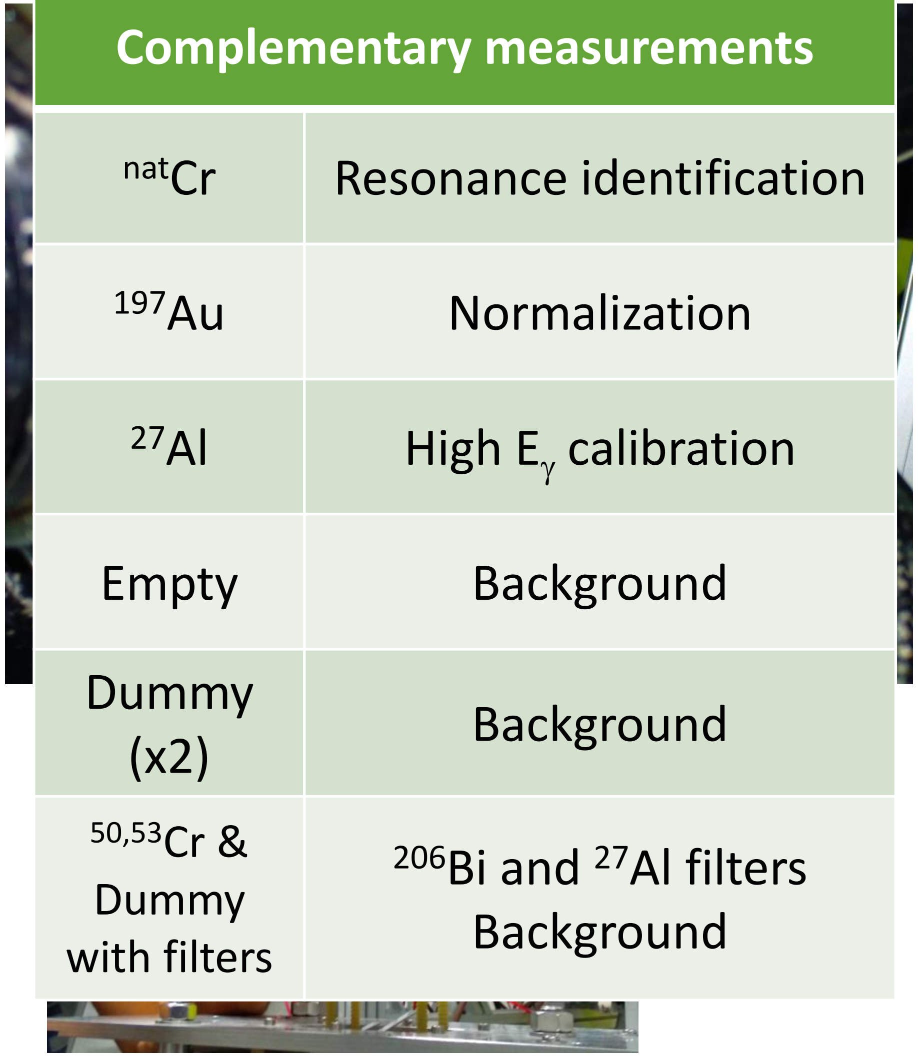
Backup. Samples and detector set-up (EAR1)





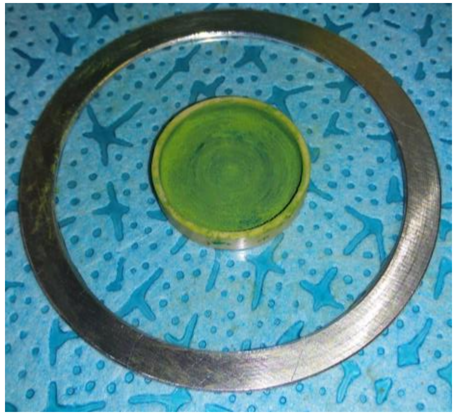
- 12 weeks of experiment (Summer '22)
- Stay funded by the H2020-ARIEL project
- 42 days of beam: 11/07 → 22/08
- $4{,}6 \cdot 10^{18}$ protons in total

Sample	Protons$\cdot 10^{17}$ (meas.)	Protons$\cdot 10^{17}$ (proposal)
^{50}Cr – thin	5,5	5 (110%)
^{50}Cr – thick	**14,7**	**8 (184%)**
^{53}Cr – thin	6,8	5 (136%)
^{53}Cr – thick	**6,9**	**17 (40%)**
Back. & norm.	13,0	5 (260%)
Total	**45,9**	**40 (115%)**

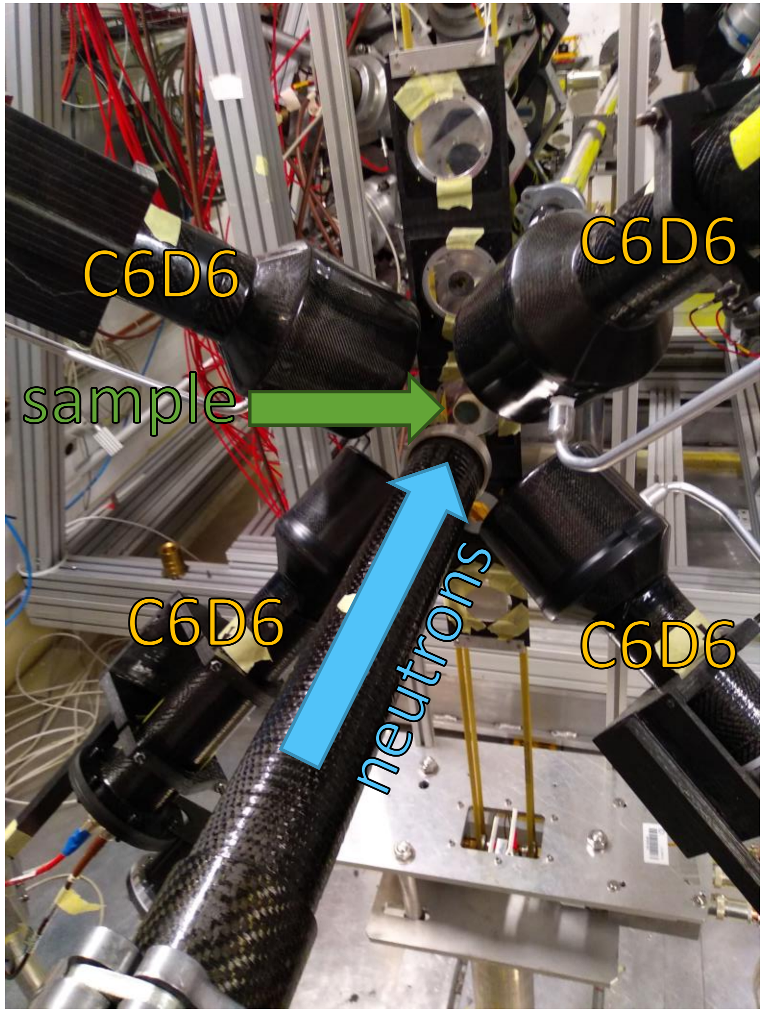


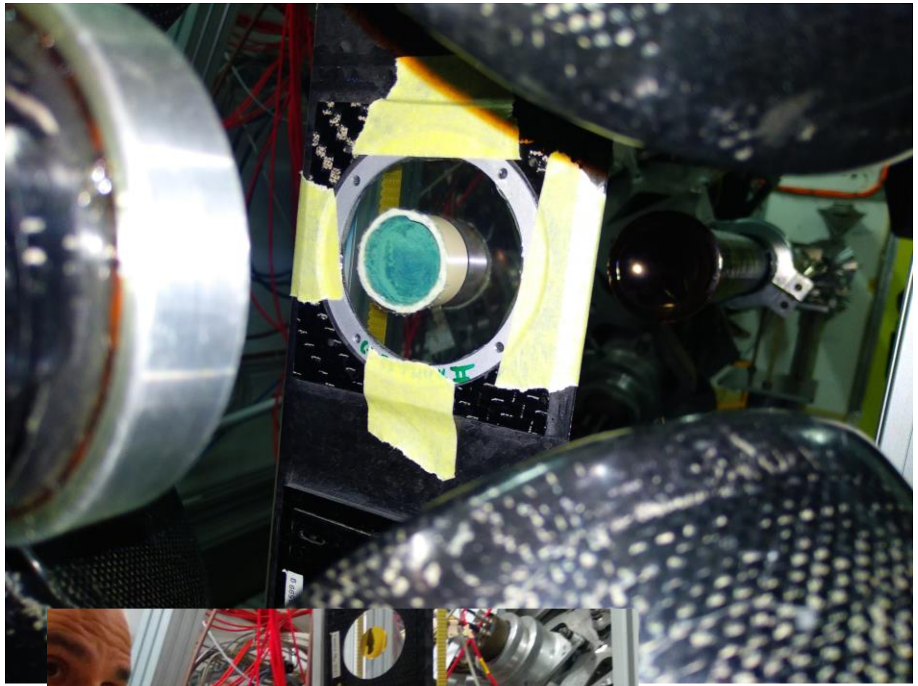
Complementary measurements	
^{nat}Cr	Resonance identification
^{197}Au	Normalization
^{27}Al	High E_γ calibration
Empty	Background
Dummy (x2)	Background
^{50,53}Cr & Dummy with filters	^{206}Bi and ^{27}Al filters Background

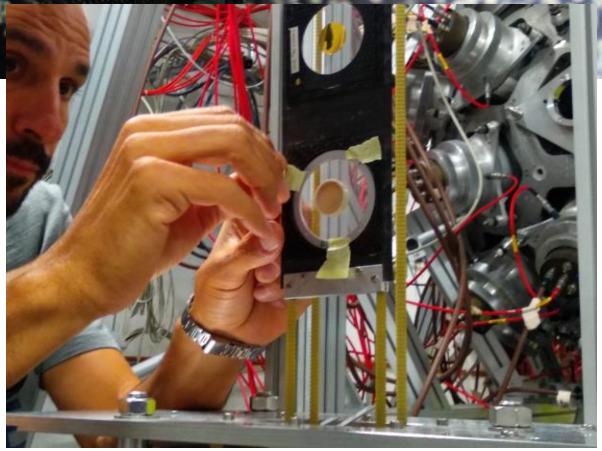
Backup. Samples and detector set-up (EAR1)



Cr_2O_3 powder pressed in a PEEK capsule & Al holder







Backup. Planning

1st week		Mon	Tue	Wed	Thu	Fri	Sat	Sun
		11	12	13	14	15	16	17
50-53Cr(n, g) @EAR1	Sample	Au / Dummy	Empty/Cr-53 thin	Cr-53 thin	Cr-53 thin	Cr-53 thin	Cr-53 thin	Cr-53 thin
	Planned Protons	5.00E+16	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17
	Real protons	5.31E+16	1.08E+17	7.77E+16	1.26E+17	1.10E+17	1.49E+17	9.98E+16
	Others	Calibration		NEAR intervention				

2st week		Mon	Tue	Wed	Thu	Fri	Sat	Sun
		18	19	20	21	22	23	24
50-53Cr(n, g) @EAR1	Sample	Au / Dummy	Al / Cr-53 thick	Cr-53 thick	Cr-53 thick	Cr-53 thick	Cr-53 thick	Cr-53 thick
	Planned Protons	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17
	Real protons	1.26E+17	7.97E+16	7.50E+16	1.02E+17	1.05E+17	8.48E+16	1.08E+17
	Others	Make Cr-53 thick	Tomography	Calibration				
				NEAR intervention				

3d week		Mon	Tue	Wed	Thu	Fri	Sat	Sun
		25	26	27	28	29	30	31
50-53Cr(n, g) @EAR1	Sample	Cr-53 thick	Cr-53 thick	Au / Dummy-2	Cr-50 thin	Cr-50 thin	Cr-50 thin	Cr-50 thin
	Planned Protons	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17
	Real protons	1.05E+17	1.15E+17	8.98E+16	1.22E+17	1.00E+17	1.24E+17	1.17E+17
	Others		Make Cr-50 thin	Calibration				
			Tomography	NEAR intervention				

4th week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
	1	2	3	4	5	6	7
Sample	Cr-50 thin	Au / Dummy	Cr-50 thick	Cr-50 thick	Cr-50 thick	Cr-50 thick	Cr-50 thick
nned Protons	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17
eal protons	1.44E+17	8.41E+16	9.08E+16	9.79E+16	1.18E+17	1.25E+17	1.30E+17
Others			Calibration				
			NEAR intervention				
			Make Cr-50 thick				

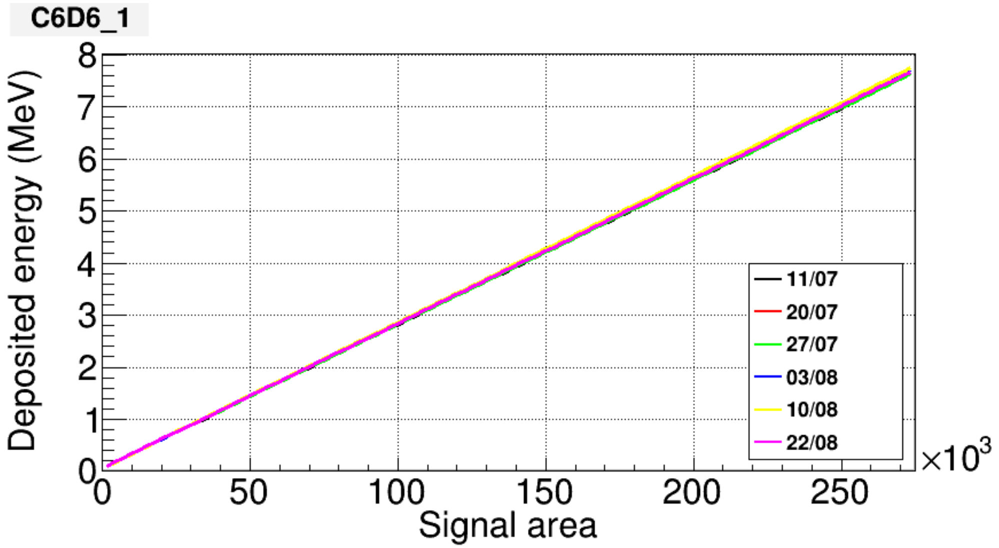
5th week	Mon	Tue	Wed	Thu	Fri	Sat	Sun
	8	9	10	11	12	13	14
Sample	Cr-50 thick	Cr-50 thick	Au / Cr-50 thick	Cr-50 thick	Cr-50 thick	Cr-50 thick	Cr-50 thick
nned Protons	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17
eal protons	9.90E+16	1.15E+17	8.06E+16	1.08E+17	1.12E+17	1.26E+17	1.28E+17
Others			Calibration				
			NEAR intervention				

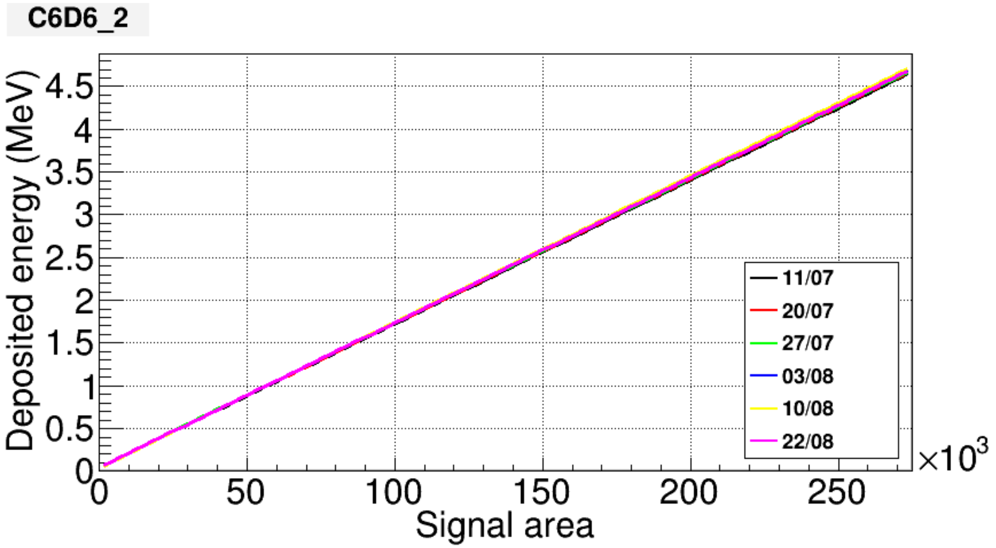
6th week		Mon	Tue	Wed	Thu	Fri	Sat	Sun
		15	16	17	18	19	20	21
50-53Cr(n, g) @EAR1	Sample	Cr-50 thick	Cr-nat	Au / Cr-nat	Empty	Dummy (F)	Cr-53 thick (2)(F)	Cr-50 thick (F)
	Planned Protons	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17	1.00E+17
	Real protons	1.36E+17	1.01E+17	1.20E+17	1.03E+17	1.04E+17	1.35E+17	1.10E+17
	Others							

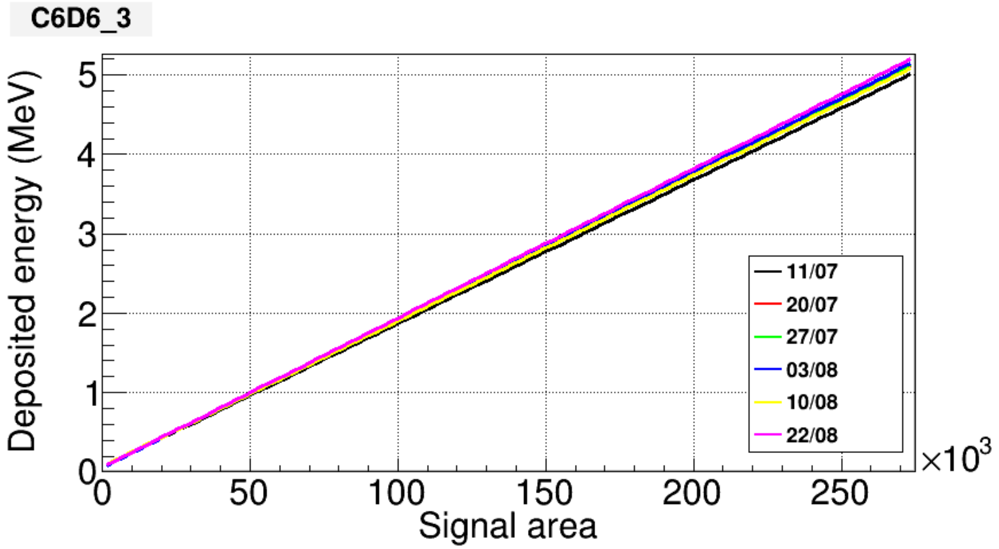
Backup. Final number of protons

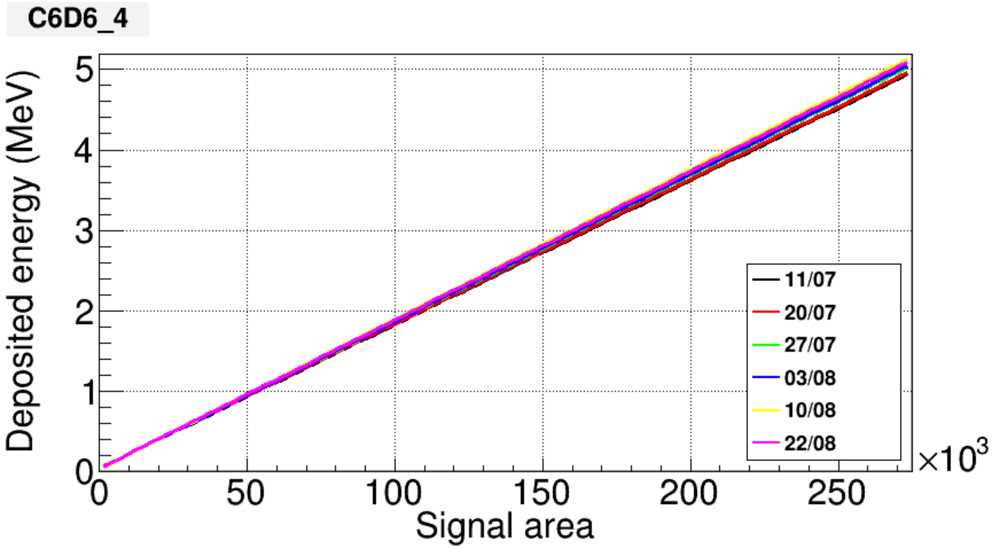
J	K	L	M	N	O	P
Mass (mg)	Sample	Planned	Measured	Progress (%)	53Cr thick (2) first part (%)	Measured /Planned
2500	53Cr thick (2)	7.50E+17	6.94E+17	92.55	92.55	93.80%
500	53Cr thin	6.00E+17	6.76E+17	112.61		
750	50Cr thick	1.30E+18	1.37E+18	105.36		
250	50Cr thin	5.00E+17	5.49E+17	109.88		
2500	natCr	2.00E+17	2.02E+17	100.84		
	197Au	1.00E+17	9.71E+16	97.06		
	Dummy 1	3.00E+17	3.05E+17	101.76		
	Dummy 2	1.00E+17	1.19E+17	119.36		
	Empty	1.00E+17	1.47E+17	146.89		
	27Al	5.00E+16	7.58E+16	151.68		
	Dummy 1 (F)	1.00E+17	1.20E+17	119.89		**FILTERS:**
	53Cr thick (2)(F)	1.00E+17	9.93E+16	99.34		10mm Bi
	50Cr thick (F)	1.00E+17	1.28E+17	127.51		50mm Al
	197Au 80mm					
	Total	**4.30E+18**	**4.58E+18**	**106.55**		
	Total x day		**1.09E+17**			

Backup. Calibrations

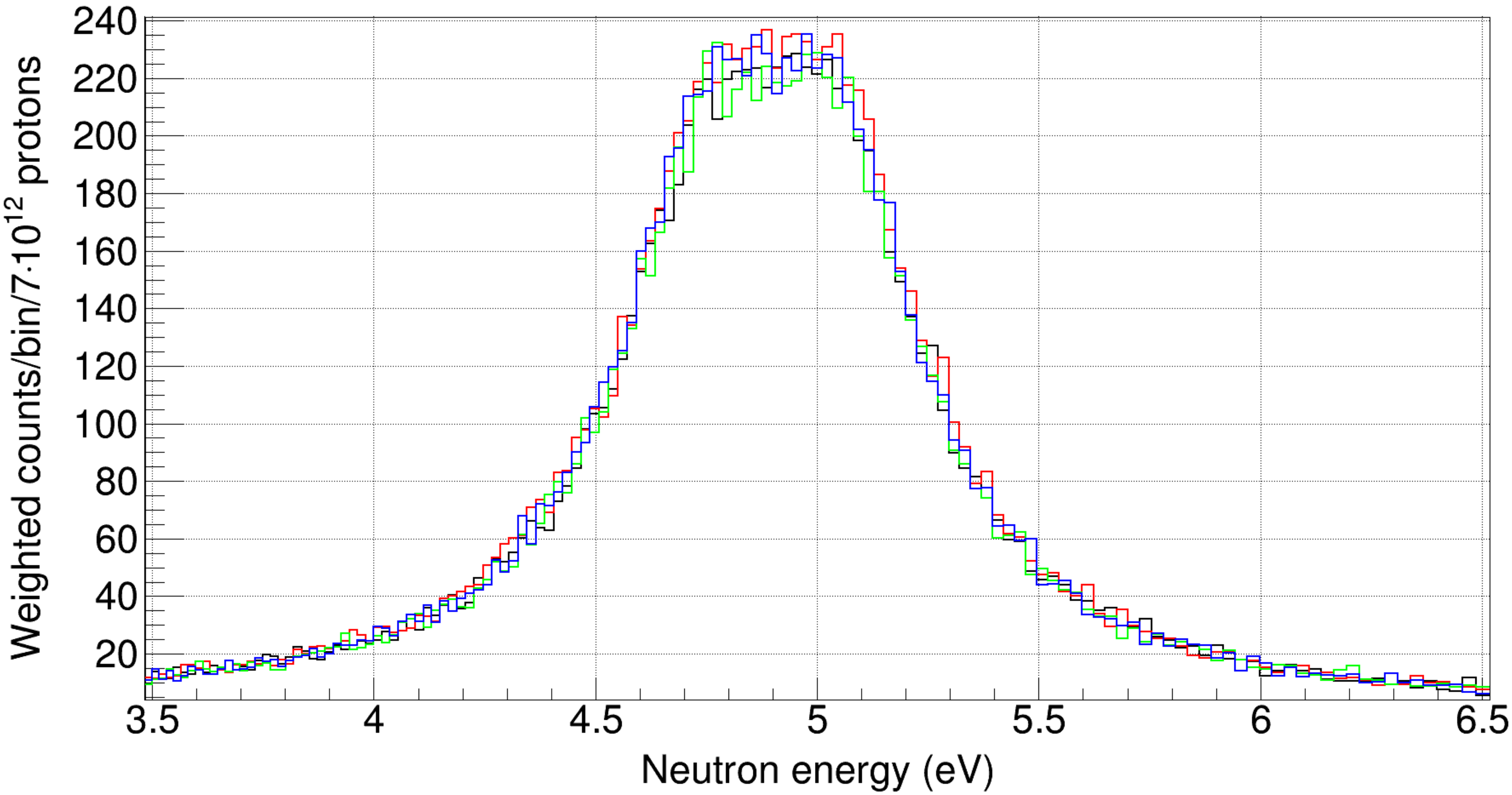




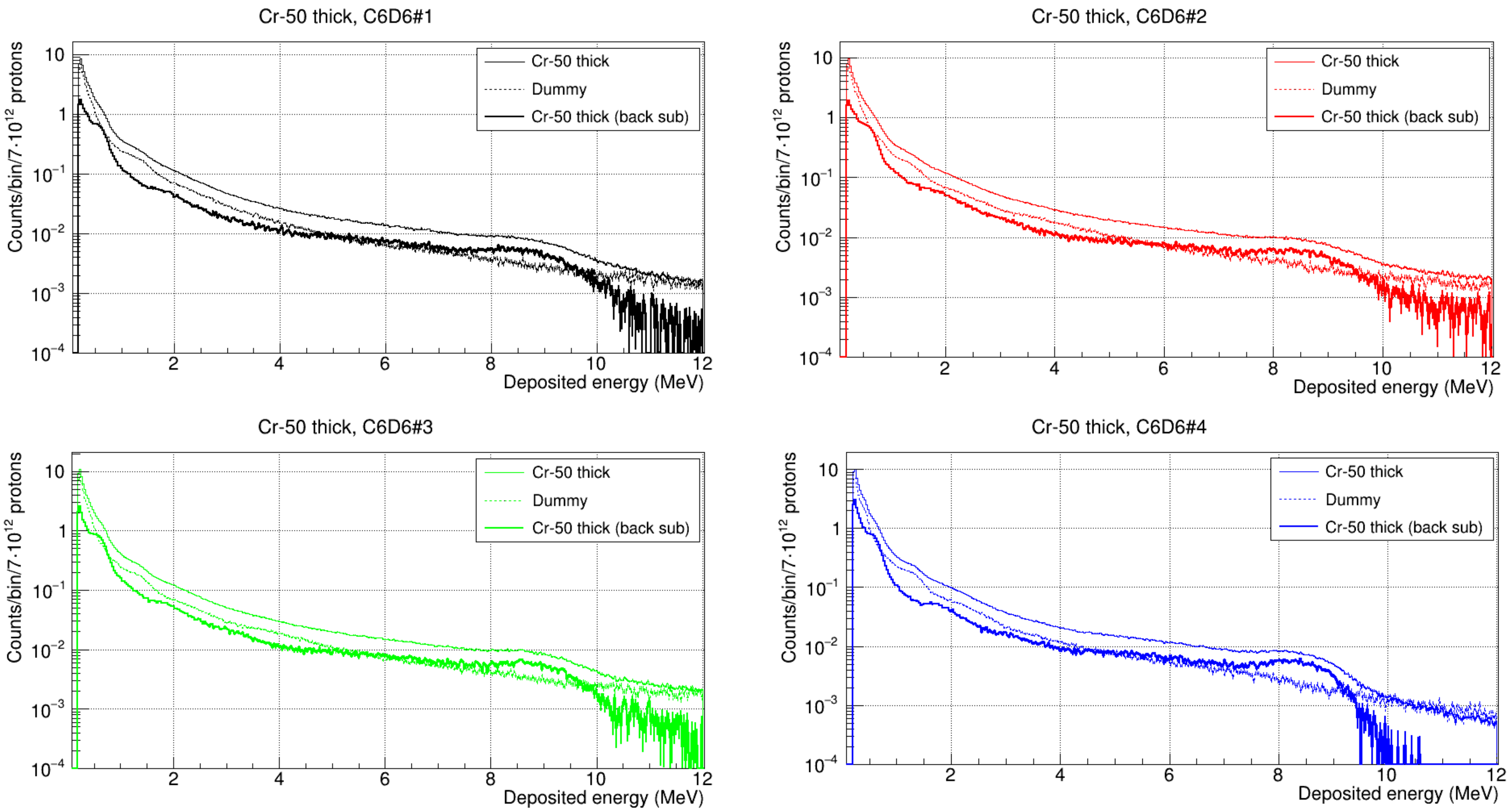




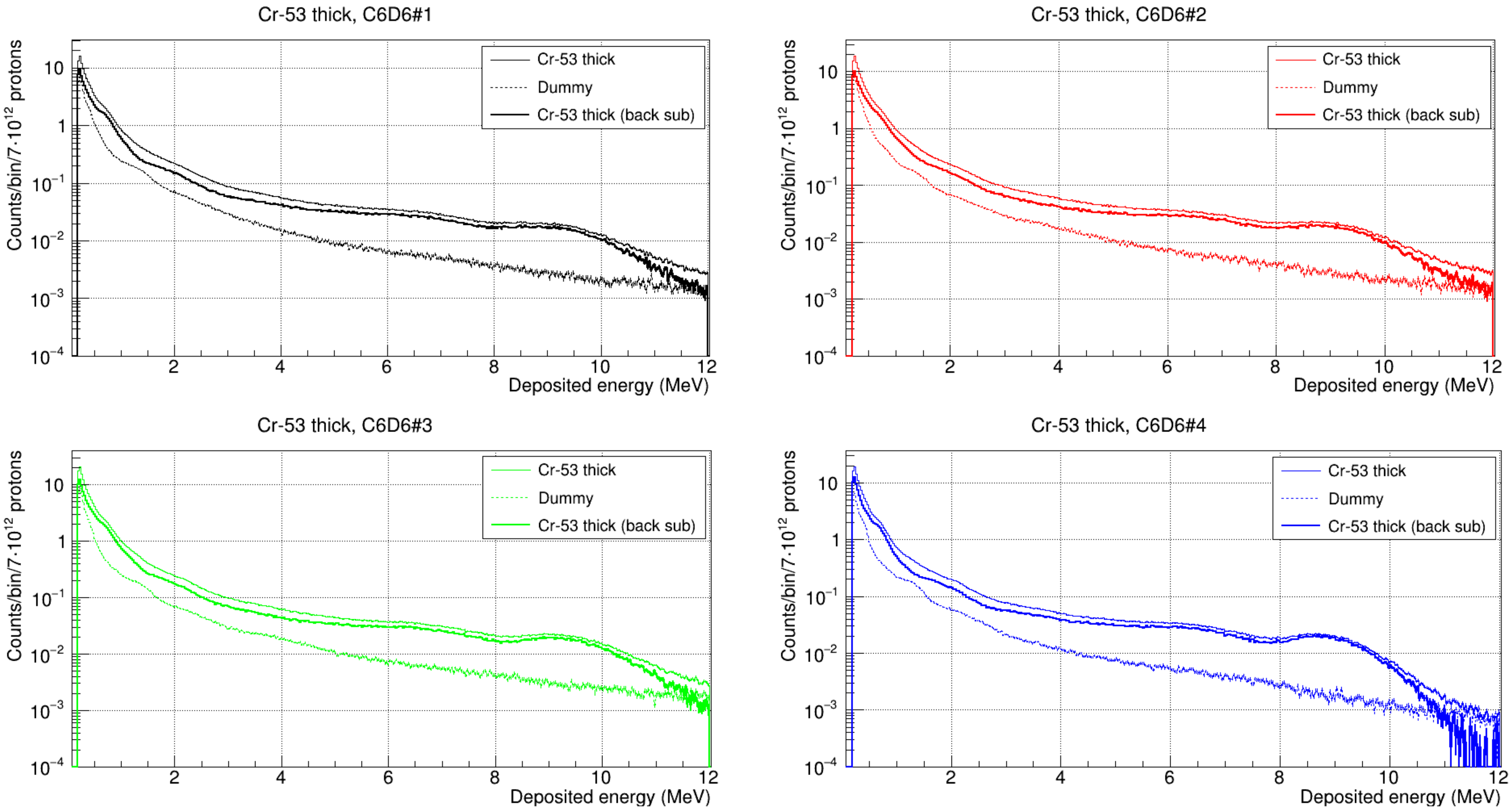
Backup. Weighted ^{197}Au resonance



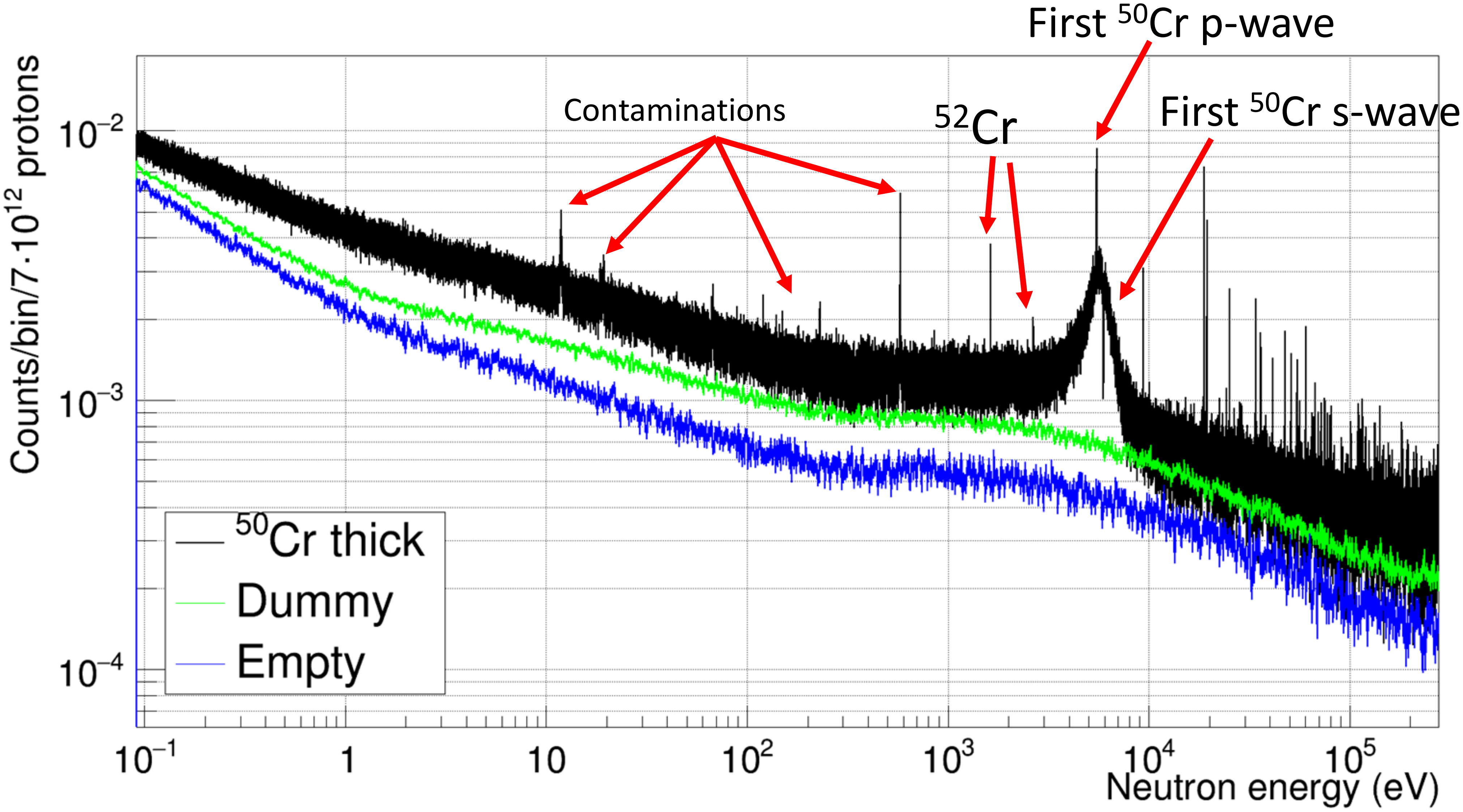
Backup. ^{50}Cr cascades (S_n=9,3 MeV)



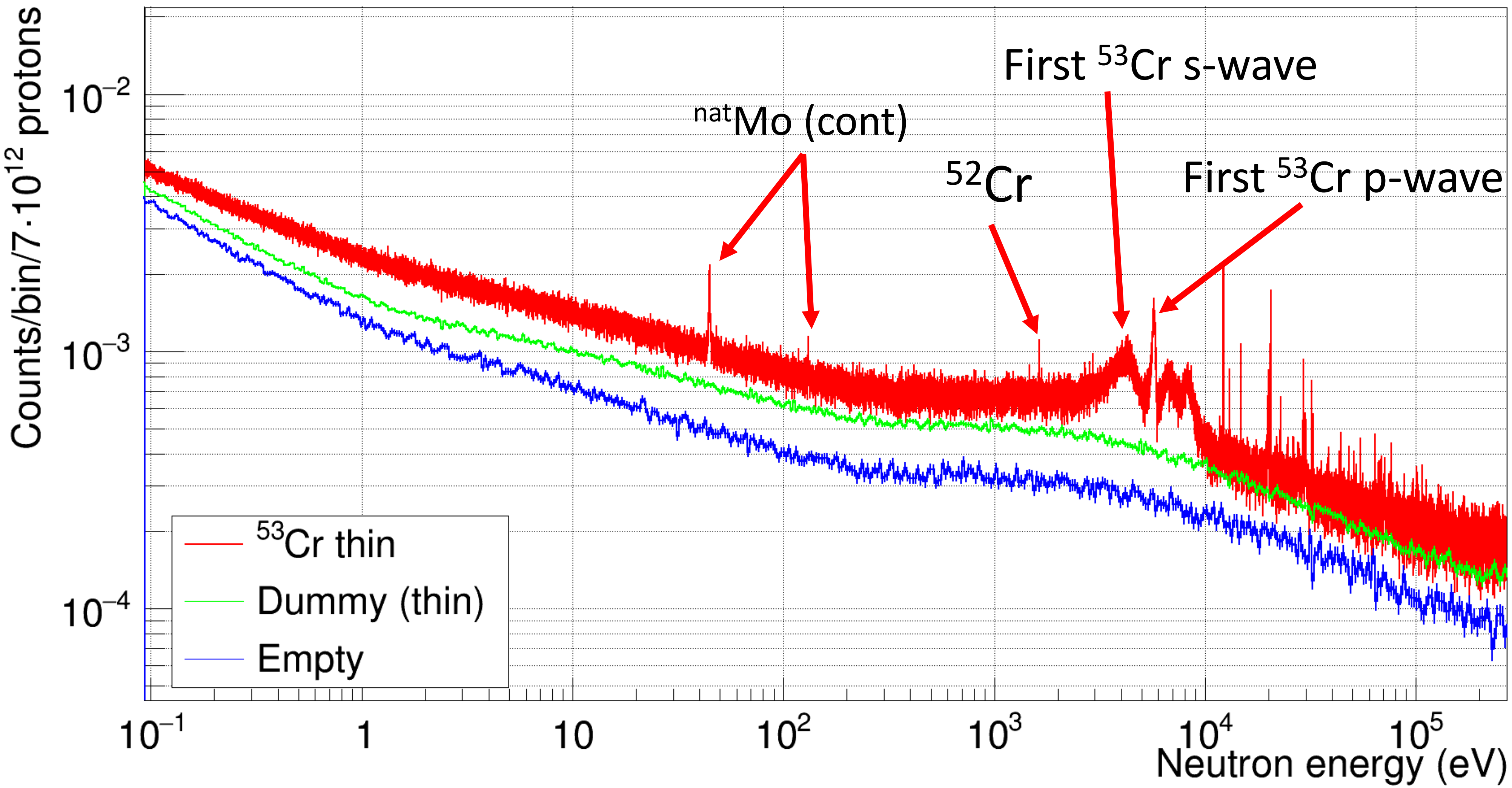
Backup. ^{53}Cr cascades (S_n=9,7 MeV)



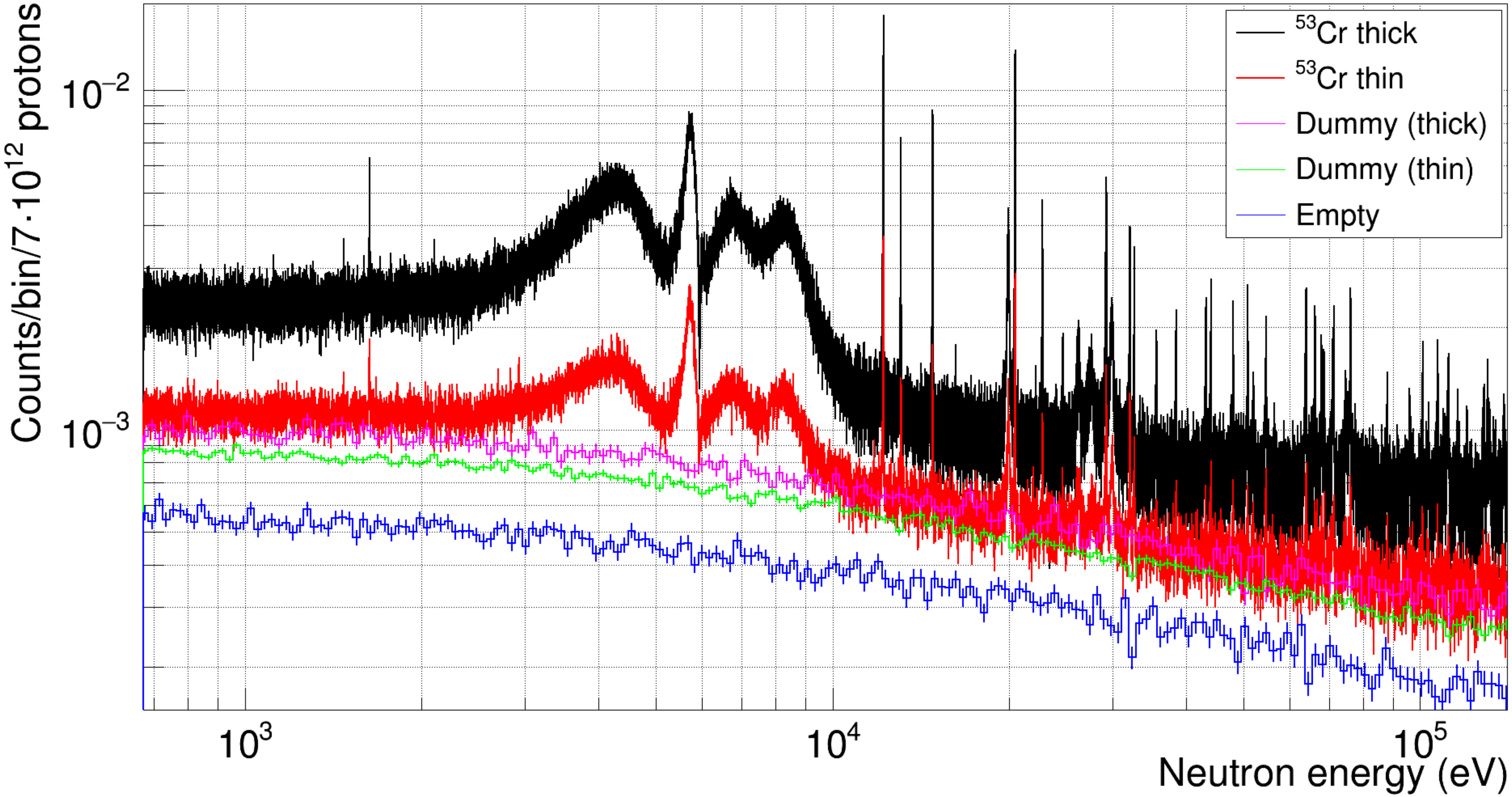
Backup. Preliminary results (^{50}Cr-thick)



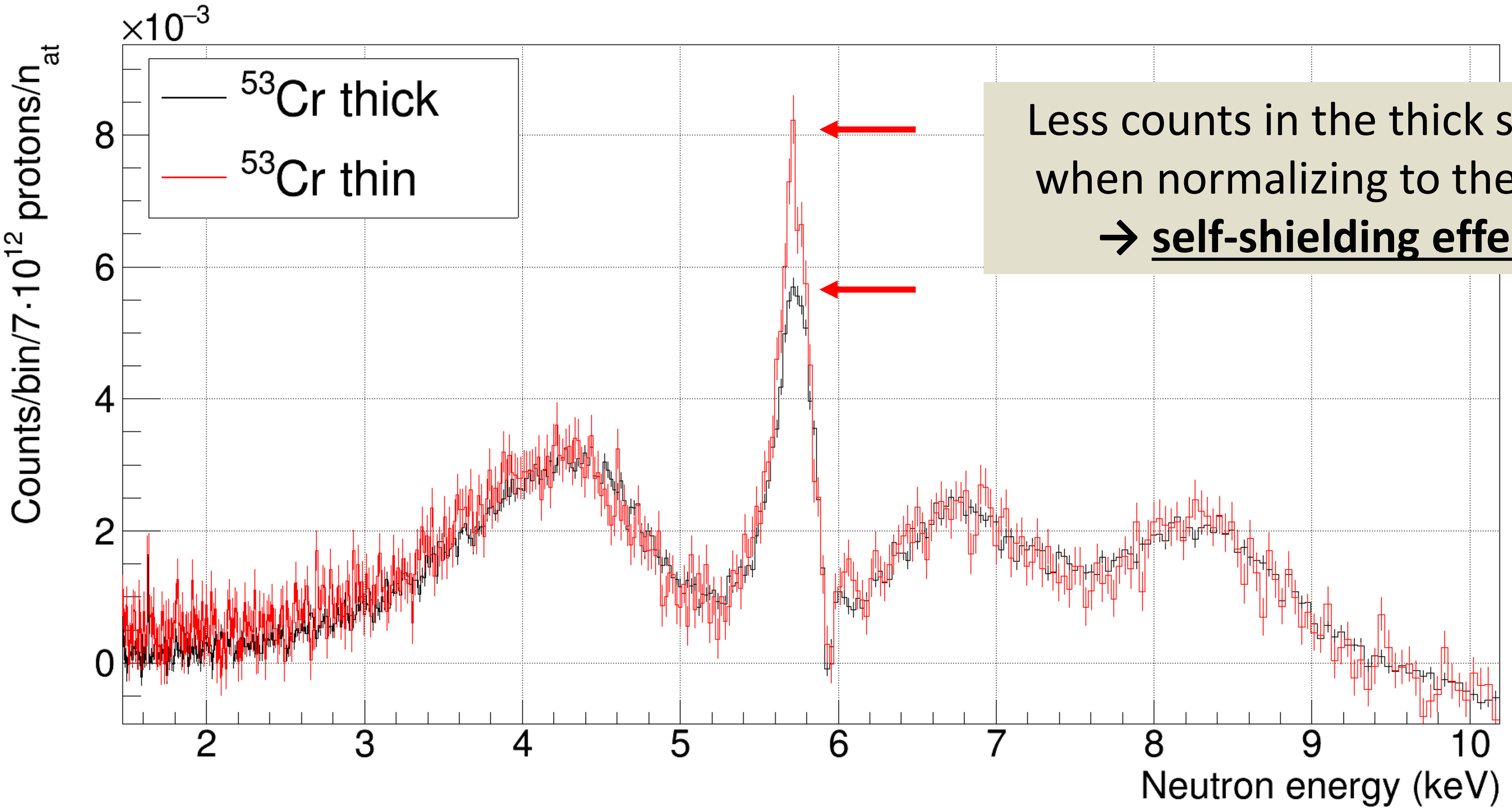
Backup. Preliminary results (^{53}Cr-thin)



Backup. Preliminary results (^{53}Cr: thin vs. thick)

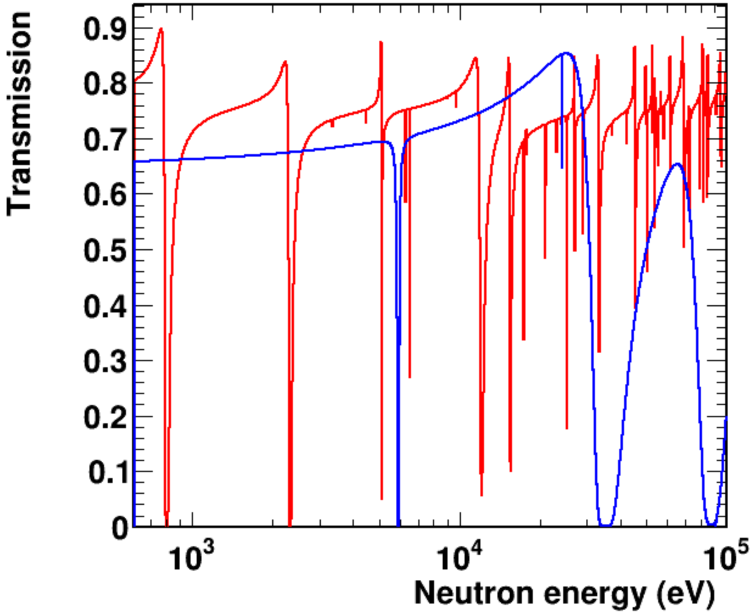


Backup. Preliminary results (^{53}Cr: thin vs. thick)

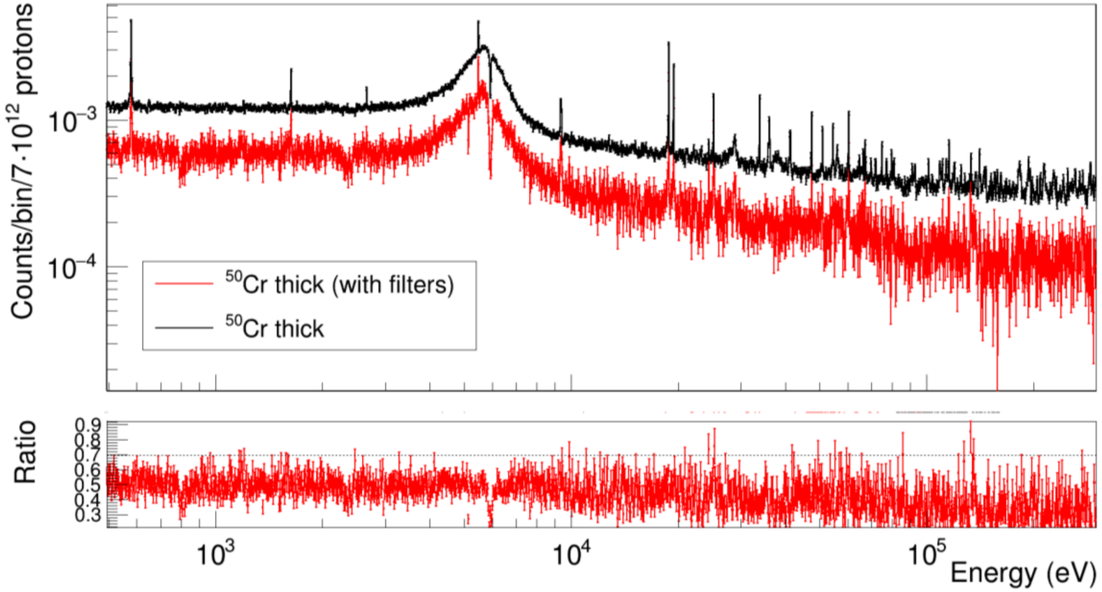


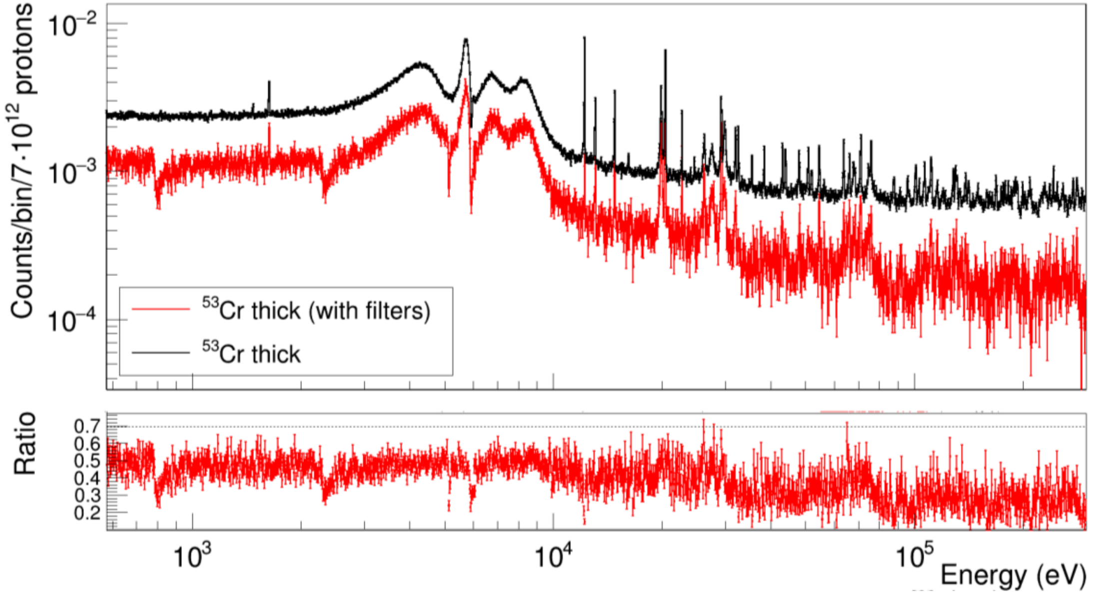
Less counts in the thick sample when normalizing to the mass → **self-shielding effects**

Backup. Filters

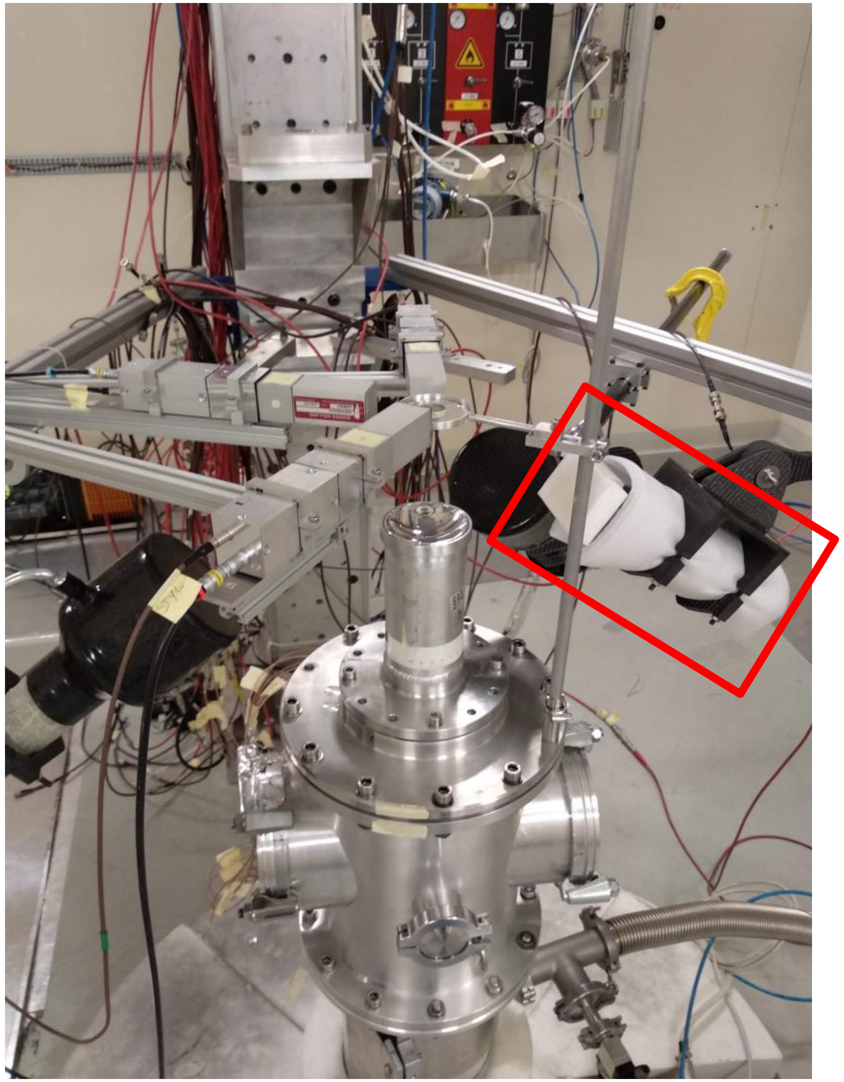


- For neutron scattering background
- 10 mm ^{209}Bi & 50mm ^{27}Al filters
- Dummy and thick samples

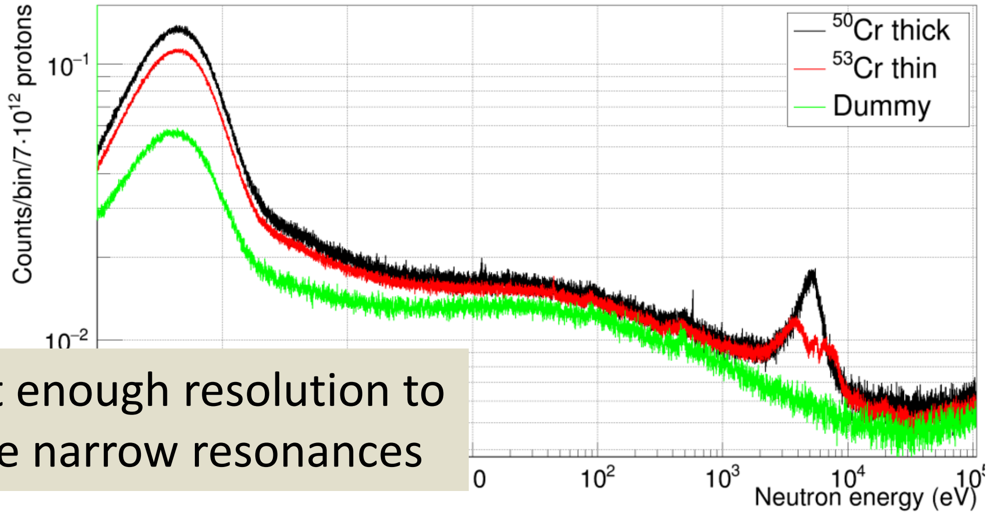




Backup. Cascades at EAR2

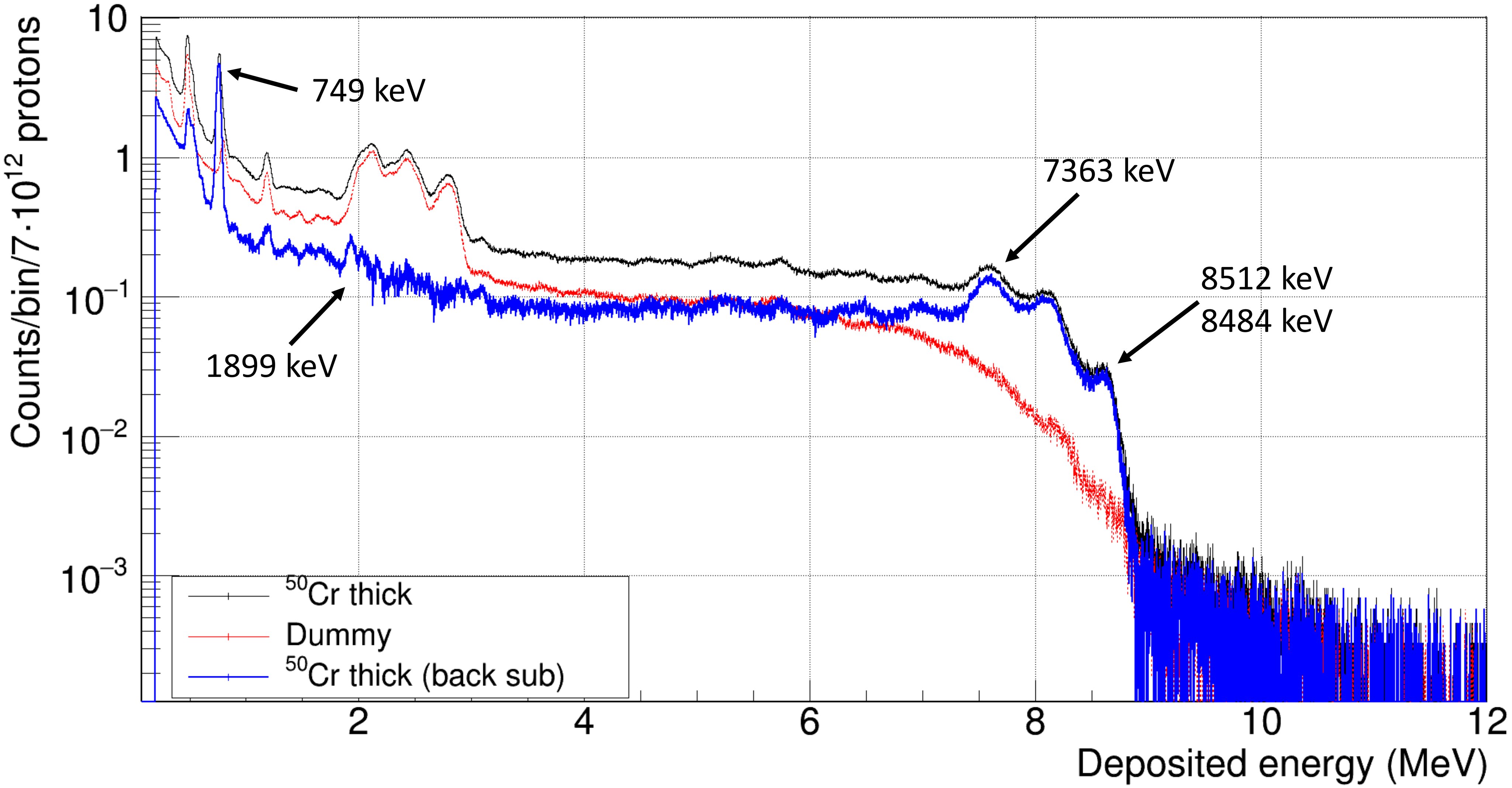


- Goal → measure the cascades with high resolution to validate future simulations
- 3 sTED's & 2 C6D6's for monitoring, **1 $LaCl_3$** for the cascades
- Gain shift depending on counting rate (malfunctioning PMT?) → thin samples, low voltage and not too close to the beam

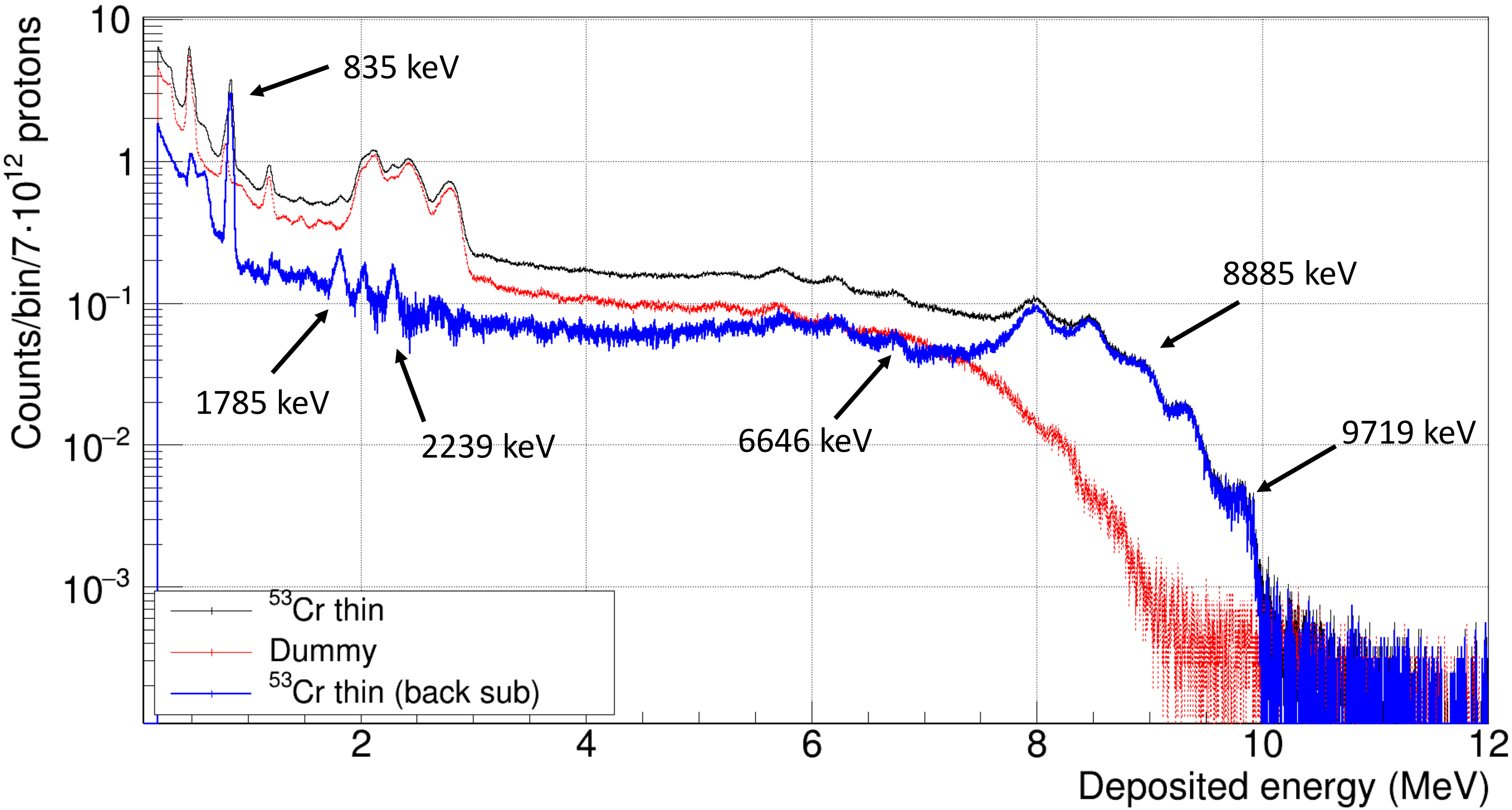


Not enough resolution to see narrow resonances

Backup. $^{50}Cr(n,\gamma)$ cascades at EAR2 (preliminary)



Backup. $^{53}Cr(n,\gamma)$ cascades at EAR2 (preliminary)



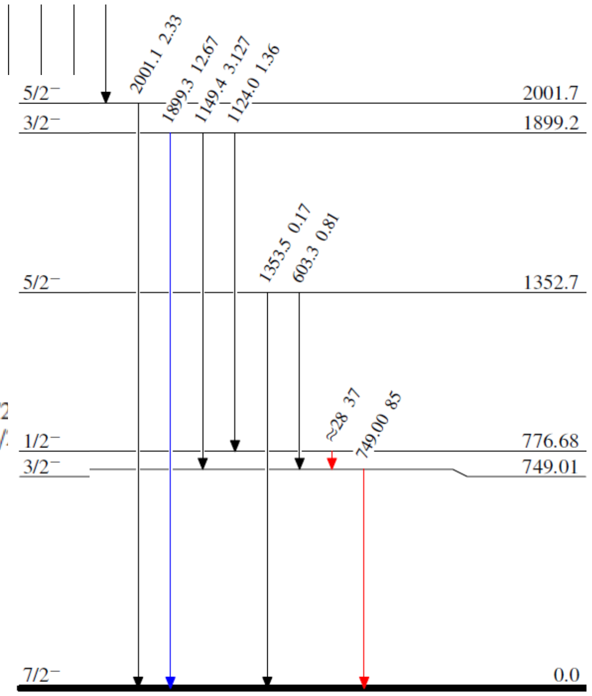
Backup. ^{51}Cr gamma emission

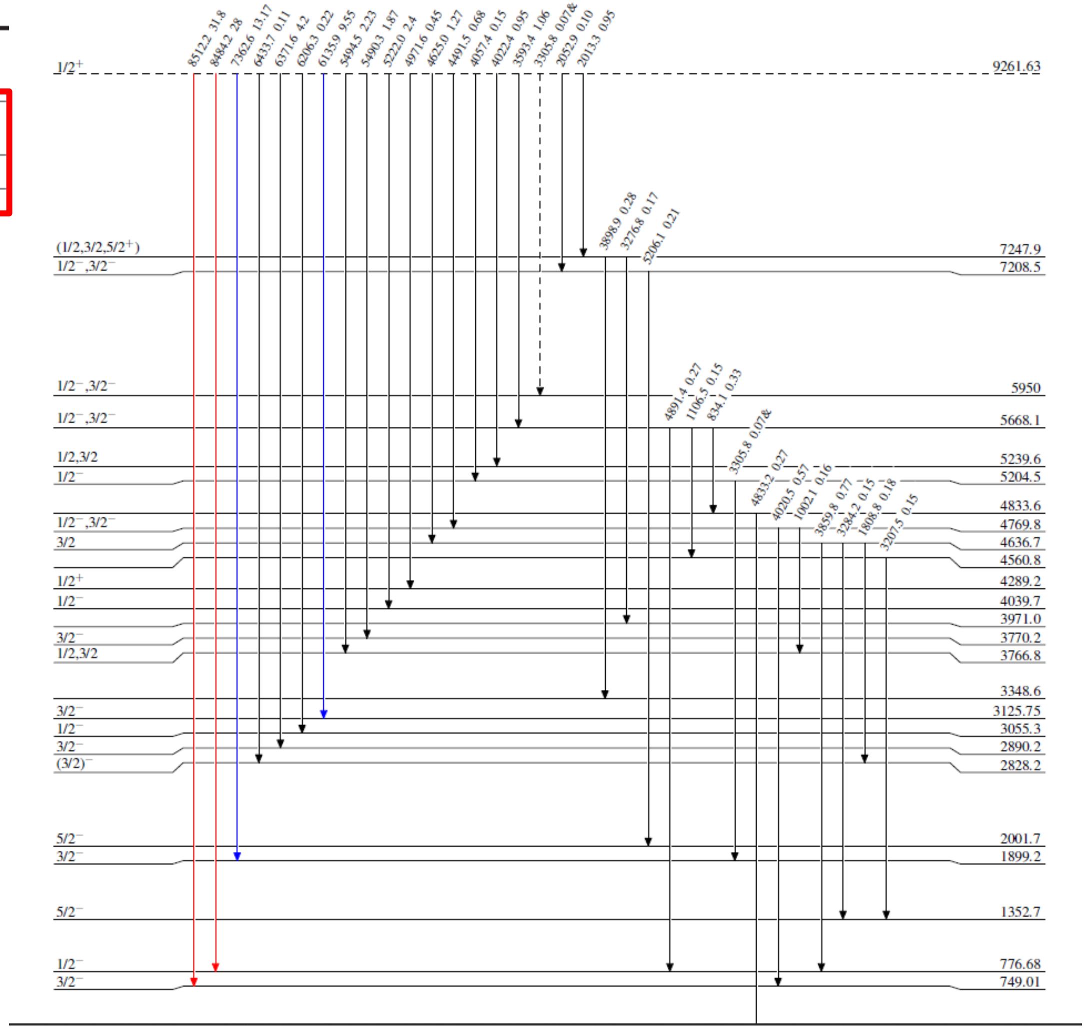
E_γ†	I_γ‡@	E_i(level)	J^π_i	E_f	J^π_f
≈28	35 3	776.68	1/2⁻	749.01	3/2⁻
603.3 4	0.76 15	1352.7	5/2⁻	749.01	3/2⁻
749.00 12	80 8	749.01	3/2⁻	0.0	7/2⁻
826.9 8	0.28 7	2828.2	(3/2)⁻	2001.7	5/2⁻
834.1 8	0.31 7	5668.1	1/2⁻,3/2⁻	4833.6	
845.2 8	0.36 8	3971.0		3125.75	3/2⁻
ˣ857.1 9	0.05 2				
862.3 6	0.07 4	3770.2	3/2⁻	2908.0	
888.2 8	2.17 22	2890.2	3/2⁻	2001.7	5/2⁻
913.2 9	0.17 5	4039.7	1/2⁻	3125.75	3/2⁻
928.2 9	0.14 4	2828.2	(3/2)⁻	1899.2	3/2⁻
990.4 9	0.78 16	2890.2	3/2⁻	1899.2	3/2⁻
1002.1 9	0.15 4	4769.8	1/2⁻,3/2⁻	3766.8	1/2,3/2
1106.5 9	0.14 4	5668.1	1/2⁻,3/2⁻	4560.8	
1124.0 9	1.28 14	1899.2	3/2⁻	776.68	1/2⁻
1149.4 9	2.94# 2	1899.2	3/2⁻	749.01	3/2⁻
1353.5 9	0.16 4	1352.7	5/2⁻	0.0	7/2⁻

• • •

E_γ†	I_γ‡@	E_i(level)	J^π_i	E_f	J^π_f
1537.2 8	1.9 2	2890.2	3/2⁻	1352.7	5/2⁻
1808.8 7	0.17 4	4636.7	3/2	2828.2	(3/2)⁻
1899.3 5	11.95# 6	1899.2	3/2⁻	0.0	7/2⁻
2001.1 9	2.1 2	2001.7	5/2⁻	0.0	7/2⁻
2013.3 6	0.8 2	(9261.63)	1/2⁺	7247.9	(1/2,3/2
2052.9 5	0.09 3	(9261.63)	1/2⁺	7208.5	1/2⁻,3/
2080.1 7	0.30 6	2828.2	(3/2)⁻	749.01	3/2⁻
2113.4 7	1.1 3	2890.2	3/2⁻	776.68	1/2⁻
2141.3&a 7	0.35& 9	2890.2	3/2⁻	749.01	3/2⁻
2141.3& 7	0.35& 9	4039.7	1/2⁻	1899.2	3/2⁻
2159.0 7	0.07 4	2908.0		749.01	3/2⁻
2279.2 7	0.28 7	3055.3	1/2⁻	776.68	1/2⁻
2348.9 5	2.3 4	3125.75	3/2⁻	776.68	1/2⁻
2376.7 5	5.00# 2	3125.75	3/2⁻	749.01	3/2⁻
ˣ2579.0 8	0.07 4				
2598.9 7	0.09 4	3348.6		749.01	3/2⁻

E_γ†	I_γ‡@	E_i(level)	J^π_i	E_f	J^π_f
ˣ6643.2 6	0.24 14				
ˣ6710.0 9	0.06 4				
7362.6 6	12.42# 12	(9261.63)	1/2⁺	1899.2	3/2⁻
8484.2 7	26 3	(9261.63)	1/2⁺	776.68	1/2⁻
8512.2 7	30.0# 4	(9261.63)	1/2⁺	749.01	3/2⁻





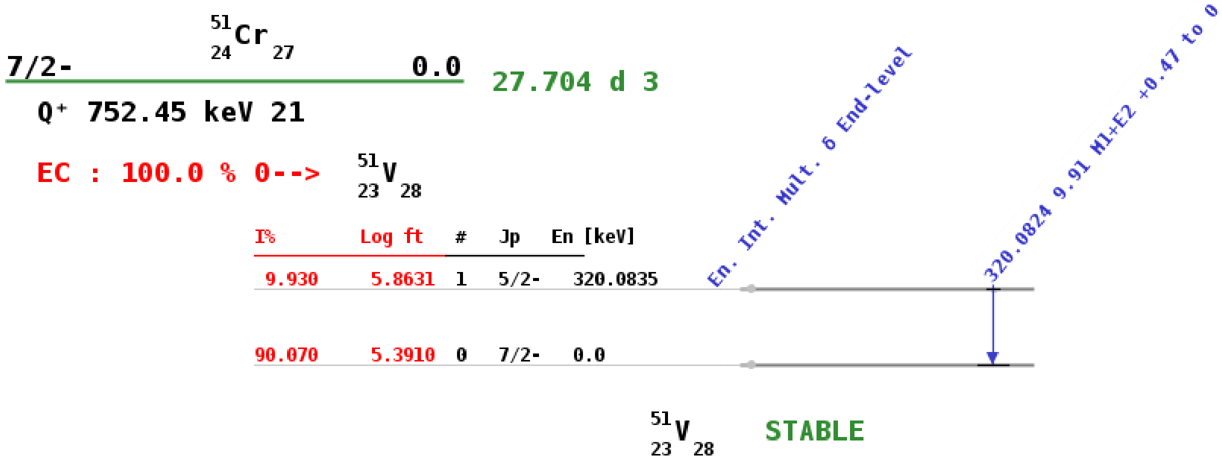
Backup. ^{54}Cr gamma emission

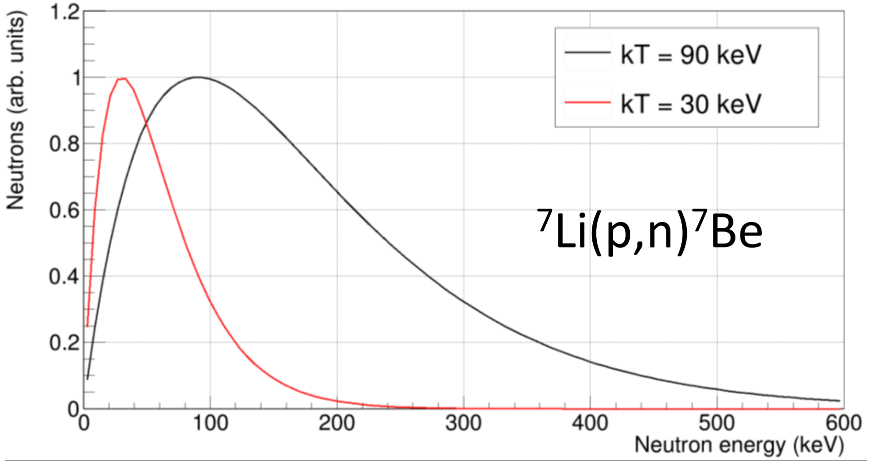
E_γ[†]	I_γ[‡]	E_i(level)	J_i^π	E_f	J_f^π	Mult.[@]	δ[@]
205.62 *20*	0.05 *1*	3925.59	2^+	3719.99	2^+		
745.37 *16*	0.06 *1*	4872.36	2^+	4127.08	3^-		
^{x}789.22 *2*	0.07 *1*						
817.20 *7*	0.07 *1*	3436.88	2^+	2619.69	2^+		
834.87 *2*	79.0[#] *2*	834.879	2^+	0.0	0^+		
845.57 *12*	0.17 *2*	5226.22	2^+	4380.74	2^-		
847.90 *17*	0.08 *1*	6143.59		5294.47	$1^+,(2^+)$		
890.41 *2*	0.43 *3*	3719.99	2^+	2829.56	0^+		
944.57 *19*	0.03 *1*	4872.36	2^+	3927.70	2^+		
946.80 *15*	0.05 *1*	4872.36	2^+	3925.59	2^+		
989.08 *2*	0.76 *5*	1823.96	4^+	834.879	2^+	E2	
1100.38 *6*	0.64 *4*	3719.99	2^+	2619.69	2^+		
1106.38 *10*	0.02 *1*	5189.62	2^+	4083.24	3^+		
^{x}1205.33 *10*	0.05 *1*						
1241.36 *7*	0.78 *5*	3861.02	2^+	2619.69	2^+		
1335.26 *6*	0.06 *1*	3159.21	4^+	1823.96	4^+		
1340.81 *10*	0.12 *2*	5268.47	2^+	3927.70	2^+		
1435.49 *18*	0.23 *2*	4872.36	2^+	3436.88	2^+		
1460.10 *14*	0.04 *2*	5586.92	$1^+,2^+$	4127.08	3^-		
1463.33 *14*	0.07 *2*	4083.24	3^+	2619.69	2^+		
1503.62 *9*	0.06 *2*	5586.92	$1^+,2^+$	4083.24	3^+		
1508.24 *25*	0.06 *2*	4127.08	3^-	2619.69	2^+		
1597.72 *4*	0.03 *2*	4217.56	$(2^+),3^+$	2619.69	2^+		
^{x}1619.17 *7*	0.09 *2*						
1784.69 *5*	10.14[#] *4*	2619.69	2^+	834.879	2^+	M1+E2	−0.53 *18*
1798.22 *5*	0.25 *2*	4872.36	2^+	3074.06	2^+		
1804.00 *14*	0.24 *2*	4633.57	2^+	2829.56	0^+		
1831.34 *17*	0.03 *2*	5268.47	2^+	3436.88	2^+		
1994.56 *5*	2.93 *15*	2829.56	0^+	834.879	2^+	E2	
2066.99 *7*	0.04 *2*	5226.22	2^+	3159.21	4^+		
2101.43 *12*	0.10 *2*	5821.49		3719.99	2^+		
2233.09 *6*	0.07 *3*	6316.42		4083.24	3^+		
2239.07 *5*	10.70[#] *5*	3074.06	2^+	834.879	2^+	M1+E2	0.02 *5*
2259.22 *5*	0.21 *2*	4083.24	3^+	1823.96	4^+		
2393.70 *7*	0.10 *2*	4217.56	$(2^+),3^+$	1823.96	4^+		
2464.23 *19*	0.09 *3*	5294.47	$1^+,(2^+)$	2829.56	0^+		
2558.45 *5*	1.15 *7*	3393.42	2^+	834.879	2^+		
2601.91 *8*	2.31 *13*	3436.88	2^+	834.879	2^+	M1+E2	−0.11 *+12−16*
2619.57 *9*	0.42 *3*	2619.69	2^+	0.0	0^+		
3393.35 *7*	0.67 *6*	3393.42	2^+	0.0	0^+		
3403.55 *9*	0.17 *7*	(9720.18)	(1^-)	6316.42			
^{x}3509.86 *17*	0.21 *2*						
3545.92 *13*	0.32 *4*	4380.74	2^-	834.879	2^+		
3576.08 *9*	0.20 *4*	(9720.18)	(1^-)	6143.59			
3719.84 *7*	3.69[#] *2*	3719.99	2^+	0.0	0^+		
3863.64 *11*	0.39 *5*	(9720.18)	(1^-)	5856.39			
3898.51 *14*	0.11 *2*	(9720.18)	(1^-)	5821.49			
3927.57 *9*	0.52 *7*	3927.70	2^+	0.0	0^+		
4133.15 *8*	0.48 *5*	(9720.18)	(1^-)	5586.92	$1^+,2^+$		
^{x}4168.1 *6*	0.12 *4*						
^{x}4229.9 *3*	0.10 *4*						
^{x}4393.28 *9*	0.06 *4*						
4425.63 *16*	0.50 *6*	(9720.18)	(1^-)	5294.47	$1^+,(2^+)$		
4433.43 *21*	0.20 *3*	5268.47	2^+	834.879	2^+		
4451.47 *18*	0.45 *5*	(9720.18)	(1^-)	5268.47	2^+		
4459.28 *21*	0.38 *5*	5294.47	$1^+,(2^+)$	834.879	2^+		
4494.00 *14*	0.13 *5*	(9720.18)	(1^-)	5226.22	2^+		
4530.38 *21*	0.19 *5*	(9720.18)	(1^-)	5189.62	2^+		
4751.83 *10*	0.18 *4*	5586.92	$1^+,2^+$	834.879	2^+		
4847.54 *11*	1.96 *7*	(9720.18)	(1^-)	4872.36	2^+		
4872.27 *10*	1.06 *8*	4872.36	2^+	0.0	0^+		
5021.29 *34*	0.16 *6*	5856.39		834.879	2^+		
5086.36 *12*	0.23 *6*	(9720.18)	(1^-)	4633.57	2^+		
5339.27 *18*	0.29 *4*	(9720.18)	(1^-)	4380.74	2^-		
5501.78 *26*	0.13 *2*	(9720.18)	(1^-)	4217.56	$(2^+),3^+$		
5636.90 *42*	0.13 *3*	(9720.18)	(1^-)	4083.24	3^+		
5707.09 *12*	1.35 *11*	(9720.18)	(1^-)	4012.87	0^+		
5792.2 *6*	0.46 *7*	(9720.18)	(1^-)	3927.70	2^+		
5794.3 *4*	0.17 *5*	(9720.18)	(1^-)	3925.59	2^+		
5858.98 *14*	1.21 *8*	(9720.18)	(1^-)	3861.02	2^+		
5999.95 *13*	4.49[#] *4*	(9720.18)	(1^-)	3719.99	2^+	(E1)[&]	
6283.02 *14*	2.03 *14*	(9720.18)	(1^-)	3436.88	2^+		
6326.41 *14*	1.19 *12*	(9720.18)	(1^-)	3393.42	2^+		
6645.64 *13*	9.71[#] *8*	(9720.18)	(1^-)	3074.06	2^+	(E1)[&]	
6890.16 *15*	2.35 *16*	(9720.18)	(1^-)	2829.56	0^+		
7100.11 *14*	7.61[#] *7*	(9720.18)	(1^-)	2619.69	2^+		
8884.81 *18*	44.4[#] *6*	(9720.18)	(1^-)	834.879	2^+	(E1)[&]	
9718.79 *19*	15.8[#] *2*	(9720.18)	(1^-)	0.0	0^+	(E1)[&]	

Backup. ^{50}Cr MACS at HiSPANoS@CNA

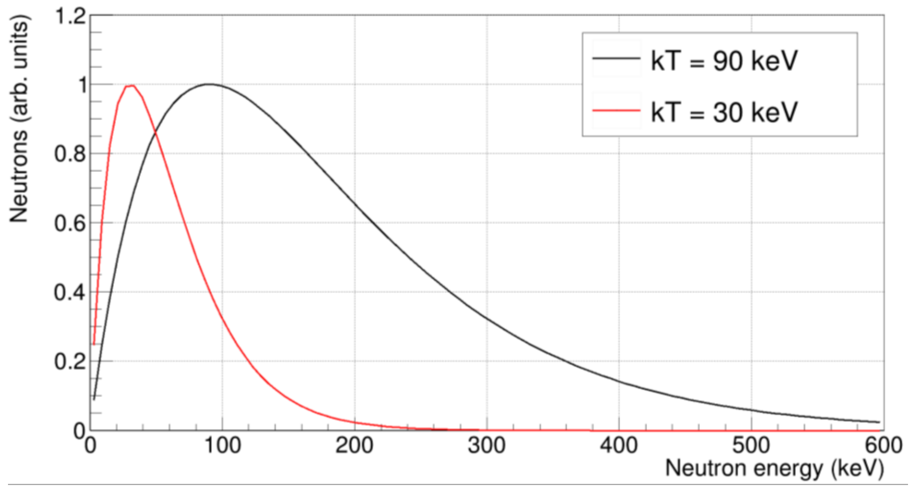
- Time-of-flight measurement → n_TOF@CERN (Geneva, Switzerland) with very thin samples to minimize multiple-scattering effects
- ^{50}Cr activation measurement → HiSPANoS@CNA (Seville, Spain). MACS at 30 and 90 keV

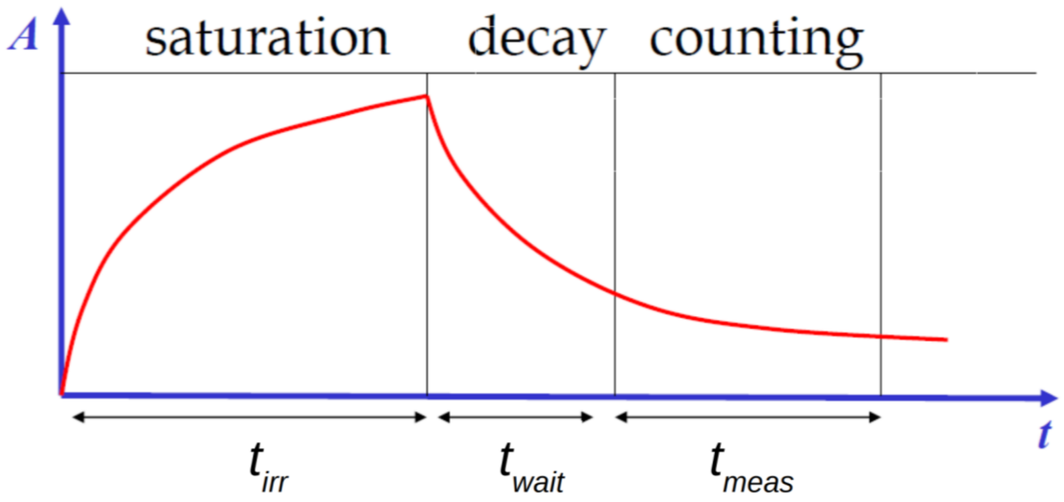
Nucleus	$T_{1/2}$ (days)	E_γ (keV)	I_γ (%)
^{51}Cr	27,7	320,1	9,9
^{198}Au	2,69	411,8	95,5





Backup. Averaged cross section equations





$$N_{act} = \frac{A_{EOI}}{\lambda} = \frac{\dot{C} t_{meas} e^{\lambda t_{wait}}}{I_\gamma \varepsilon (1 - e^{-\lambda t_{meas}})}$$

$$\downarrow$$

$$\varepsilon = \varepsilon_\lambda K_\Omega K_\gamma$$

$$SACS = \frac{1}{n_{at}} \frac{N_{act}}{N_{neutrons}} = \frac{1}{n_{at}} \frac{N_{act}}{N_{act\ ^7Be}}$$

$$\langle \sigma \rangle = \frac{\int \sigma(E_n)\Phi(E_n) dE_n}{\int \Phi(E_n)\, dE_n} \rightarrow MACS = \frac{2}{\sqrt{\pi}} \frac{\langle \sigma \rangle_{kT}}{\langle \sigma_\Phi \rangle} SACS$$