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

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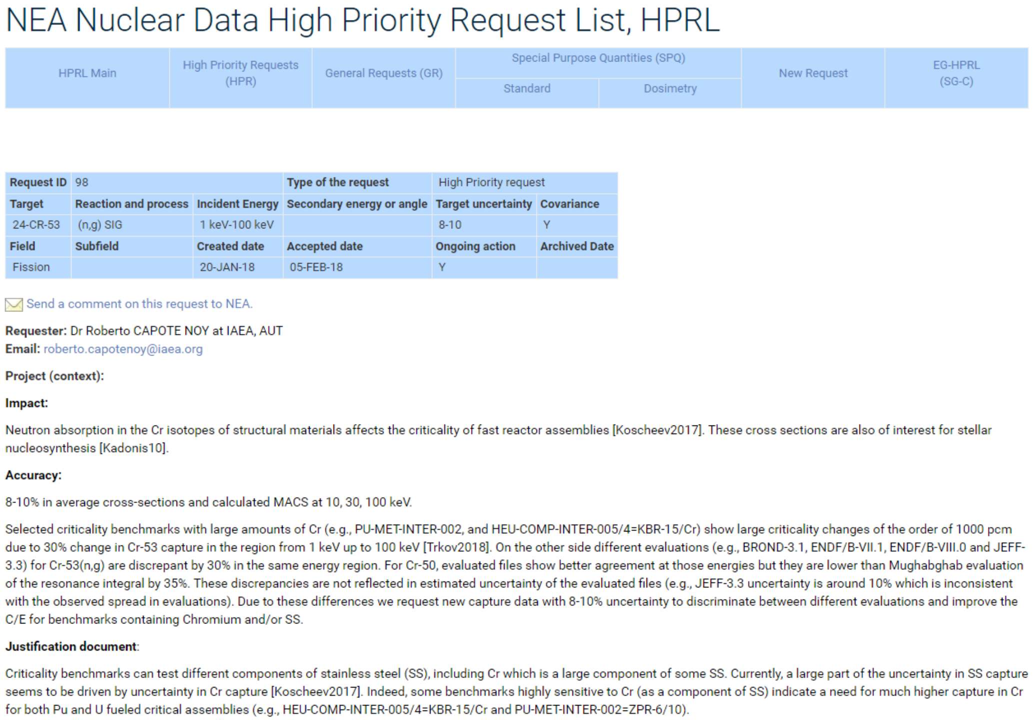
B. FERNÁNDEZ, N. PATRONIS & THE N_TOF COLLABORATION.

WONDER 2023, AIX-EN-PROVENCE. 05/06/2023

Motivation: nuclear data for criticality safety



NEA Nuclear Data High Priority Request List, HPRL

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).

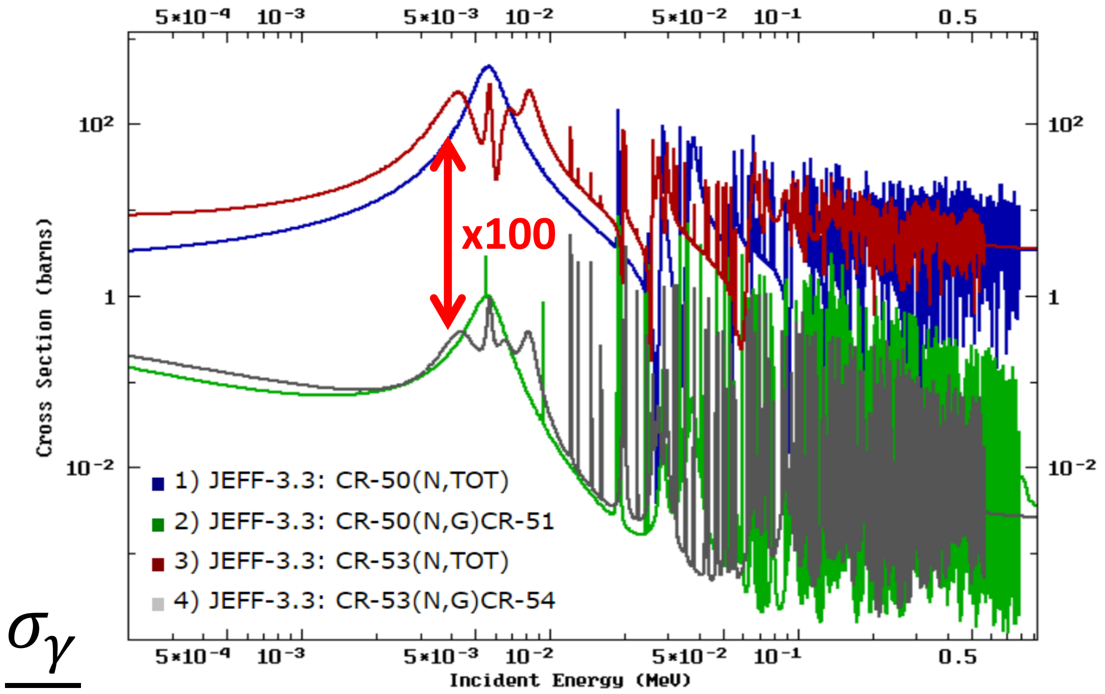
- Stainless Steel is often used as a **structural material in nuclear reactors** and contains between **11-26% of chromium**.

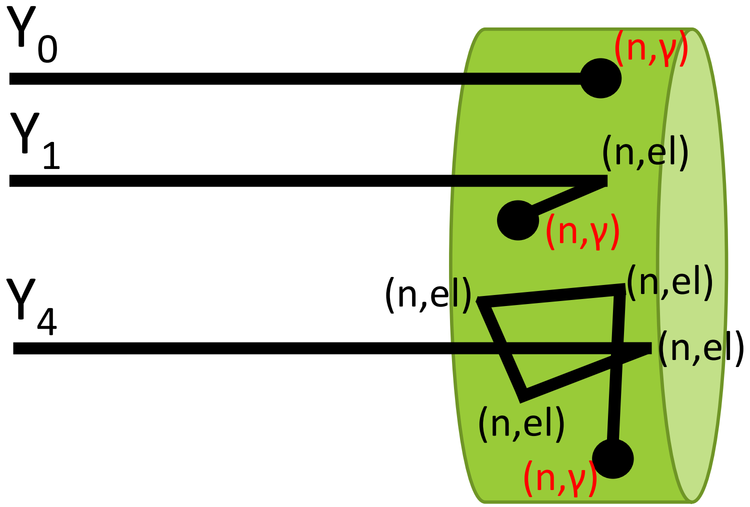
- There are **serious discrepancies** (~30%) between the different evaluated data of **^{50}Cr and ^{53}Cr capture cross section**, which is not present in the corresponding estimated uncertainties.

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

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) $\rightarrow Y = \underbrace{Y_0 + Y_1}_{\text{Analytical (accurate)}} \underbrace{+ \mathrm{Y}_2 + \mathrm{Y}_3 \ldots}_{\text{Numerical (aproximate)}}$

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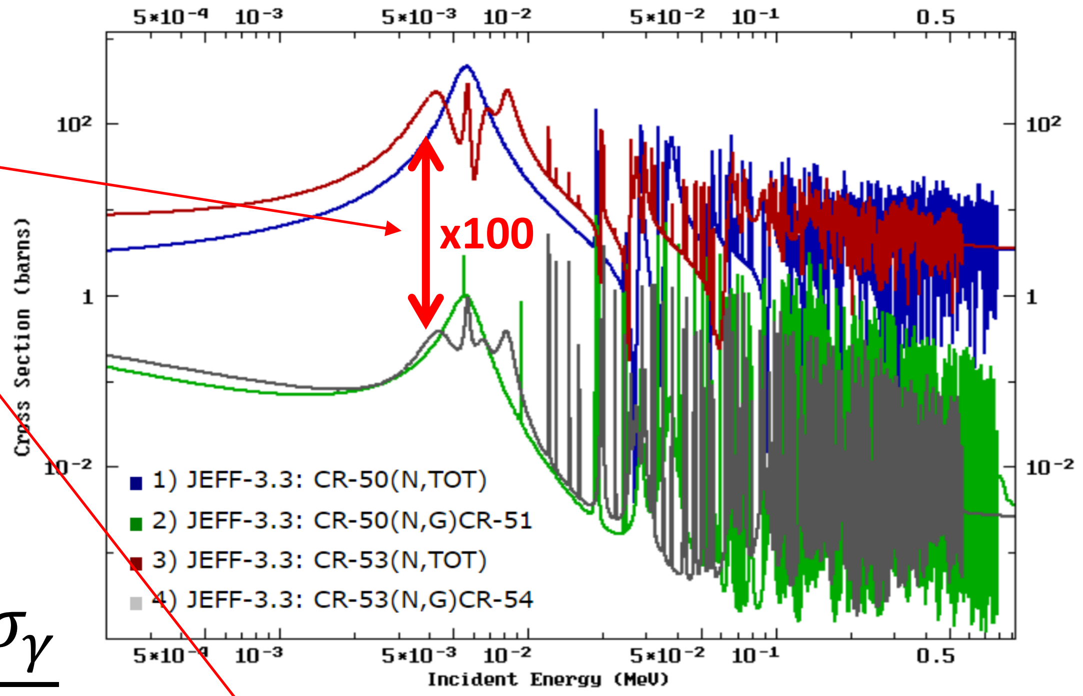

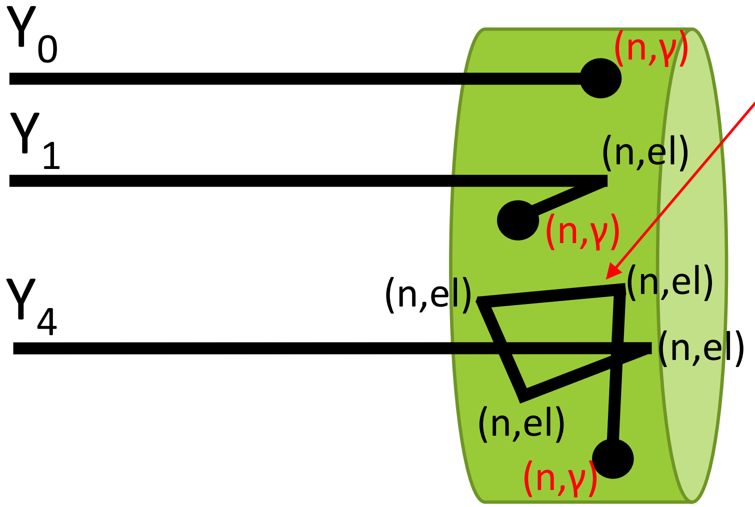

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How to improve $\sigma(n,\gamma)$ down to a few %?

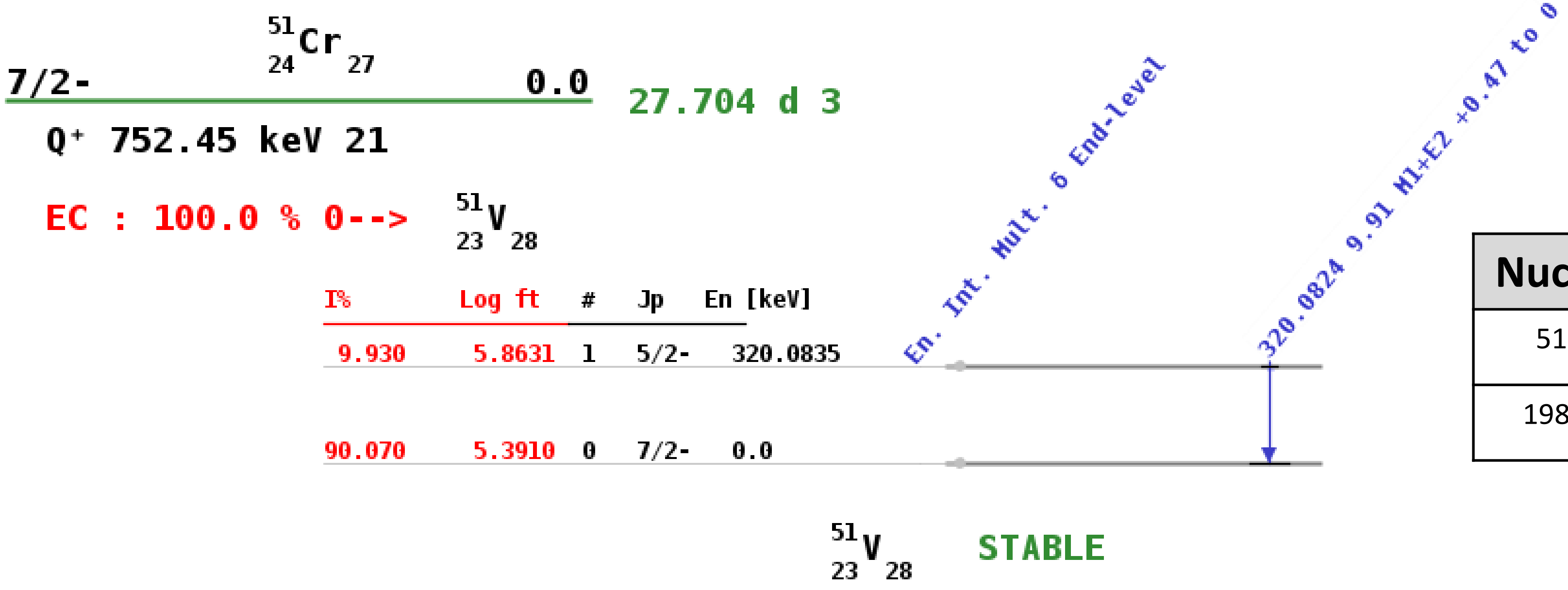
- Enriched (expensive and scarce) material with high purity → 94,6% ^{50}Cr & 97,7% ^{53}Cr
- Controlling multiple-scattering effects:
  - Very thin/thin sample approach
  - C_6D_6 detectors (low sensitivity to scattered neutrons)

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

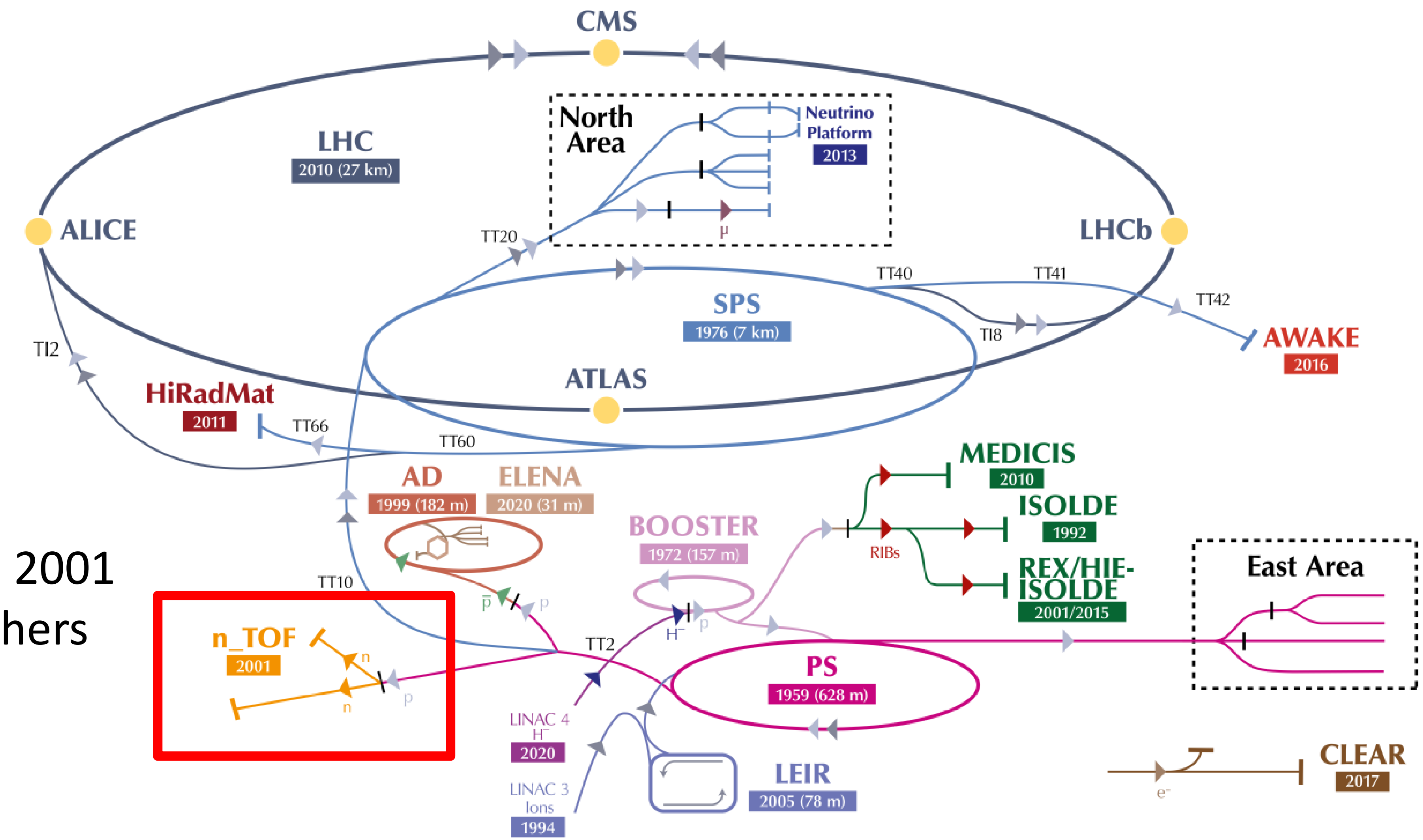
How to improve σ(n,γ) down to a few %?

- 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 (Seville, Spain)



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

The neutron Time-Of-Flight facility at CERN



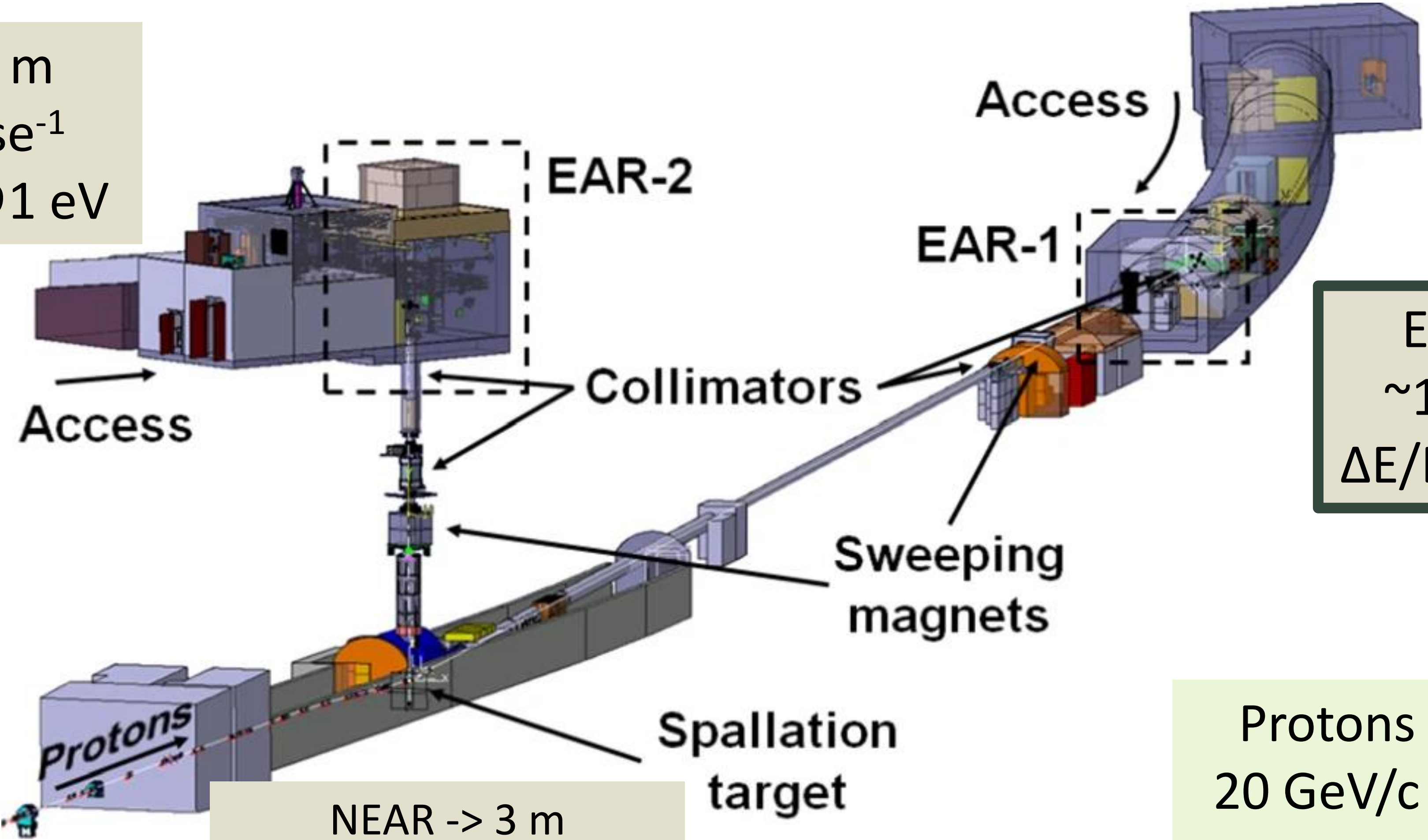
n_TOF@CERN

In operation since 2001

2022: 131 researchers from 37 institutes

The neutron Time-Of-Flight facility at CERN

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



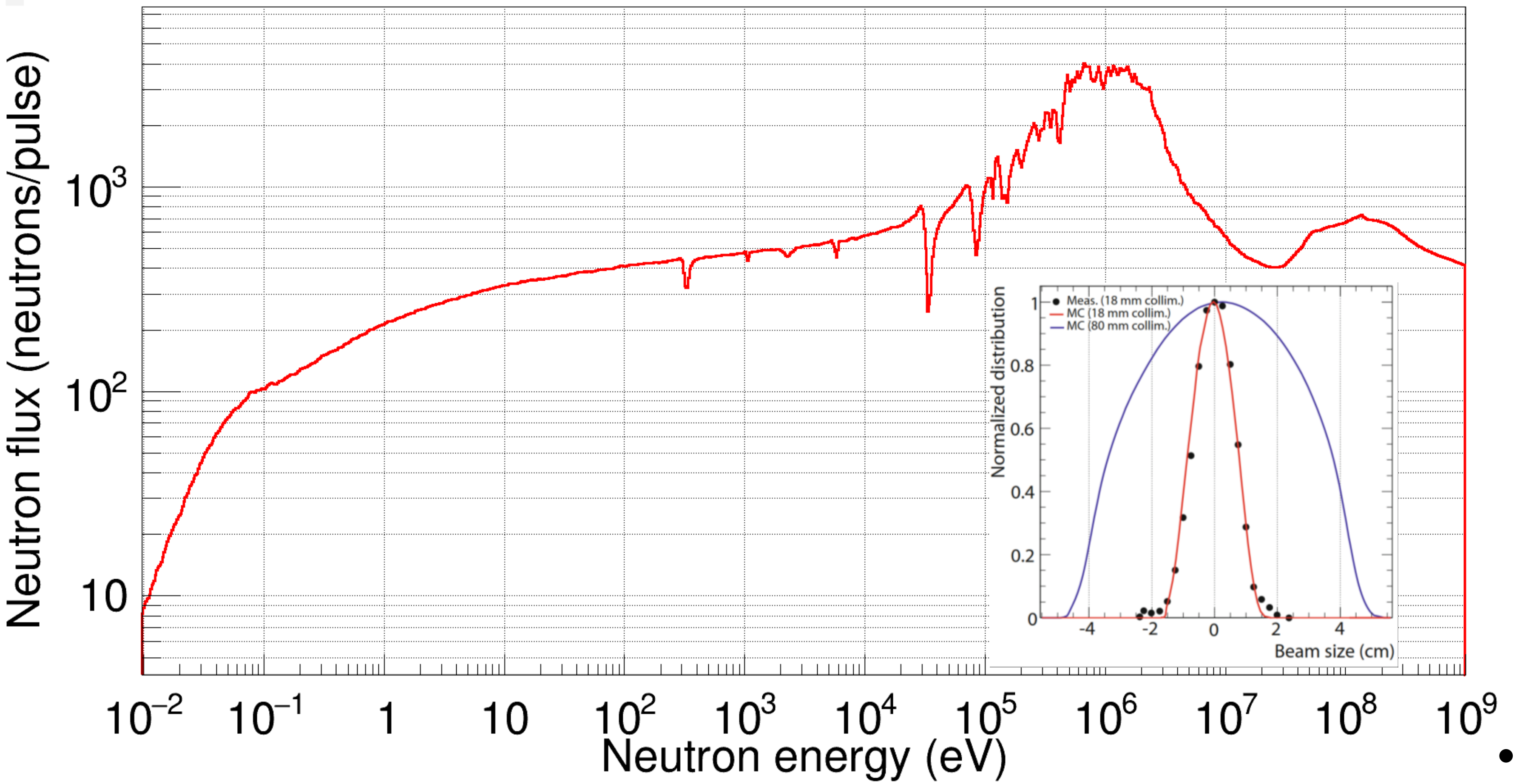
EAR1 -> 185 m
~10^{4} $cm^{-2}pulse^{-1}$
$\Delta E/E \sim 5\cdot10^{-4}$ @1 eV

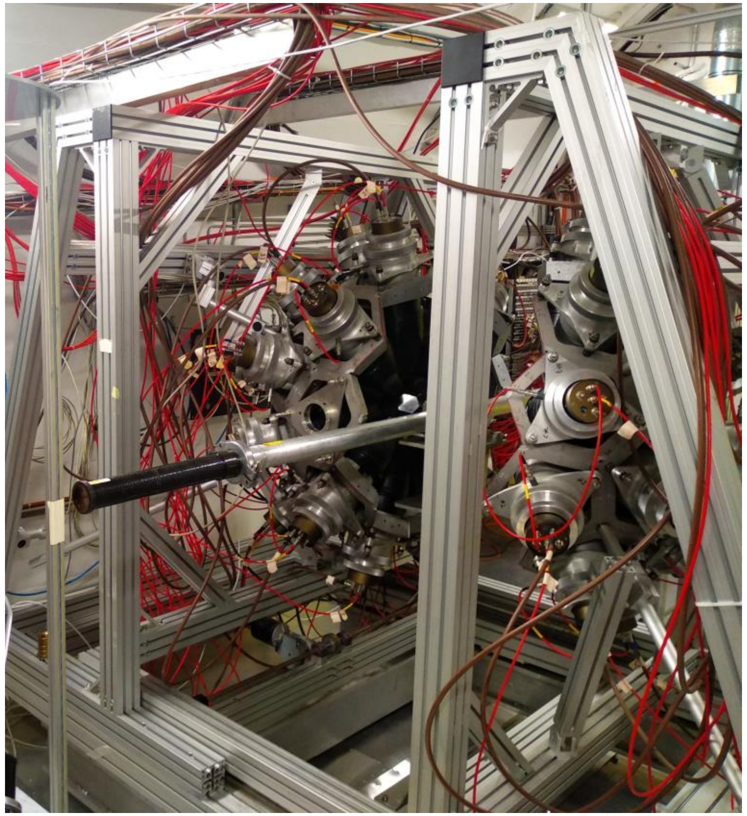
NEAR -> 3 m
(under commissioning)

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

N. Colonna

n_TOF – EAR1. Detection techniques

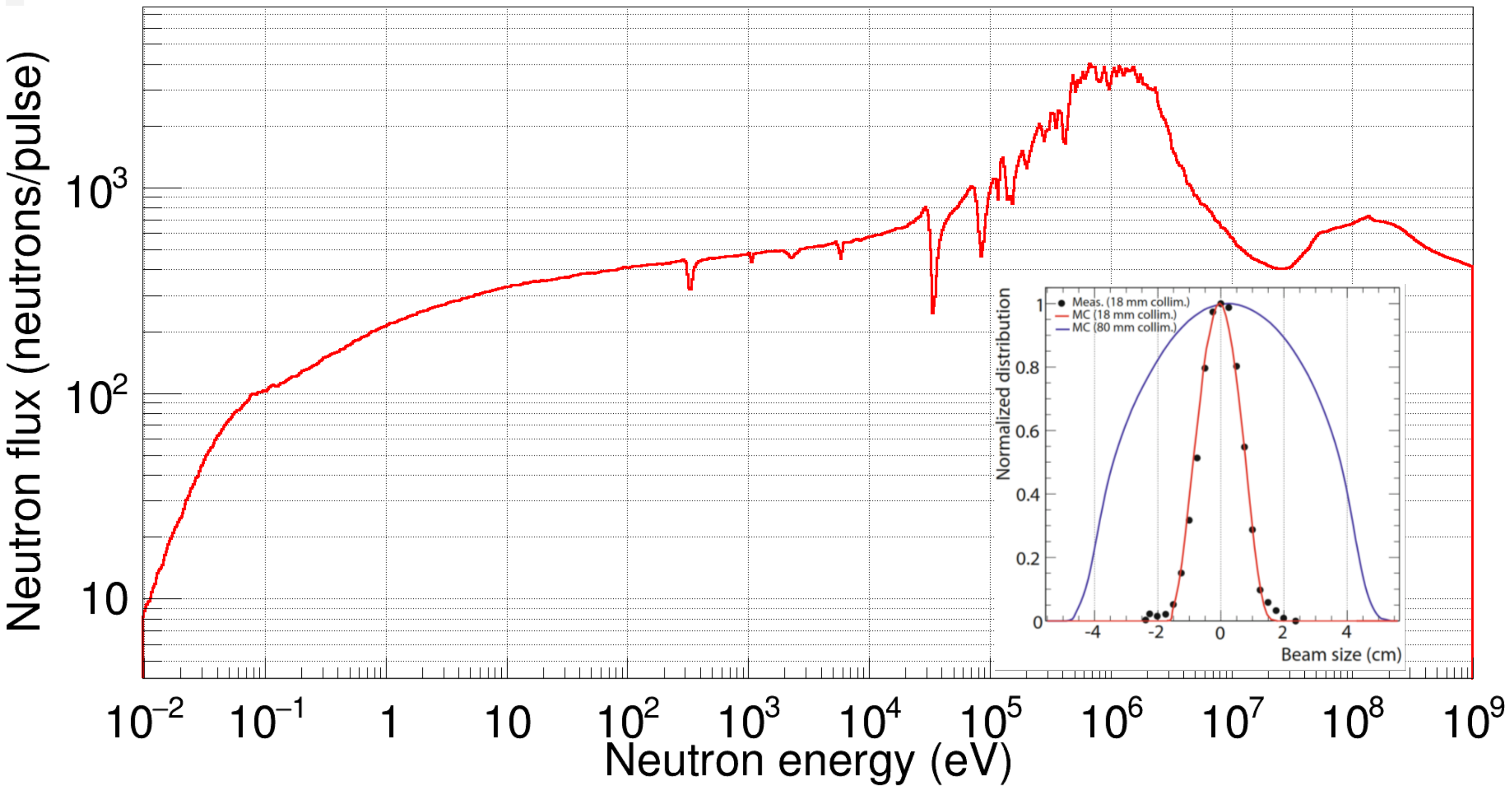


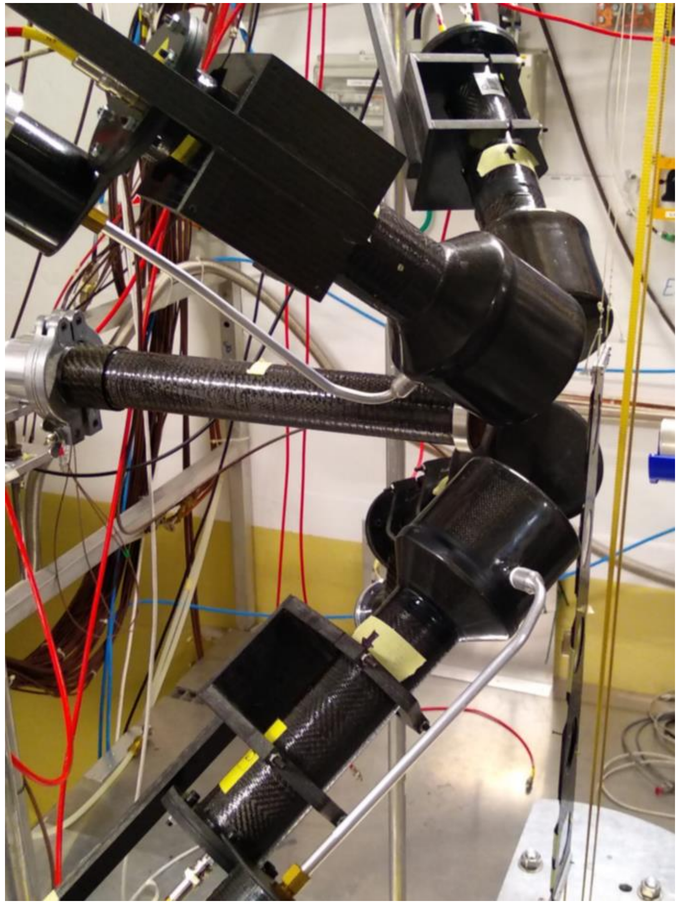


❌

- Total Absorption technique
- Full γ-ray cascade detected
- High neutron sensitivity

n_TOF – EAR1. Detection techniques

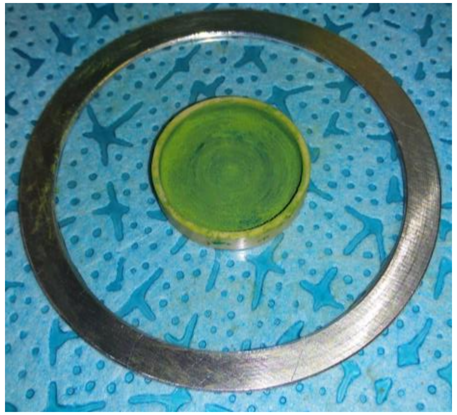




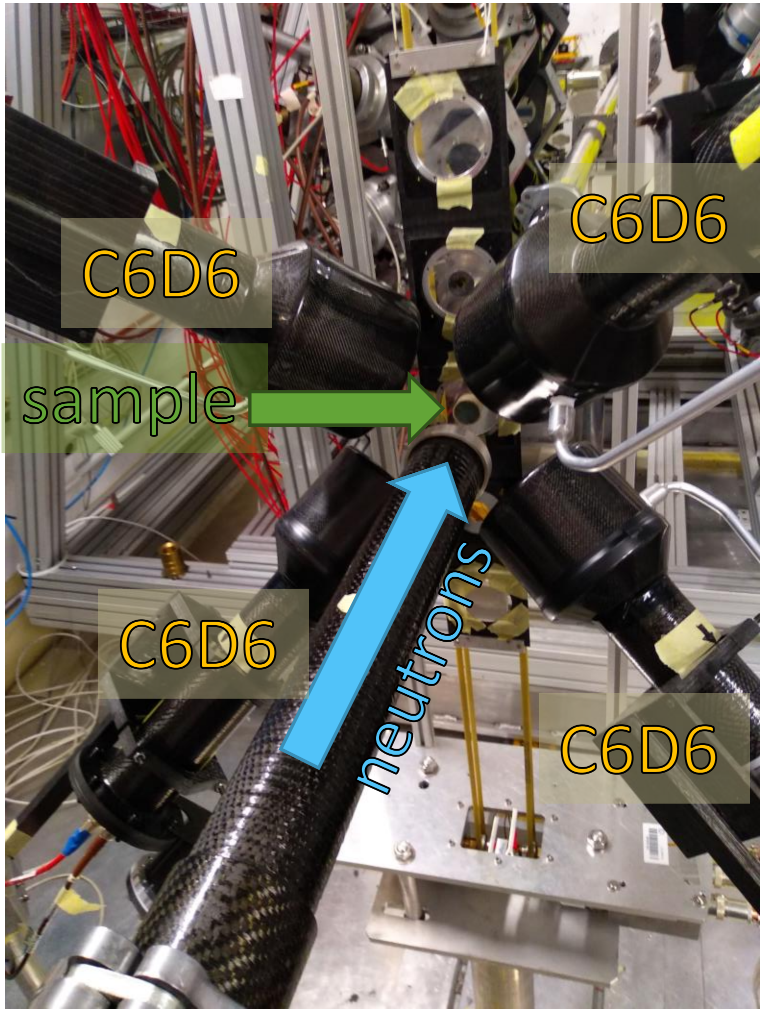
- Total Energy Detection
- Only one γ-ray detected
- Low neutron sensitivity

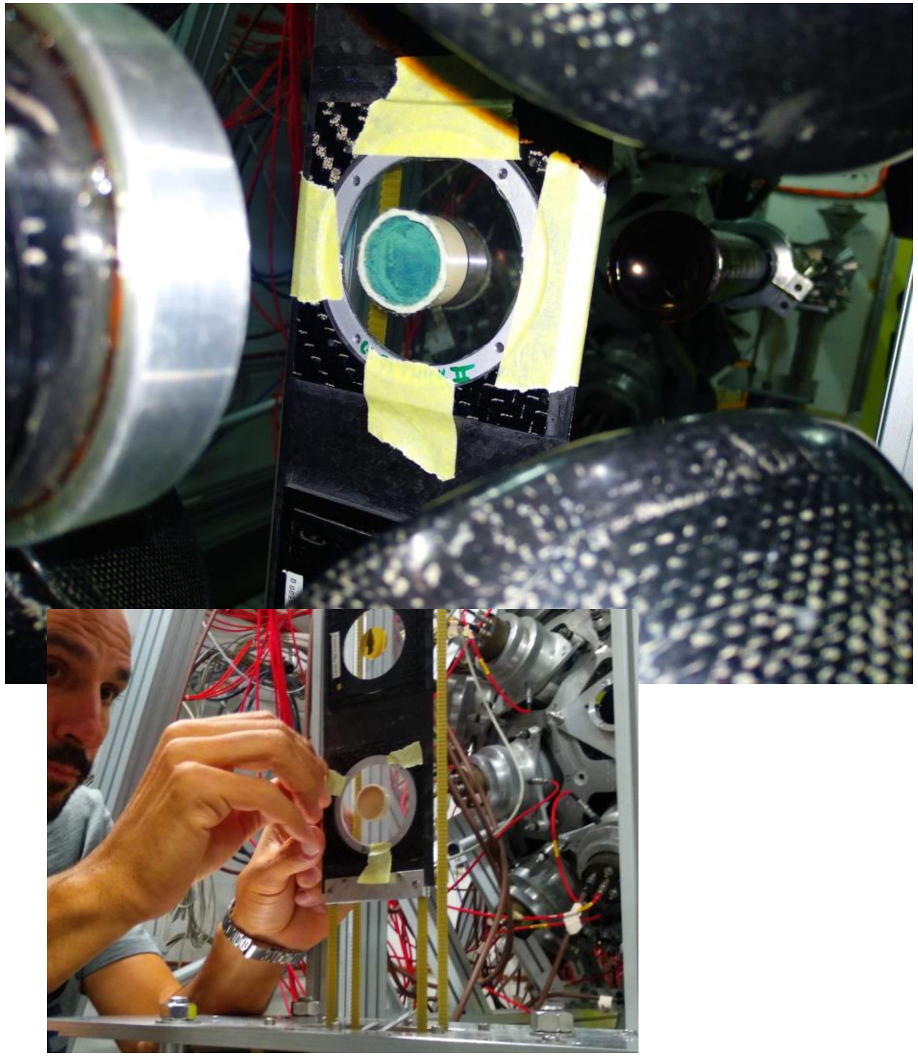
✓

Samples and detector set-up (EAR1)

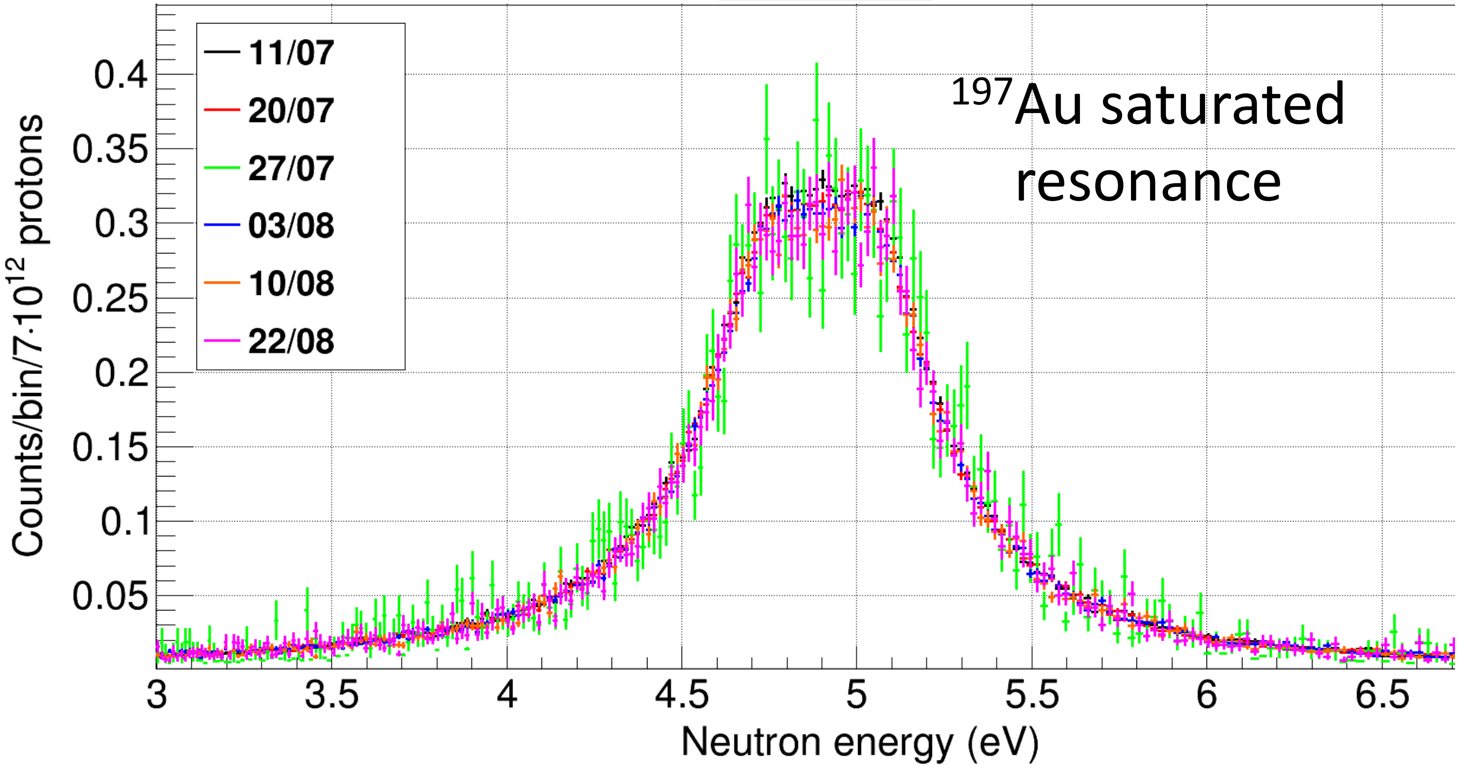


Cr$_2$O$_3$ powder pressed in a PEEK capsule & Al holder

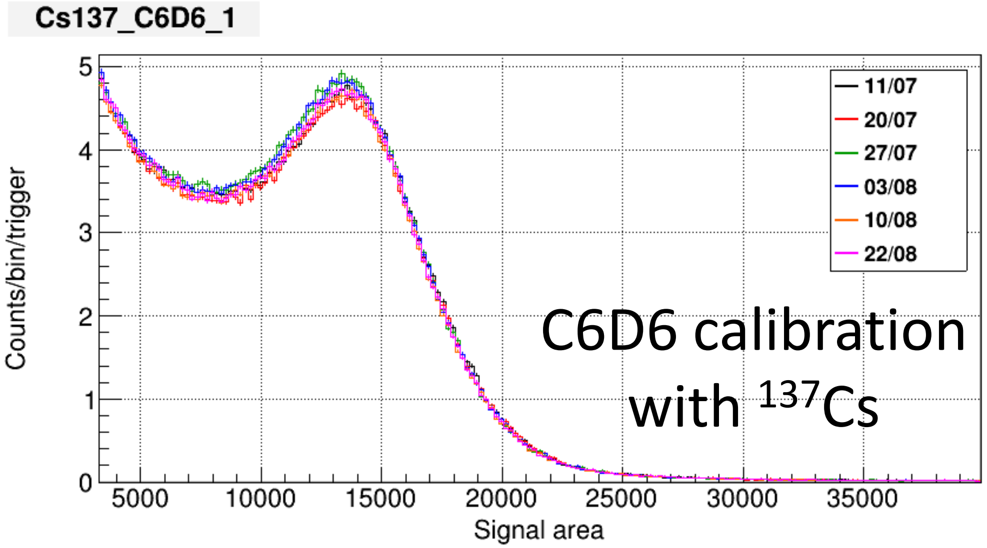




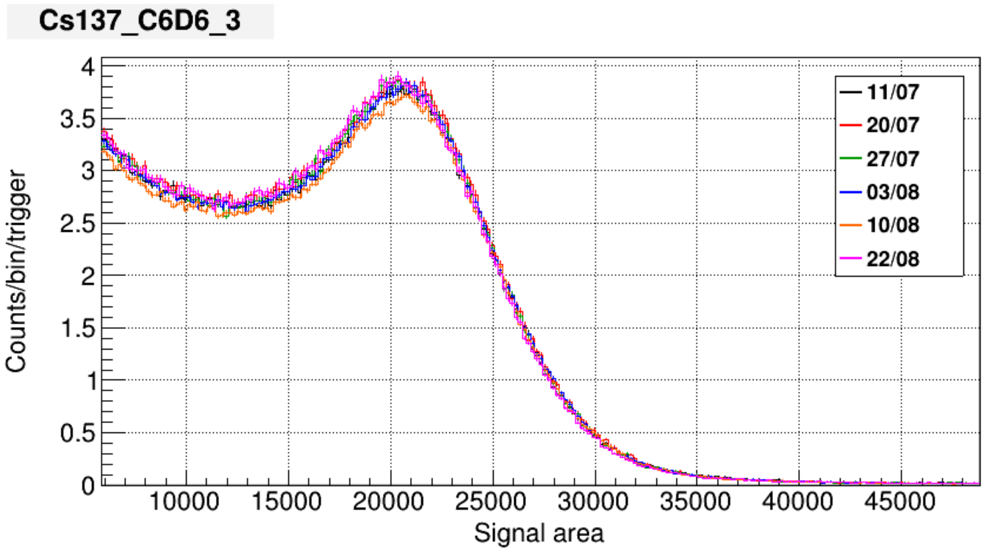
Monitoring the measurement



^{197}Au saturated resonance

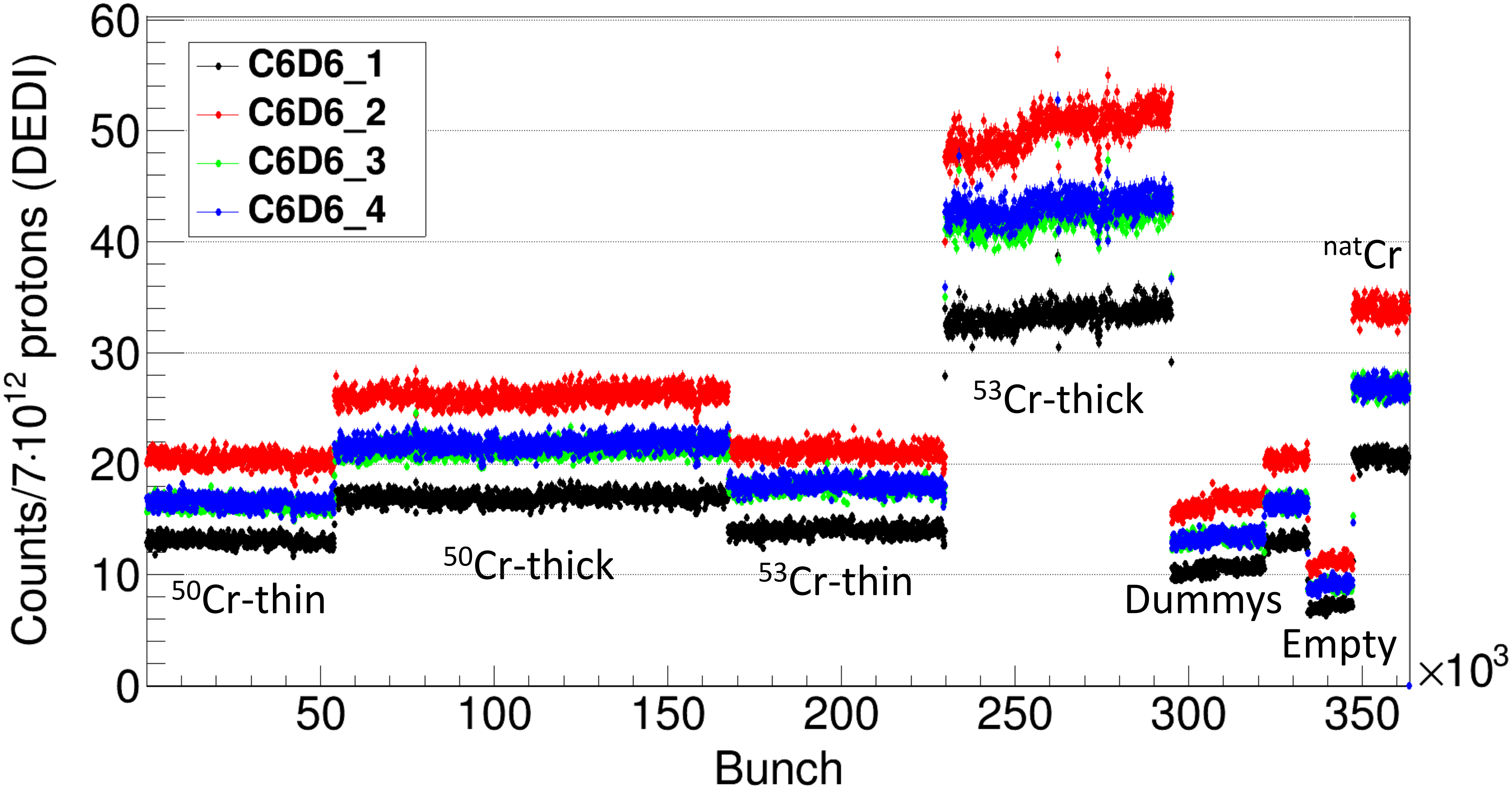


C6D6 calibration with ^{137}Cs

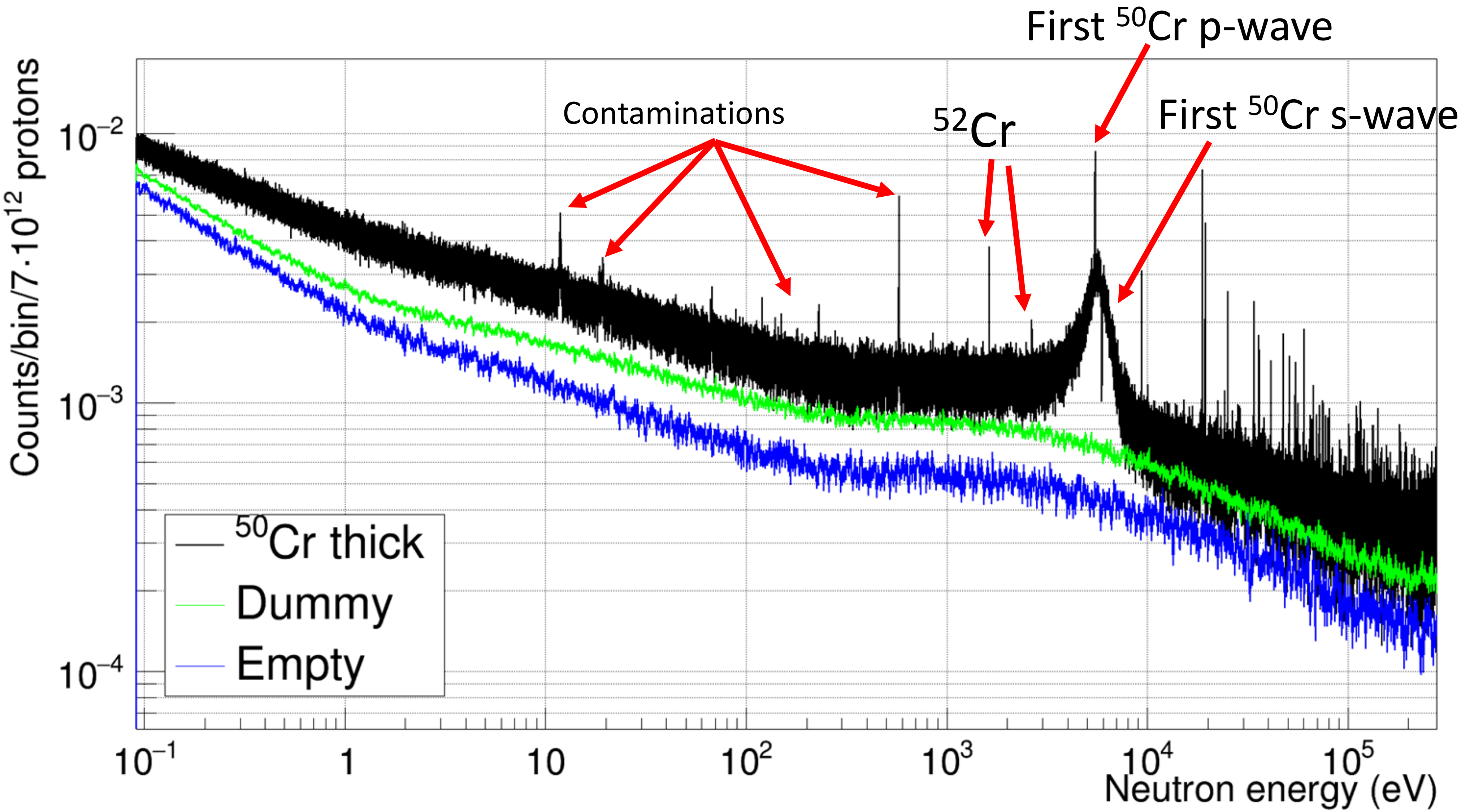


- Several monitors and stability checks regarding proton beam, neutron flux, detector gain-shifts…
- Very good behavior during the whole campaign.
- Dummy, empty, ^{nat}Cr, filters,…

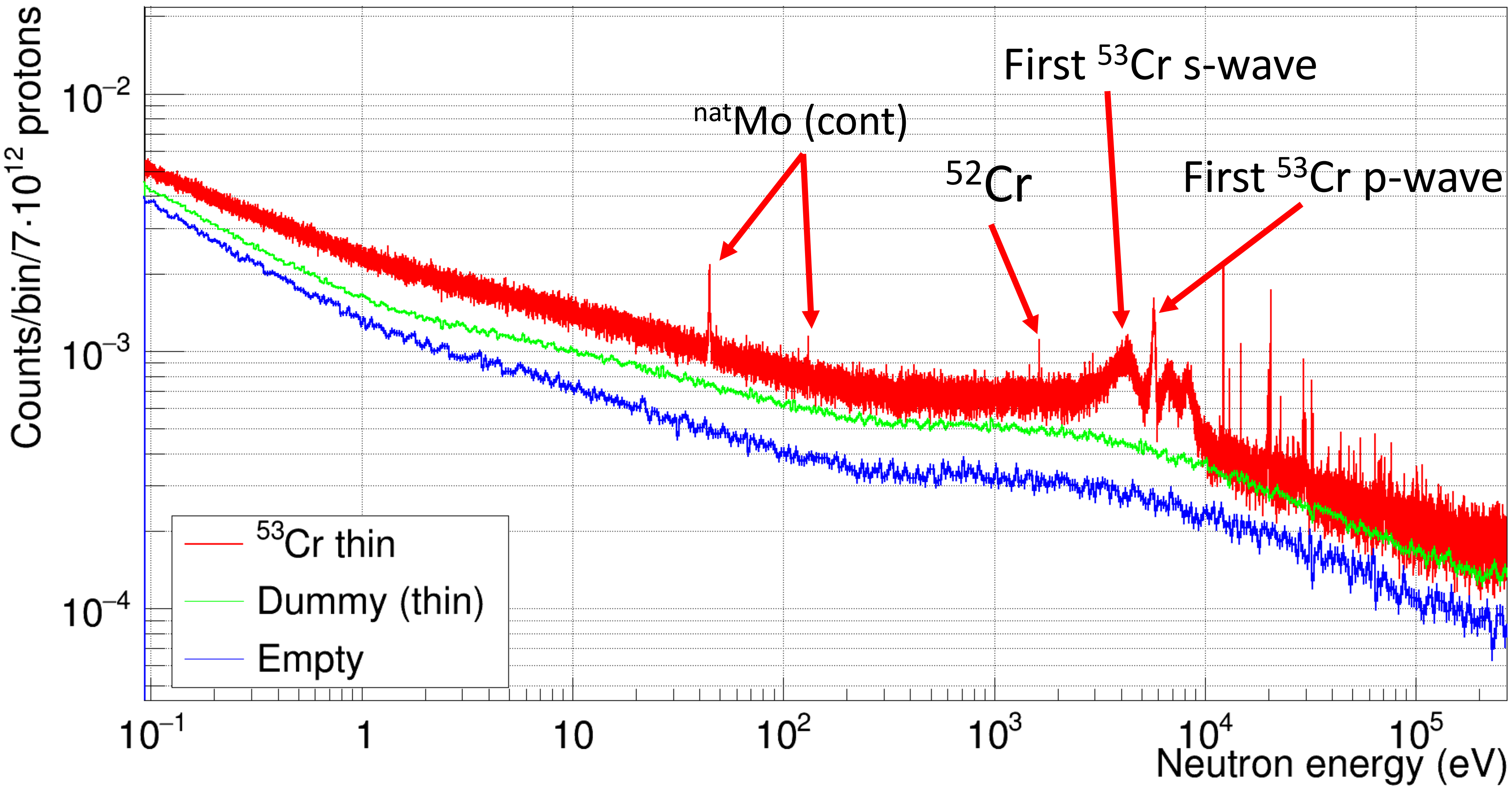
Monitoring the measurement



Preliminary results (^{50}Cr-thick)



Preliminary results (^{53}Cr-thin)



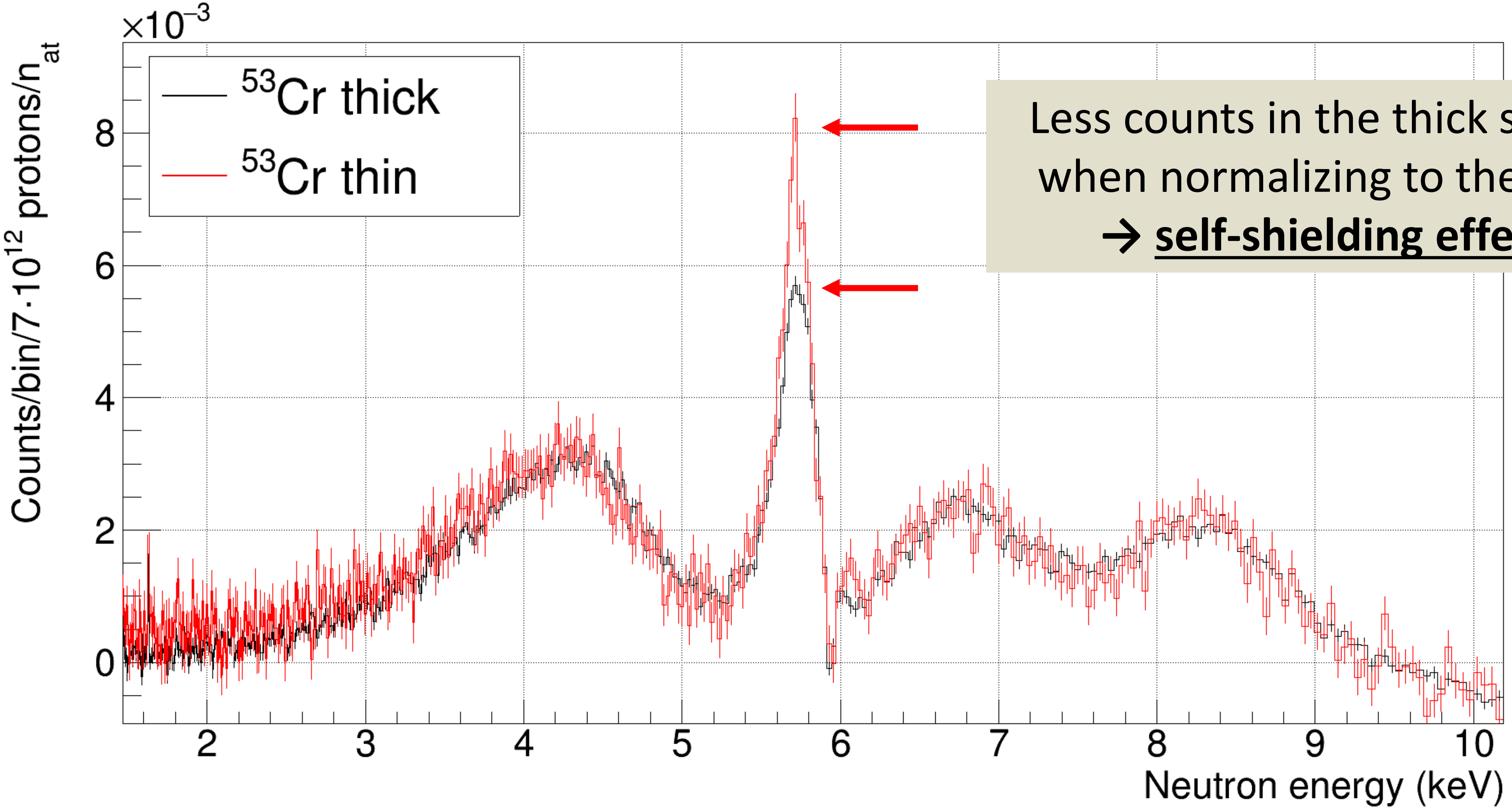
First ^{53}Cr s-wave

^{nat}Mo (cont)

^{52}Cr

First ^{53}Cr p-wave

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



Less counts in the thick sample when normalizing to the mass

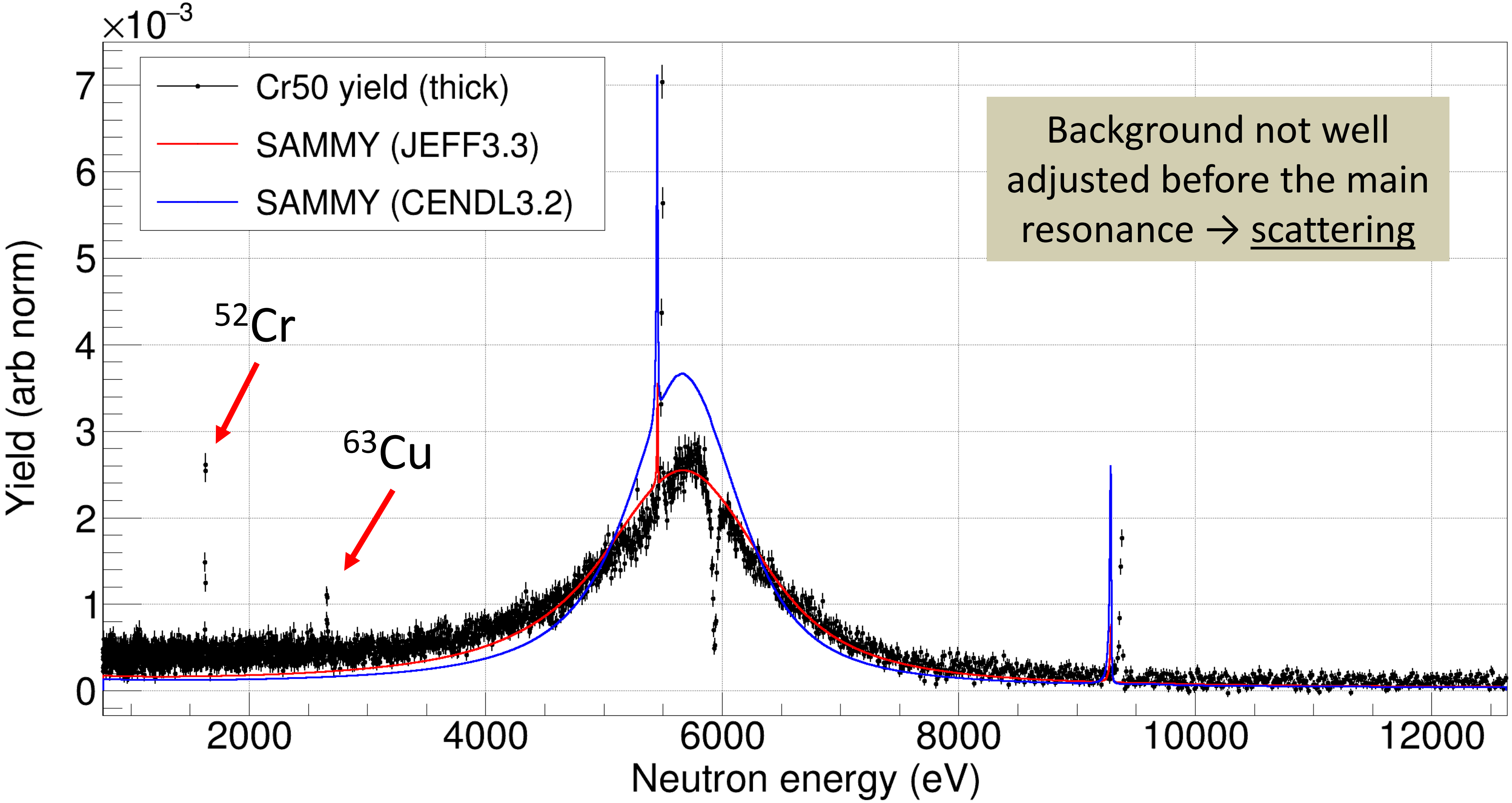
→ **self-shielding effects**

Preliminary yield (^{50}Cr)

- We have obtained a preliminary “yield” to check our experimental data.
- To do so:
  1. Only background from dummy considered
  2. Normalize to the main resonance
  3. n_TOF Resolution Function to be included
  4. Compared with SAMMY + JEFF3.3 & CENDL3.2

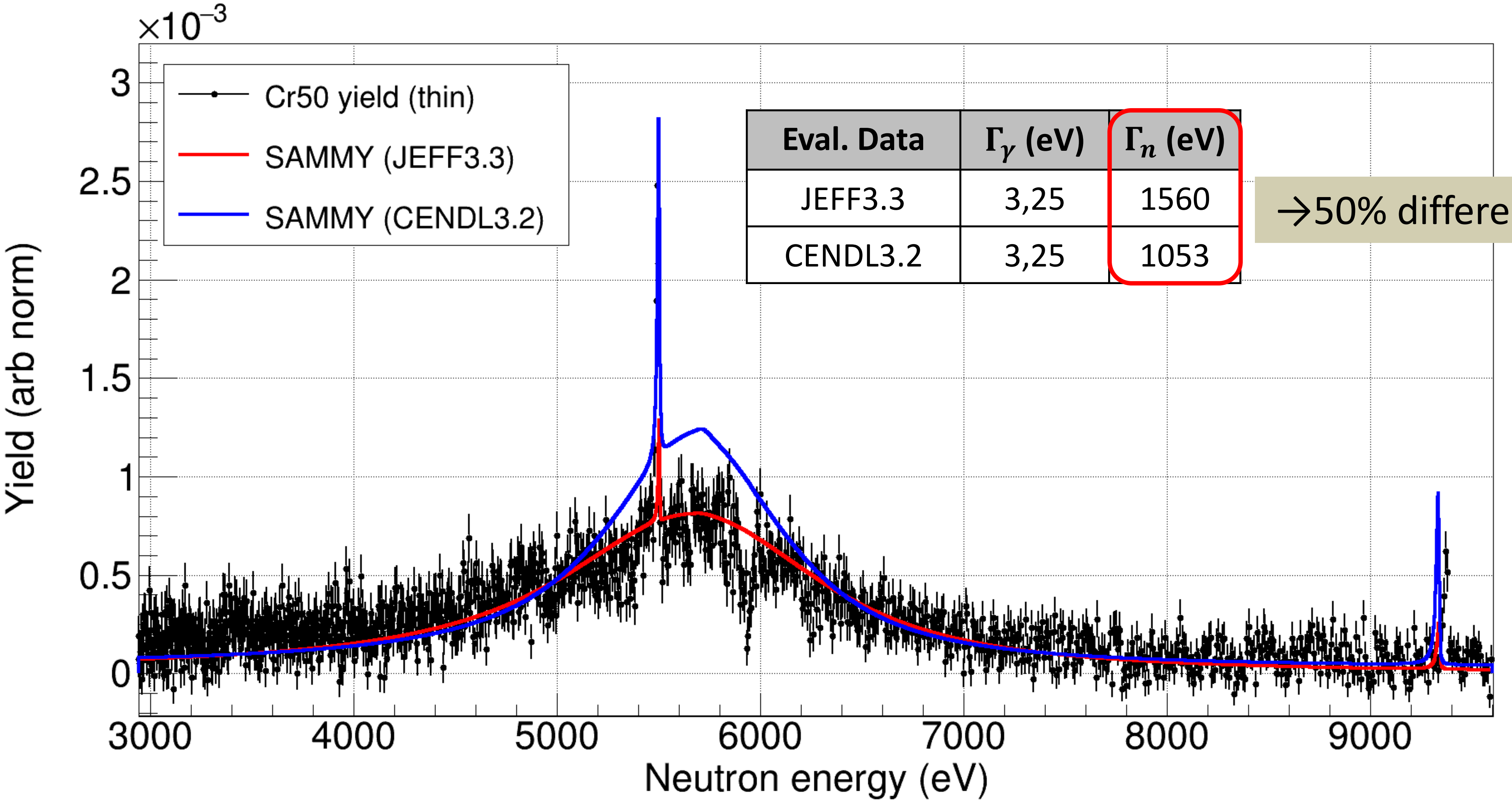
$$Y(E_n) = F\,\frac{C(E_n) - B(E_n)}{\Phi(E_n)\varepsilon_\gamma}$$

Preliminary yield (^{50}Cr)



Background not well adjusted before the main resonance → <u>scattering</u>

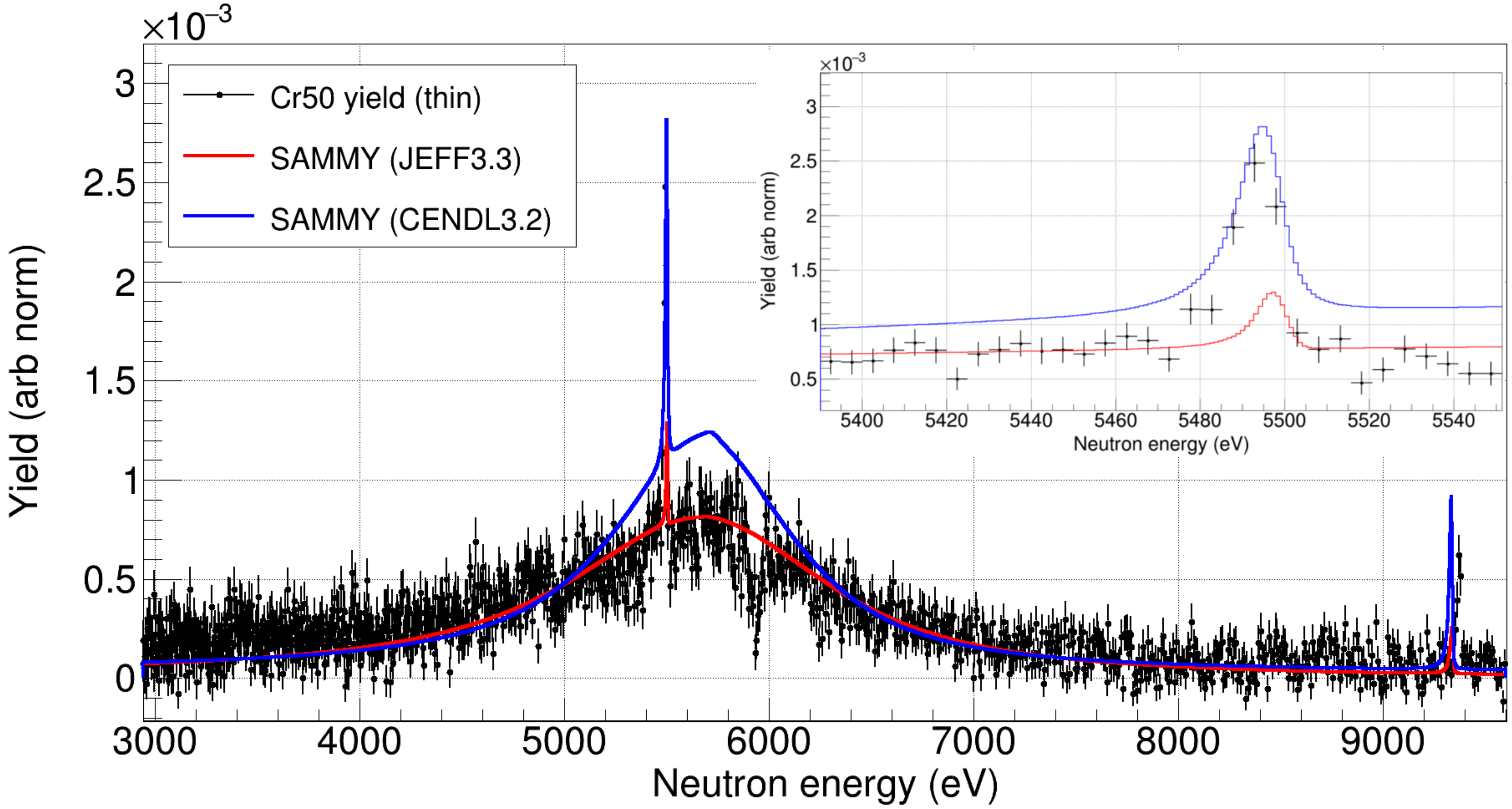
Preliminary yield (^{50}Cr)



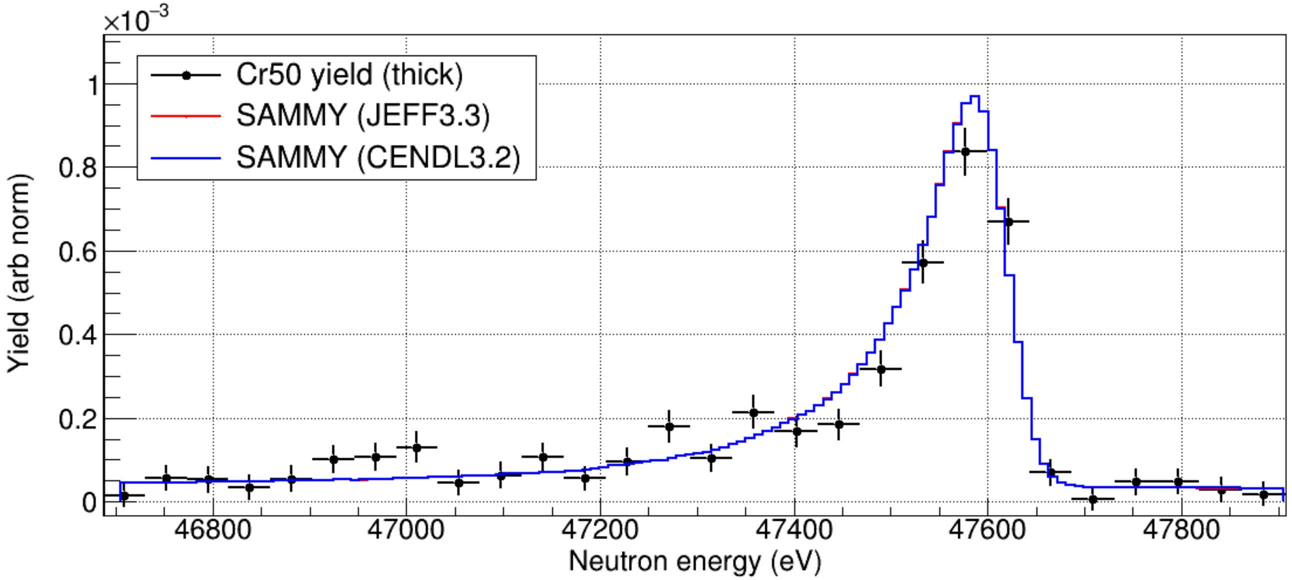
Eval. Data	Γ_γ (eV)	Γ_n (eV)
JEFF3.3	3,25	1560
CENDL3.2	3,25	1053

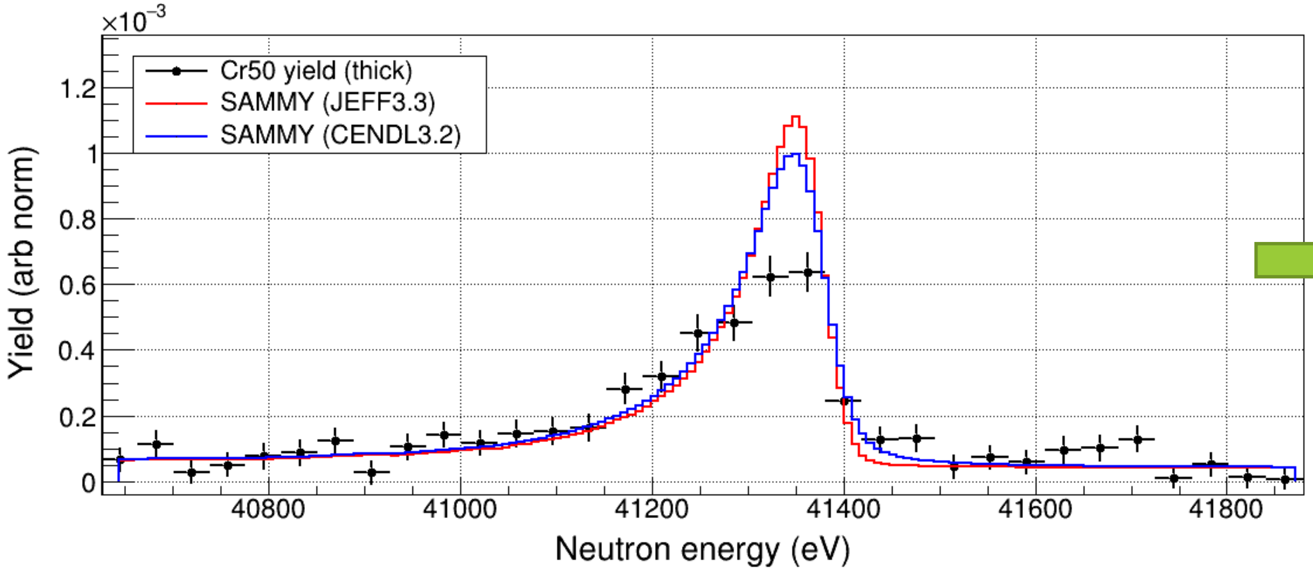
→50% difference

Preliminary yield (^{50}Cr)



Preliminary yield (^{50}Cr)

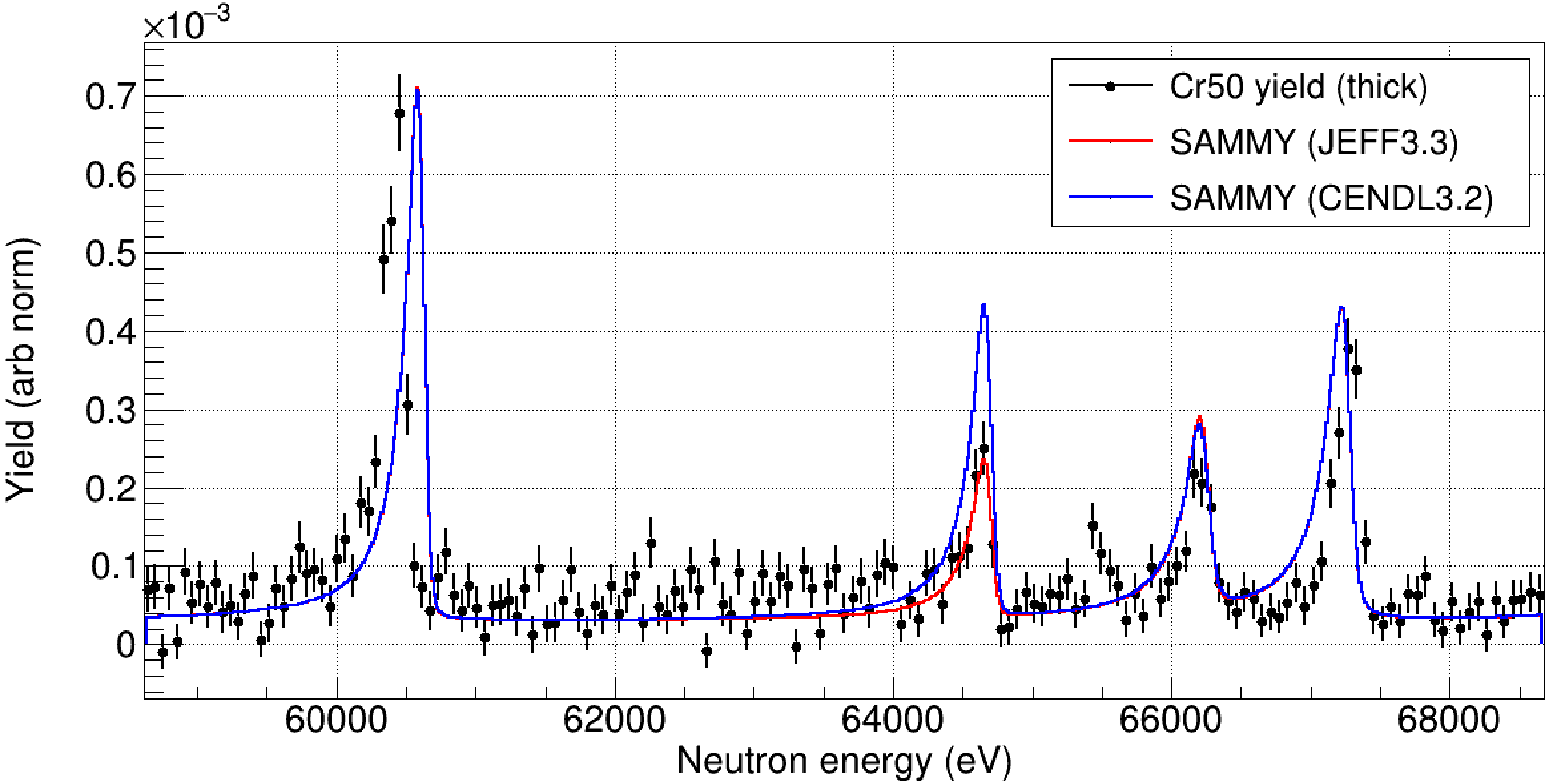




- The shape of the yield matches the one obtained with SAMMY.
- This is the case for most of the resonances, for a few of them there are differences → bigger scattering contribution?

Eval. Data	Γ_γ (eV)	Γ_n (eV)
JEFF3.3	0,43	3,5
CENDL3.2	0,43	18,1

Preliminary yield (^{50}Cr)

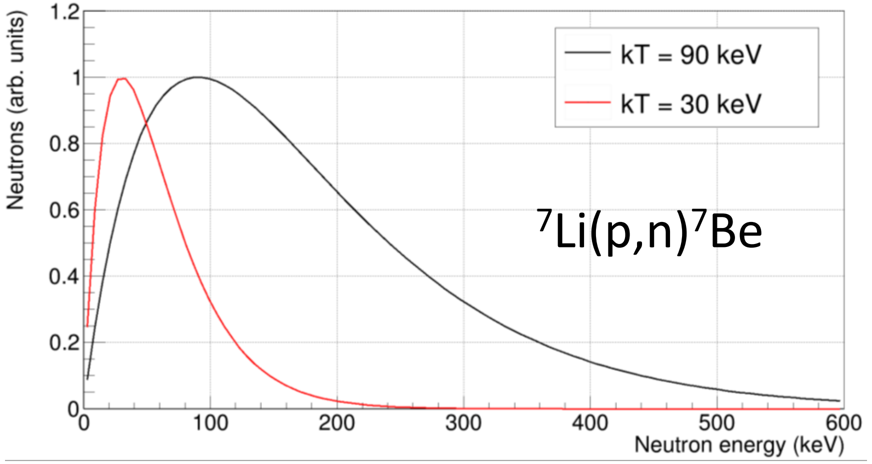


- In general, if there are discrepancies between evaluations, we agree with JEFF3.3
- A new measurement to solve the problem was indeed necessary.
- Let's wait for the results of our data!

^{50}Cr MACS measurement at HiSPANoS@CNA

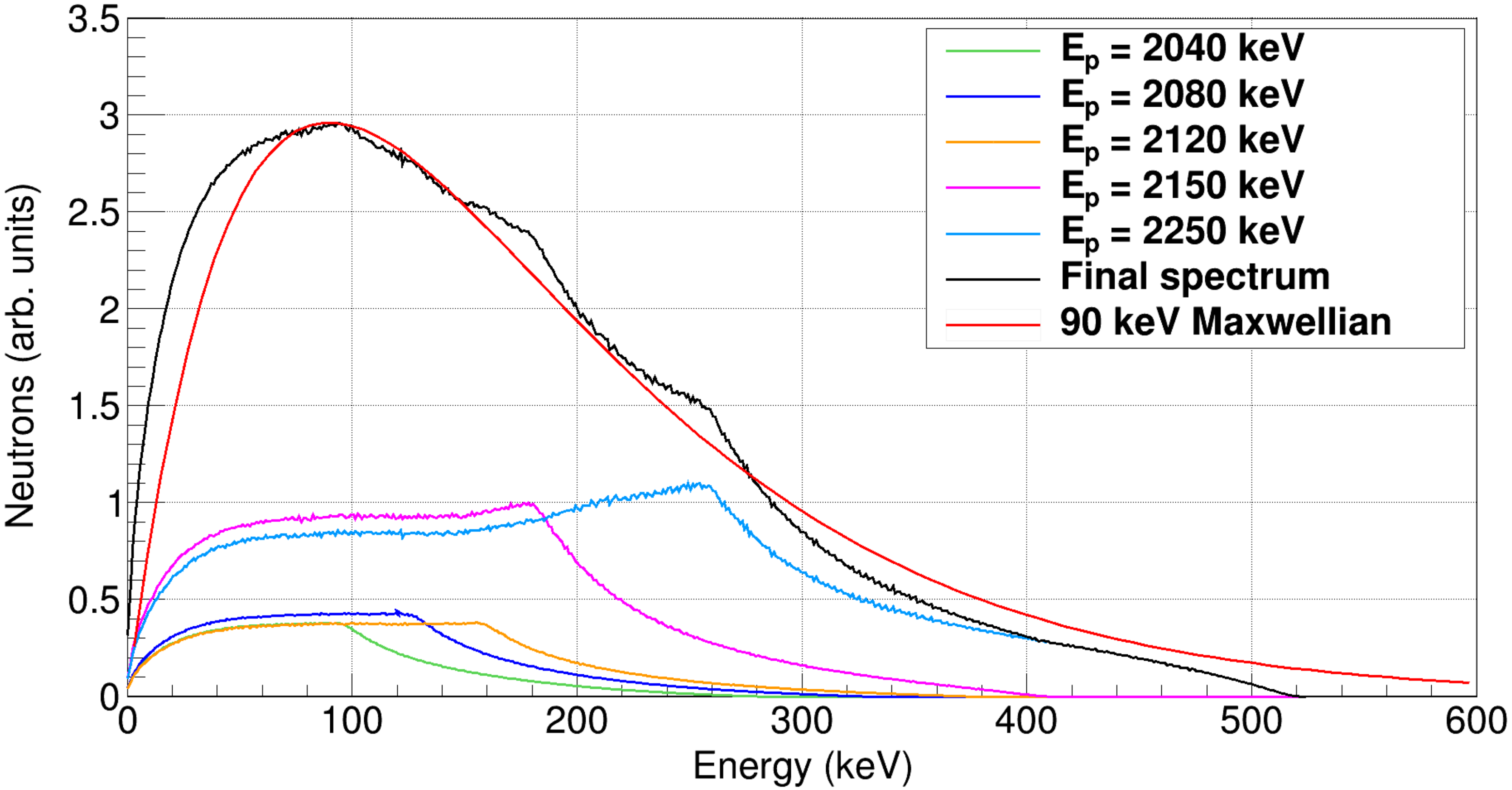
	Time of flight technique	**Neutron activation**
Energy and resonance shape	Very well defined	Limited “resolution” (MB distribution)
Absolute value	Susceptible to systematic effects	Very accurate (“easily” ~5%)

- An integral measurement can be very helpful with the analysis.
- ***“Development of a 90 keV Maxwellian neutron spectrum and measurement of the 30 & 90 keV ^{50}Cr MACS for criticality safety”*** (H2020-ARIEL Transnational Access).



^{7}Li(p,n)^{7}Be

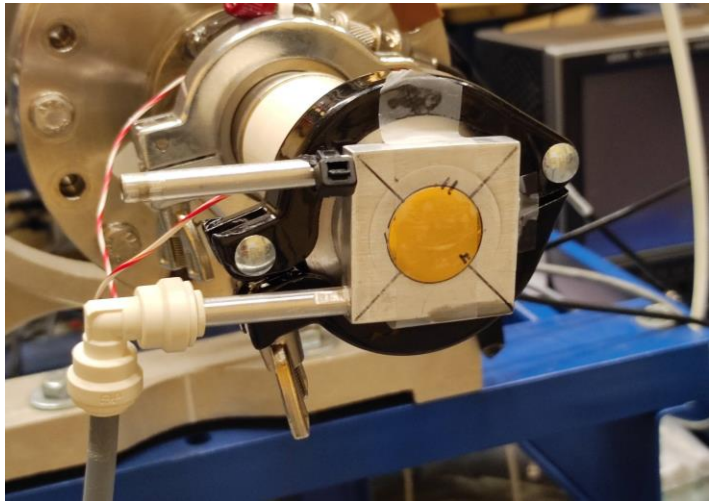
^{50}Cr activation: 90 keV MB neutron distribution



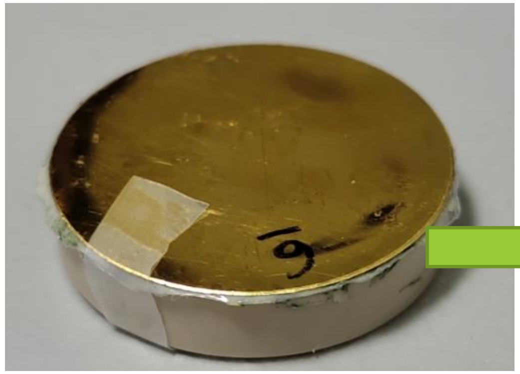
- A 30 keV spectrum can be produced with E_p = 1912 keV.
- For the 90 keV spectrum we need a linear combination of different proton energies.
- Maybe subtracting 1912 keV fits better a 90kev MB.

^{50}Cr activation: set-up

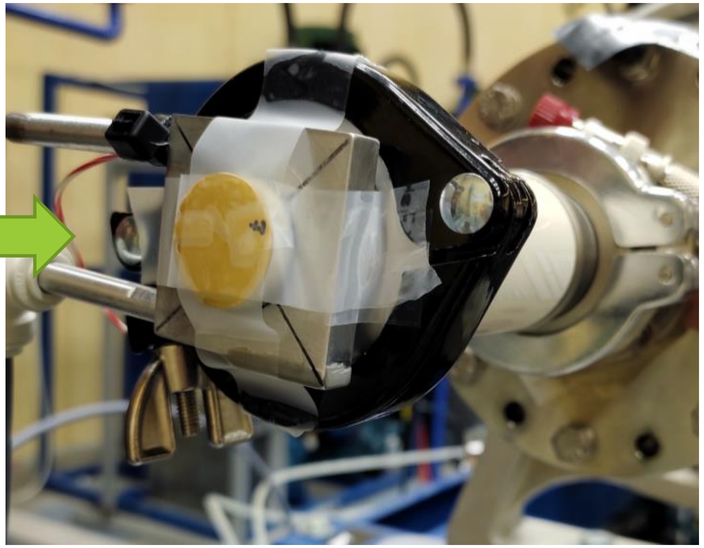
Metallic Li for higher production → cooled target

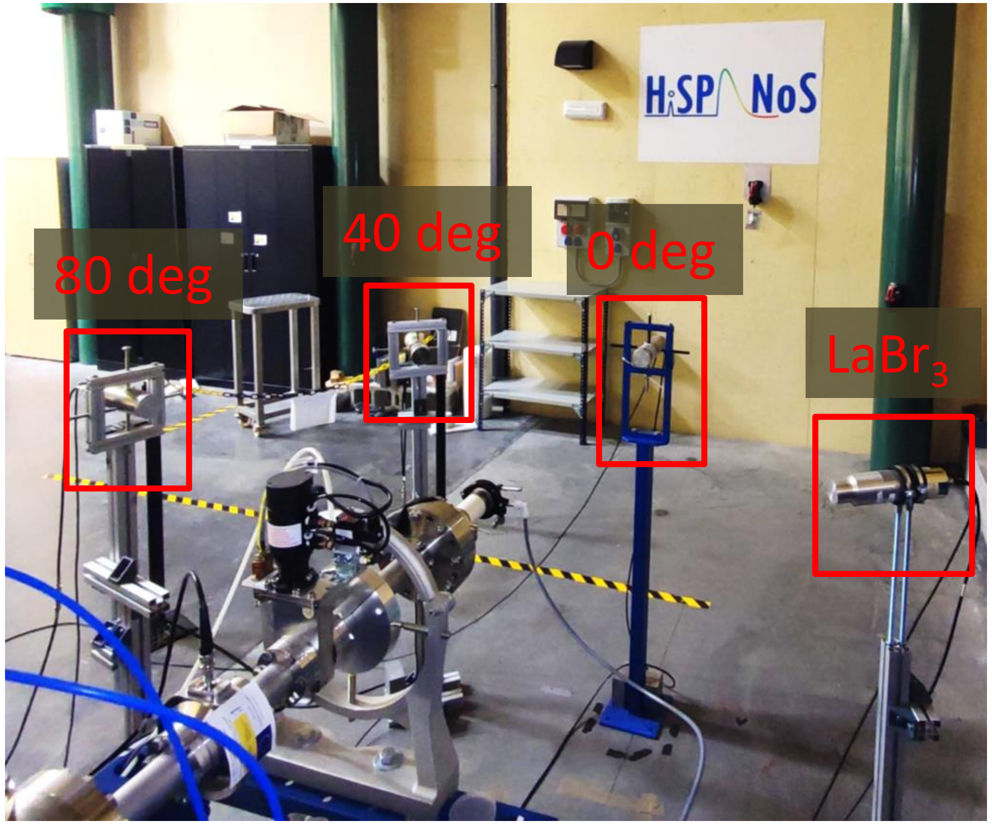


^{197}Au irradiation for activation checks



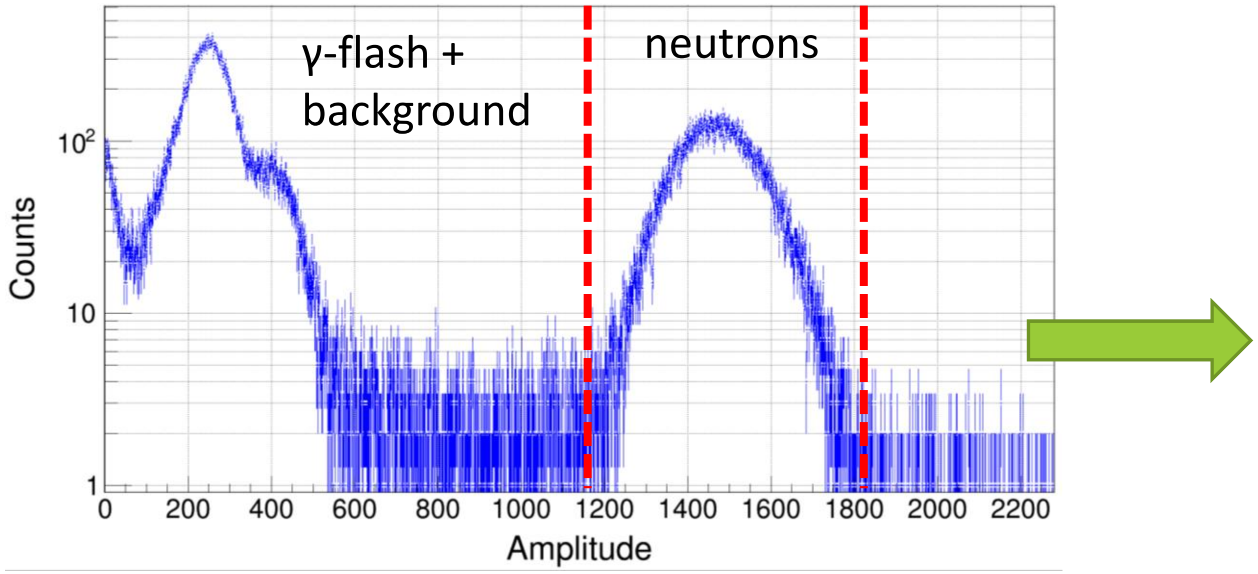
^{197}Au + ^{50}Cr + ^{197}Au sample

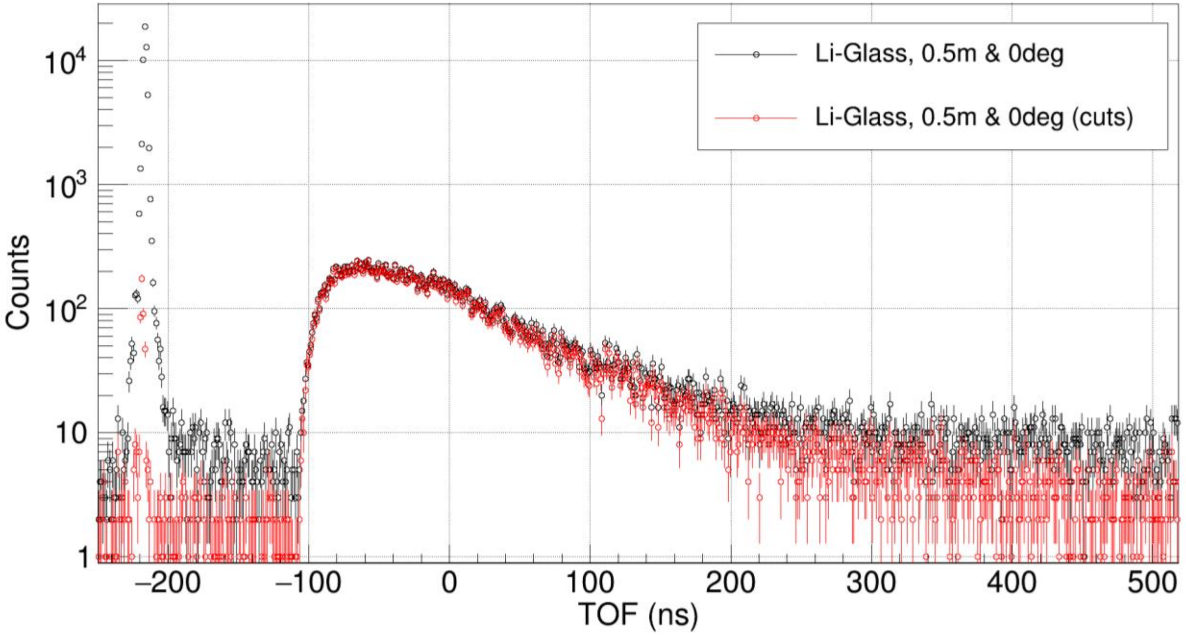




- 3 Lithium-glass neutron monitors
- 1 $LaBr_3$ for ^{7}Be decay
- 1 $LaBr_3$ for ^{198}Au and ^{51}Cr decay

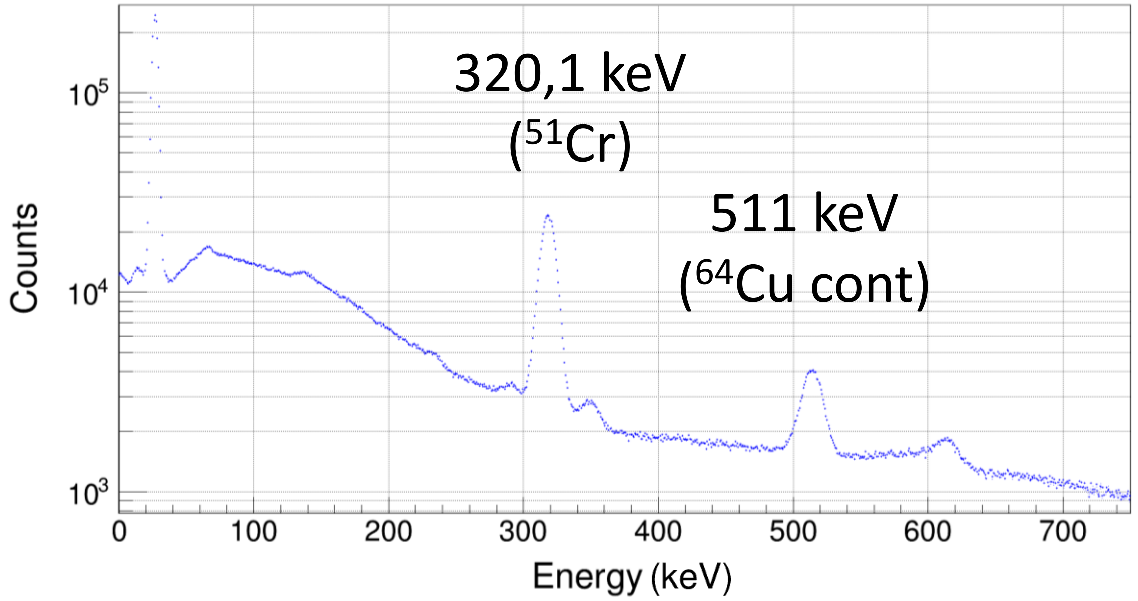
^{50}Cr activation: preliminary results (1912 keV)

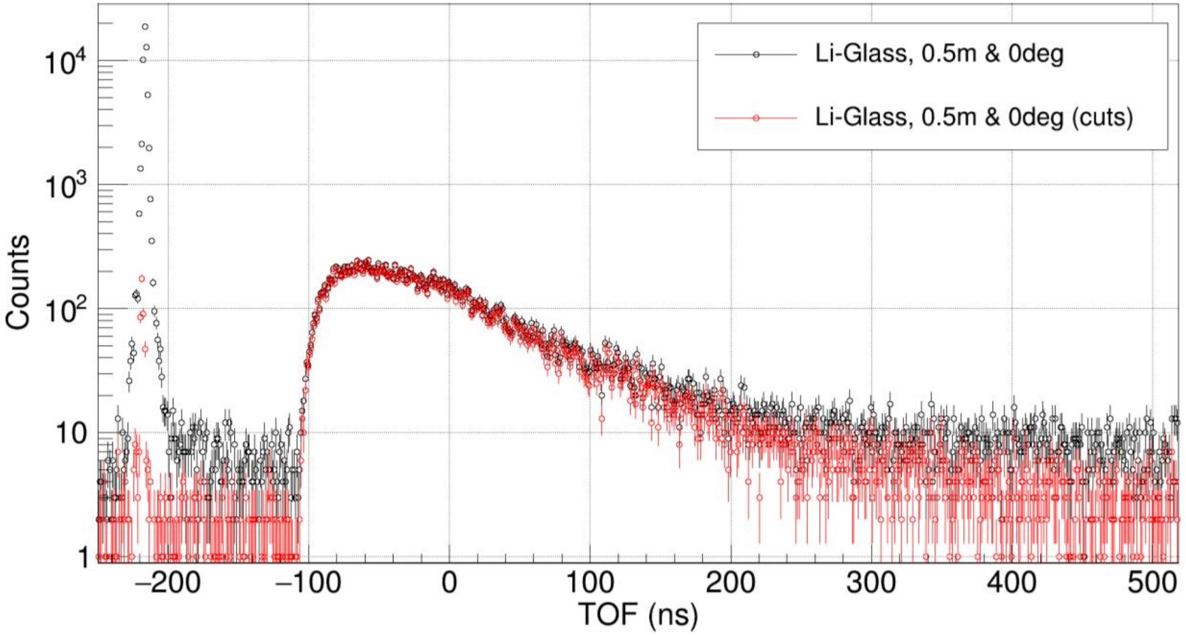




- Every neutron flux measured with Lithium-glass detectors at 3 angles.
- Flight paths of 0,5m (Ep = 1912 & 2080 keV) and 1m (the rest).
- With cuts in deposited energy we remove the gamma flash.

^{50}Cr activation: preliminary results (1912 keV)





- Every neutron flux measured with Lithium-glass detectors at 3 angles.
- Flight paths of 0,5m (Ep = 1912 & 2080 keV) and 1m (the rest).
- With cuts in deposited energy we remove the gamma flash.
- A lot of work ahead!

$$SACS = \frac{N_{^{198}Au}}{N_{^{7}Be^{nat}}}$$

$$MACS = \frac{2}{\sqrt{\pi}} \frac{\langle \sigma_{MB} \rangle}{\langle \sigma_{\Phi} \rangle} SACS$$

HiSPANoS SACS	584 mb*
HiSPANoS MACS	631 mb*
KADONIS MACS	612(6) mb
IAEA MACS	620(11) mb

*(Uncertainties not yet estimated)

Summary & Outlook

- The goal is to improve the $^{50,53}Cr(n,\gamma)$ 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:
  - Identify (and correct?) systematic effects
  - Counts/pulse → Yield (capture/neutrons)
  - Resonance analysis with SAMMY
  - Activation @CNA data analysis (2023)

} n_TOF experiment data analysis (2023)

Thank you!

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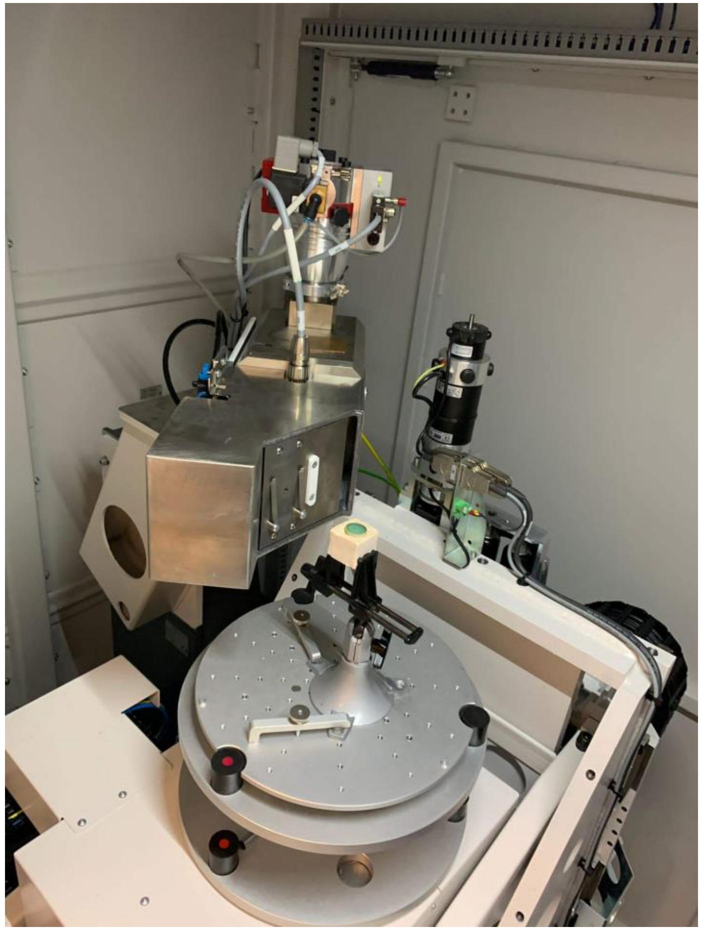
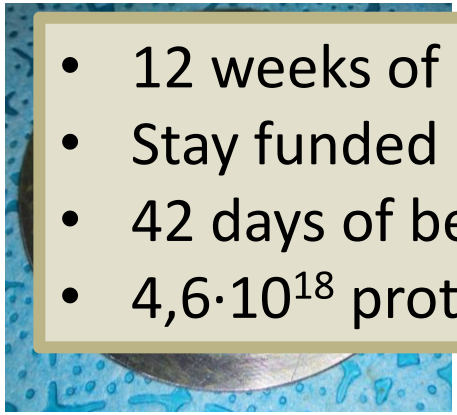
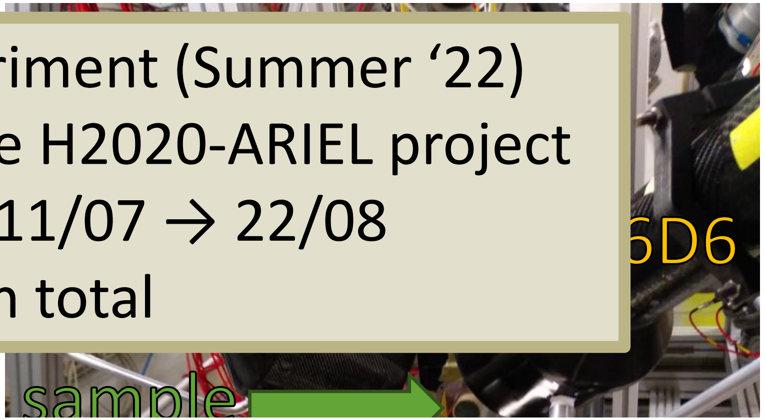
Backup. Tomography for homogeneity check



- 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.**

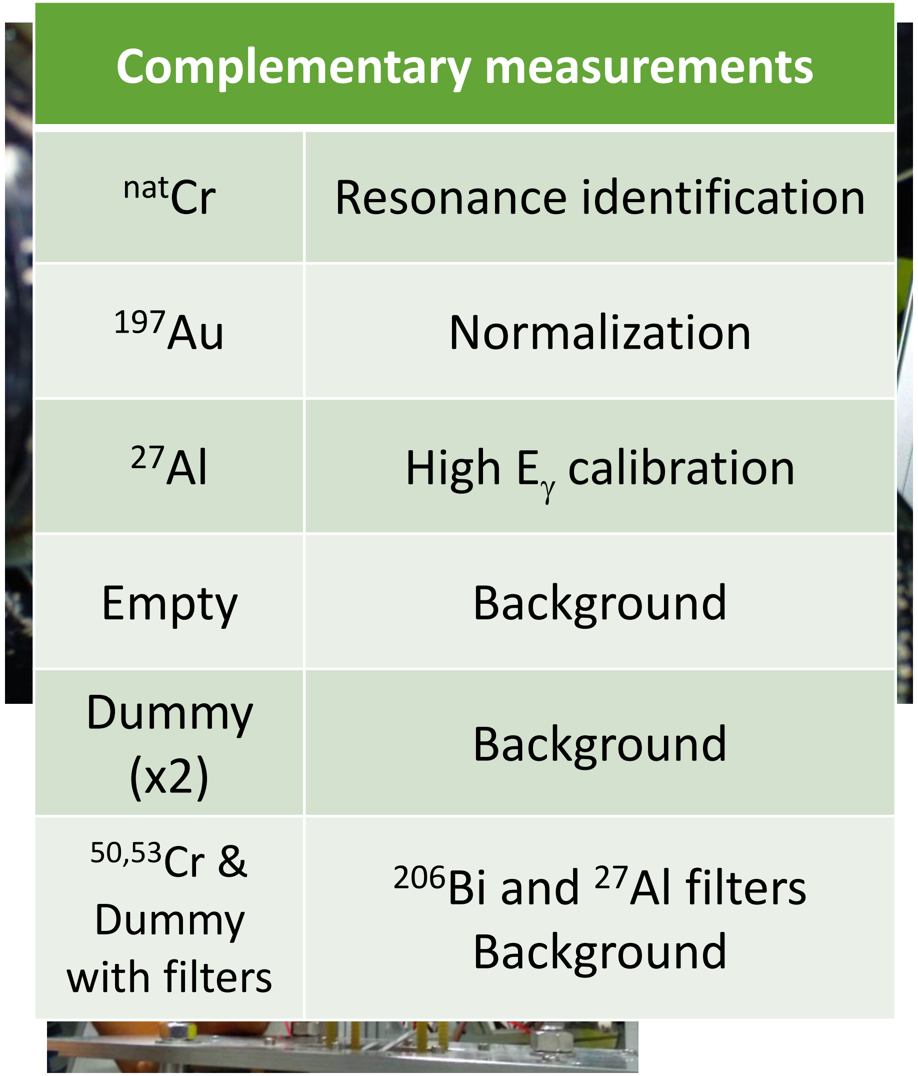
Backup. Samples and detector set-up (EAR1)





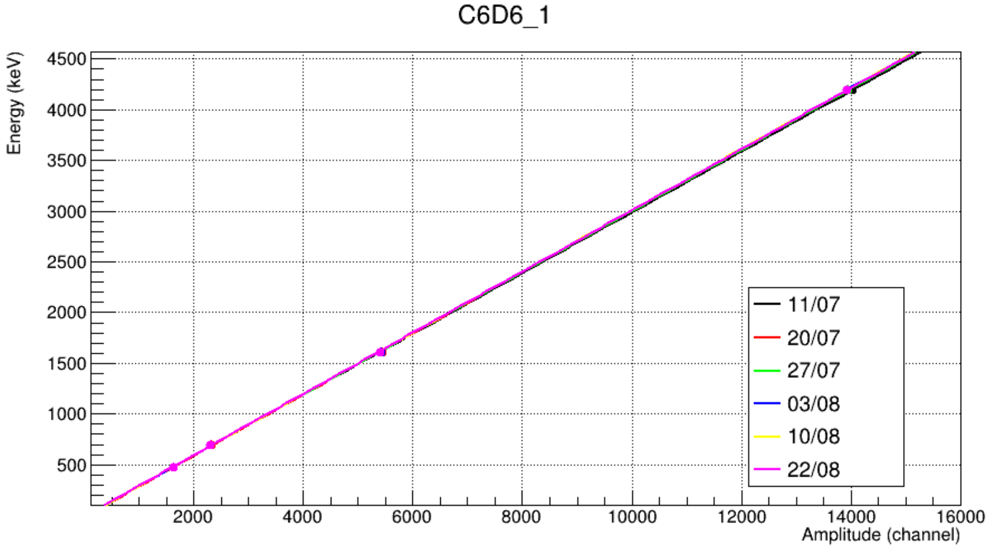
- 12 weeks of experiment (Summer ‘22)
- Stay funded by the H2020-ARIEL project
- 42 days of beam: 11/07 → 22/08
- 4,6·10^{18} protons in total

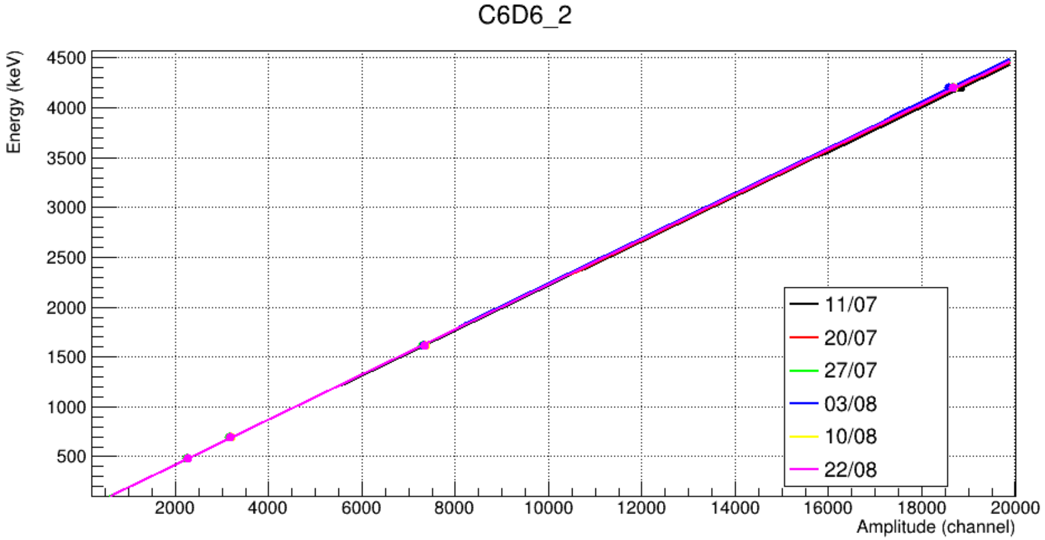
Sample	Protons·10^{17} (meas.)	Protons·10^{17} (proposal)
^{50}Cr – thin	5,5	5 (110%)
^{50}Cr – thick	**14,7**	**8 (184%)**
^{53}Cr – thin	6,8	5 (136%)
^{53}Cr – thick	**6,9**	**17 (40%)**
Back. & norm.	13,0	5 (260%)
Total	**45,9**	**40 (115%)**

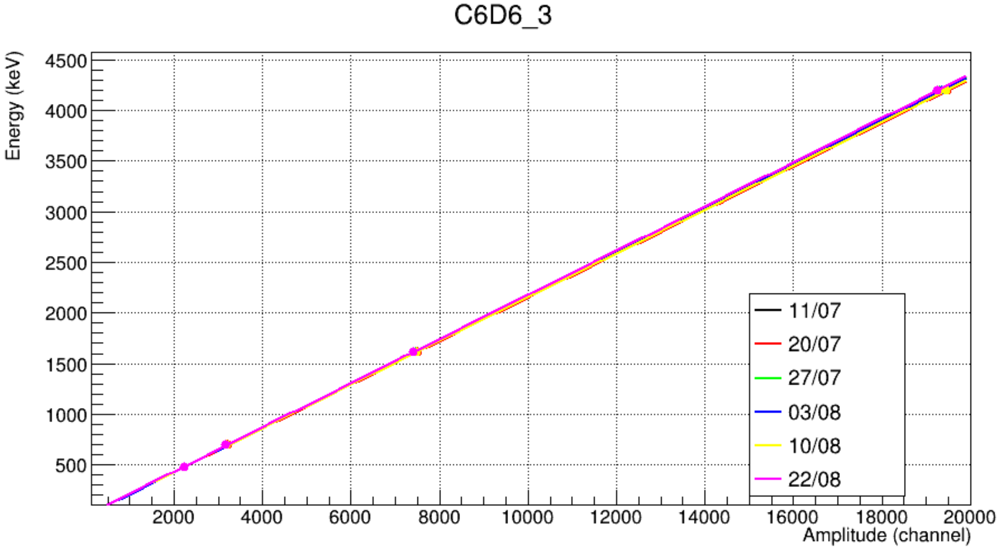


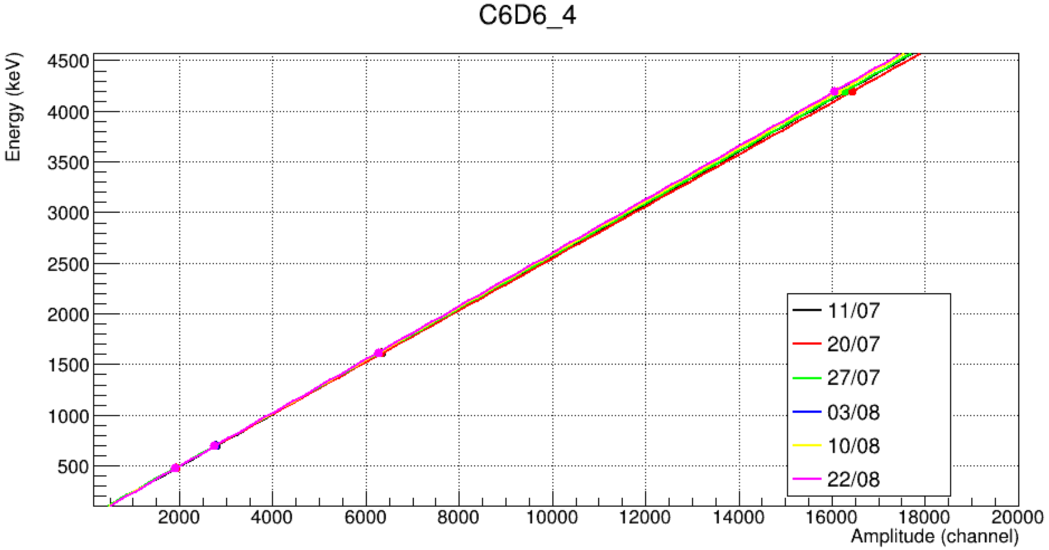
Complementary measurements	
^{nat}Cr	Resonance identification
^{197}Au	Normalization
^{27}Al	High E_γ calibration
Empty	Background
Dummy (x2)	Background
^{50,53}Cr & Dummy with filters	^{206}Bi and ^{27}Al filters Background

Backup. C6D6 gain stability

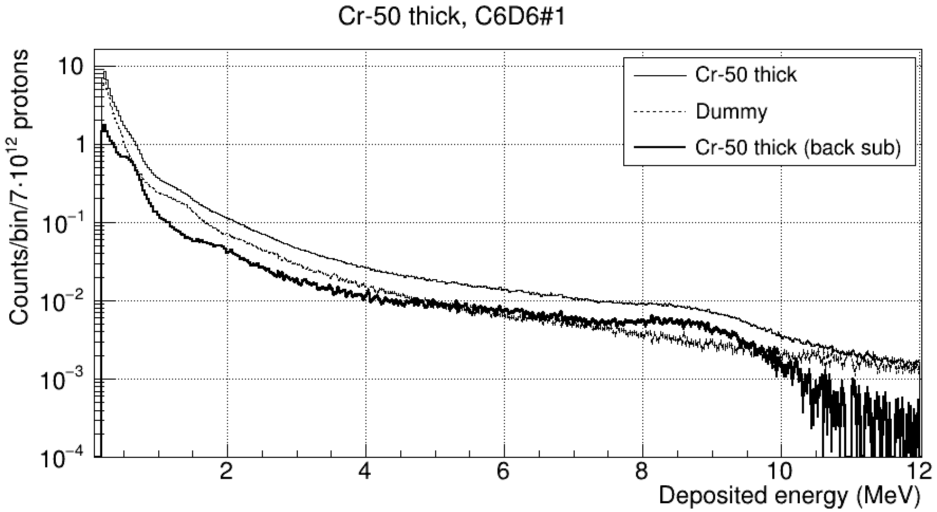


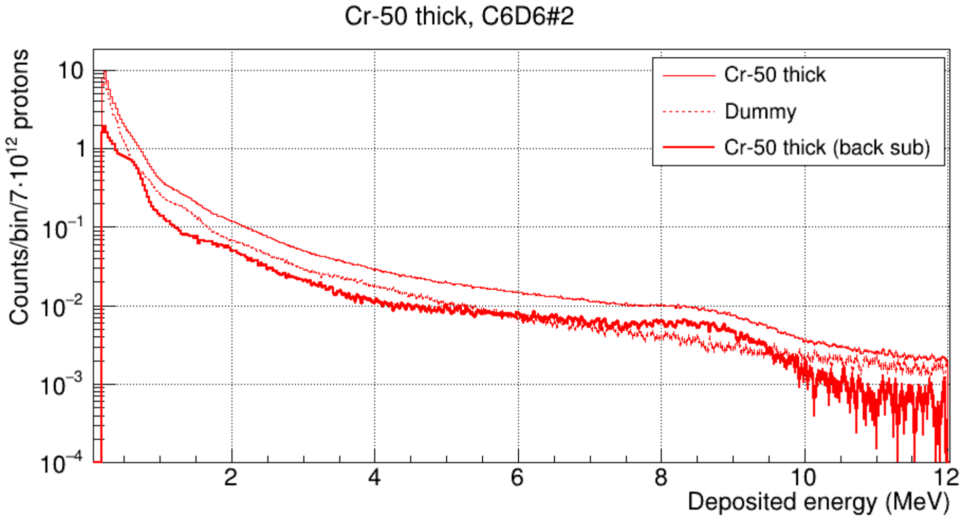


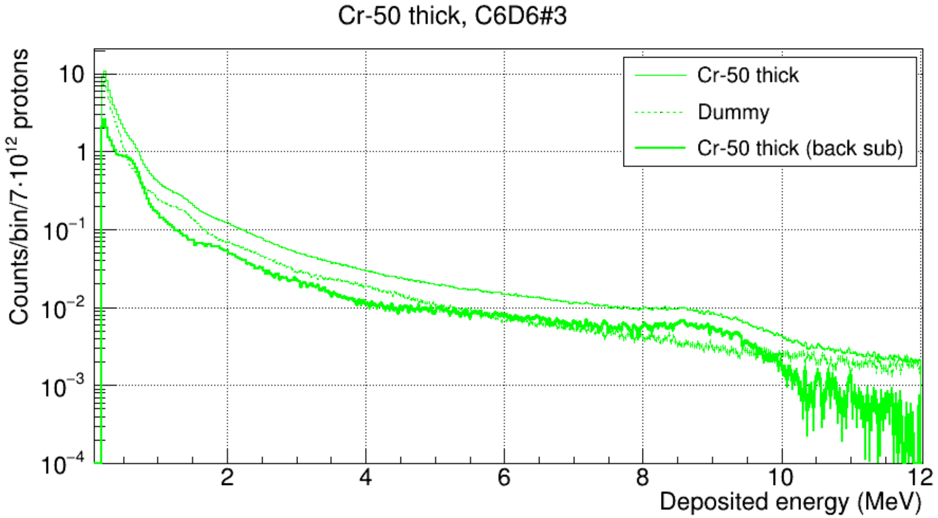


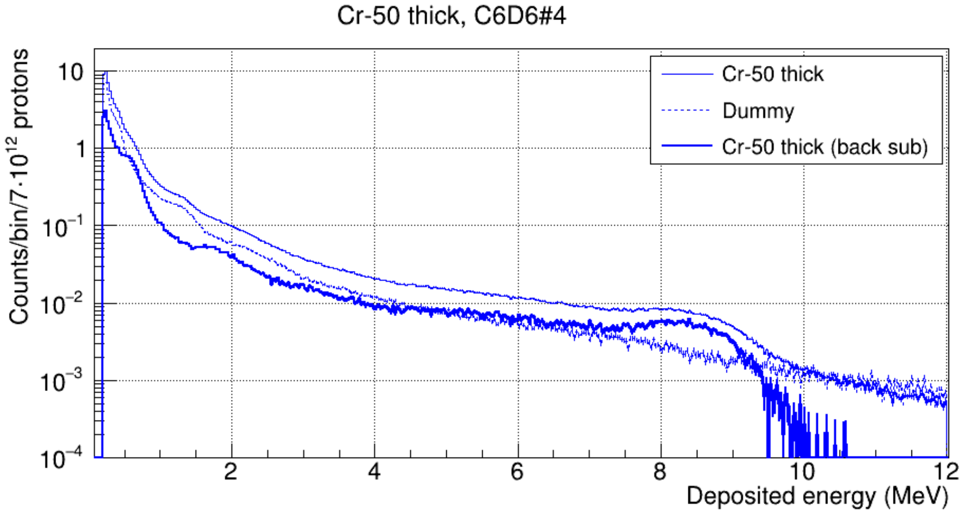


Backup. ^{50}Cr cascades (S_n=9,3 MeV)



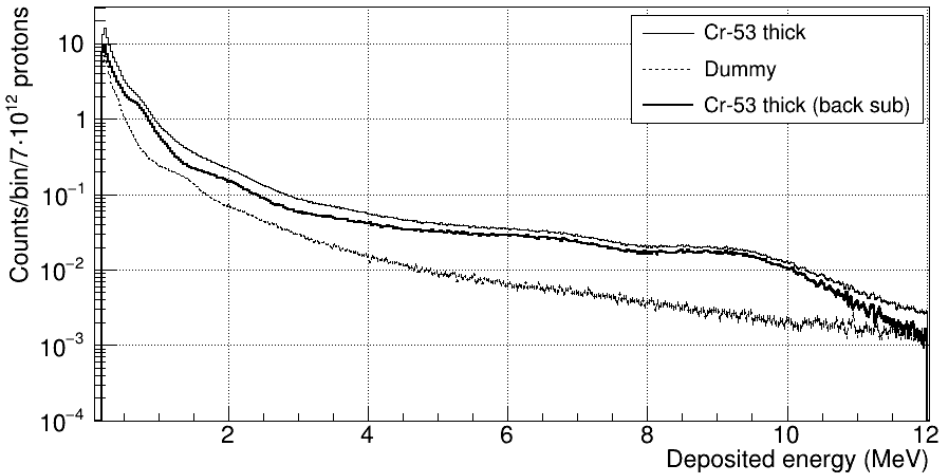




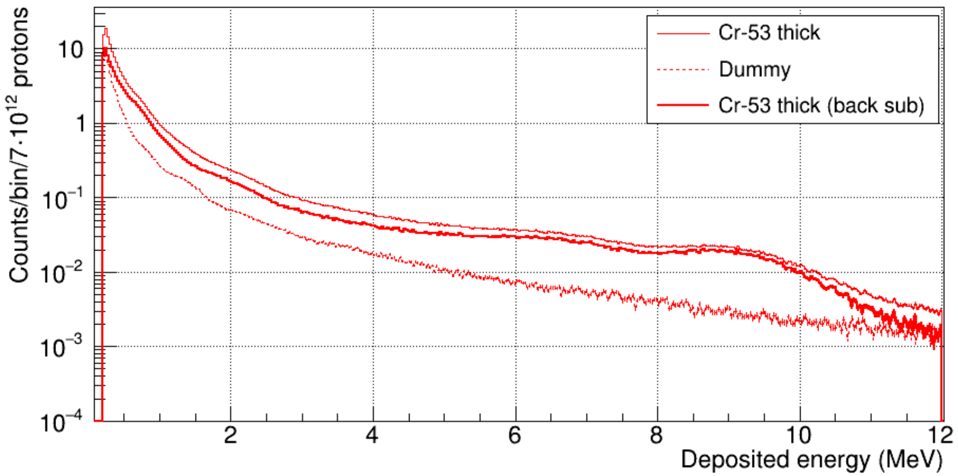


Backup. ^{53}Cr cascades (S_n=9,7 MeV)

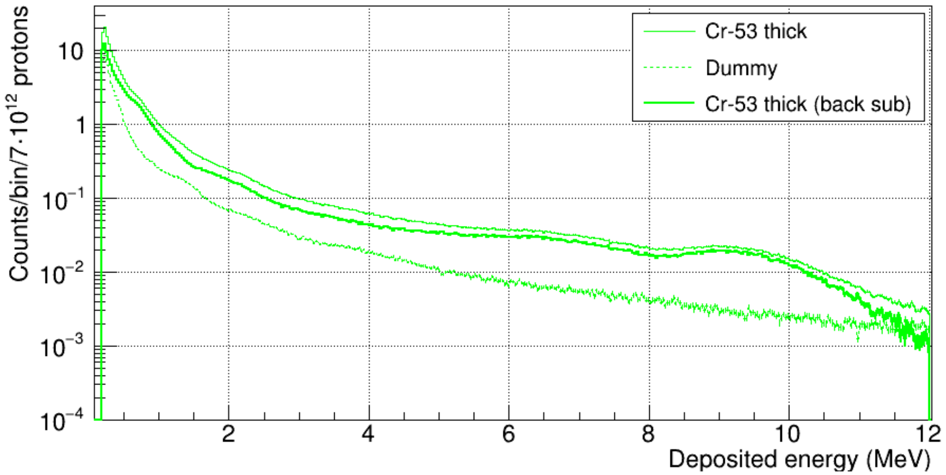
Cr-53 thick, C6D6#1



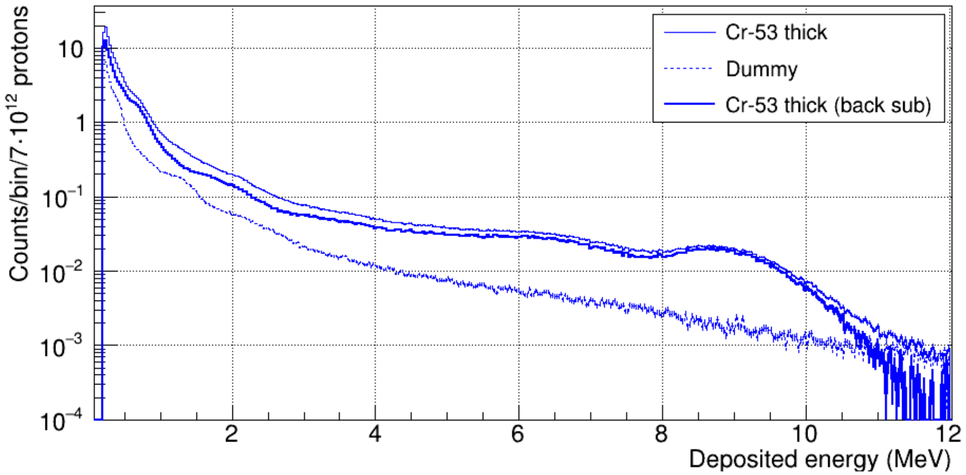
Cr-53 thick, C6D6#2



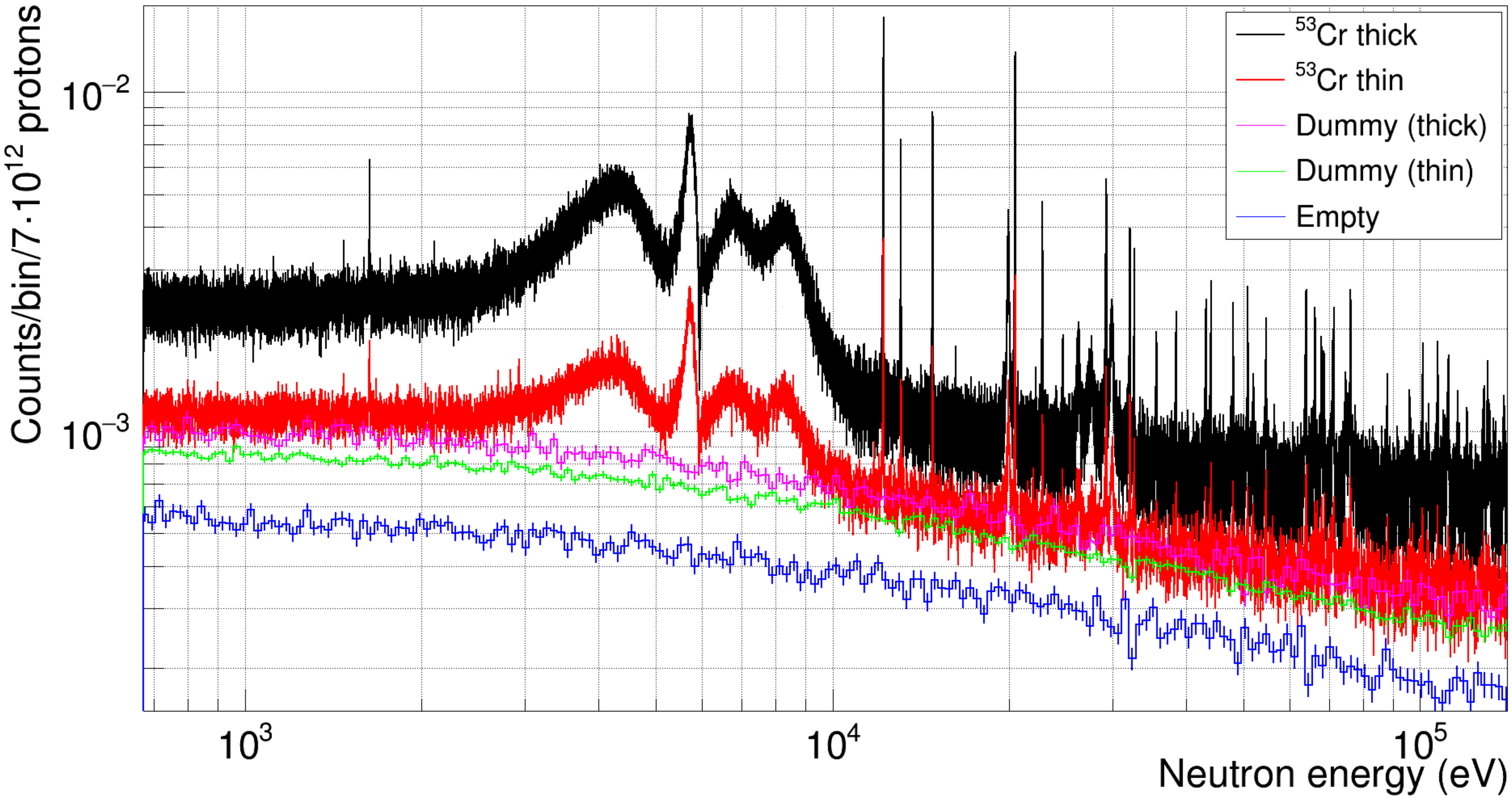
Cr-53 thick, C6D6#3



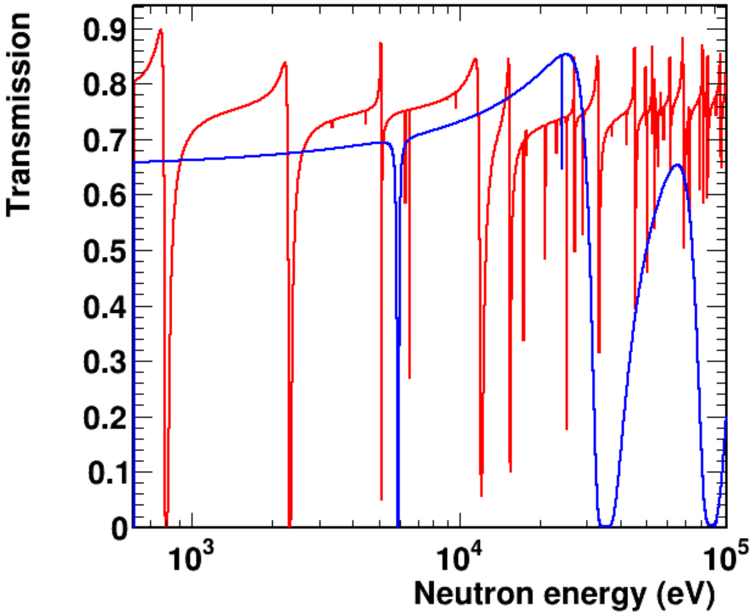
Cr-53 thick, C6D6#4

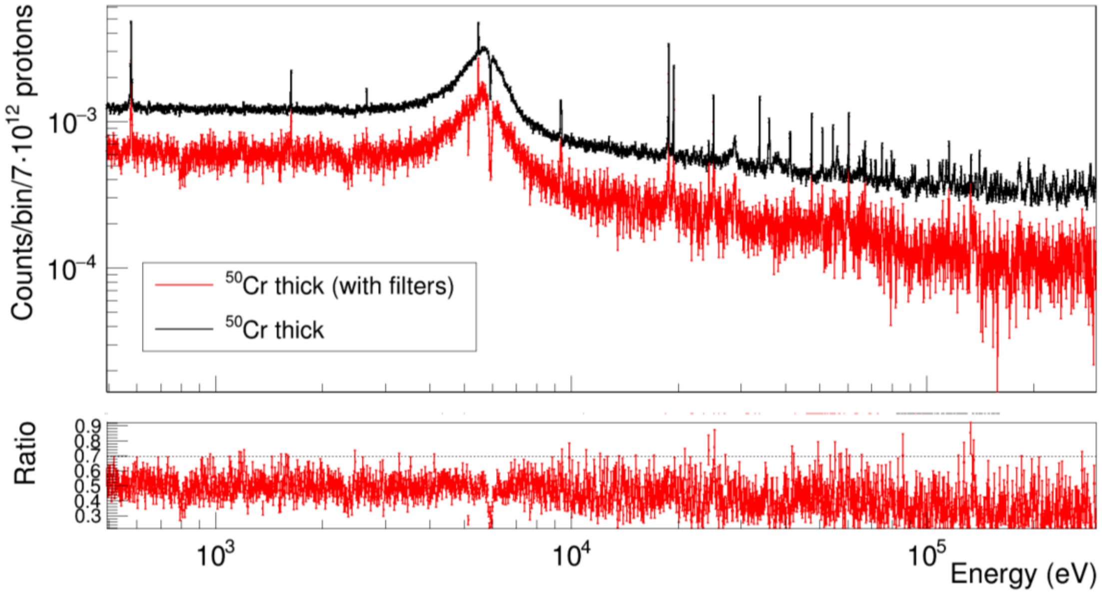


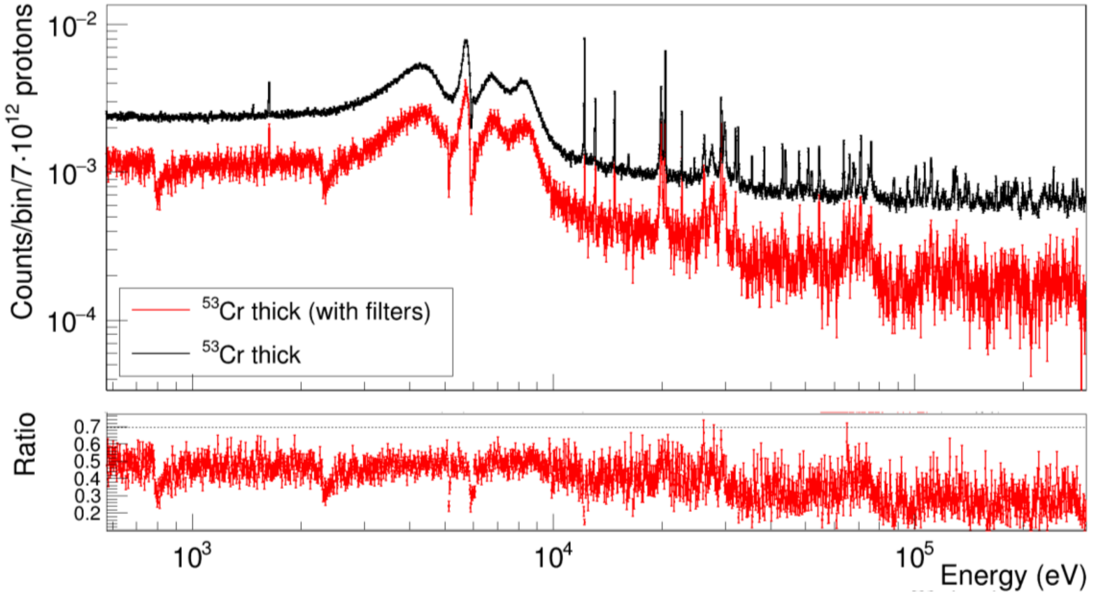
Backup. Preliminary results (^{53}Cr: thin vs. thick)



Backup. Filters

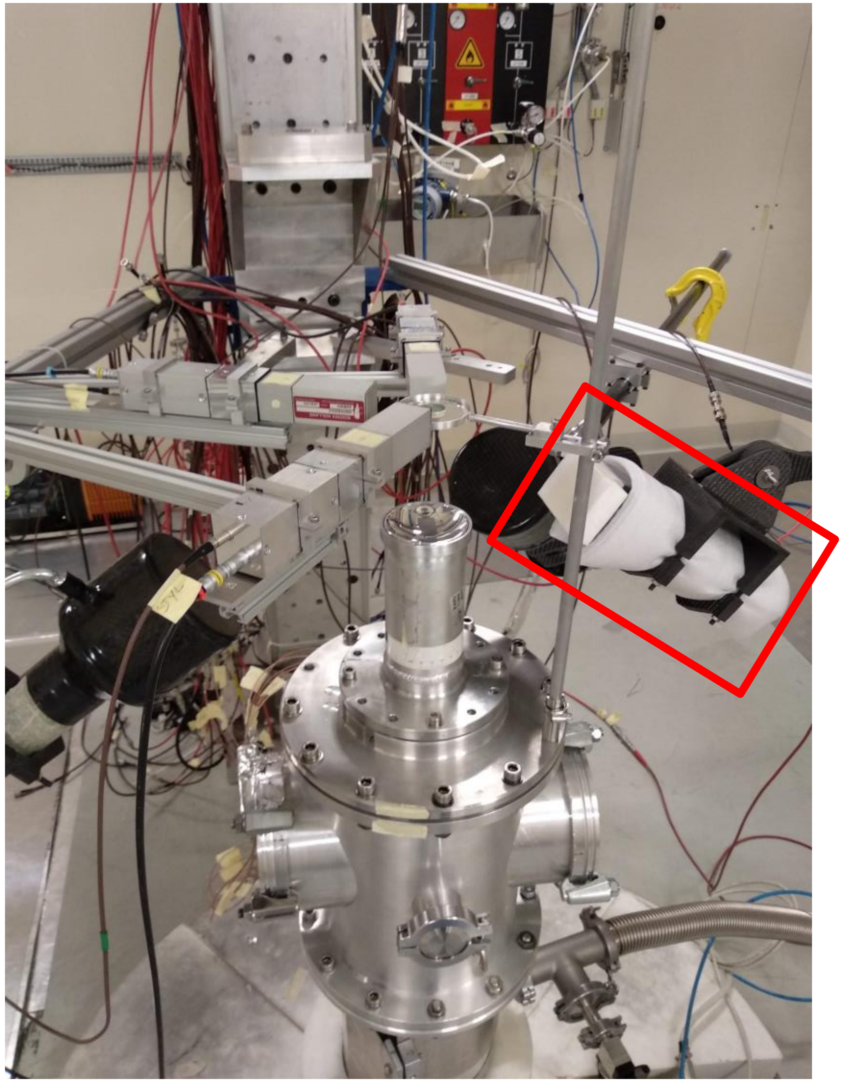




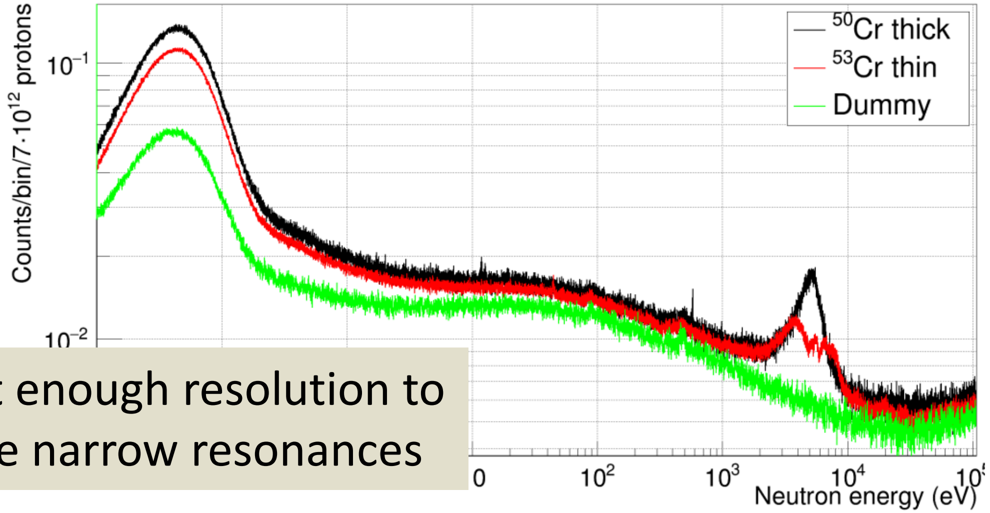


- For neutron scattering background
- 10 mm ^{209}Bi & 50mm ^{27}Al filters
- Dummy and thick samples

Backup. Cascades at EAR2

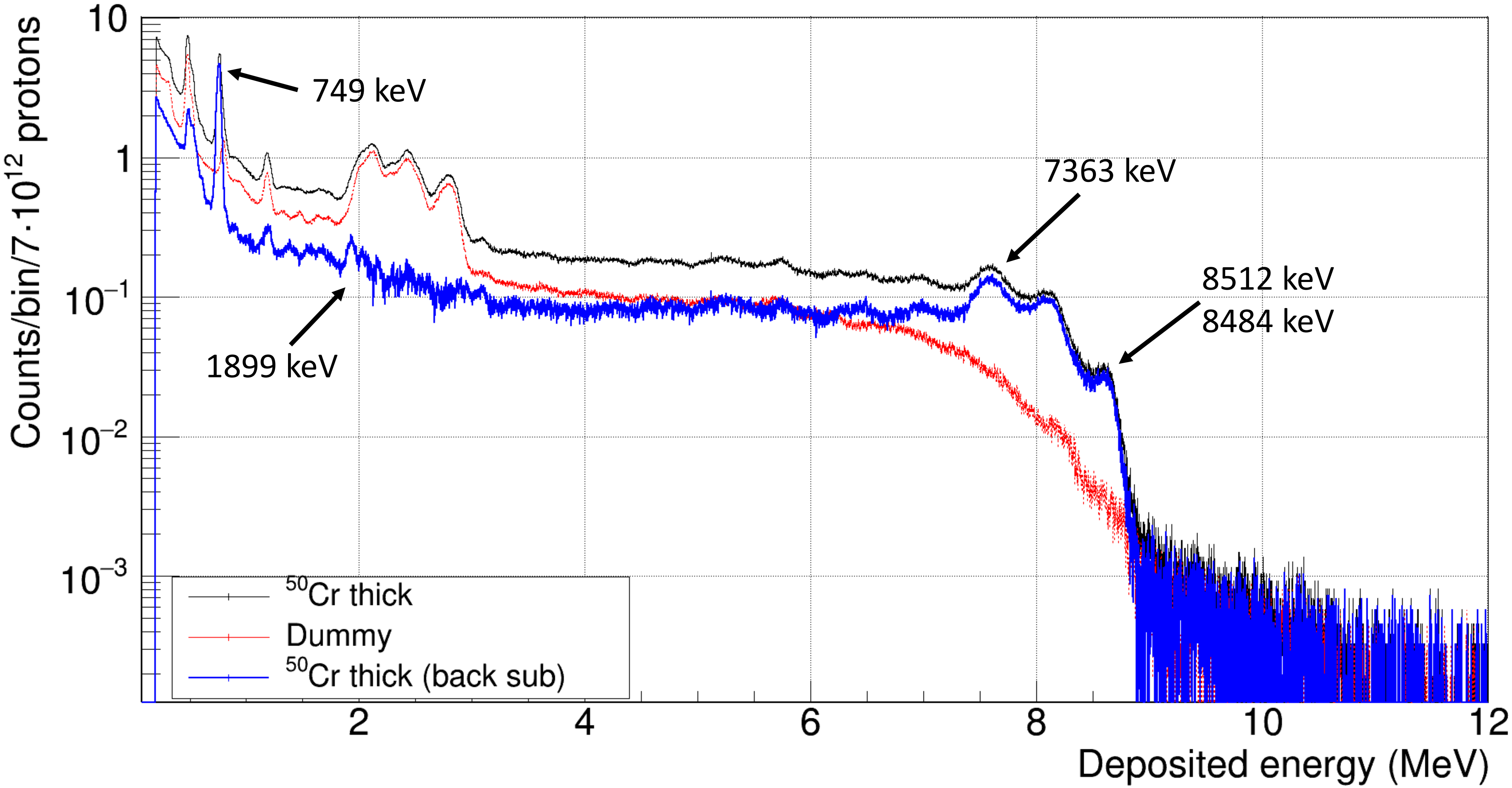


- Goal → measure the cascades with high resolution to validate future simulations.
- 3 sTED's & 2 C6D6's for monitoring, **1 $LaCl_3$** for the cascades.
- Gain shift depending on counting rate (malfunctioning PMT?) → thin samples, low voltage and not too close to the beam.

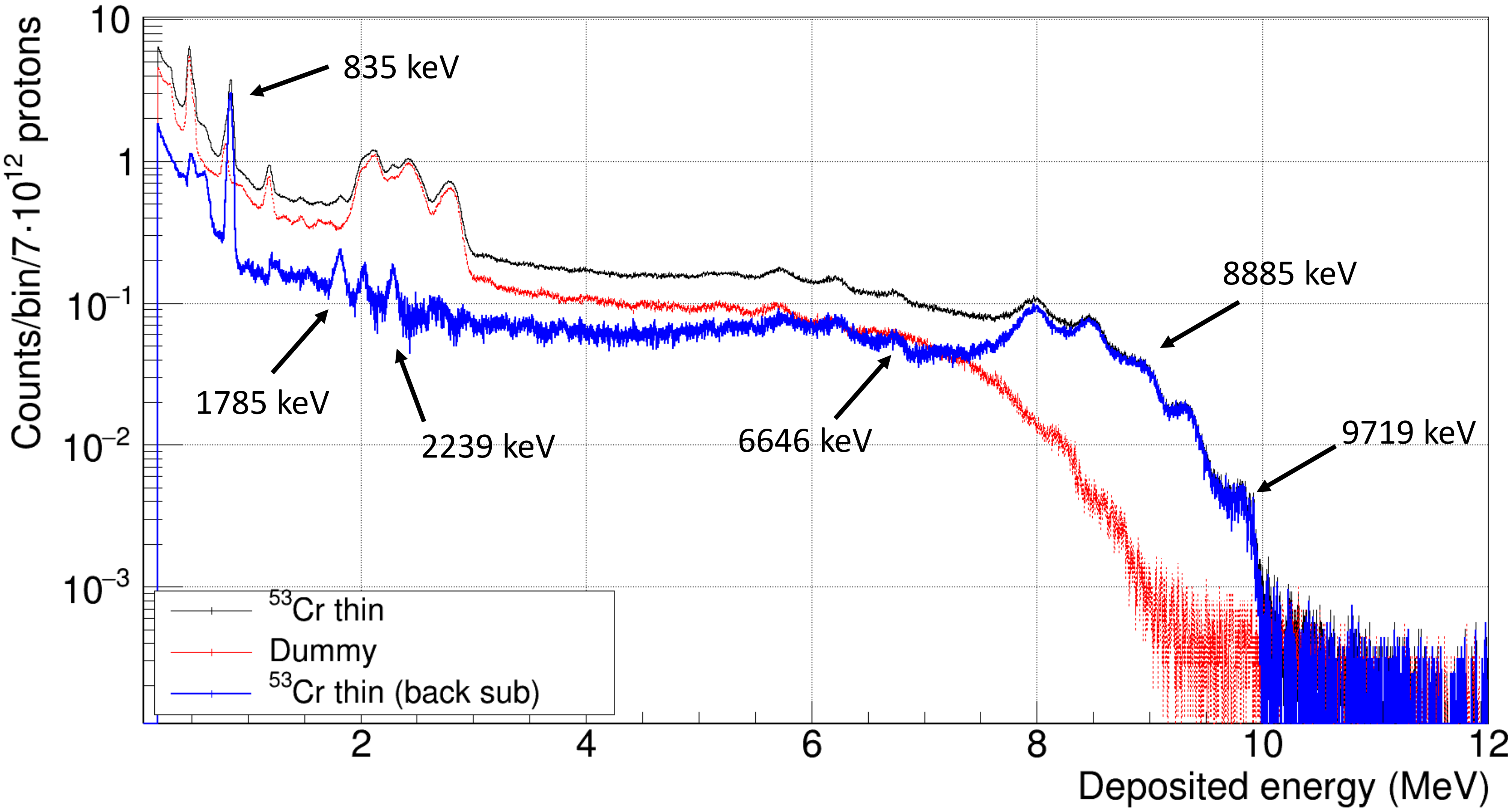


Not enough resolution to see narrow resonances

Backup. ^{50}Cr(n,γ) cascades at EAR2 (preliminary)



Backup. ^{53}Cr(n,γ) cascades at EAR2 (preliminary)



835 keV

1785 keV

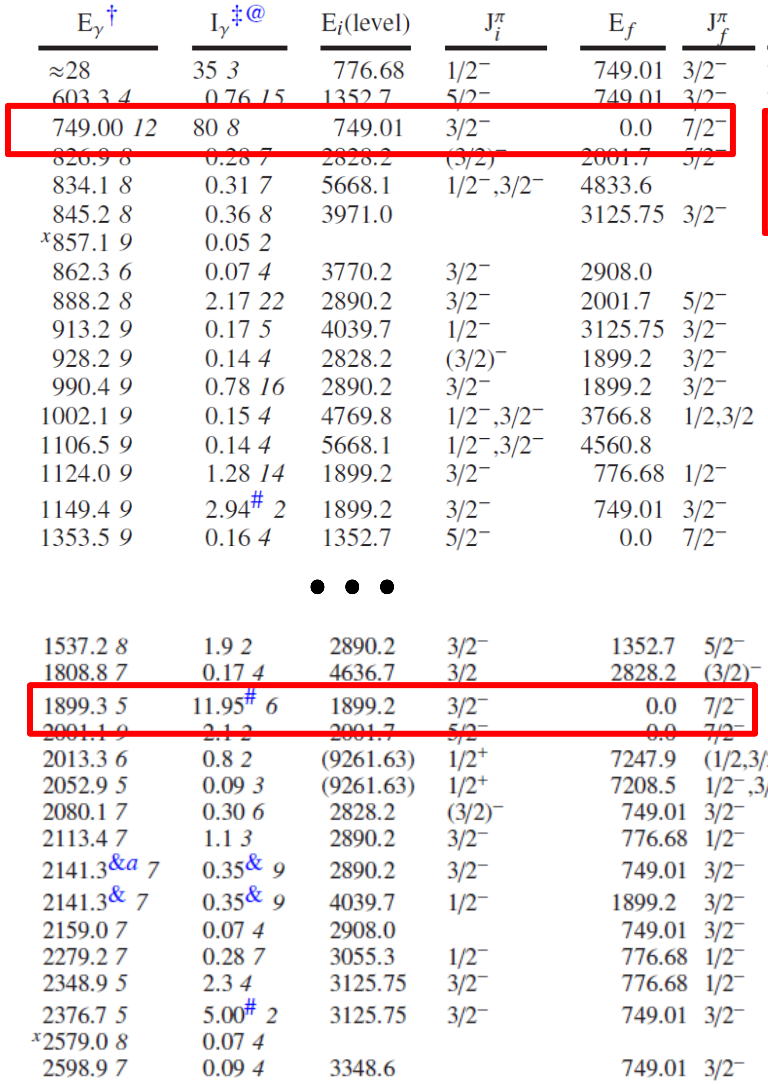
2239 keV

6646 keV

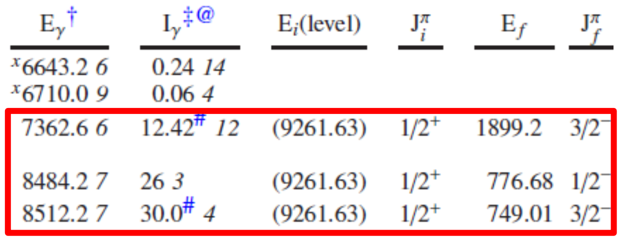
8885 keV

9719 keV

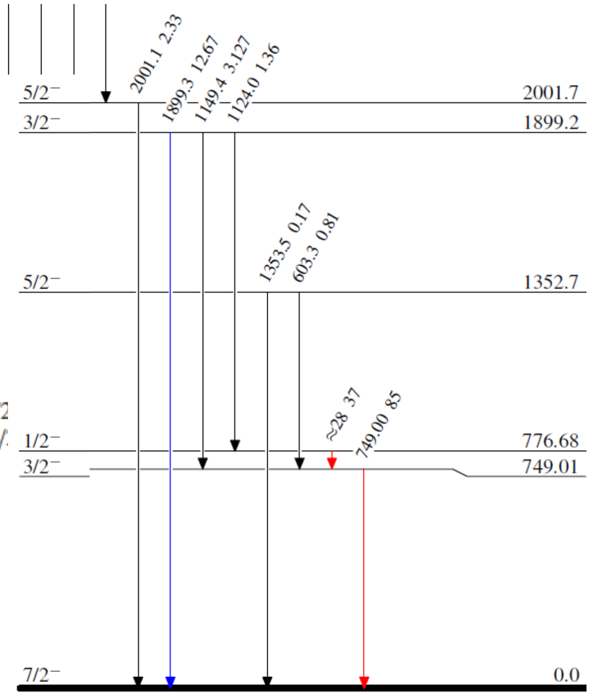
Backup. ^{51}Cr gamma emission

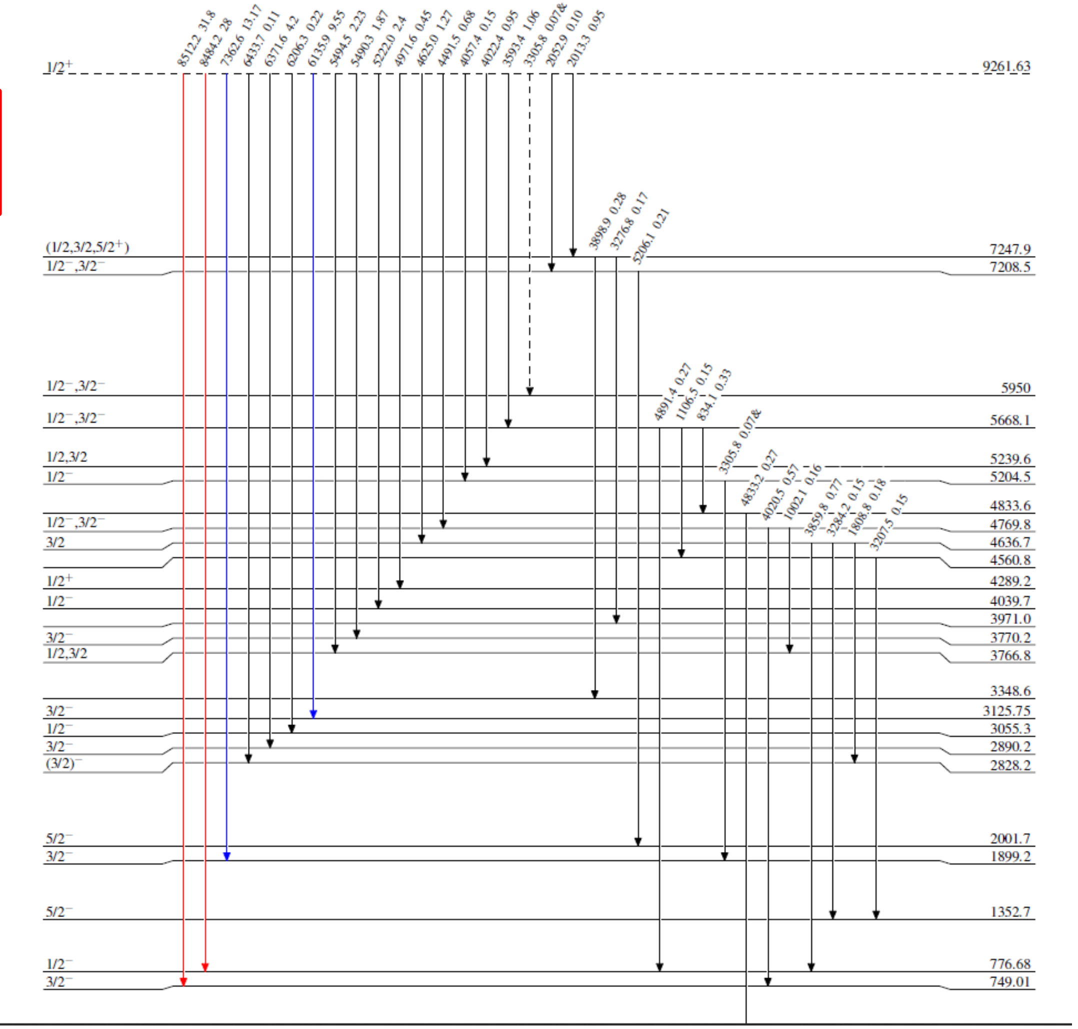


E_γ †	I_γ ‡@	E_i(level)	J_i^π	E_f	J_f^π
≈28	35 3	776.68	$1/2^-$	749.01	$3/2^-$
603.3 4	0.76 15	1352.7	$5/2^-$	749.01	$3/2^-$
749.00 12	80 8	749.01	$3/2^-$	0.0	$7/2^-$
826.9 8	0.28 7	2828.2	$(3/2)^-$	2001.7	$5/2^-$
834.1 8	0.31 7	5668.1	$1/2^-,3/2^-$	4833.6	
845.2 8	0.36 8	3971.0		3125.75	$3/2^-$
^{x}857.1 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	$7/2^-$
• • •					
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	$3/2^-$
^{x}2579.0 8	0.07 4				
2598.9 7	0.09 4	3348.6		749.01	$3/2^-$

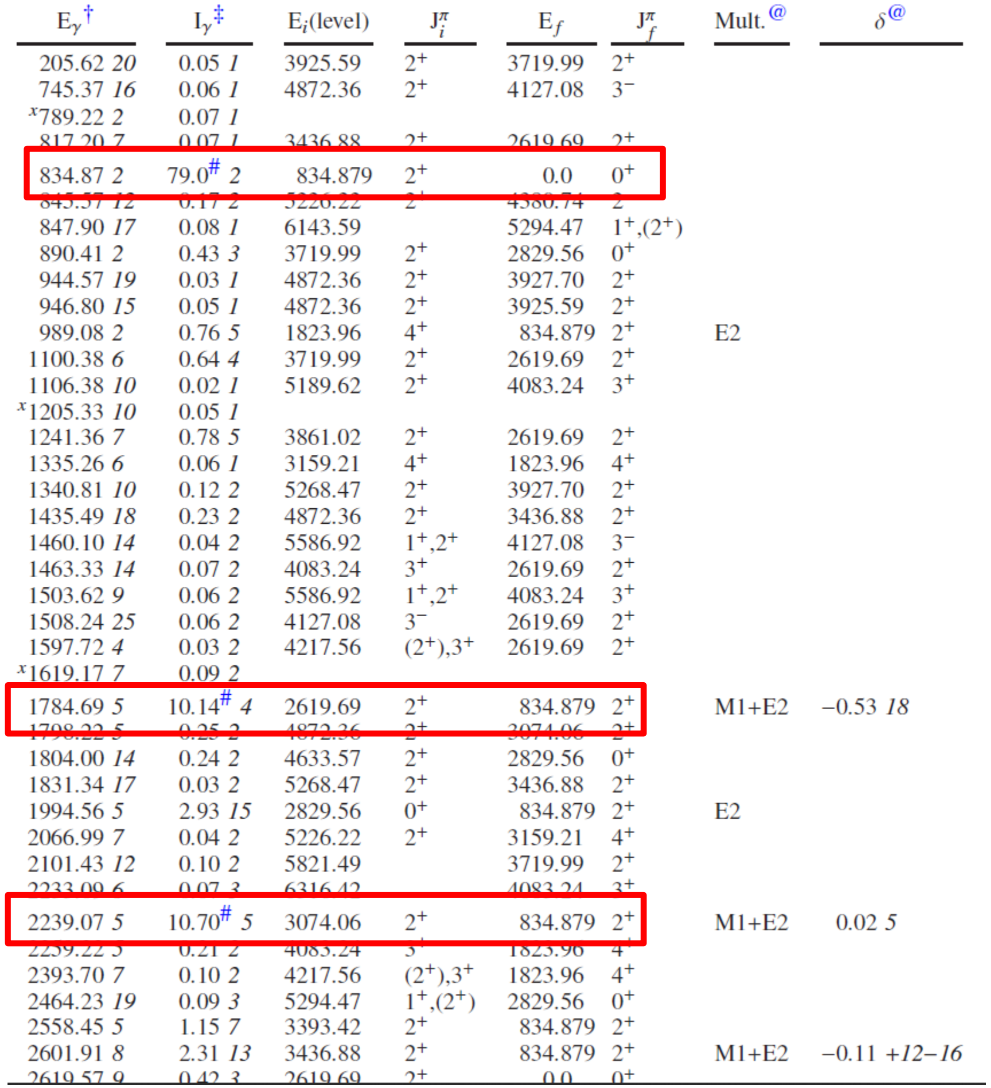
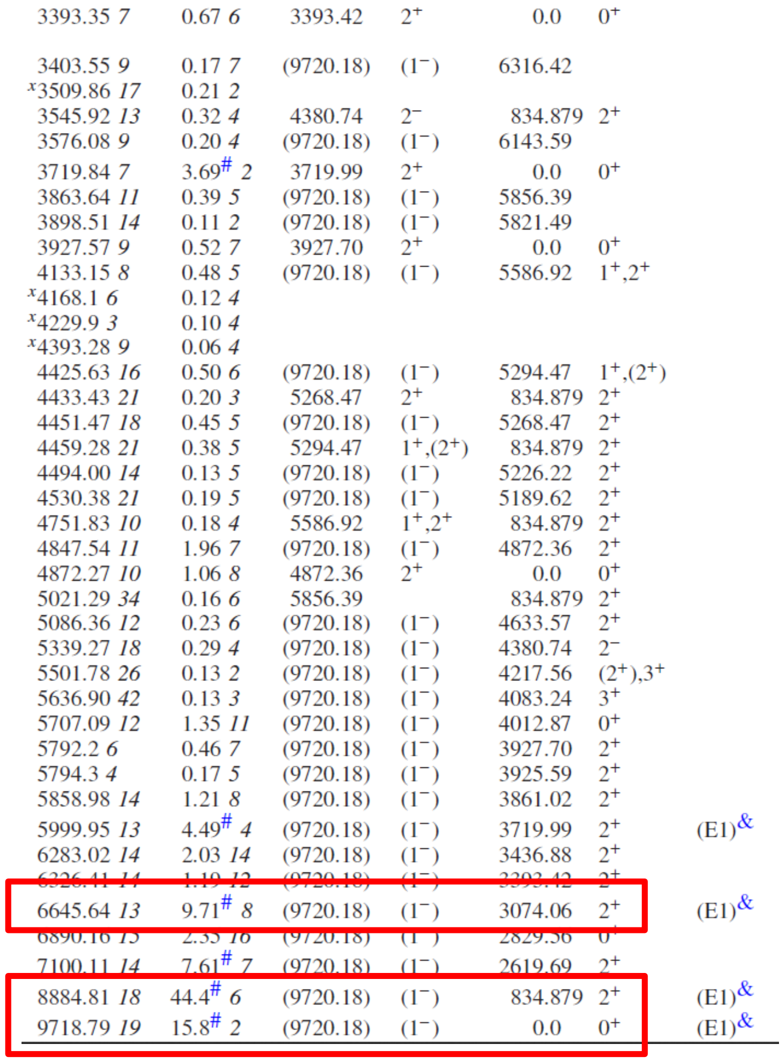


E_γ †	I_γ ‡@	E_i(level)	J_i^π	E_f	J_f^π
^{x}6643.2 6	0.24 14				
^{x}6710.0 9	0.06 4				
7362.6 6	$12.42^{\#}$ 12	(9261.63)	$1/2^+$	1899.2	$3/2^-$
8484.2 7	26 3	(9261.63)	$1/2^+$	776.68	$1/2^-$
8512.2 7	$30.0^{\#}$ 4	(9261.63)	$1/2^+$	749.01	$3/2^-$



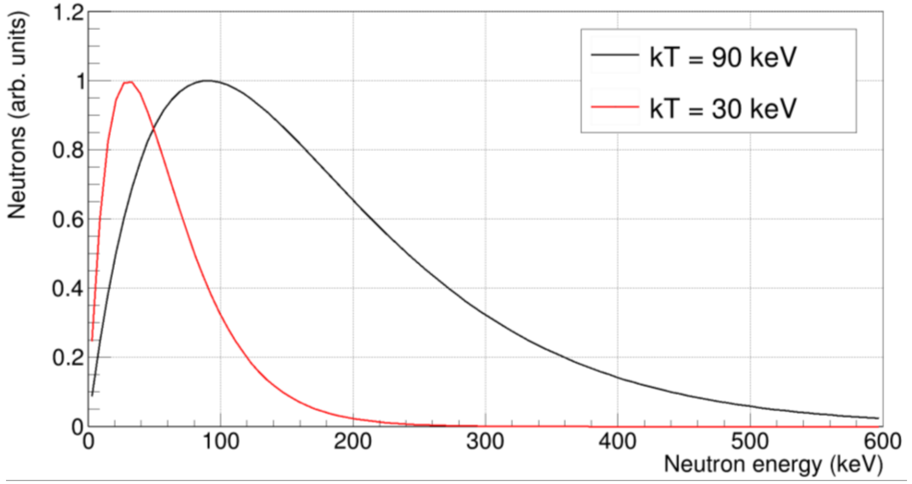


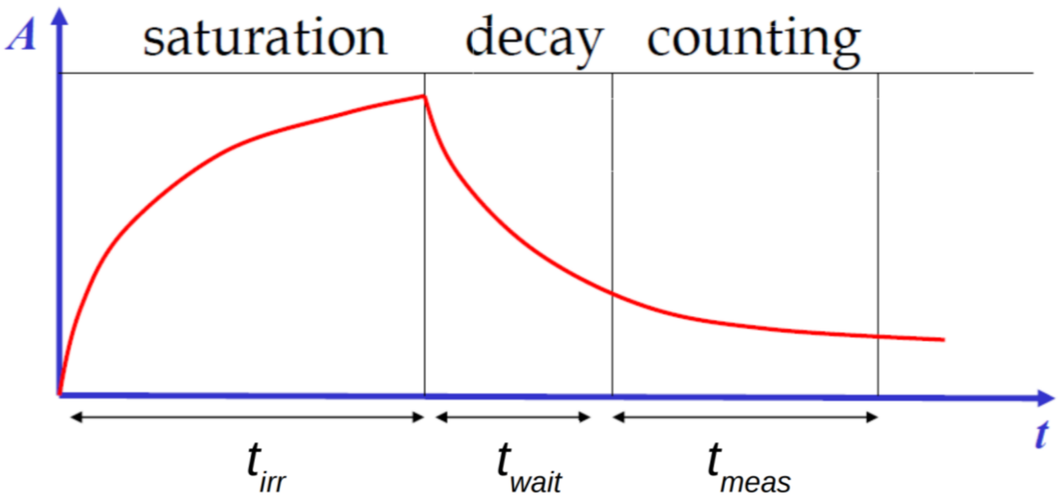
Backup. ^{54}Cr gamma emission

E_γ†	I_γ‡	E_i(level)	J^π_i	E_f	J^π_f	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. Averaged cross section equations





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

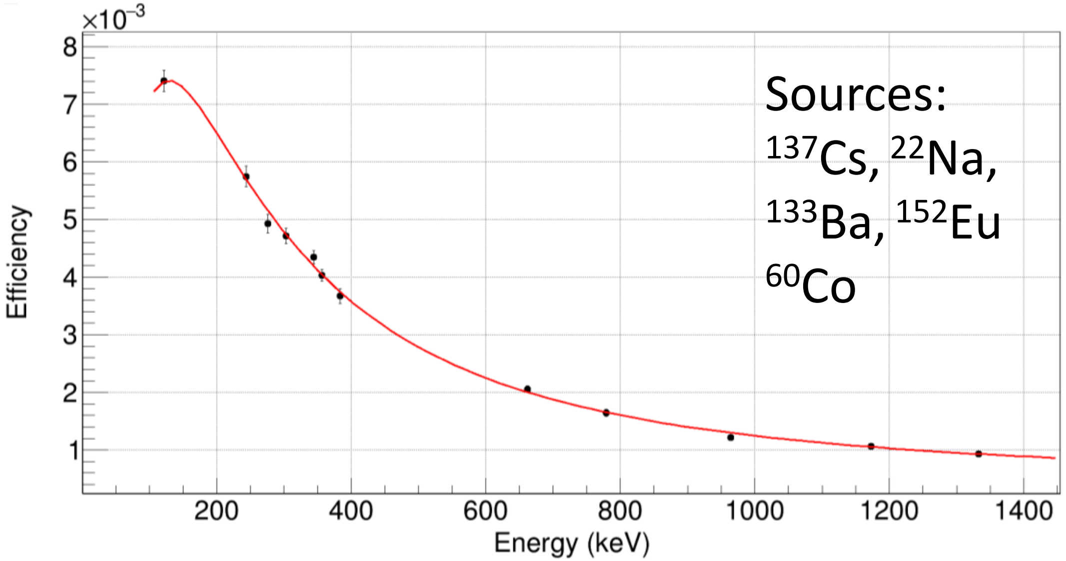
$$\downarrow$$

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

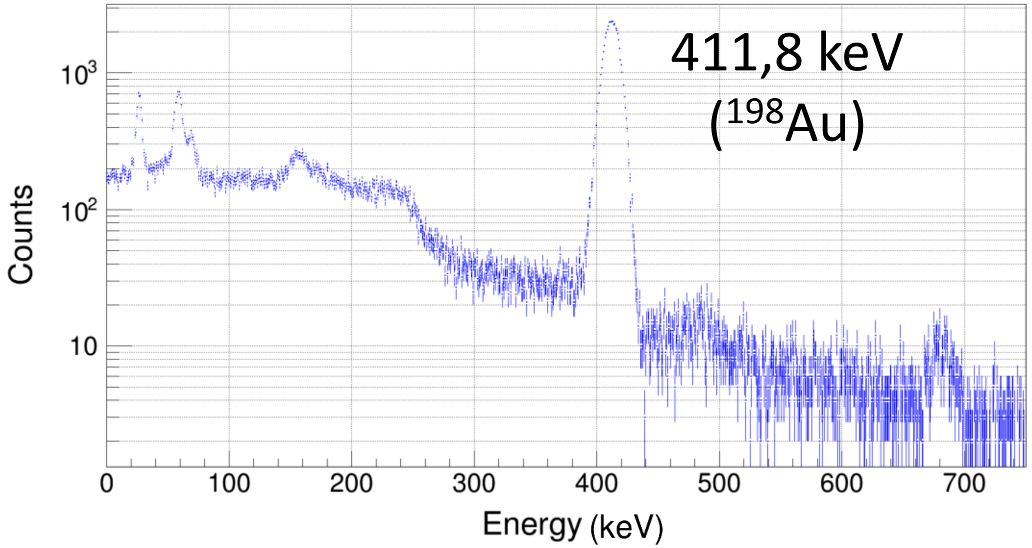
$$\sigma_{exp} = \frac{1}{n_{at}} \frac{N_{act}}{N_{neutrons}} = \frac{1}{n_{at}} \frac{N_{act}}{N_{act\ {}^7Be}}$$

$$\langle \sigma \rangle = \frac{\int \sigma(E_n) \Phi(E_n) dE_n}{\int \Phi(E_n)\, dE_n}$$

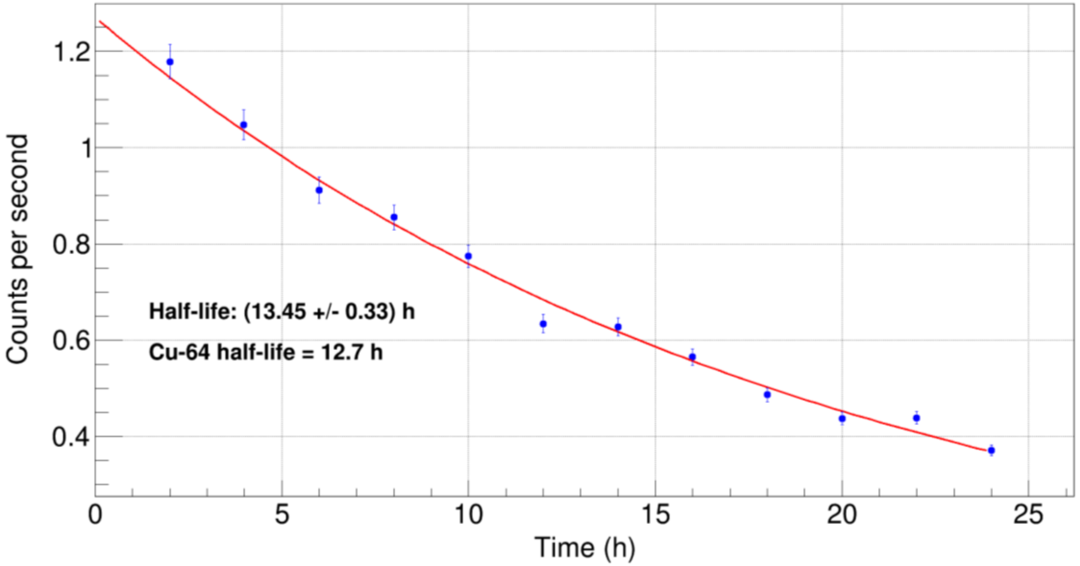
Backup. ^{50}Cr activation: preliminary results



Sources:
^{137}Cs, ^{22}Na, ^{133}Ba, ^{152}Eu ^{60}Co

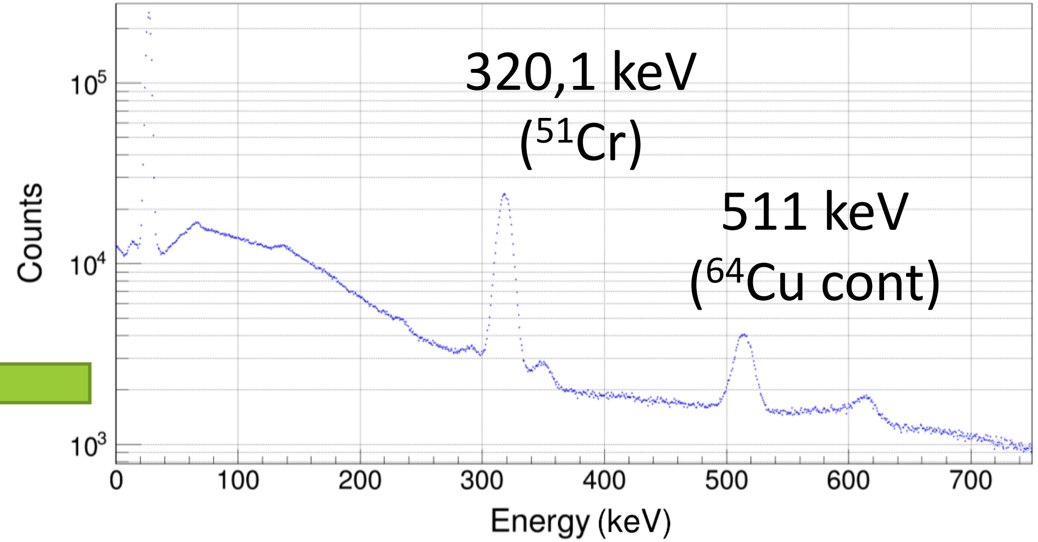


411,8 keV (^{198}Au)



Half-life: (13.45 +/- 0.33) h

Cu-64 half-life = 12.7 h



320,1 keV (^{51}Cr)

511 keV (^{64}Cu cont)