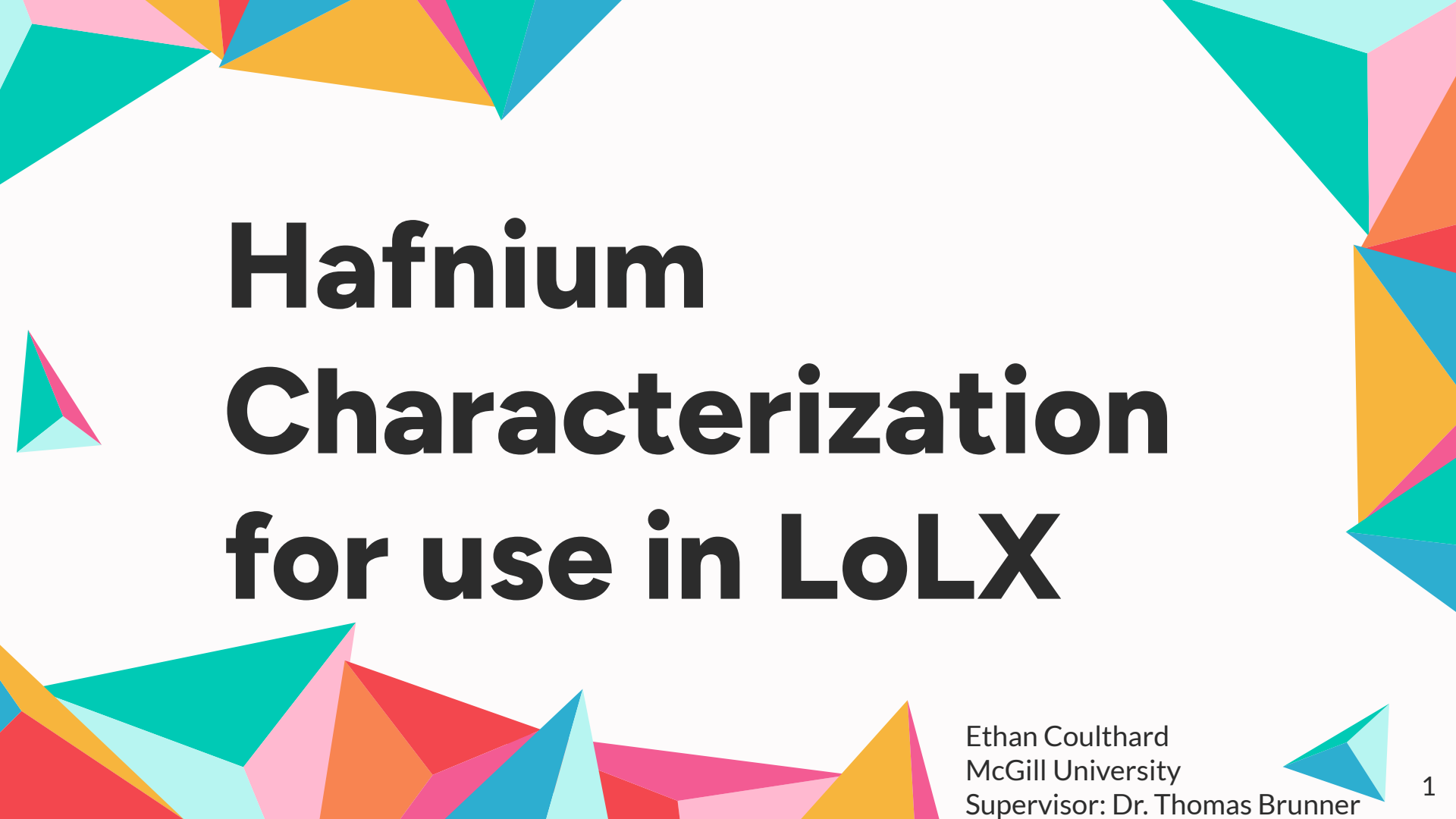




Hafnium Characterization for use in LoLX

Ethan Coulthard
McGill University
Supervisor: Dr. Thomas Brunner



Who am I?

(Former) Undergraduate from the university of Calgary

Working with Dr. Thomas Brunner at McGill over the summer under a NSERC USRA



UNIVERSITY OF
CALGARY



McGill
UNIVERSITY

BVL

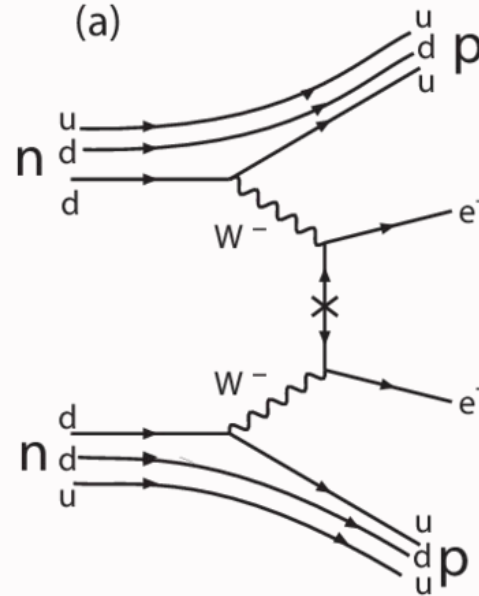


What is $0\nu\beta\beta$?

Proposed process where a double beta decays occurs without emitting a neutrino

Would violate lepton number conservation

We expect to see scintillation and electrons if double beta decays occur in certain media



a) Possible path for $0\nu\beta\beta$

Credit: Searches for Majorana neutrinos in β - decays
<https://doi.org/10.1103/PhysRevD.85.112004>

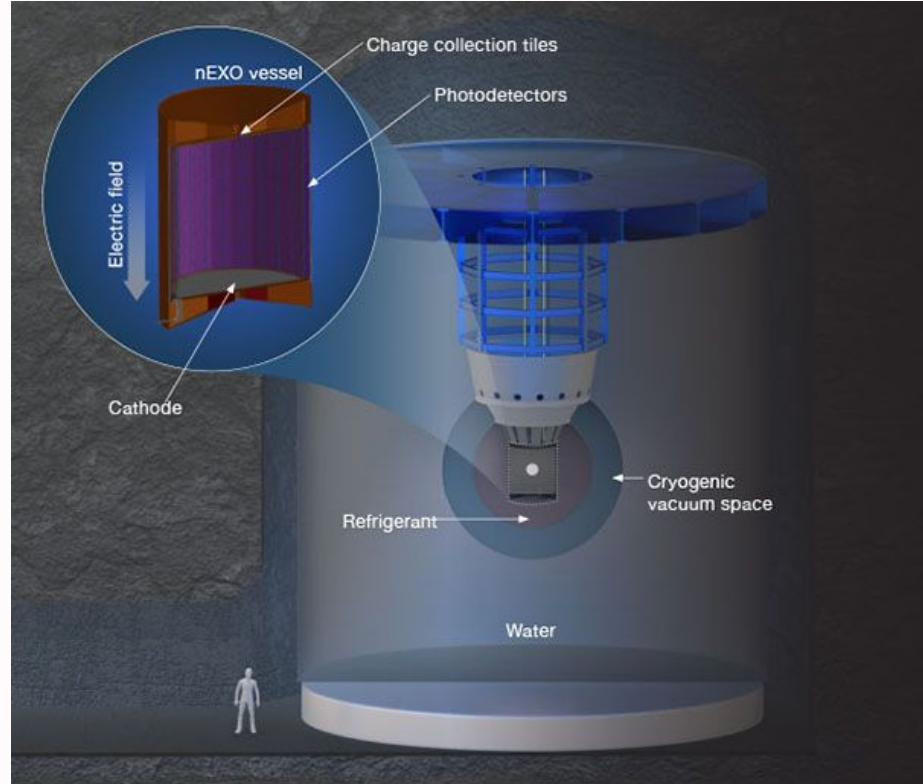
nEXO

(will be a) Ultra-Low background detector.

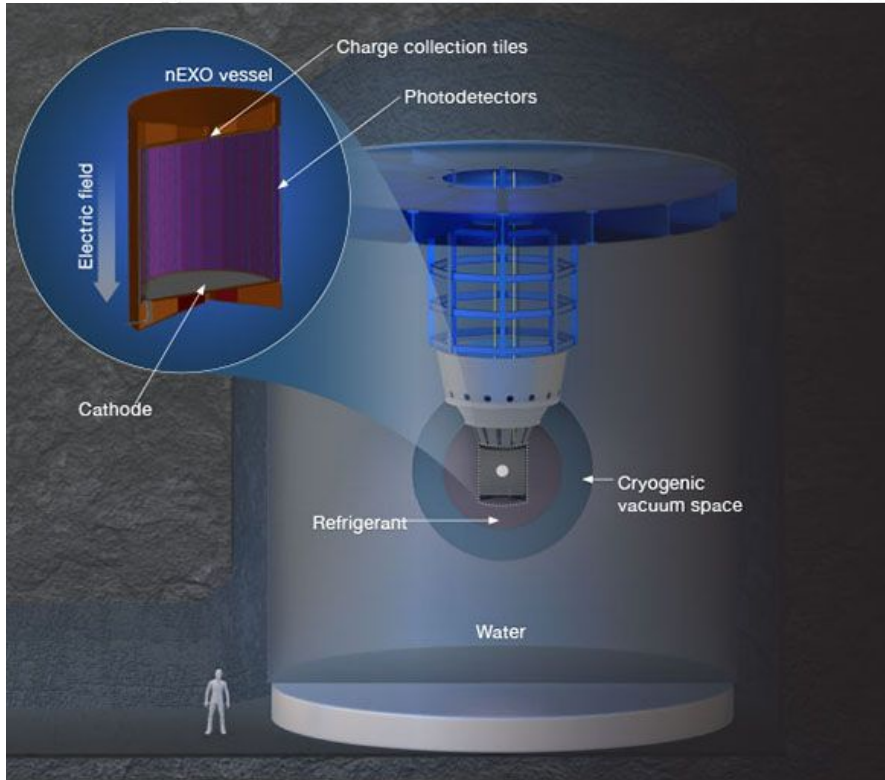
Sensitive to a projected half life of 10^{28} years.

2 ways to detect $0\nu\beta\beta$

- Light emission
- Charge collection

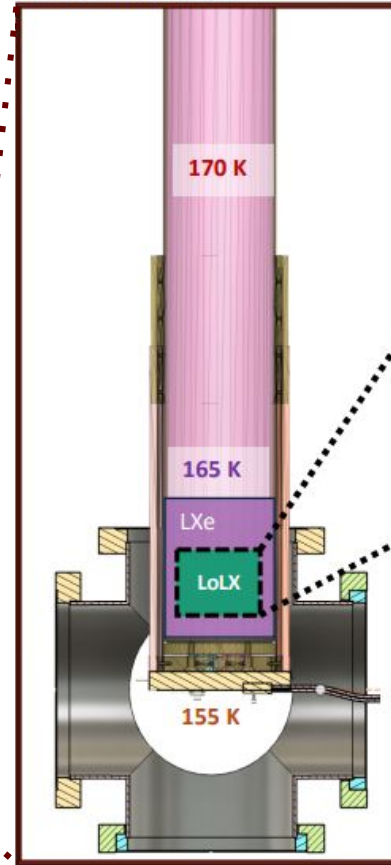


nEXO: 40-50k SiPMs



nEXO Experiment.
Credit: <https://nexo.llnl.gov/nexo-overview>

The LoLX cryostat. Credit:
David Gallacher



Size comparison. Credit: Sandhya Rottoo

LoLX: 80 SiPMs

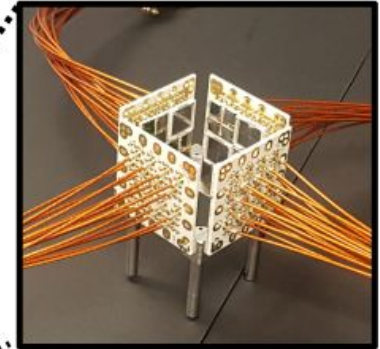


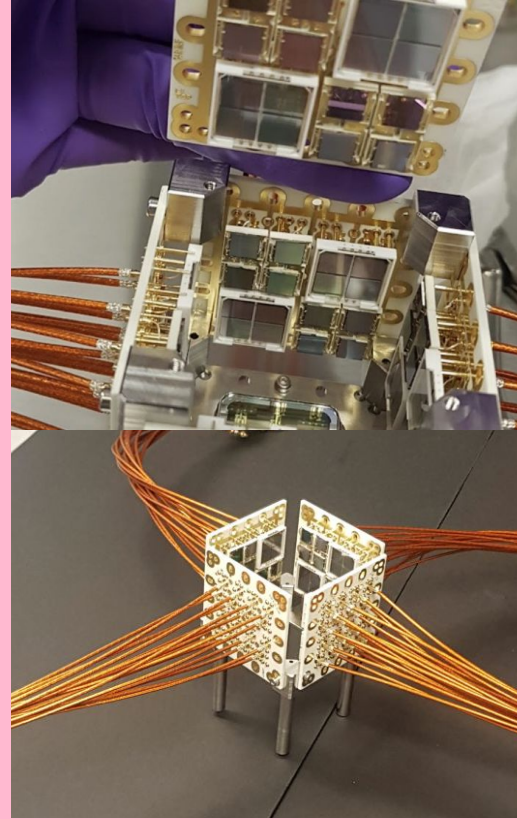
Photo: Stéphanie Bron

LoLX

Small detector with silicon photomultiplier (SiPM) walls filled with liquid xenon.

Studies

- Scintillation
- Cherenkov Emissions
- SiPMs



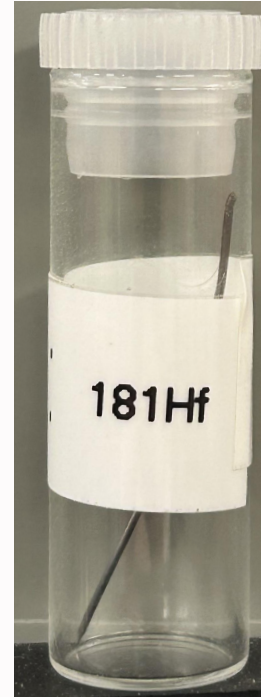
The Source

Neutron rich isotope of hafnium
(Hf 181)

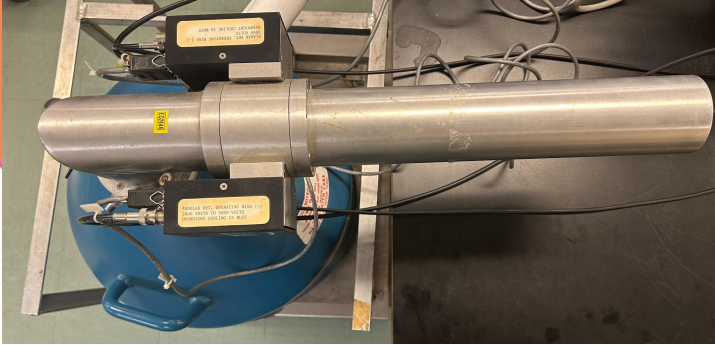
Emits gamma radiation

Will be use to study SiPMs:

- Light yield
- Energy resolution



High Purity Germanium Detector



A large bias is put across the Germanium crystal. (Roughly 2 kV)

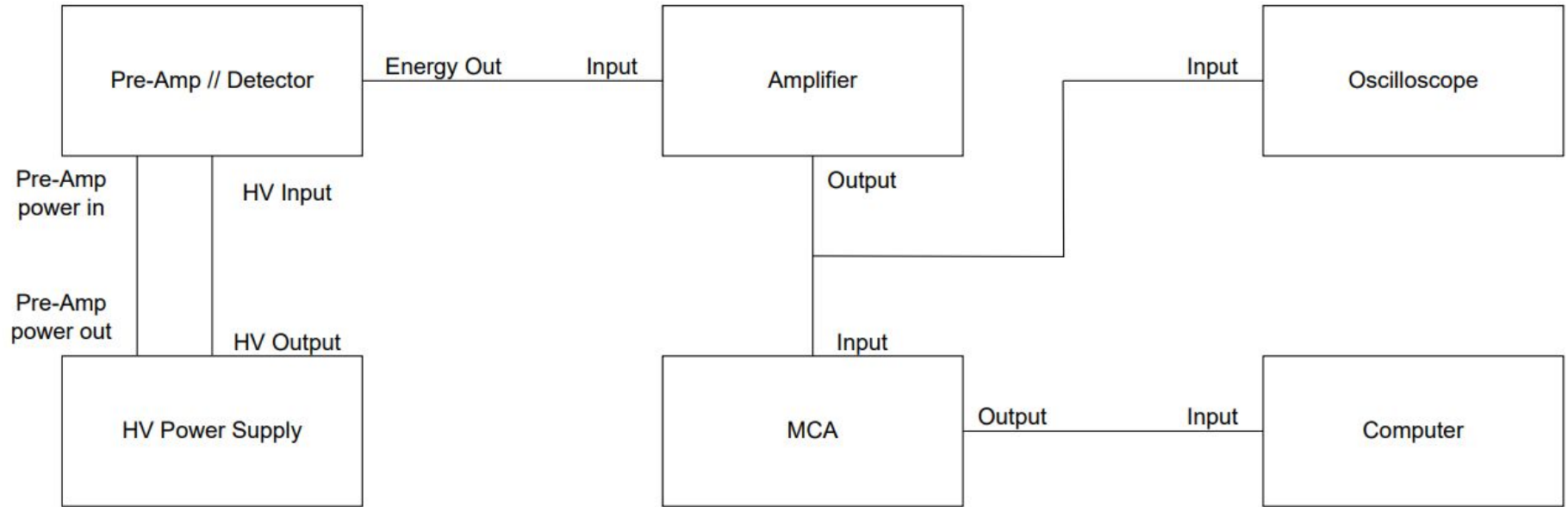


Gamma interactions create electron-hole pairs, which are measured, and their relative energy is plotted.

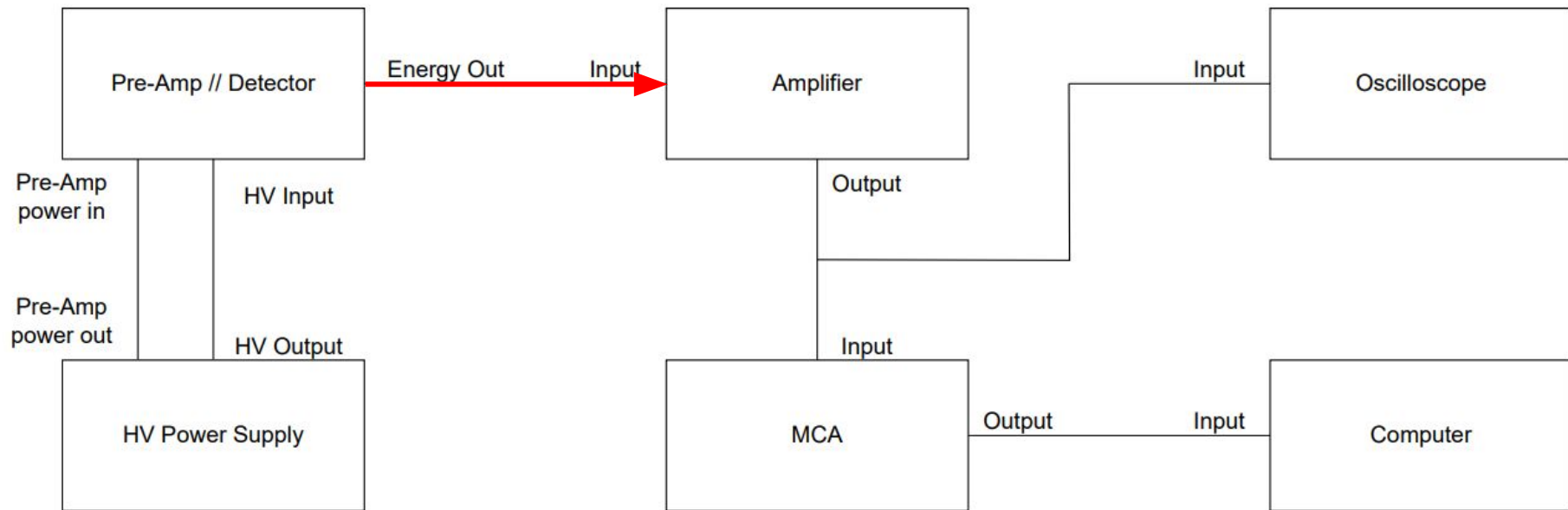
We expect $< 1\%$ Resolution



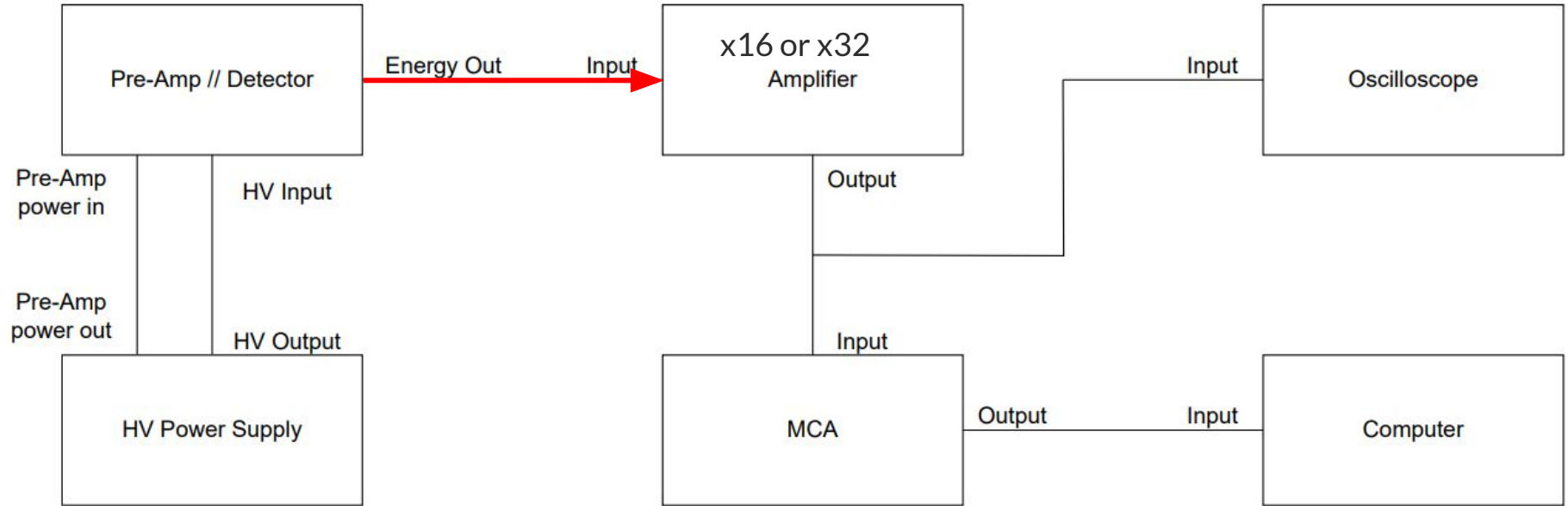
Wiring Diagram



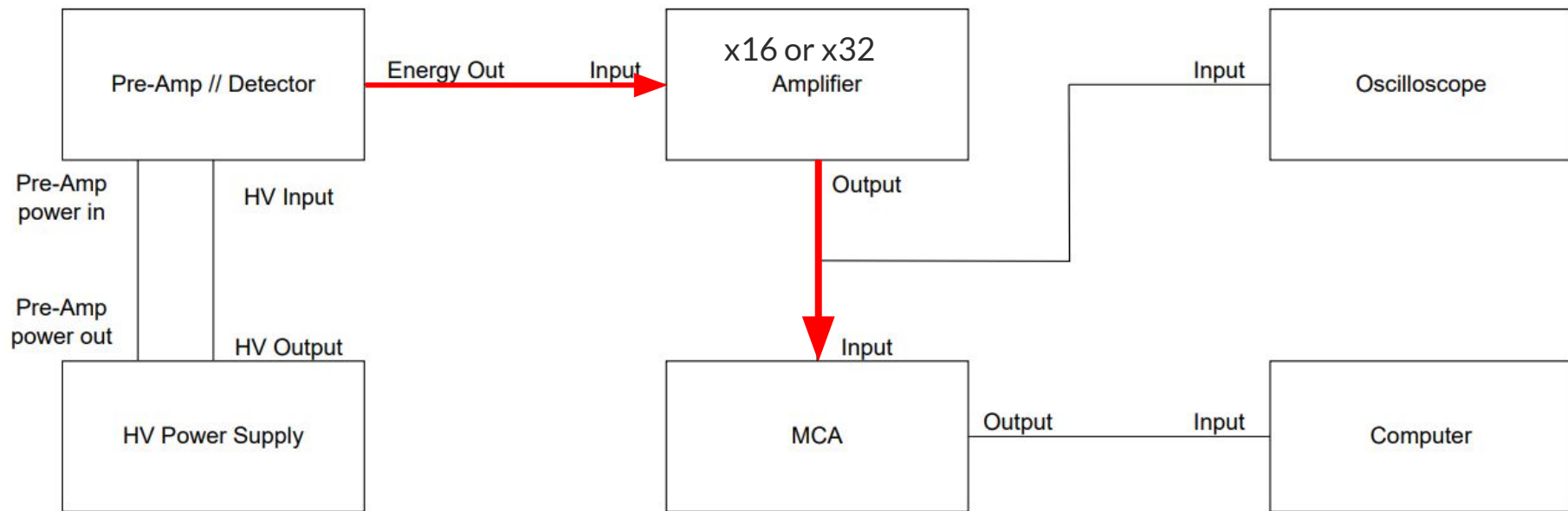
Wiring Diagram



Wiring Diagram

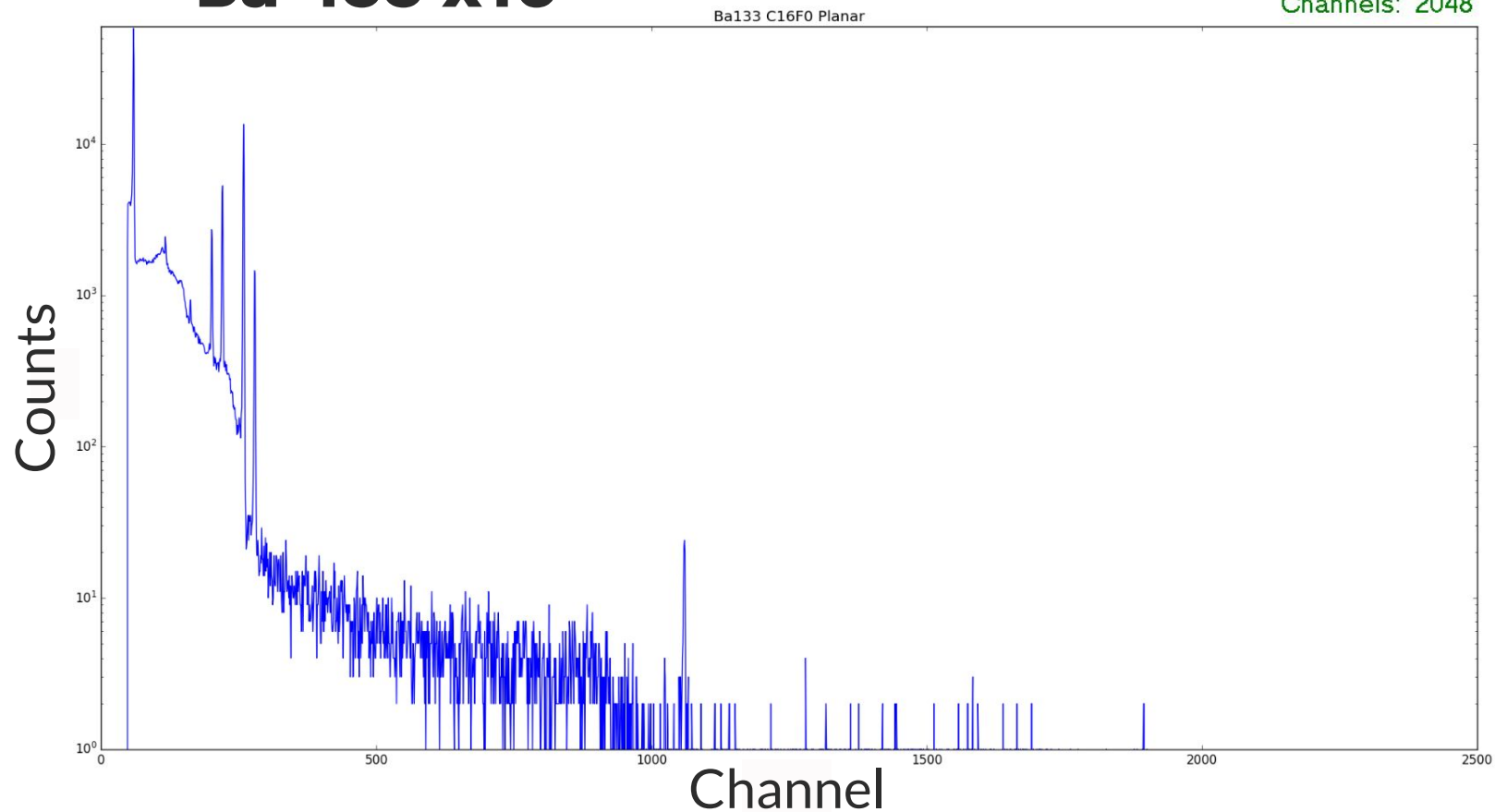


Wiring Diagram



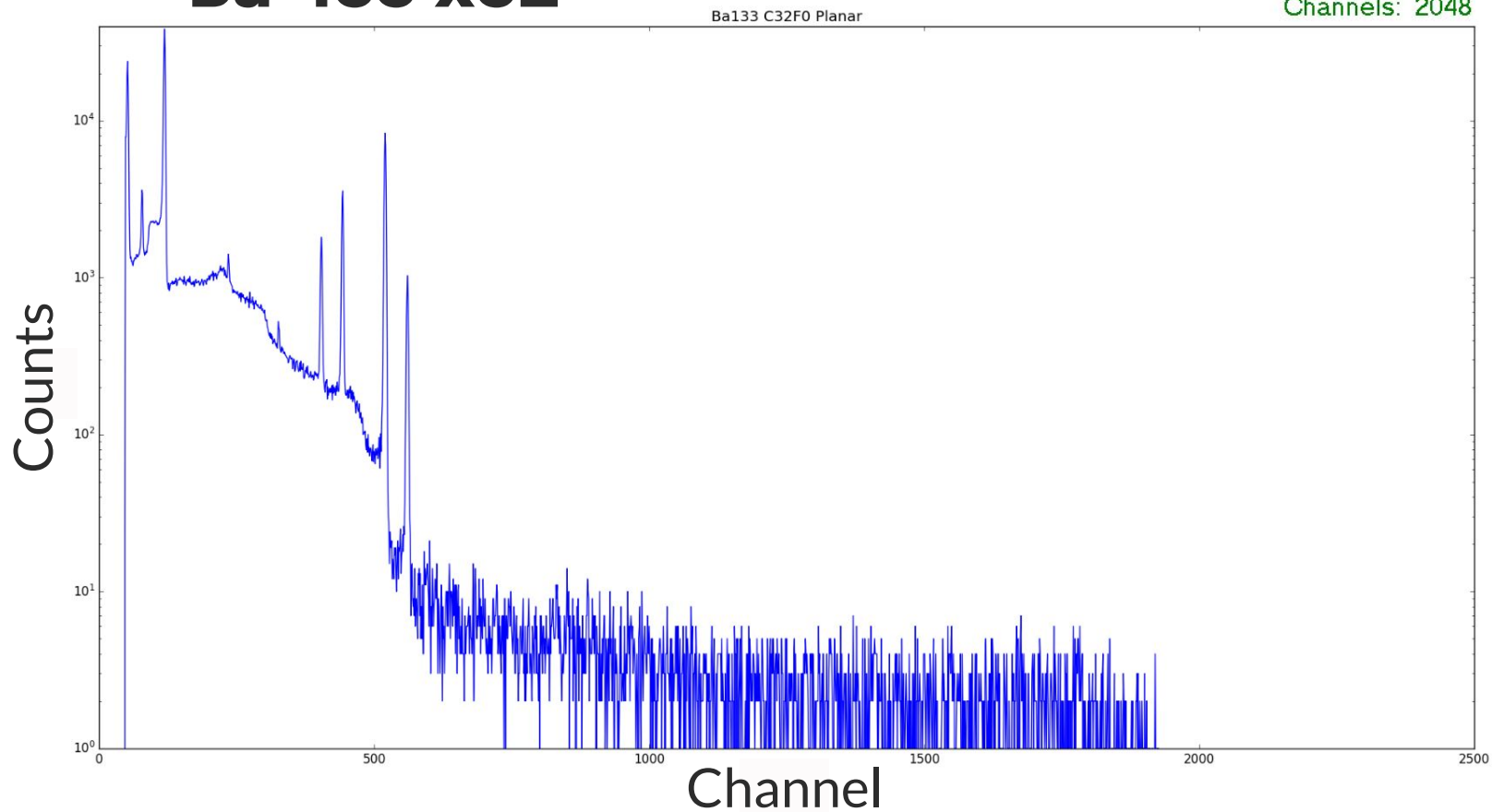
Ba-133 x16

Real Time: 1802.02 s. Live Time: 1800.00 s.
Channels: 2048



Ba-133 x32

Real Time: 2004.02 s. Live Time: 2000.00 s.
Channels: 2048

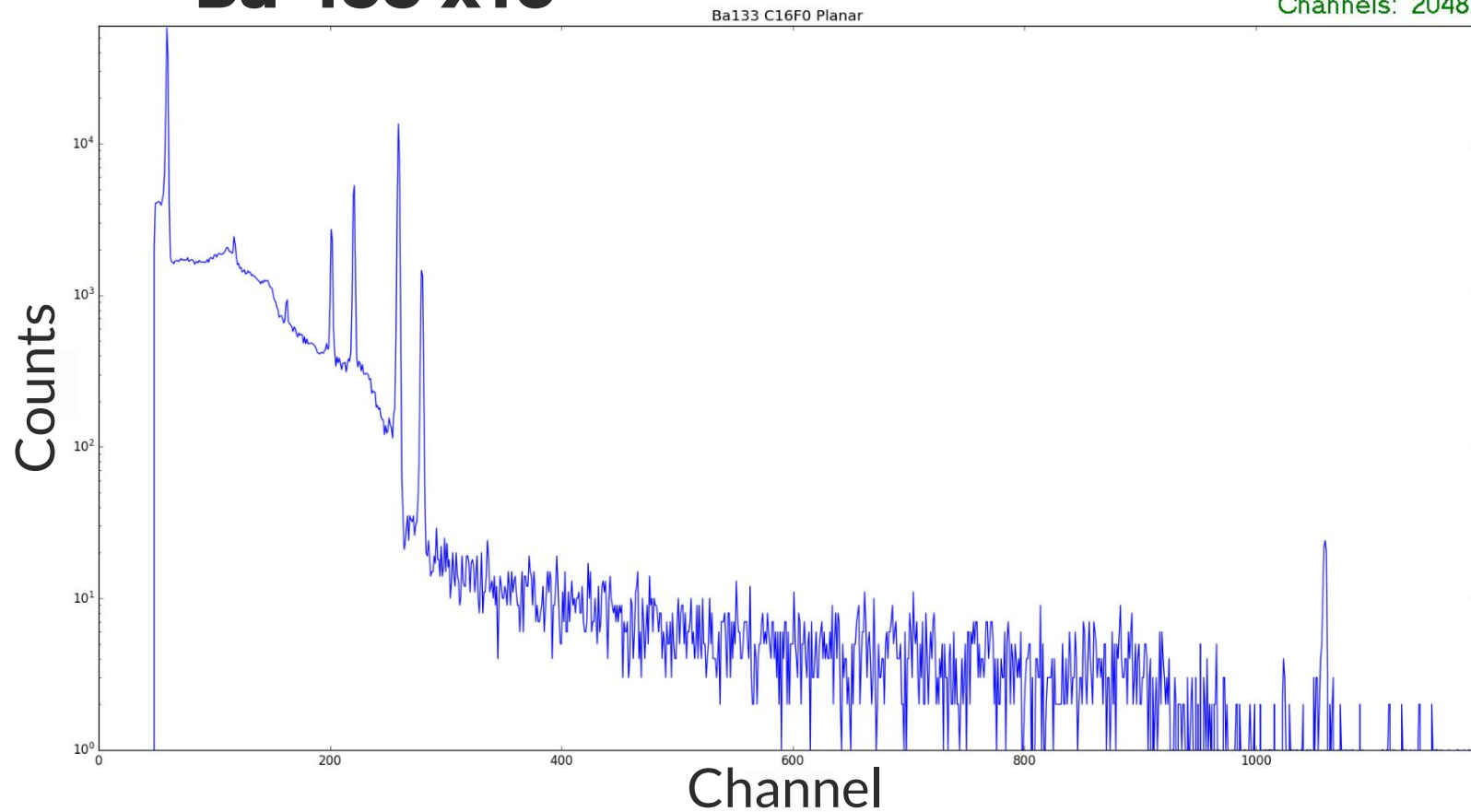




Fitting

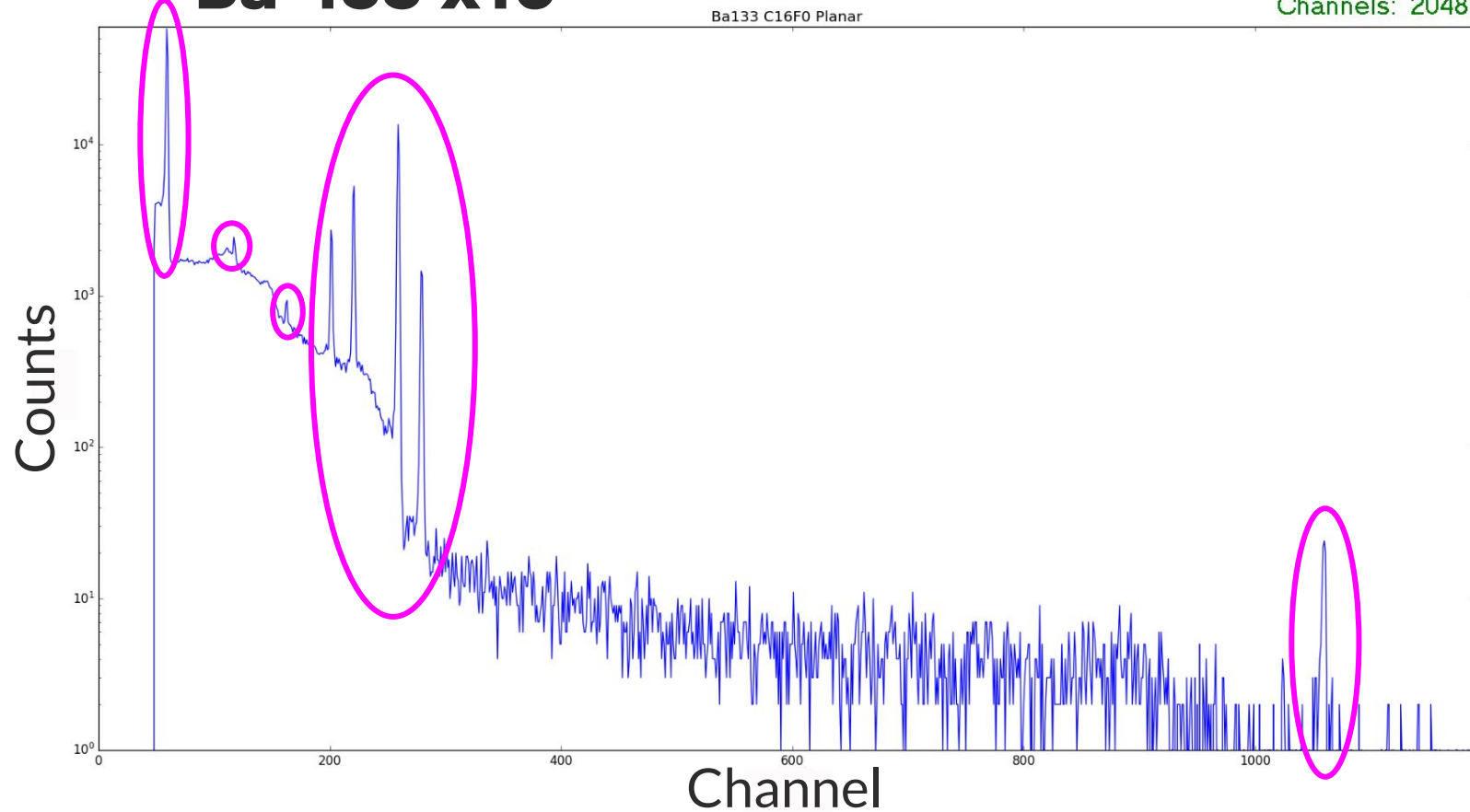
Ba-133 x16

Real Time: 1802.02 s. Live Time: 1800.00 s.
Channels: 2048



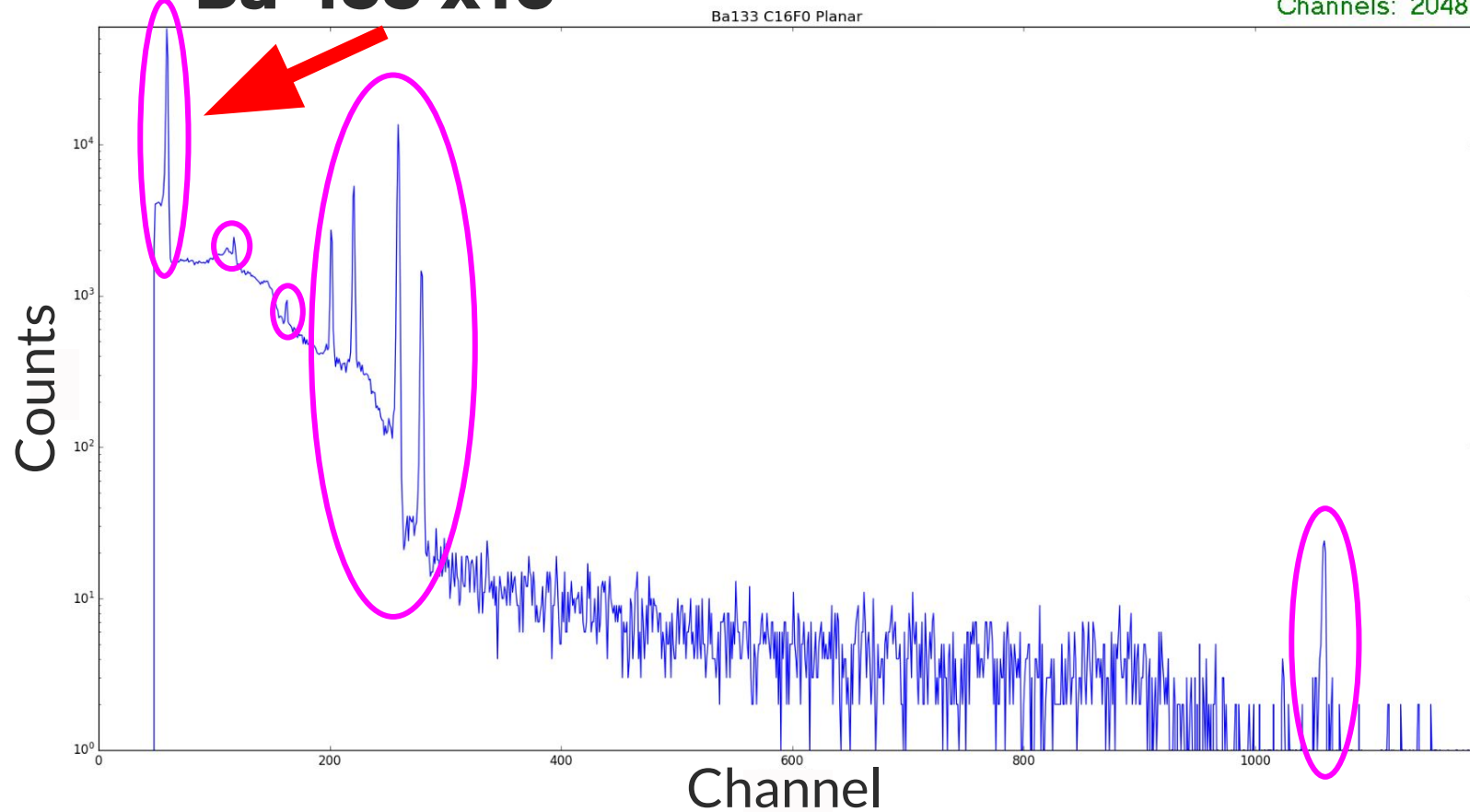
Ba-133 x16

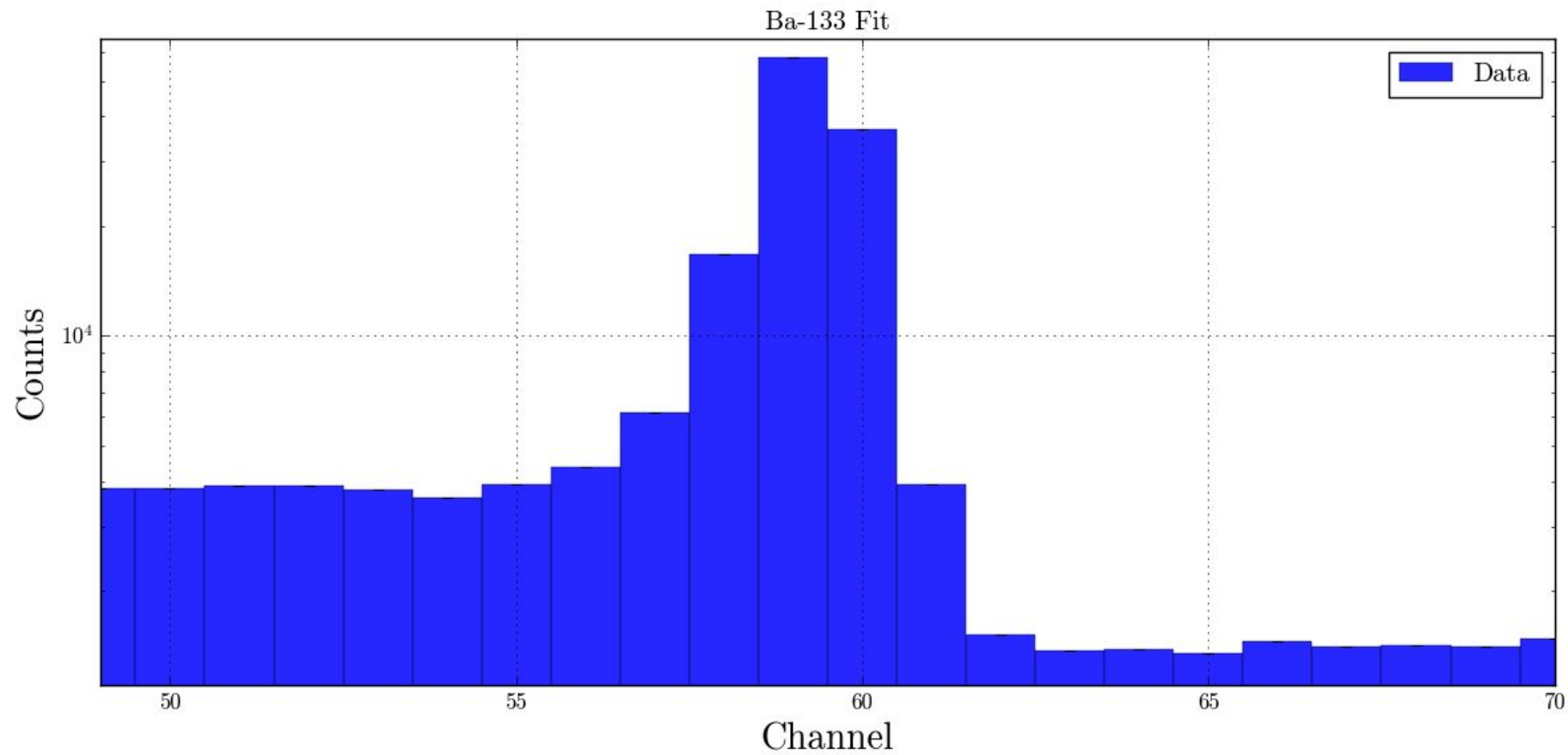
Real Time: 1802.02 s. Live Time: 1800.00 s.
Channels: 2048

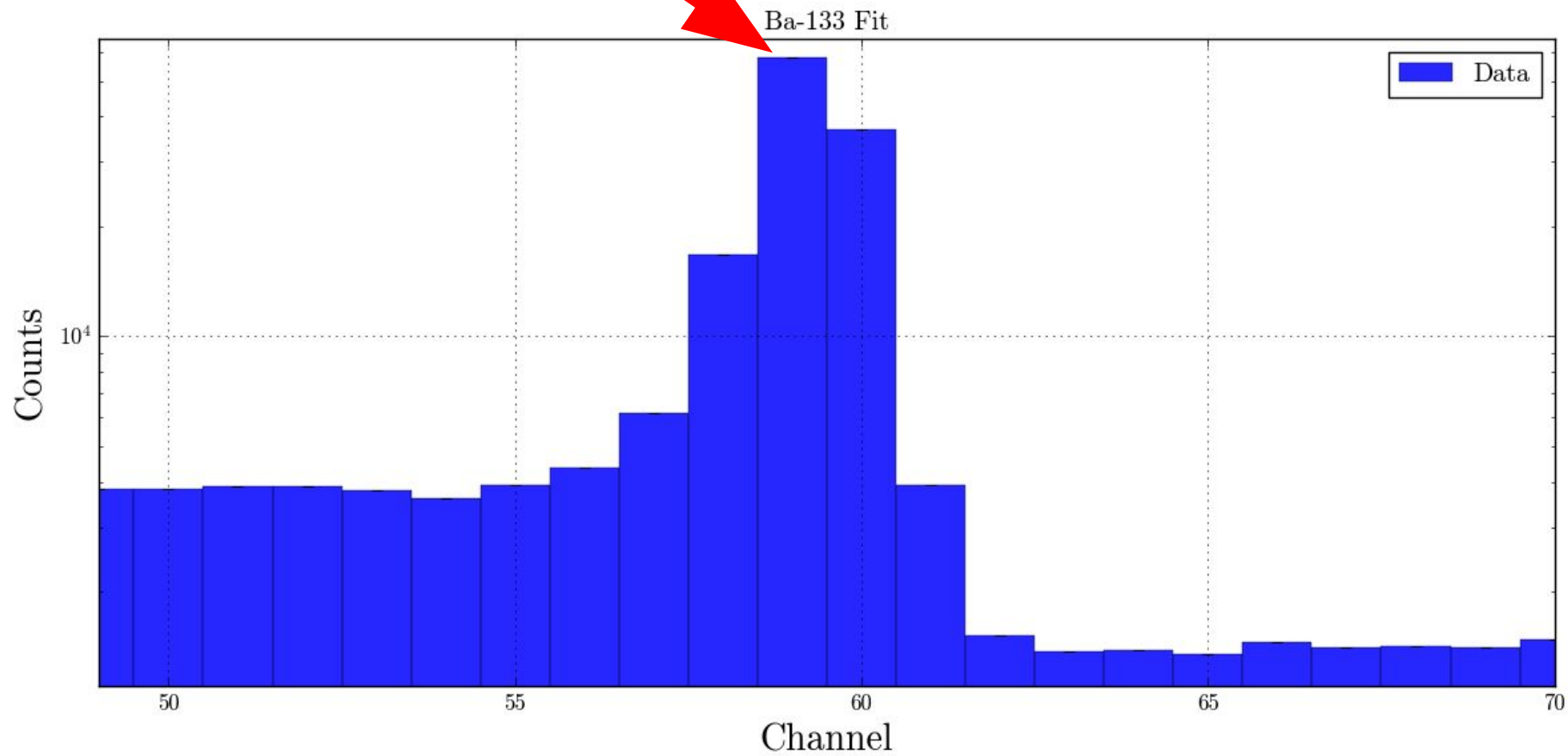


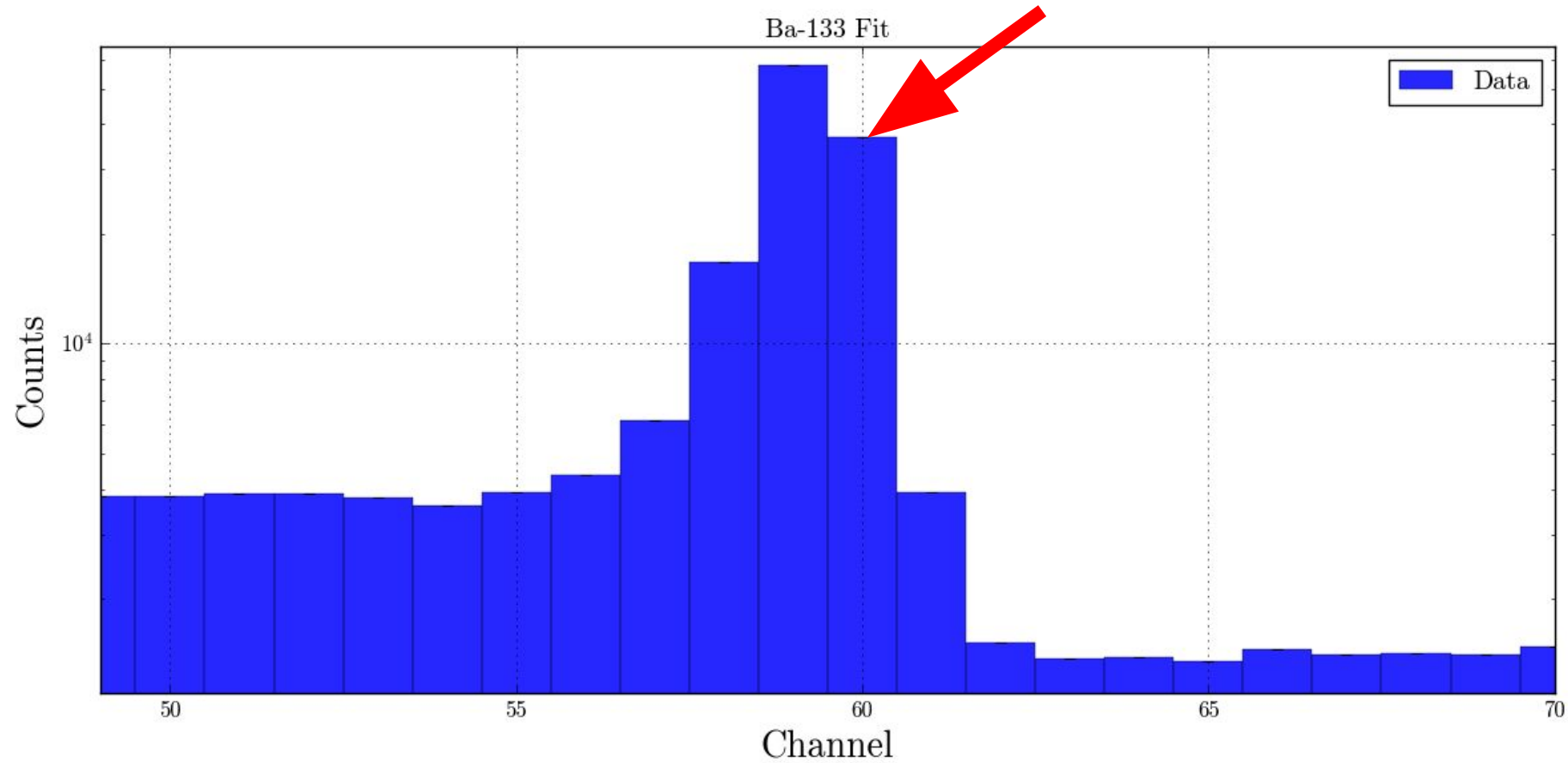
Ba-133 x16

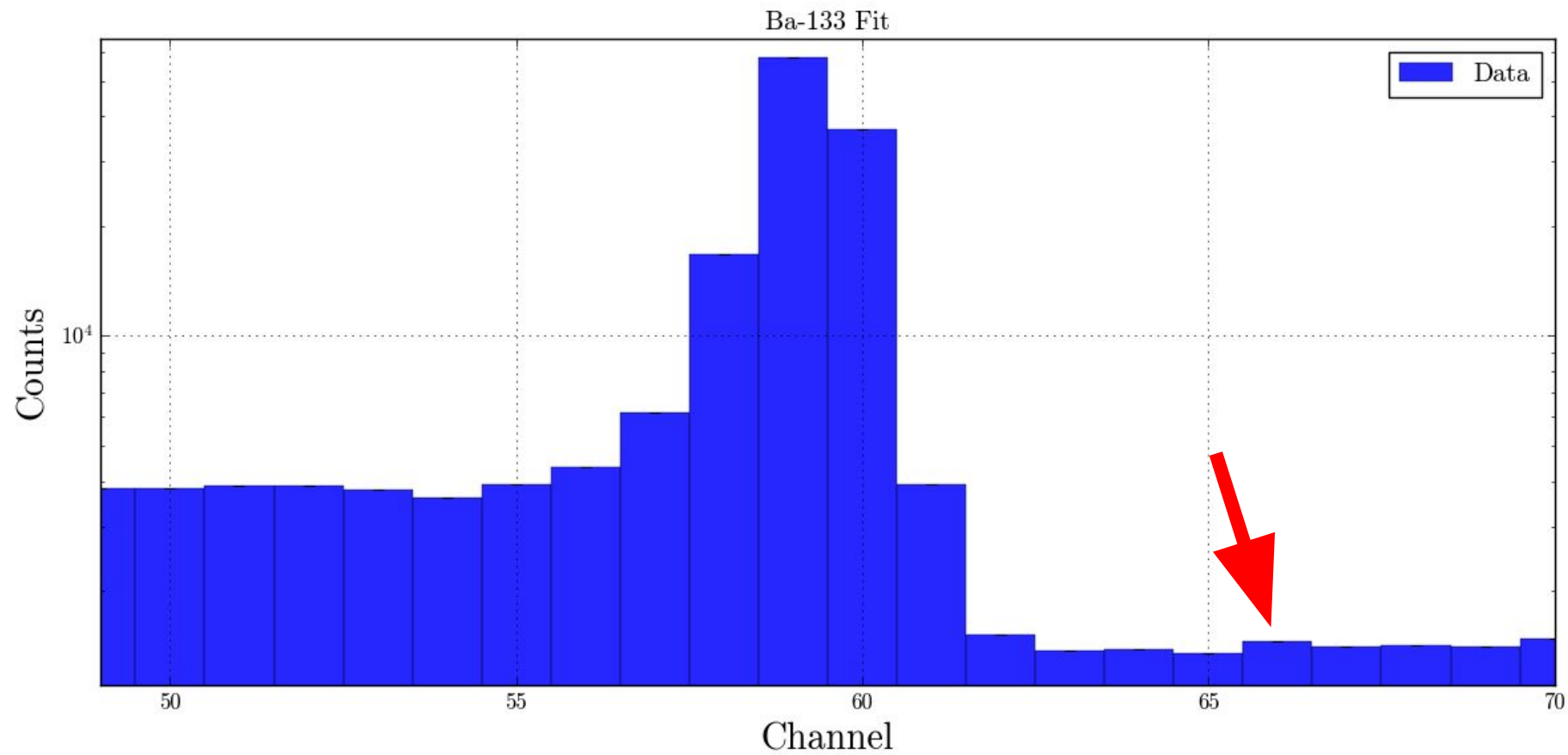
Real Time: 1802.02 s. Live Time: 1800.00 s.
Channels: 2048

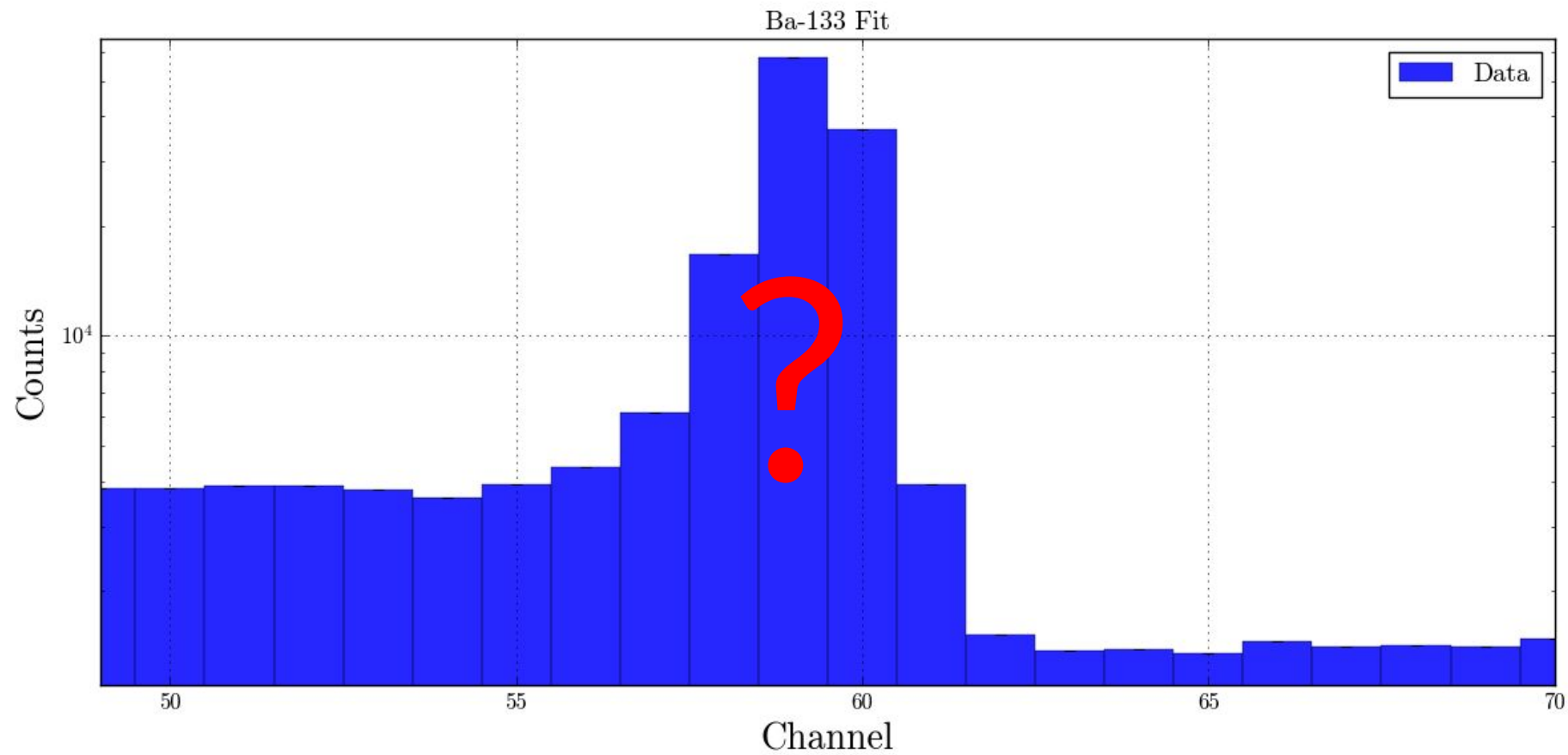


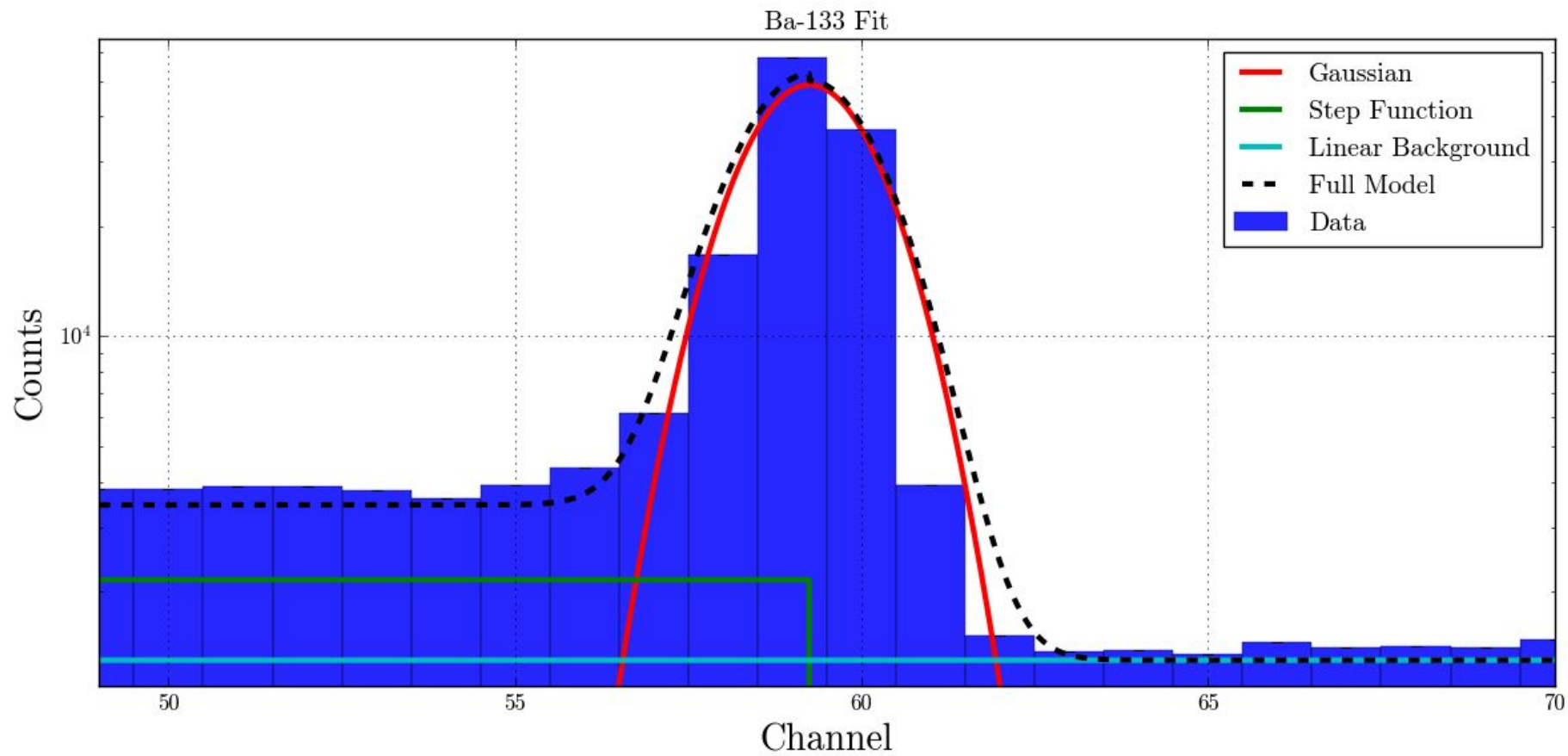


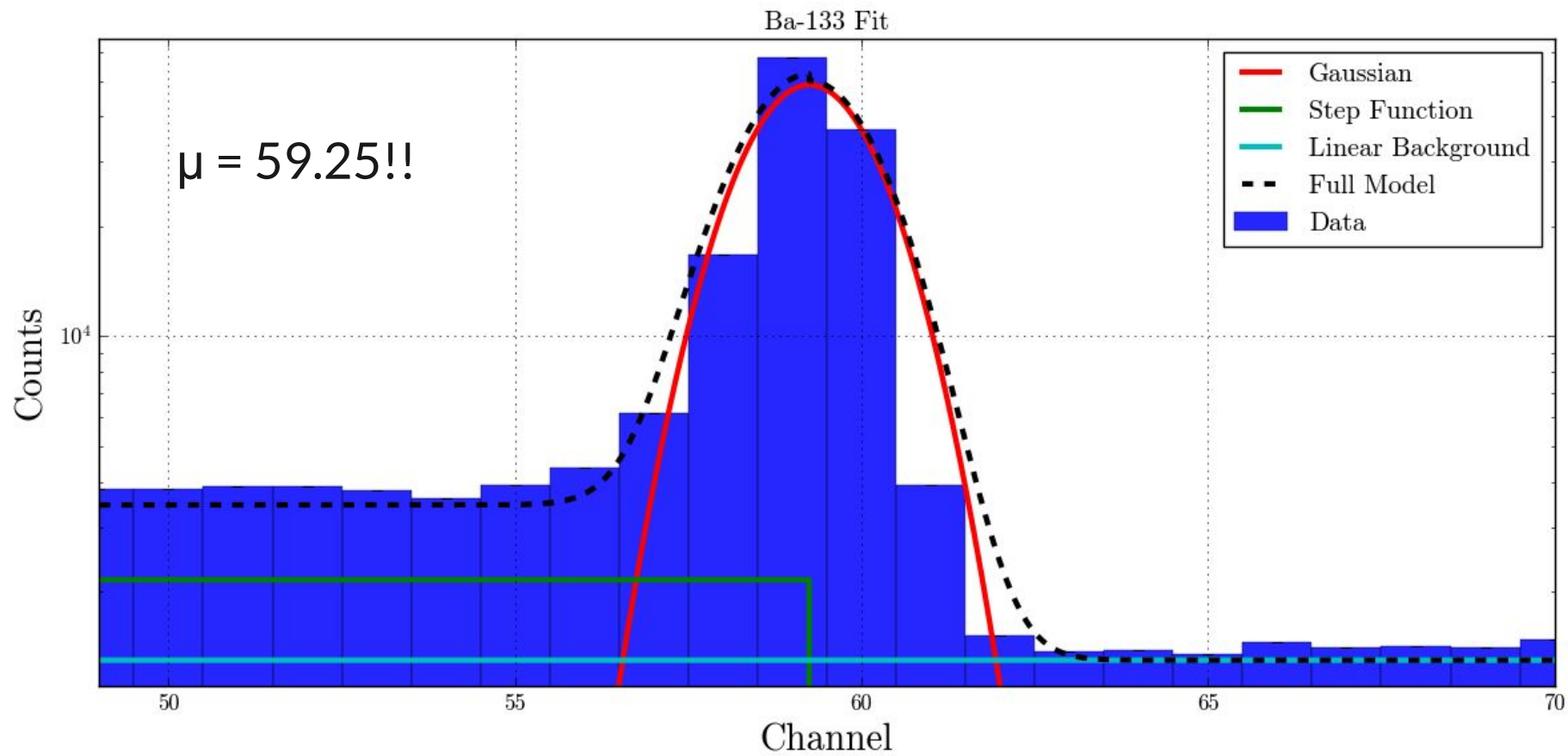










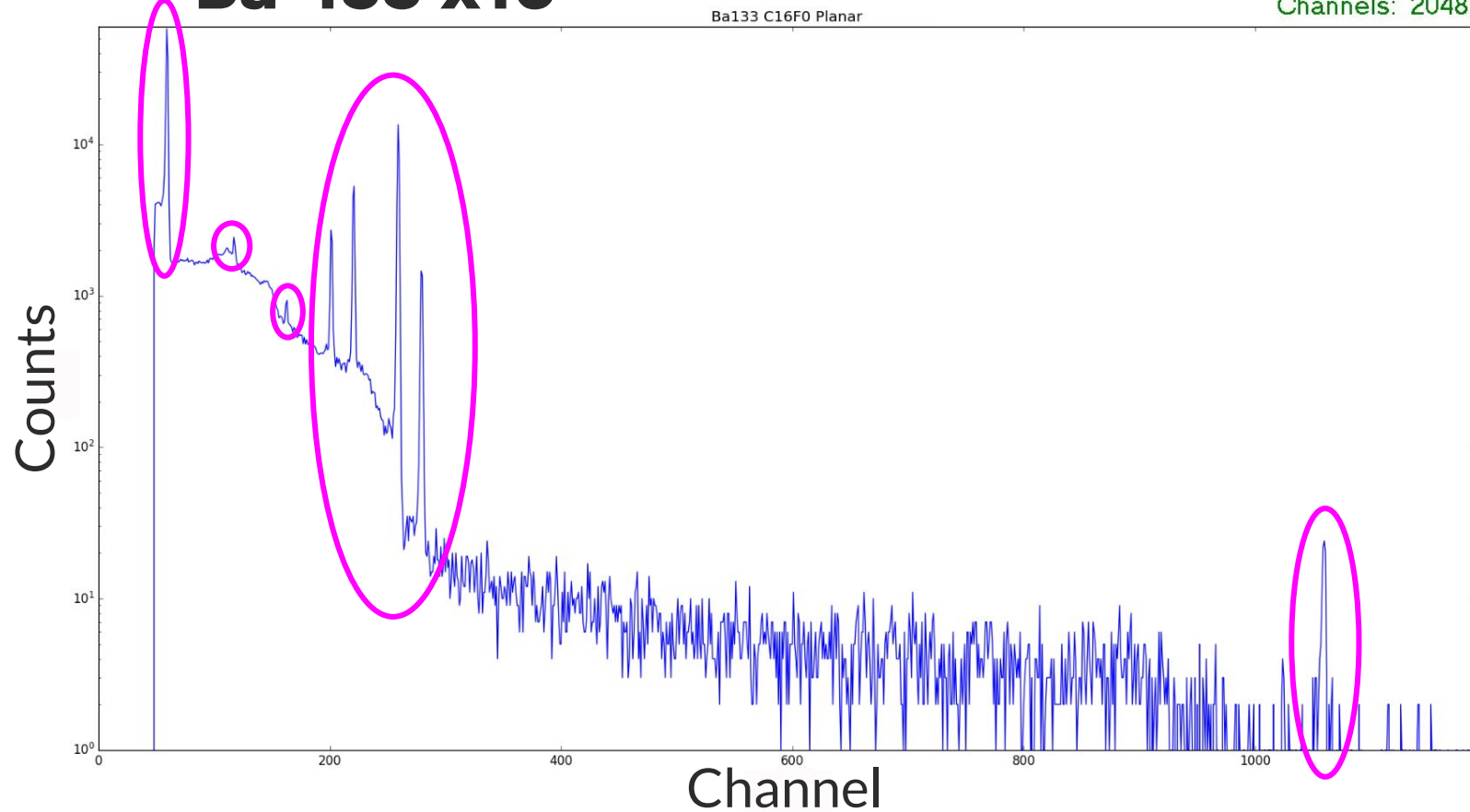




Calibration

Ba-133 x16

Real Time: 1802.02 s. Live Time: 1800.00 s.
Channels: 2048



Detector Calibration

Gamma



Data API

#	E_γ [keV]	I_γ (abs) [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	53.1622 6	2.14 3	437.0113 9	1/2+	383.8491	3/2+	M1+E2	0.08 3	5.66 10	14.3 3	
2	79.6142 12	2.65 5	160.6121 9	5/2+	80.9979	5/2+	M1+E2(+E0)	0.124 15	1.77 3	7.34 16	
3	80.9979 11	32.9 3	80.9979 8	5/2+	0.0	7/2+	M1+E2	0.158 5	1.703	89.1 12	
4	160.6120 16	0.638 5	160.6121 9	5/2+	0.0	7/2+	M1+E2	0.96 5	0.294 6	0.825 8	
5	223.2368 13	0.453 3	383.8491 8	3/2+	160.6121	5/2+	M1+E2	-0.114 14	0.0975	0.497 4	
6	276.3989 12	7.16 5	437.0113 9	1/2+	160.6121	5/2+	E2		0.0566	7.57 5	
7	302.8508 5	18.34 13	383.8491 8	3/2+	80.9979	5/2+	M1+E2	0.022 20	0.0434	19.13 13	
8	356.0129 7	62.05 19	437.0113 9	1/2+	80.9979	5/2+	E2		0.0254	63.63 20	
9	383.8485 12	8.94 6	383.8491 8	3/2+	0.0	7/2+	E2		0.0202	9.12 6	

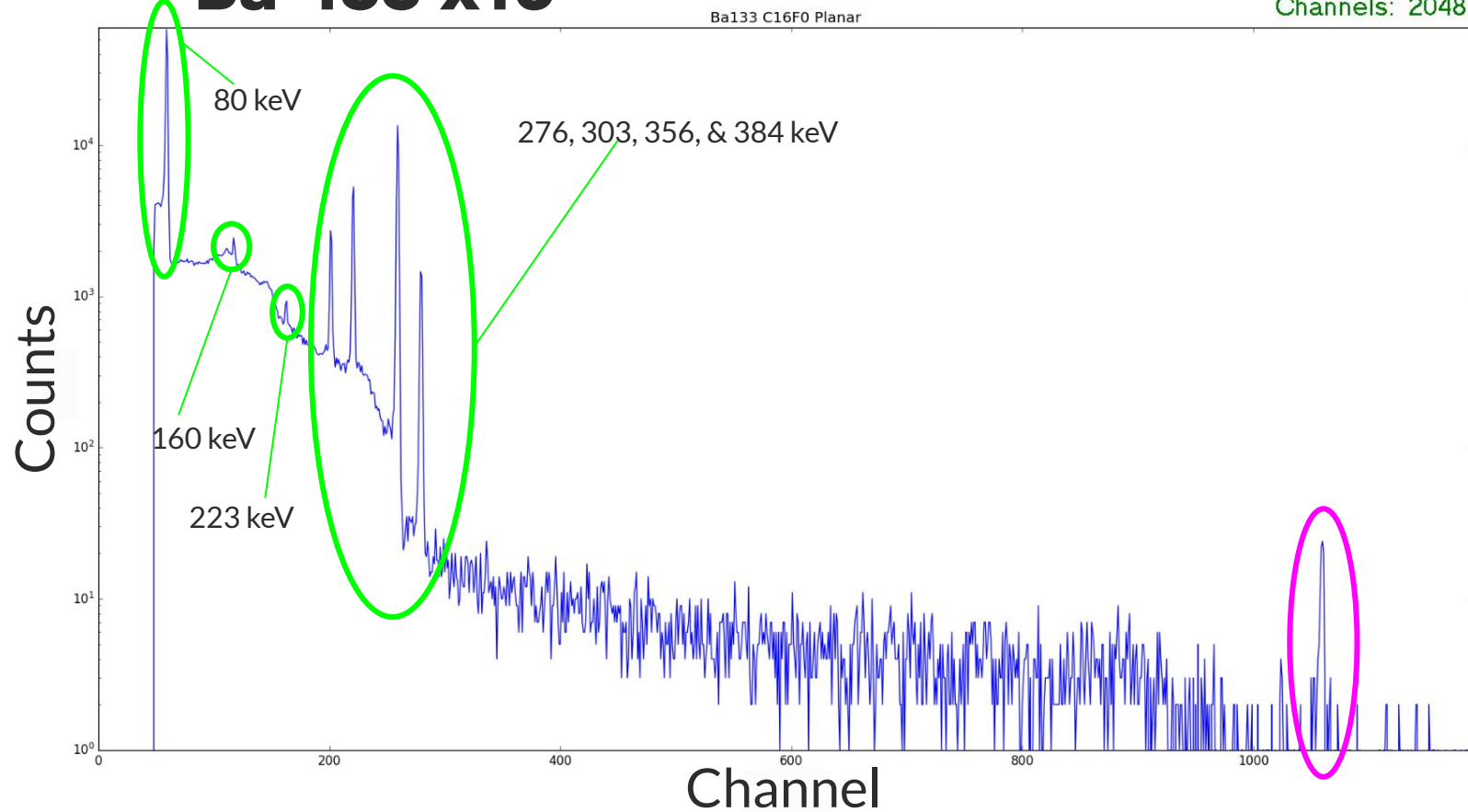
Credit: IAEA Table of nuclides

<https://www-nds.iaea.org/relnsd/vcharthtml/VChartHTML.html>

Ba-133 x16

Real Time: 1802.02 s. Live Time: 1800.00 s.

Channels: 2048

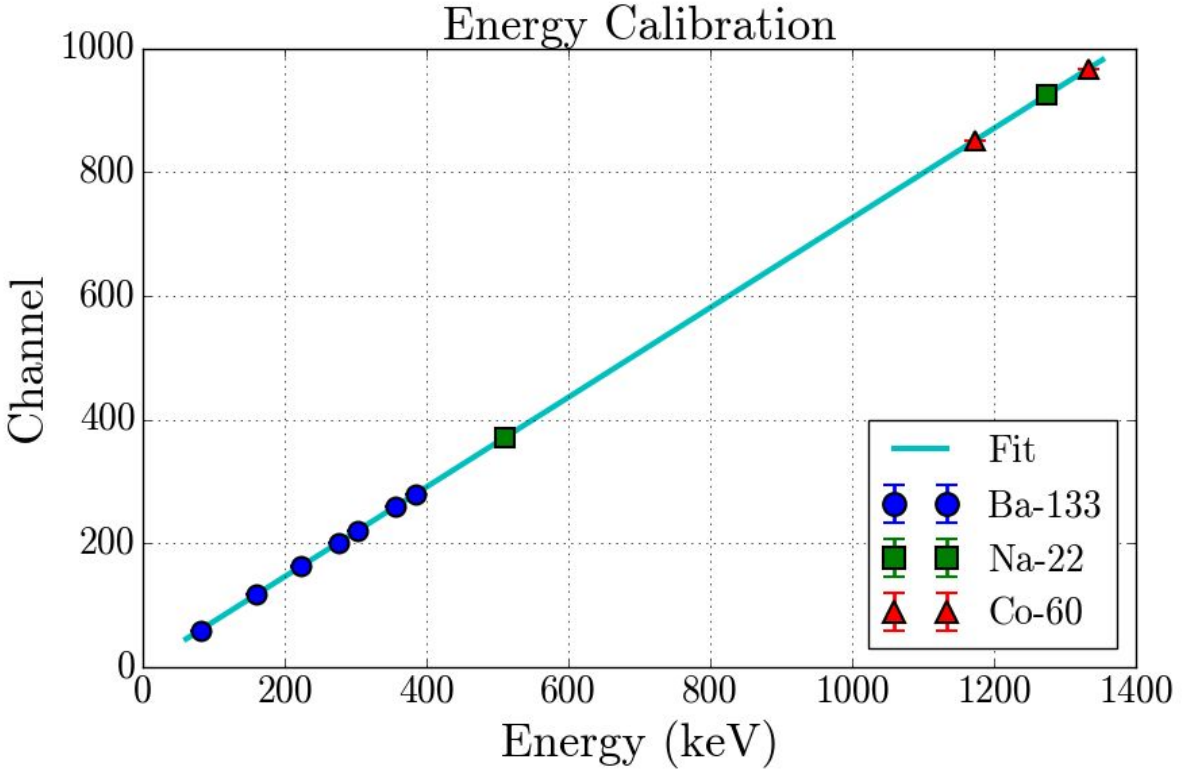




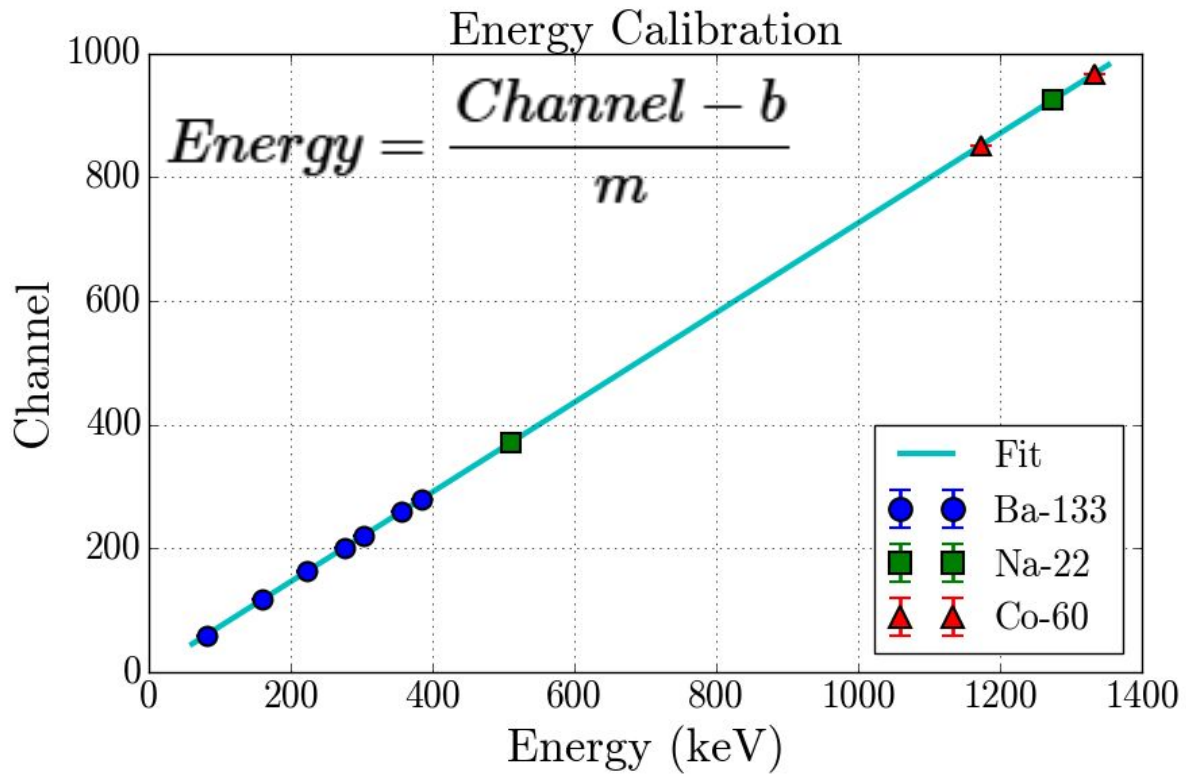
Isotope	Energy keV	Mean Channel
Ba-133	81.00	59.27
Ba-133	160.61	117.00
Ba-133	223.24	162.55
Ba-133	276.40	201.4
Ba-133	302.85	220.6
Ba-133	356.01	259.21
Ba-133	383.85	279.45
Na-22	511.00	371.63
Na-22	1274.50	924.00
Co-60	1173.20	851.51
Co-60	1332.50	966.88



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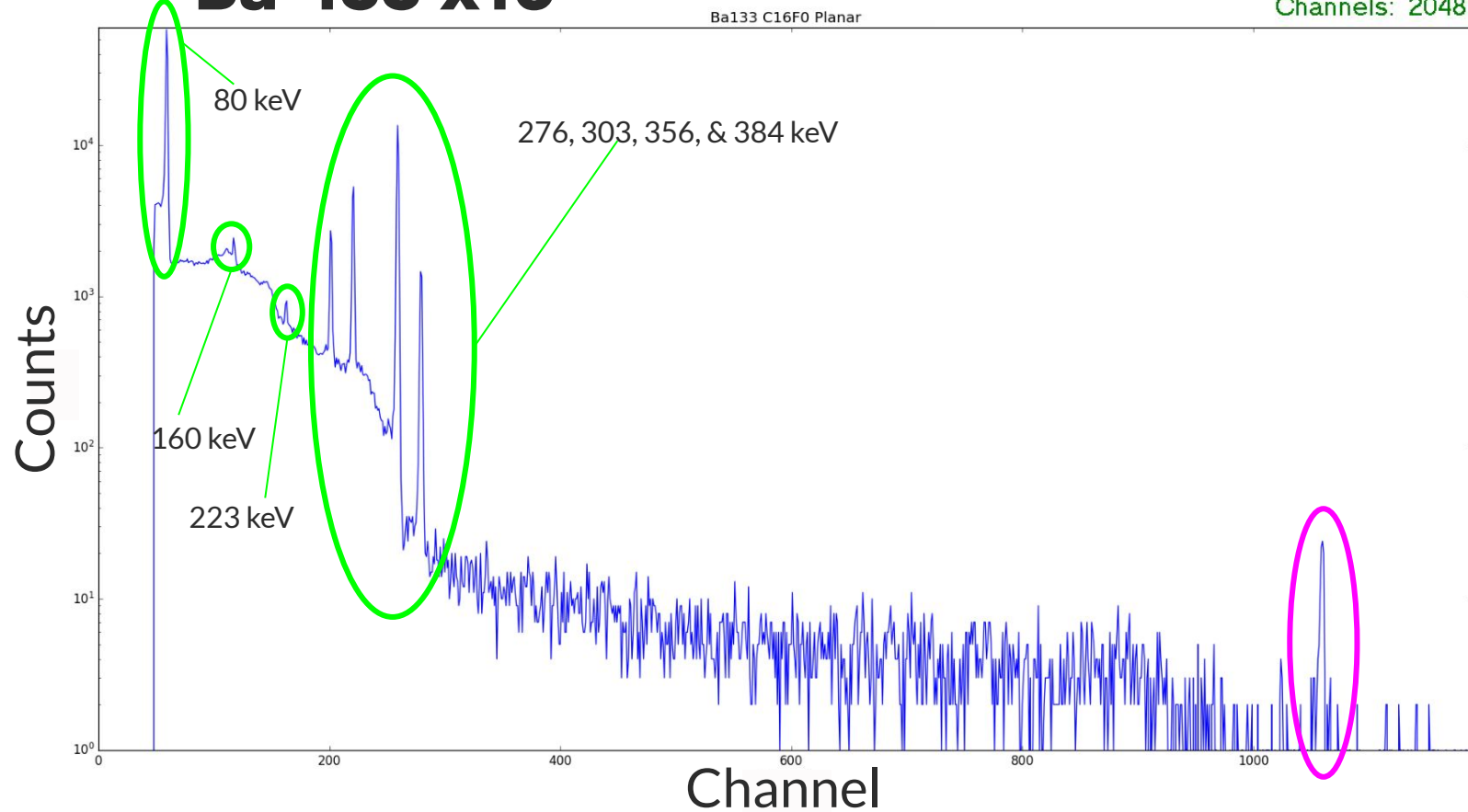
Isotope	Energy keV	Mean Channel
Ba-133	81.00	59.27
Ba-133	160.61	117.00
Ba-133	223.24	162.55
Ba-133	276.40	201.4
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Ba-133	356.01	259.21
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Na-22	511.00	371.63
Na-22	1274.50	924.00
Co-60	1173.20	851.51
Co-60	1332.50	966.88



Ba-133 x16

Real Time: 1802.02 s. Live Time: 1800.00 s.

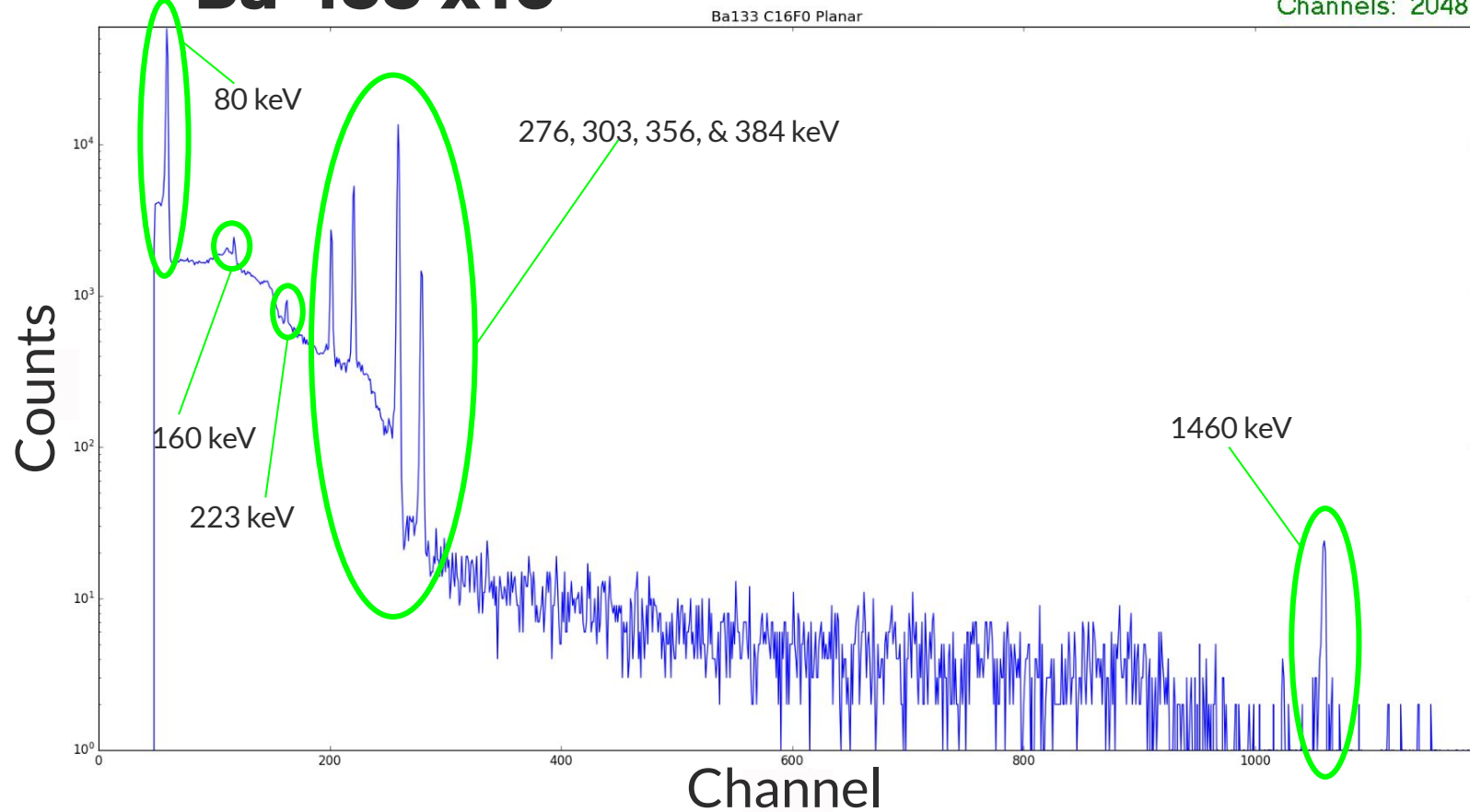
Channels: 2048



Ba-133 x16

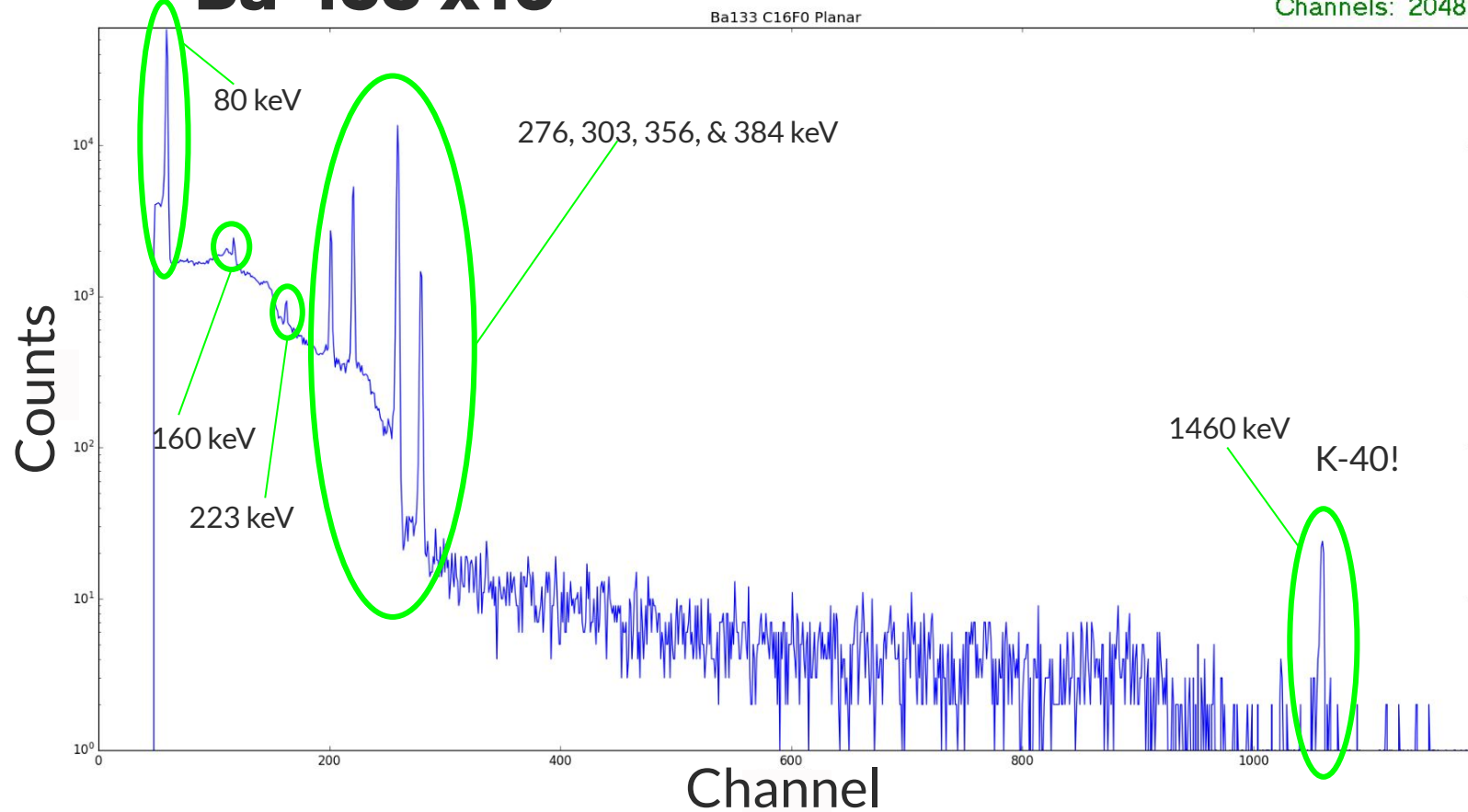
Real Time: 1802.02 s. Live Time: 1800.00 s.

Channels: 2048



Ba-133 x16

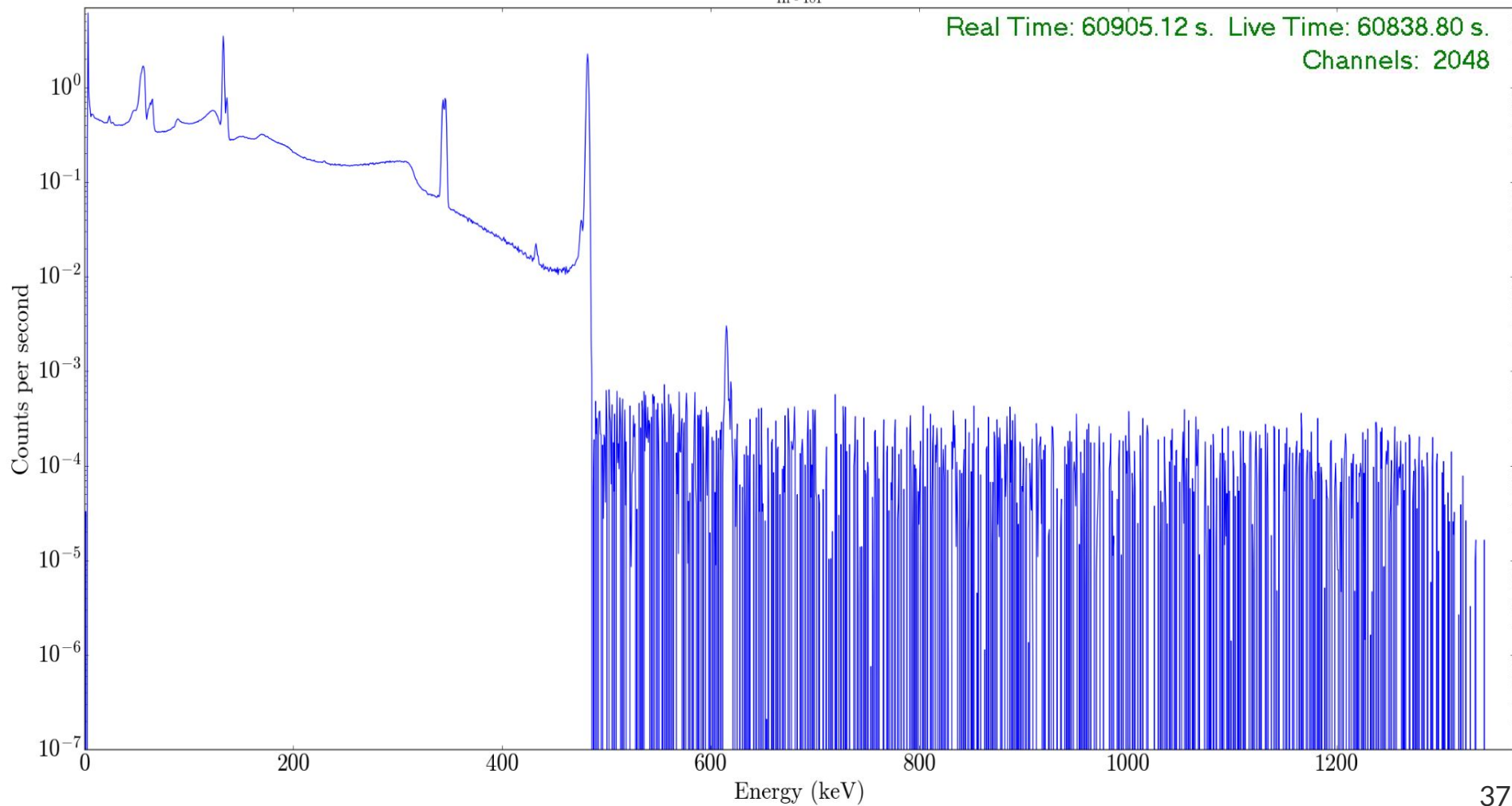
Real Time: 1802.02 s. Live Time: 1800.00 s.
Channels: 2048



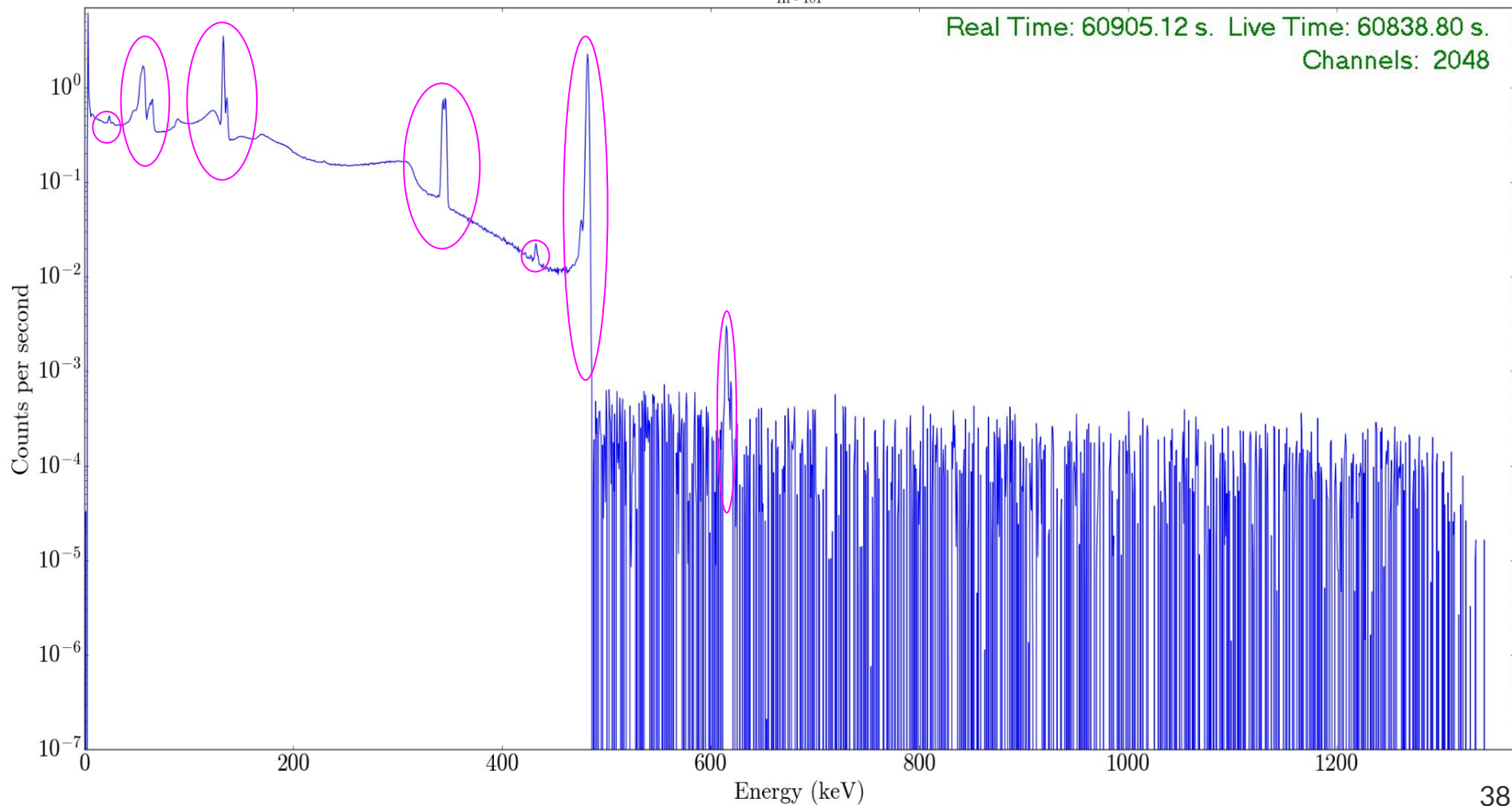


The Hafnium Wire

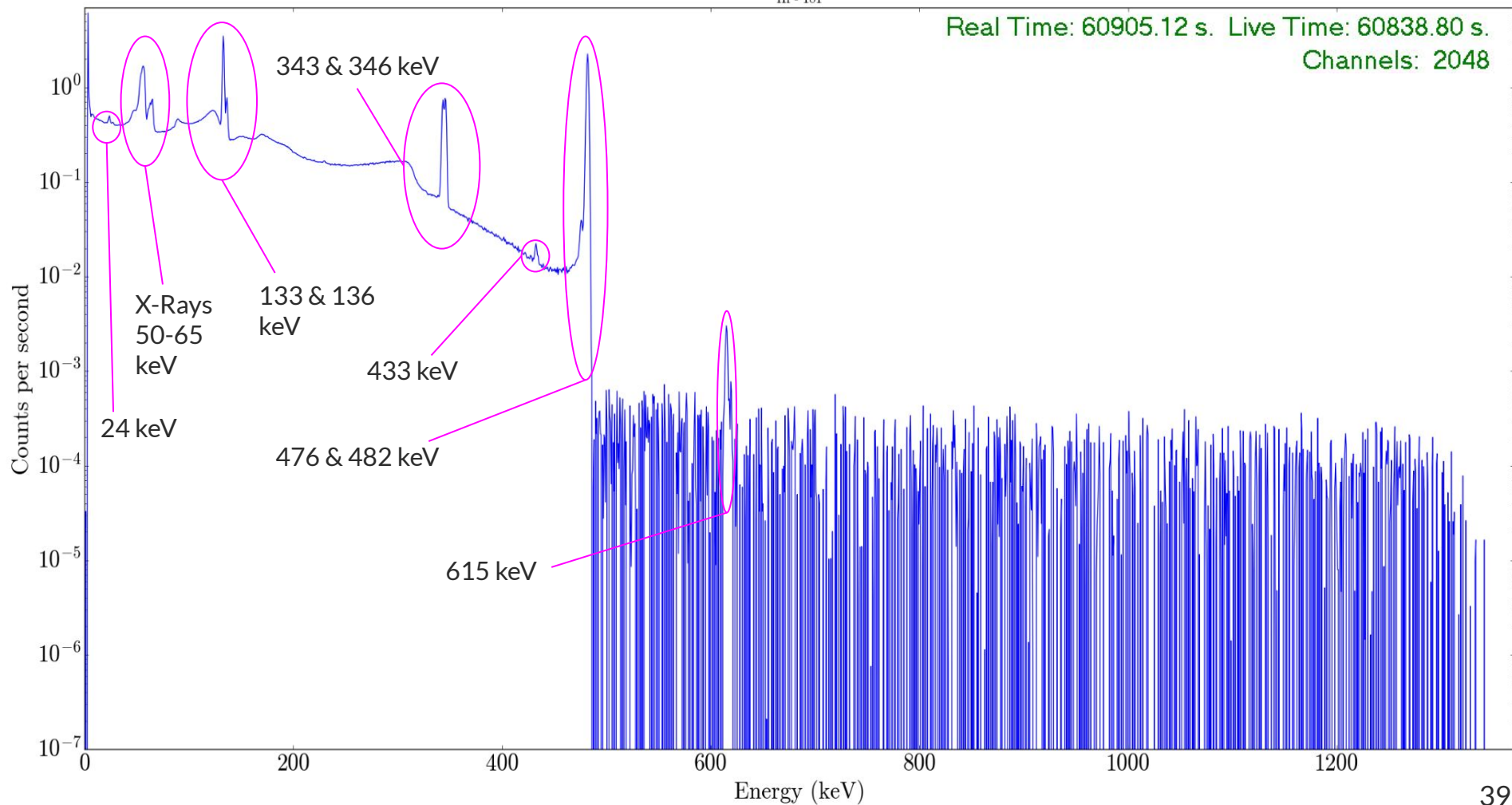
Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



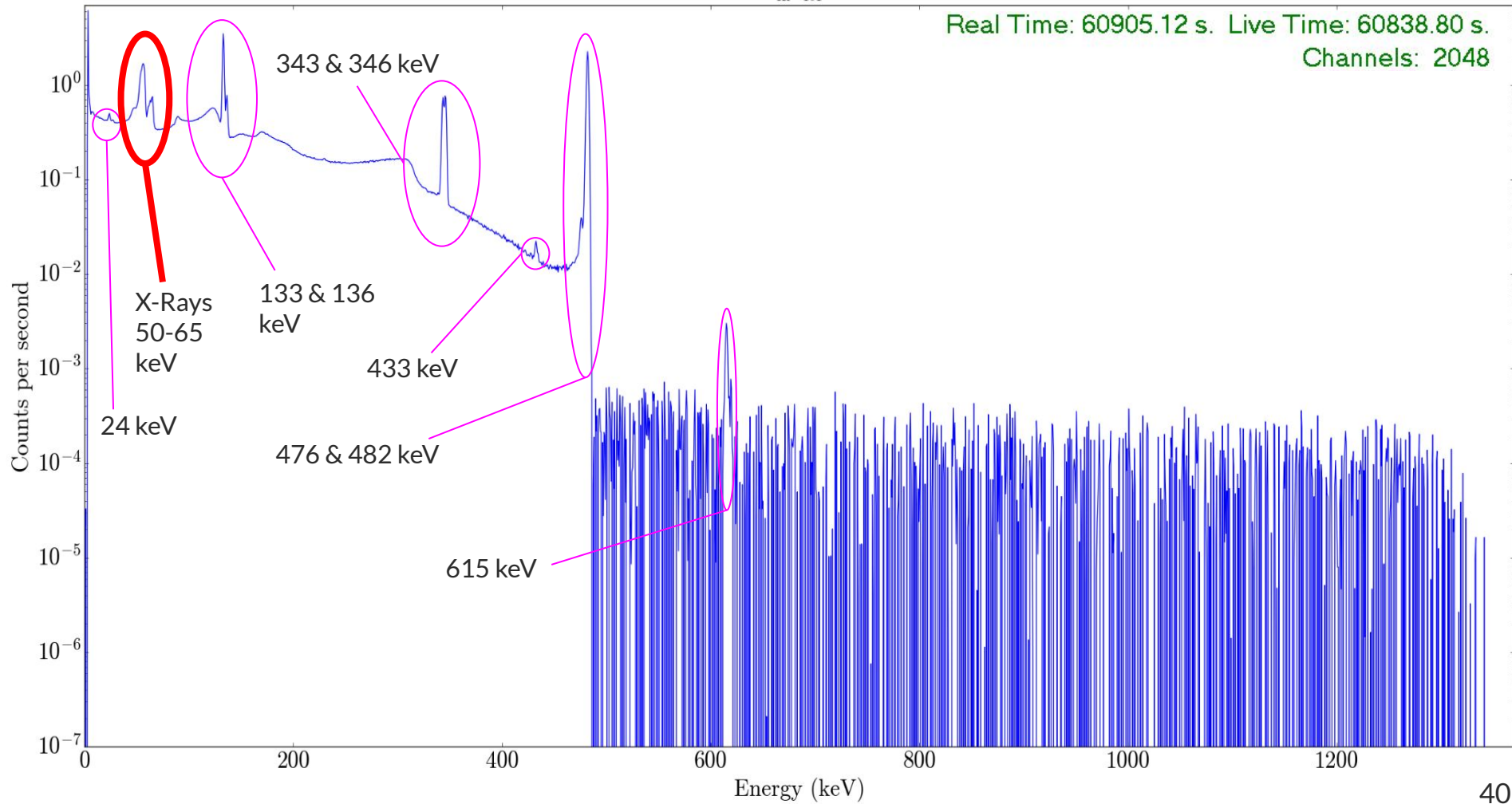
Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



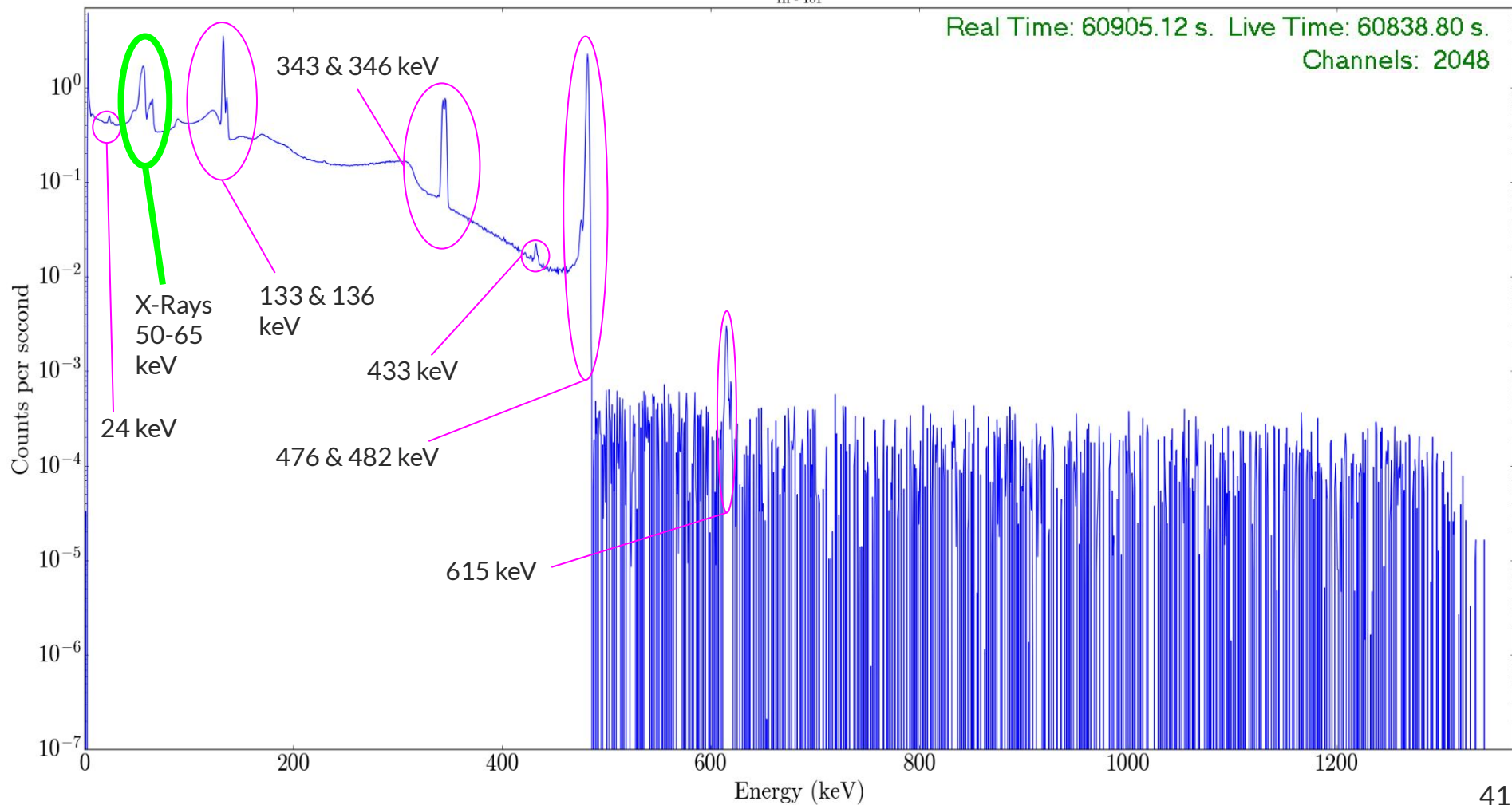
Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



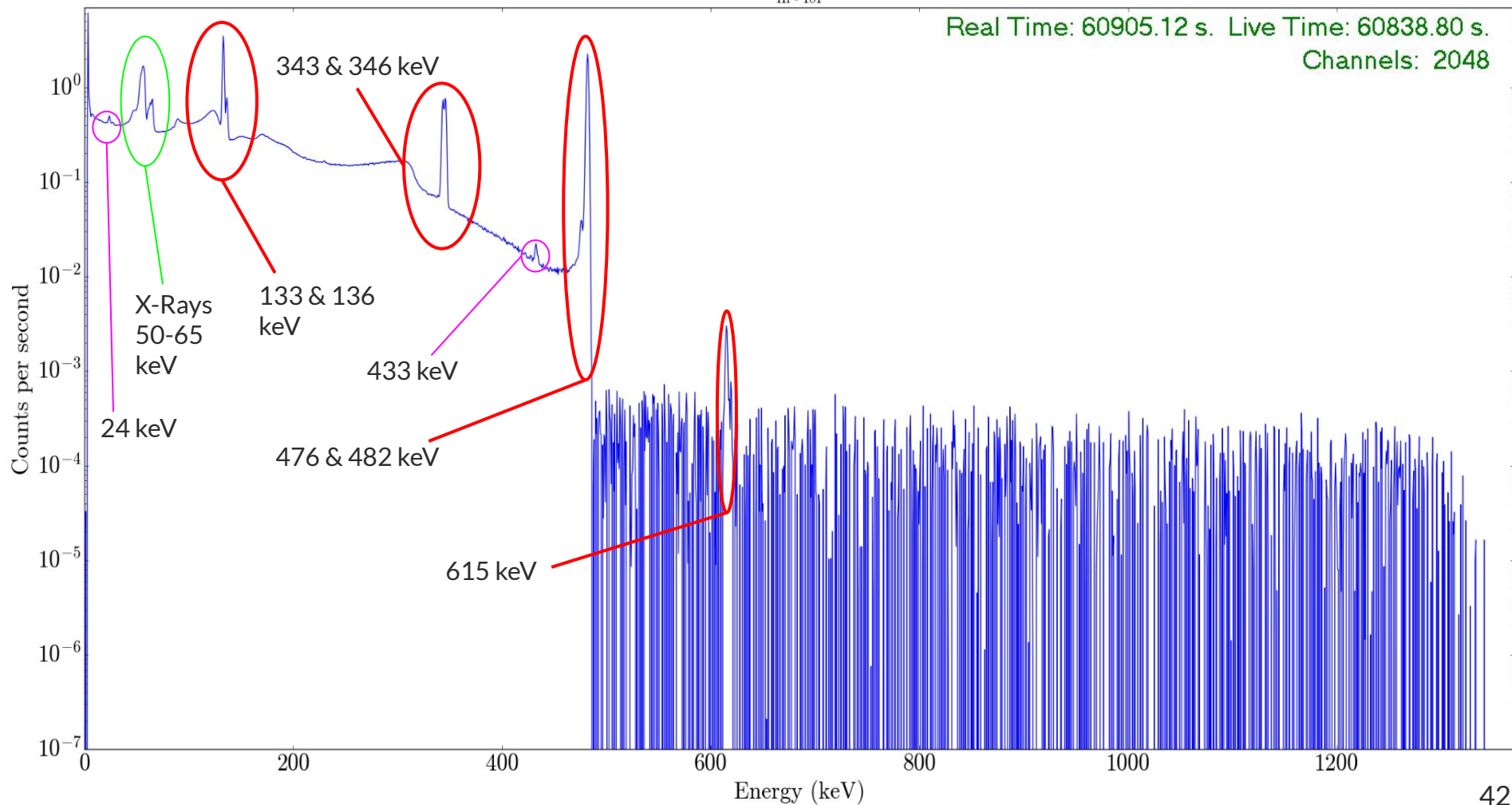
Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048





Gamma

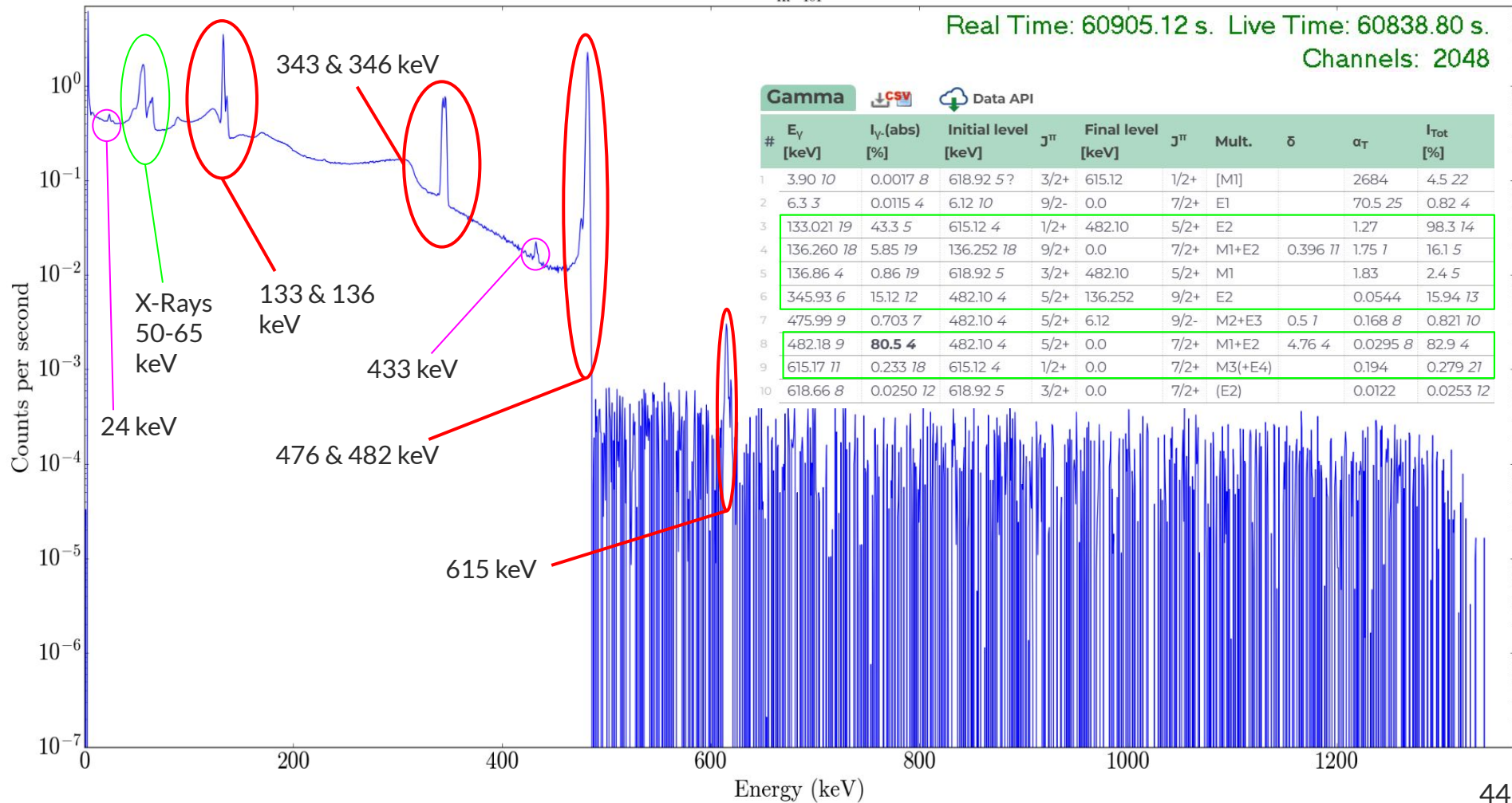


Data API

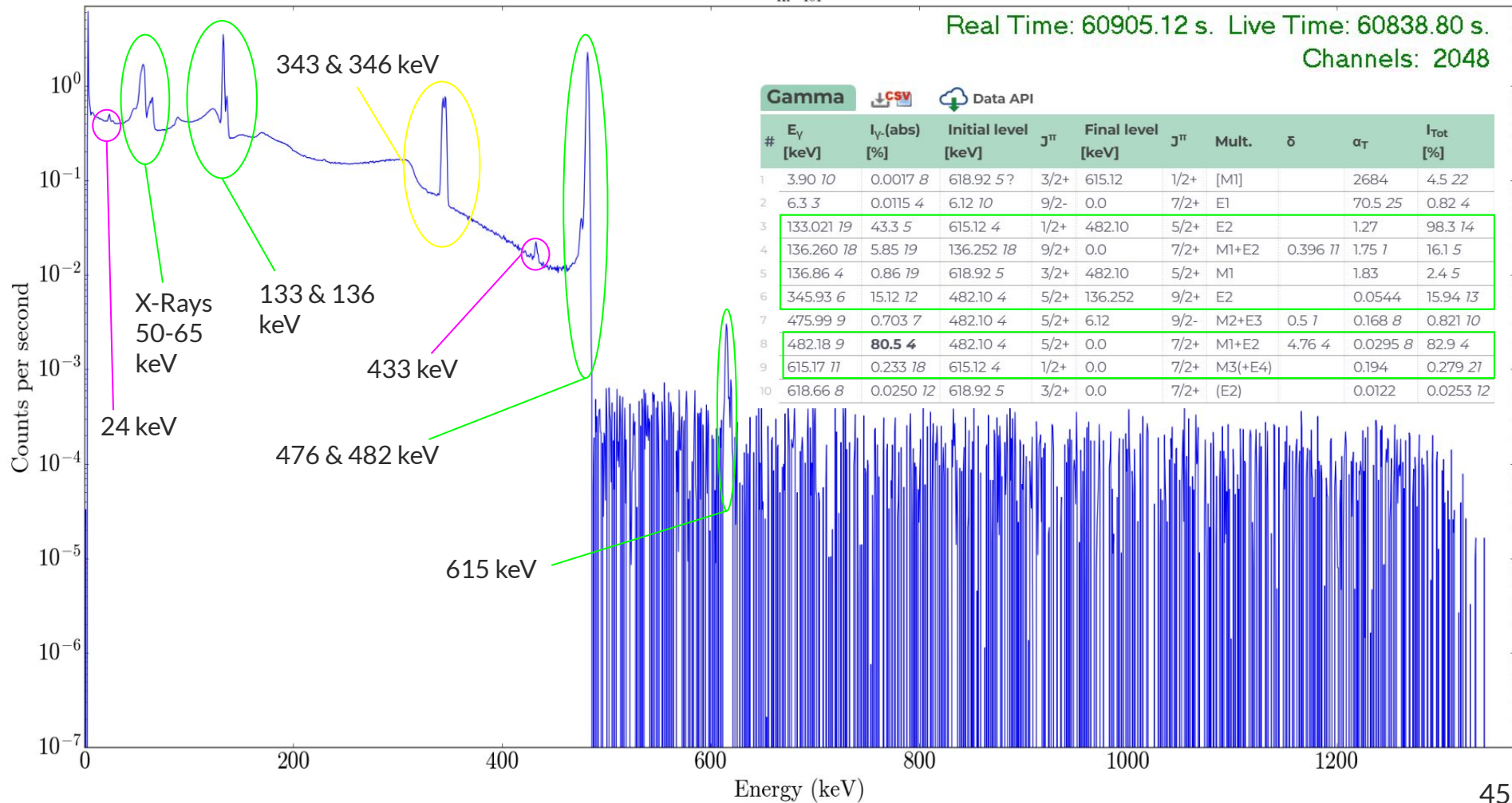
#	E_γ [keV]	I_γ (abs) [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	3.90 10	0.0017 8	618.92 5?	3/2+	615.12	1/2+	[M1]		2684	4.5 22	
2	6.3 3	0.0115 4	6.12 10	9/2-	0.0	7/2+	E1		70.5 25	0.82 4	
3	133.021 19	43.3 5	615.12 4	1/2+	482.10	5/2+	E2		1.27	98.3 14	
4	136.260 18	5.85 19	136.252 18	9/2+	0.0	7/2+	M1+E2	0.396 11	1.75 1	16.1 5	
5	136.86 4	0.86 19	618.92 5	3/2+	482.10	5/2+	M1		1.83	2.4 5	
6	345.93 6	15.12 12	482.10 4	5/2+	136.252	9/2+	E2		0.0544	15.94 13	
7	475.99 9	0.703 7	482.10 4	5/2+	6.12	9/2-	M2+E3	0.5 1	0.168 8	0.821 10	
8	482.18 9	80.5 4	482.10 4	5/2+	0.0	7/2+	M1+E2	4.76 4	0.0295 8	82.9 4	
9	615.17 11	0.233 18	615.12 4	1/2+	0.0	7/2+	M3(+E4)		0.194	0.279 21	
10	618.66 8	0.0250 12	618.92 5	3/2+	0.0	7/2+	(E2)		0.0122	0.0253 12	



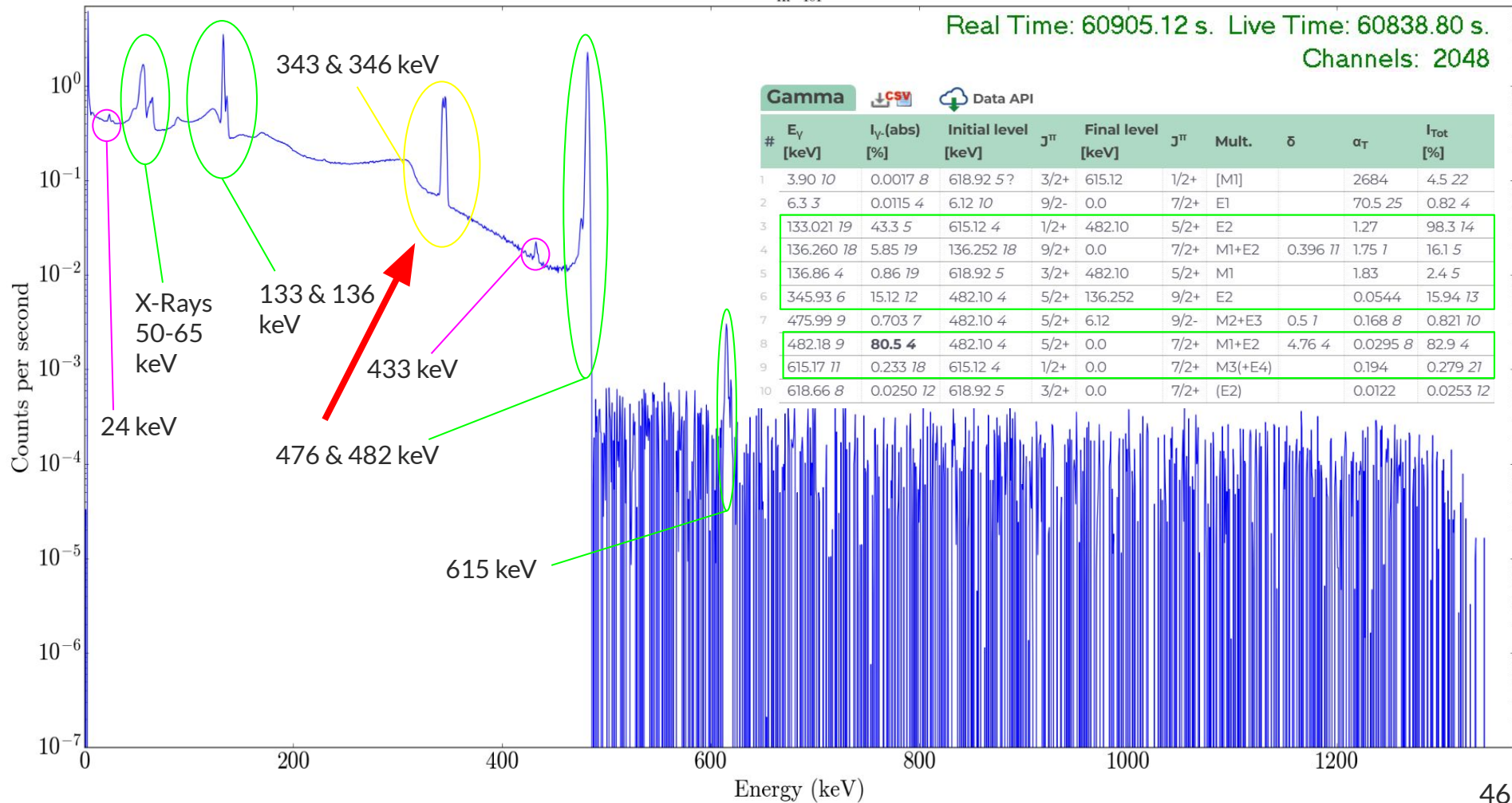
Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048

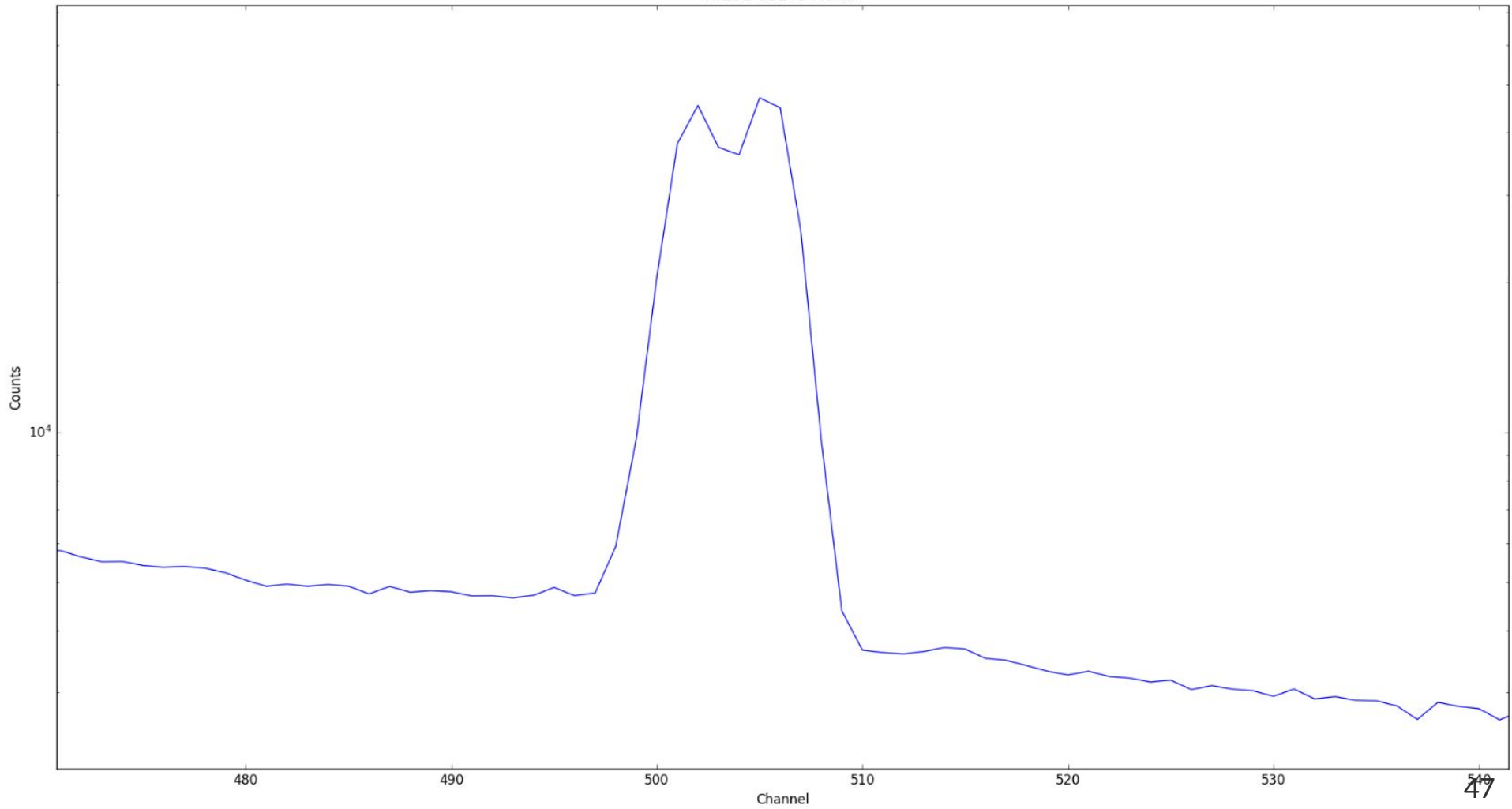


Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048

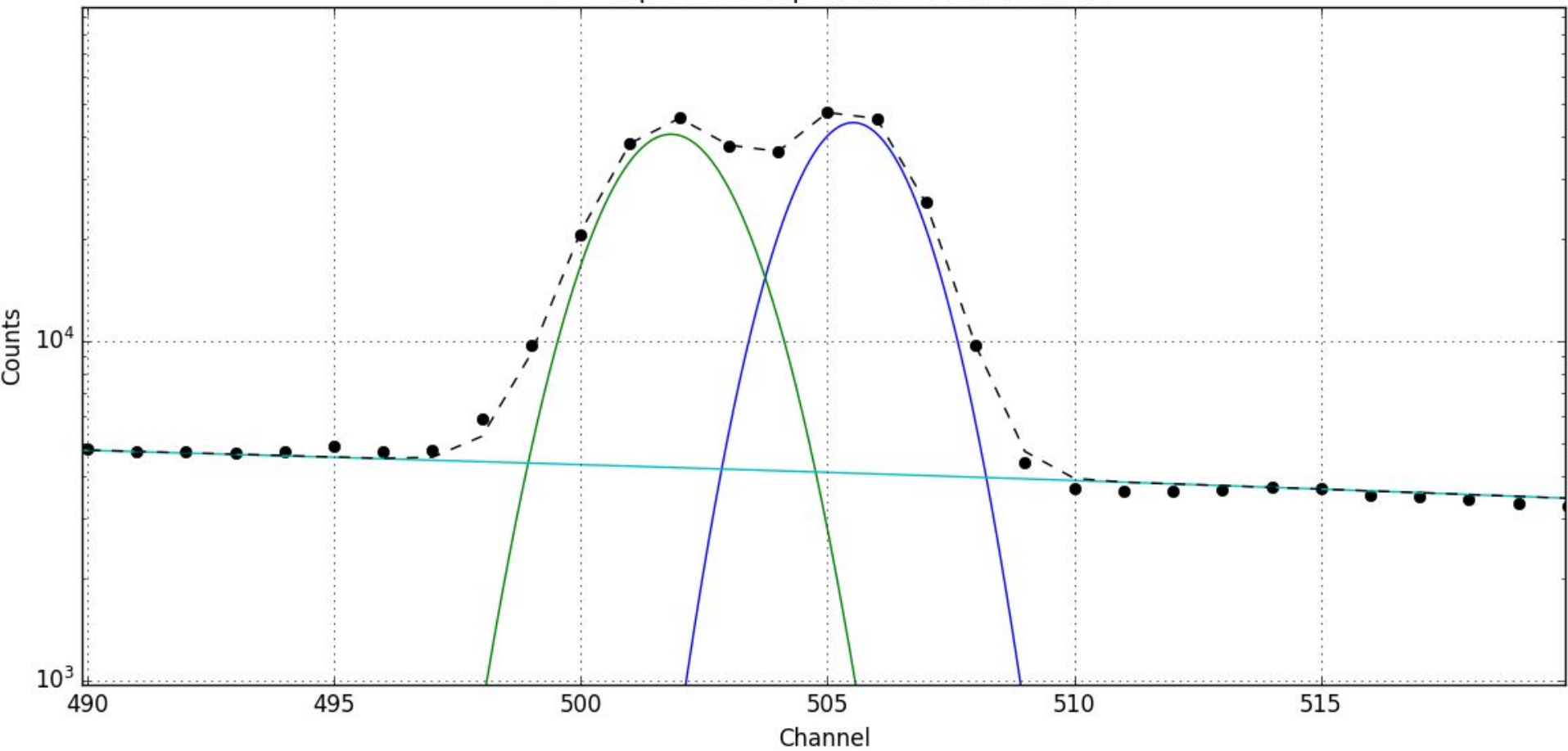


Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048

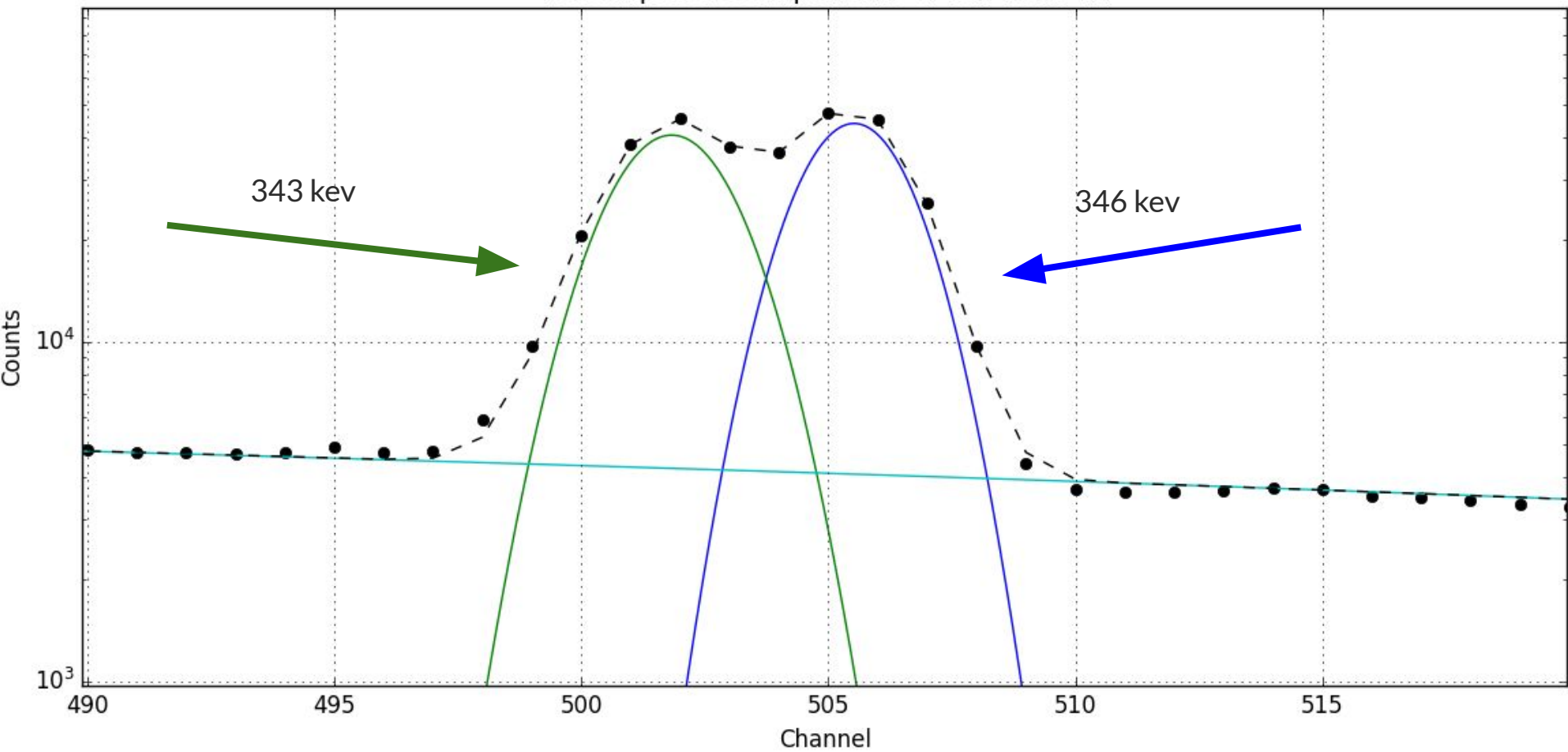




Decomposed Components of Full Peak Fit



Decomposed Components of Full Peak Fit





Gamma

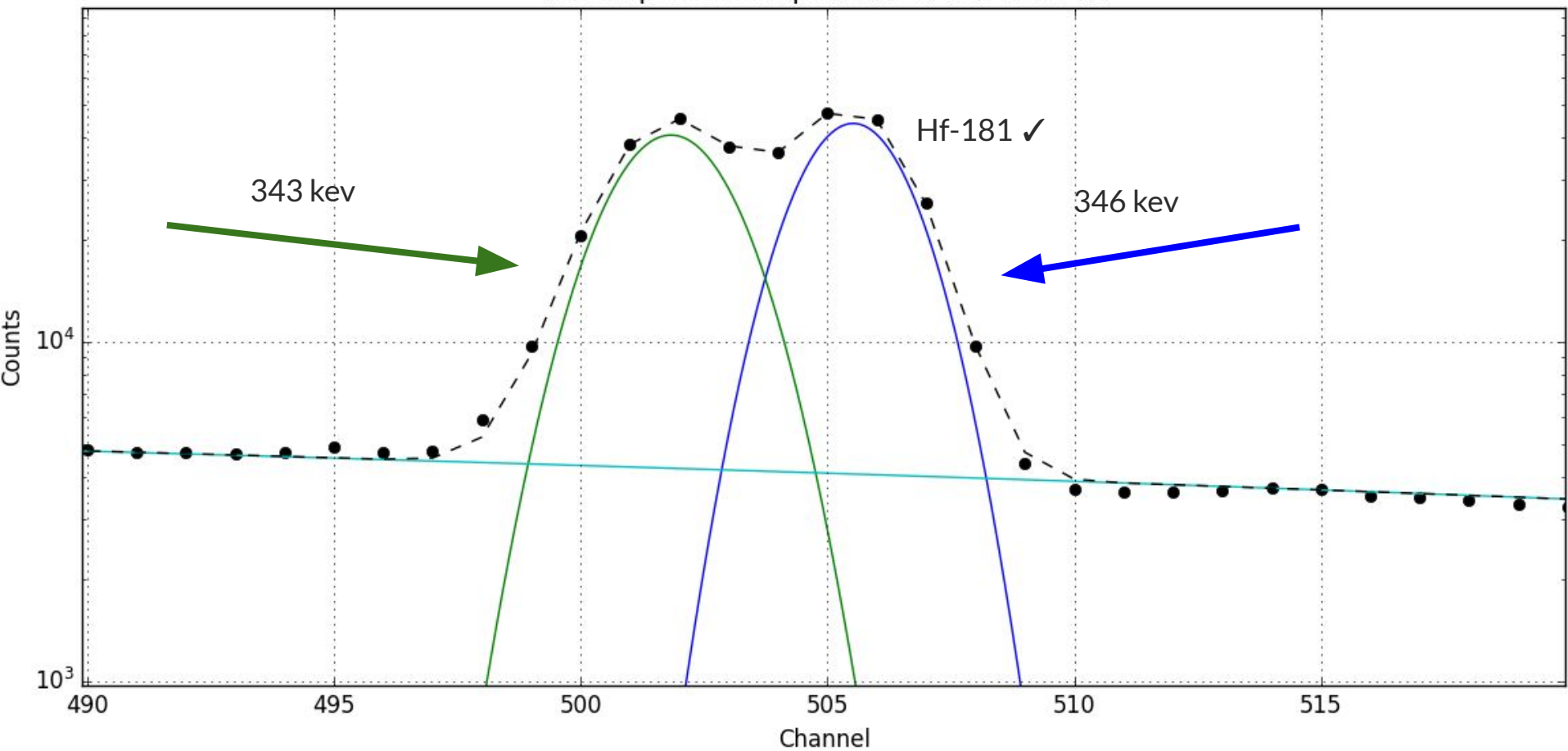


Data API

#	E_γ [keV]	I_γ (abs) [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	3.90 10	0.0017 8	618.92 5 ?	3/2+	615.12	1/2+	[M1]		2684	4.5 22	
2	6.3 3	0.0115 4	6.12 10	9/2-	0.0	7/2+	E1		70.5 25	0.82 4	
3	133.021 19	43.3 5	615.12 4	1/2+	482.10	5/2+	E2		1.27	98.3 14	
4	136.260 18	5.85 19	136.252 18	9/2+	0.0	7/2+	M1+E2	0.396 11	1.75 1	16.1 5	
5	136.86 4	0.86 19	618.92 5	3/2+	482.10	5/2+	M1		1.83	2.4 5	
6	345.93 6	15.12 12	482.10 4	5/2+	136.252	9/2+	E2		0.0544	15.94 13	
7	475.99 9	0.703 7	482.10 4	5/2+	6.12	9/2-	M2+E3	0.5 1	0.168 8	0.821 10	
8	482.18 9	80.5 4	482.10 4	5/2+	0.0	7/2+	M1+E2	4.76 4	0.0295 8	82.9 4	
9	615.17 11	0.233 18	615.12 4	1/2+	0.0	7/2+	M3(+E4)		0.194	0.279 21	
10	618.66 8	0.0250 12	618.92 5	3/2+	0.0	7/2+	(E2)		0.0122	0.0253 12	



Decomposed Components of Full Peak Fit





Gamma



Data API

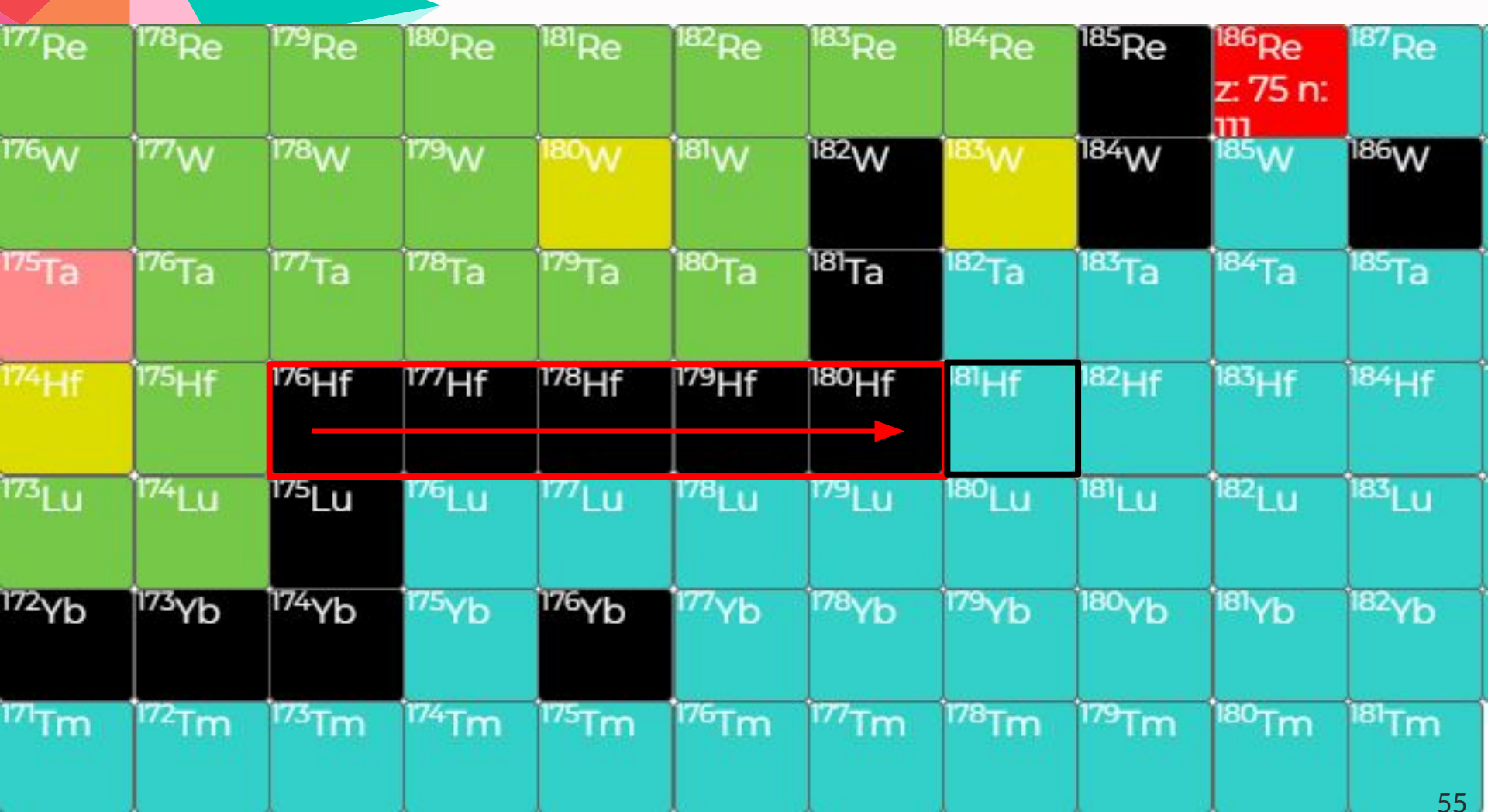
#	E_γ [keV]	I_γ (abs) [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	3.90 10	0.0017 8	618.92 5 ?	3/2+	615.12	1/2+	[M1]		2684	4.5 22	
2	6.3 3	0.0115 4	6.12 10	9/2-	0.0	7/2+	E1		70.5 25	0.82 4	
3	133.021 19	43.3 5	615.12 4	1/2+	482.10	5/2+	E2		1.27	98.3 14	
4	136.260 18	5.85 19	136.252 18	9/2+	0.0	7/2+	M1+E2	0.396 11	1.75 1	16.1 5	
5	136.86 4	0.86 19	618.92 5	3/2+	482.10	5/2+	M1		1.83	2.4 5	
6	345.93 6	15.12 12	482.10 4	5/2+	136.252	9/2+	E2		0.0544	15.94 13	
7	475.99 9	0.703 7	482.10 4	5/2+	6.12	9/2-	M2+E3	0.5 1	0.168 8	0.821 10	
8	482.18 9	80.5 4	482.10 4	5/2+	0.0	7/2+	M1+E2	4.76 4	0.0295 8	82.9 4	
9	615.17 11	0.233 18	615.12 4	1/2+	0.0	7/2+	M3(+E4)		0.194	0.279 21	
10	618.66 8	0.0250 12	618.92 5	3/2+	0.0	7/2+	(E2)		0.0122	0.0253 12	



¹⁷⁷ Re	¹⁷⁸ Re	¹⁷⁹ Re	¹⁸⁰ Re	¹⁸¹ Re	¹⁸² Re	¹⁸³ Re	¹⁸⁴ Re	¹⁸⁵ Re	¹⁸⁶ Re z: 75 n: 111	¹⁸⁷ Re
¹⁷⁶ W	¹⁷⁷ W	¹⁷⁸ W	¹⁷⁹ W	¹⁸⁰ W	¹⁸¹ W	¹⁸² W	¹⁸³ W	¹⁸⁴ W	¹⁸⁵ W	¹⁸⁶ W
¹⁷⁵ Ta	¹⁷⁶ Ta	¹⁷⁷ Ta	¹⁷⁸ Ta	¹⁷⁹ Ta	¹⁸⁰ Ta	¹⁸¹ Ta	¹⁸² Ta	¹⁸³ Ta	¹⁸⁴ Ta	¹⁸⁵ Ta
¹⁷⁴ Hf	¹⁷⁵ Hf	¹⁷⁶ Hf	¹⁷⁷ Hf	¹⁷⁸ Hf	¹⁷⁹ Hf	¹⁸⁰ Hf	¹⁸¹ Hf	¹⁸² Hf	¹⁸³ Hf	¹⁸⁴ Hf
¹⁷³ Lu	¹⁷⁴ Lu	¹⁷⁵ Lu	¹⁷⁶ Lu	¹⁷⁷ Lu	¹⁷⁸ Lu	¹⁷⁹ Lu	¹⁸⁰ Lu	¹⁸¹ Lu	¹⁸² Lu	¹⁸³ Lu
¹⁷² Yb	¹⁷³ Yb	¹⁷⁴ Yb	¹⁷⁵ Yb	¹⁷⁶ Yb	¹⁷⁷ Yb	¹⁷⁸ Yb	¹⁷⁹ Yb	¹⁸⁰ Yb	¹⁸¹ Yb	¹⁸² Yb
¹⁷¹ Tm	¹⁷² Tm	¹⁷³ Tm	¹⁷⁴ Tm	¹⁷⁵ Tm	¹⁷⁶ Tm	¹⁷⁷ Tm	¹⁷⁸ Tm	¹⁷⁹ Tm	¹⁸⁰ Tm	¹⁸¹ Tm

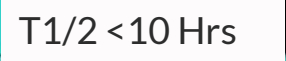
¹⁷⁷ Re	¹⁷⁸ Re	¹⁷⁹ Re	¹⁸⁰ Re	¹⁸¹ Re	¹⁸² Re	¹⁸³ Re	¹⁸⁴ Re	¹⁸⁵ Re	¹⁸⁶ Re z: 75 n: 111	¹⁸⁷ Re
¹⁷⁶ W	¹⁷⁷ W	¹⁷⁸ W	¹⁷⁹ W	¹⁸⁰ W	¹⁸¹ W	¹⁸² W	¹⁸³ W	¹⁸⁴ W	¹⁸⁵ W	¹⁸⁶ W
¹⁷⁵ Ta	¹⁷⁶ Ta	¹⁷⁷ Ta	¹⁷⁸ Ta	¹⁷⁹ Ta	¹⁸⁰ Ta	¹⁸¹ Ta	¹⁸² Ta	¹⁸³ Ta	¹⁸⁴ Ta	¹⁸⁵ Ta
¹⁷⁴ Hf	¹⁷⁵ Hf	¹⁷⁶ Hf	¹⁷⁷ Hf	¹⁷⁸ Hf	¹⁷⁹ Hf	¹⁸⁰ Hf	¹⁸¹ Hf	¹⁸² Hf	¹⁸³ Hf	¹⁸⁴ Hf
¹⁷³ Lu	¹⁷⁴ Lu	¹⁷⁵ Lu	¹⁷⁶ Lu	¹⁷⁷ Lu	¹⁷⁸ Lu	¹⁷⁹ Lu	¹⁸⁰ Lu	¹⁸¹ Lu	¹⁸² Lu	¹⁸³ Lu
¹⁷² Yb	¹⁷³ Yb	¹⁷⁴ Yb	¹⁷⁵ Yb	¹⁷⁶ Yb	¹⁷⁷ Yb	¹⁷⁸ Yb	¹⁷⁹ Yb	¹⁸⁰ Yb	¹⁸¹ Yb	¹⁸² Yb
¹⁷¹ Tm	¹⁷² Tm	¹⁷³ Tm	¹⁷⁴ Tm	¹⁷⁵ Tm	¹⁷⁶ Tm	¹⁷⁷ Tm	¹⁷⁸ Tm	¹⁷⁹ Tm	¹⁸⁰ Tm	¹⁸¹ Tm

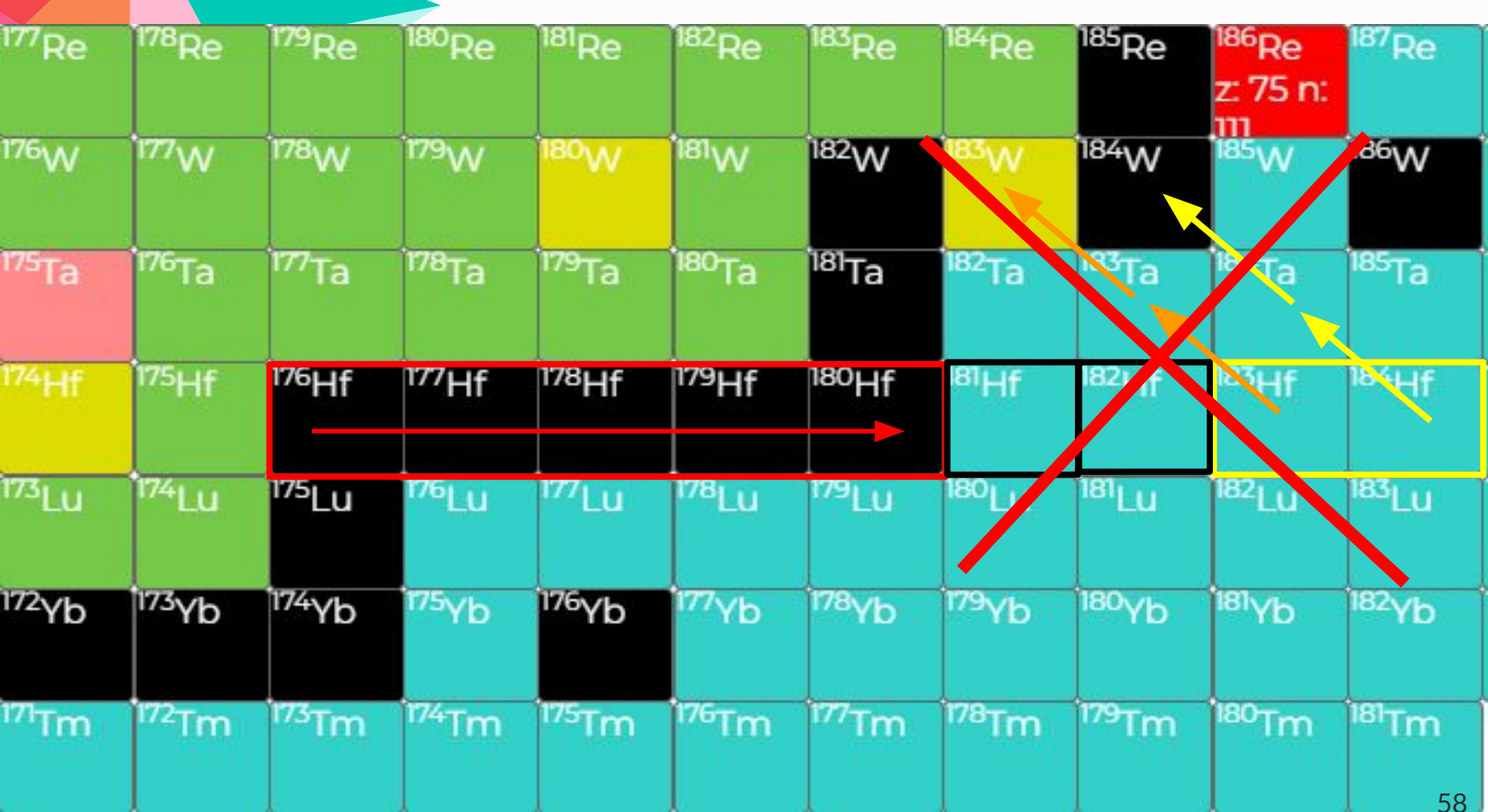


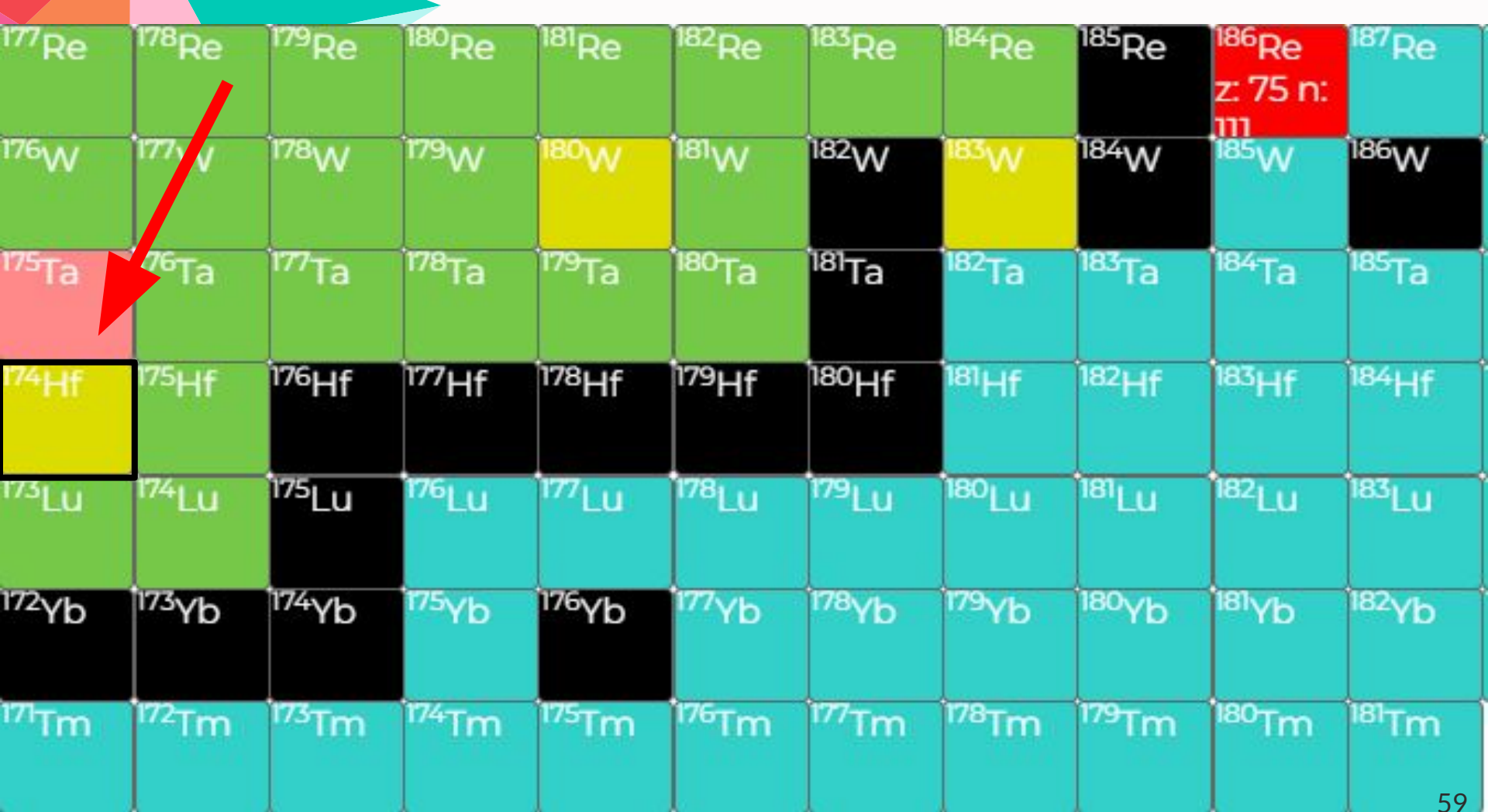


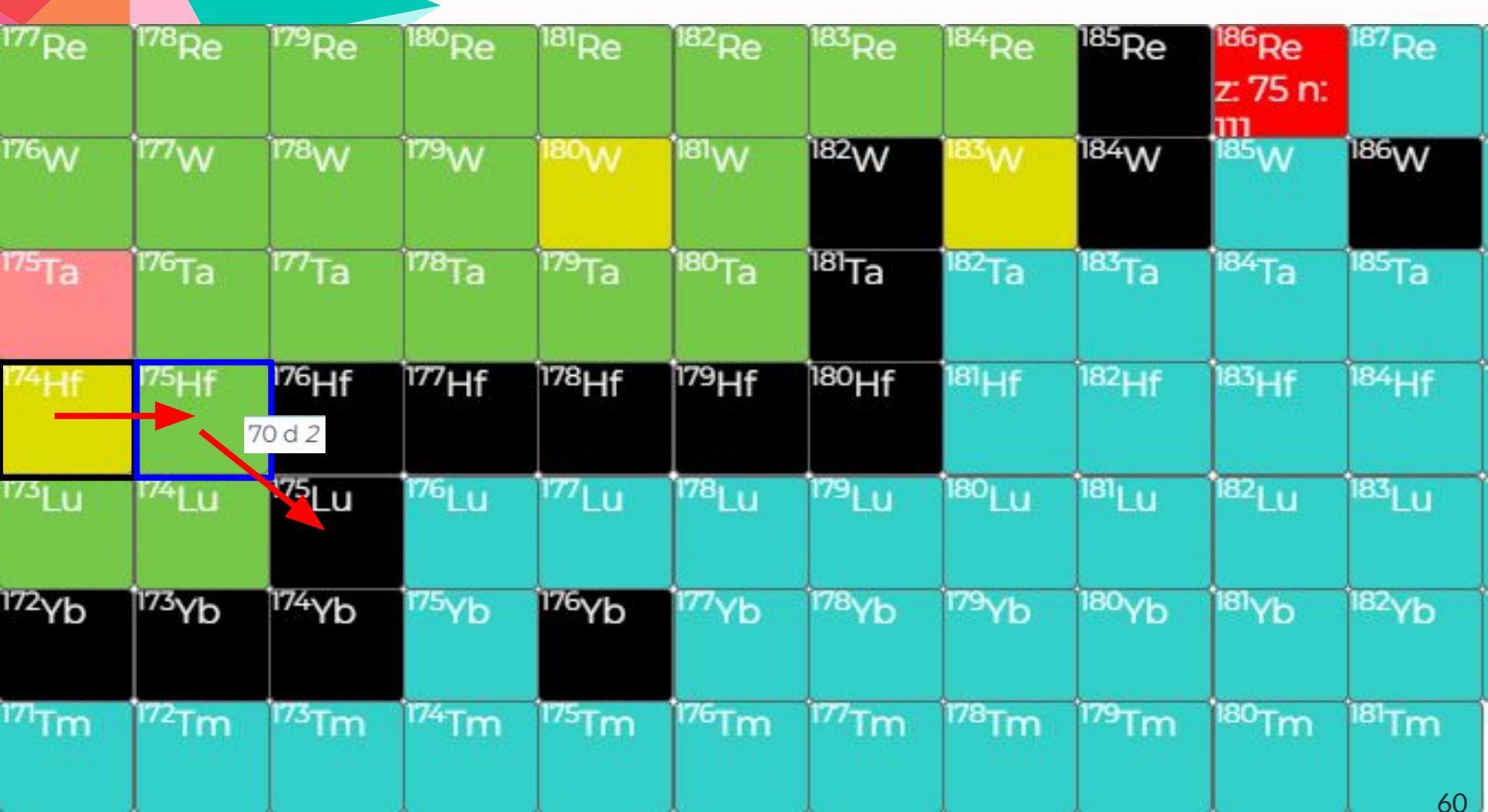
¹⁷⁷ Re	¹⁷⁸ Re	¹⁷⁹ Re	¹⁸⁰ Re	¹⁸¹ Re	¹⁸² Re	¹⁸³ Re	¹⁸⁴ Re	¹⁸⁵ Re	¹⁸⁶ Re z: 75 n: 111	¹⁸⁷ Re
¹⁷⁶ W	¹⁷⁷ W	¹⁷⁸ W	¹⁷⁹ W	¹⁸⁰ W	¹⁸¹ W	¹⁸² W	¹⁸³ W	¹⁸⁴ W	¹⁸⁵ W	¹⁸⁶ W
¹⁷⁵ Ta	¹⁷⁶ Ta	¹⁷⁷ Ta	¹⁷⁸ Ta	¹⁷⁹ Ta	¹⁸⁰ Ta	¹⁸¹ Ta	¹⁸² Ta	¹⁸³ Ta	¹⁸⁴ Ta	¹⁸⁵ Ta
¹⁷⁴ Hf	¹⁷⁵ Hf	¹⁷⁶ Hf	¹⁷⁷ Hf	¹⁷⁸ Hf	¹⁷⁹ Hf	¹⁸⁰ Hf	¹⁸¹ Hf	¹⁸² Hf	¹⁸³ Hf	¹⁸⁴ Hf
¹⁷³ Lu	¹⁷⁴ Lu	¹⁷⁵ Lu	¹⁷⁶ Lu	¹⁷⁷ Lu	¹⁷⁸ Lu	¹⁷⁹ Lu	¹⁸⁰ Lu	¹⁸¹ Lu	¹⁸² Lu	¹⁸³ Lu
¹⁷² Yb	¹⁷³ Yb	¹⁷⁴ Yb	¹⁷⁵ Yb	¹⁷⁶ Yb	¹⁷⁷ Yb	¹⁷⁸ Yb	¹⁷⁹ Yb	¹⁸⁰ Yb	¹⁸¹ Yb	¹⁸² Yb
¹⁷¹ Tm	¹⁷² Tm	¹⁷³ Tm	¹⁷⁴ Tm	¹⁷⁵ Tm	¹⁷⁶ Tm	¹⁷⁷ Tm	¹⁷⁸ Tm	¹⁷⁹ Tm	¹⁸⁰ Tm	¹⁸¹ Tm













Gamma



Data API

#	E_γ [keV]	$I_\gamma(\text{abs})$ [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	89.36 1	2.40 20	432.8 1	7/2+	343.41	5/2+	M1+E2	0.12 1	5.22	14.9 13	
2	113.81 2	0.29 3	113.81 2	9/2+	0.0	7/2+	M1+E2	0.464 5	2.51	1.03 10	
3	143.9		514.6 3	3/2-	371	(1/2-)					
4	161.3 2	0.023 8	514.6 3	3/2-	353.3	5/2-	M1		0.969	0.045 17	
5	229.6 6	0.68 3	343.41 8	5/2+	113.81	9/2+	E2		0.178	0.80 3	
6	318.9 6	0.17 4	432.8 1	7/2+	113.81	9/2+	M1+E2	0.146 12	0.147	0.19 5	
7	343.40 8	84 3	343.41 8	5/2+	0.0	7/2+	M1+E2	-0.27 2	0.118	94 3	
8	353.3 2	0.228 19	353.3 2	5/2-	0.0	7/2+	E1		0.0140	0.232 19	
9	433.0 5	1.44 6	432.8 1	7/2+	0.0	7/2+	M1		0.0663	1.53 6	





Gamma

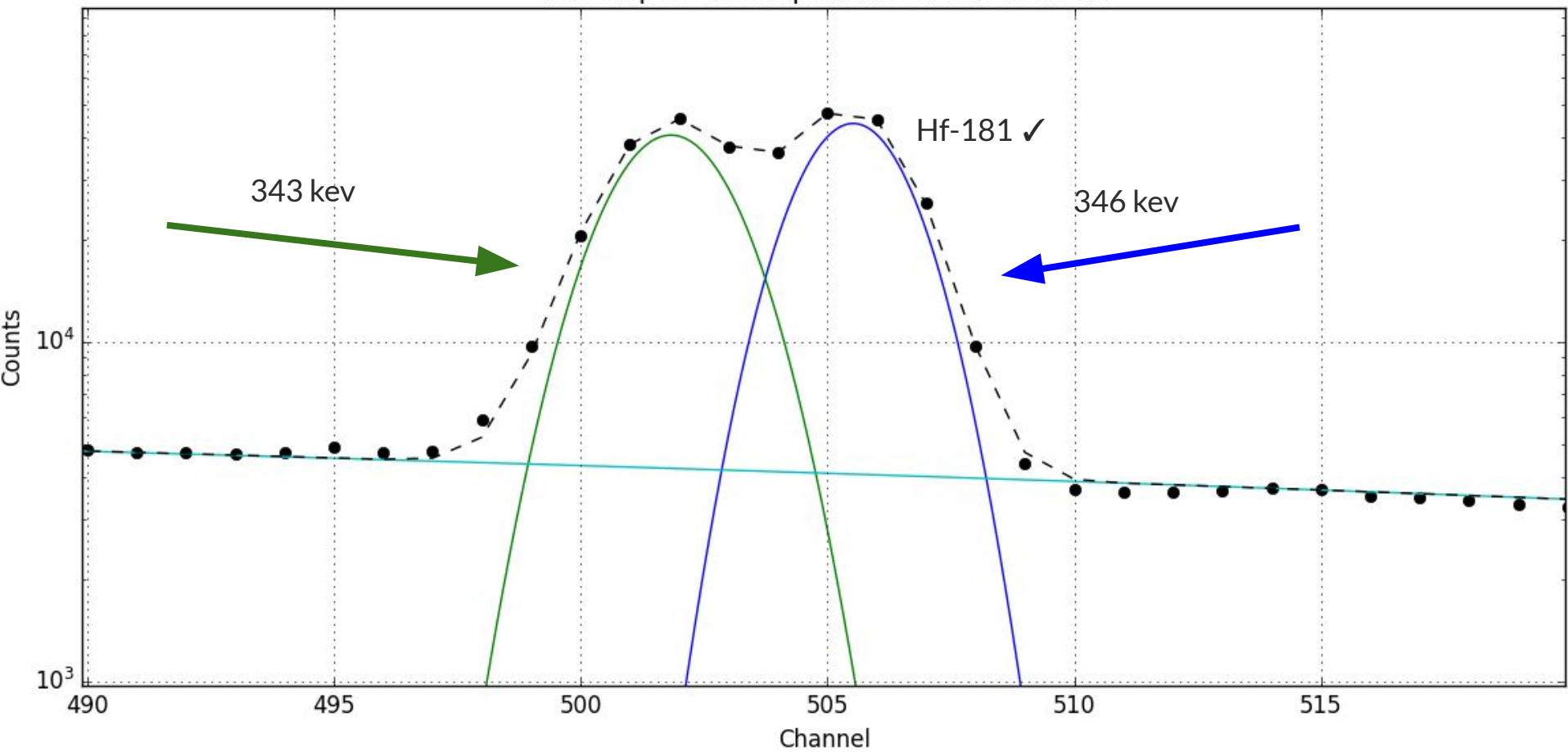


Data API

#	E_γ [keV]	$I_\gamma(\text{abs})$ [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	89.36 1	2.40 20	432.8 1	7/2+	343.41	5/2+	M1+E2	0.12 1	5.22	14.9 13	
2	113.81 2	0.29 3	113.81 2	9/2+	0.0	7/2+	M1+E2	0.464 5	2.51	1.03 10	
3	143.9		514.6 3	3/2-	371	(1/2-)					
4	161.3 2	0.023 8	514.6 3	3/2-	353.3	5/2-	M1		0.969	0.045 17	
5	229.6 6	0.68 3	343.41 8	5/2+	113.81	9/2+	E2		0.178	0.80 3	
6	318.9 6	0.17 4	432.8 1	7/2+	113.81	9/2+	M1+E2	0.146 12	0.147	0.19 5	
7	343.40 8	84 3	343.41 8	5/2+	0.0	7/2+	M1+E2	-0.27 2	0.118	94 3	
8	353.3 2	0.228 19	353.3 2	5/2-	0.0	7/2+	E1		0.0140	0.232 19	
9	433.0 5	1.44 6	432.8 1	7/2+	0.0	7/2+	M1		0.0663	1.53 6	



Decomposed Components of Full Peak Fit





Gamma

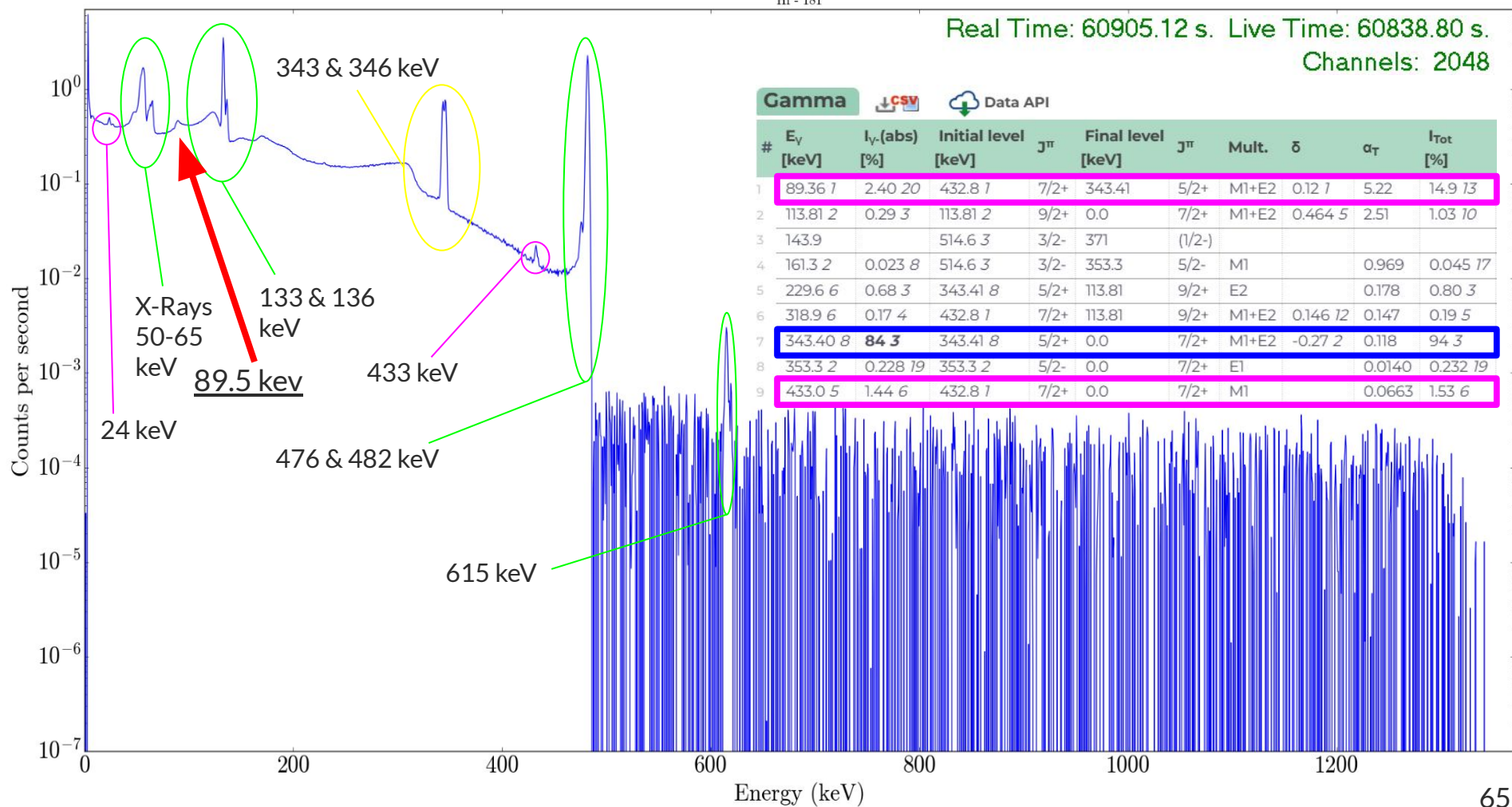


Data API

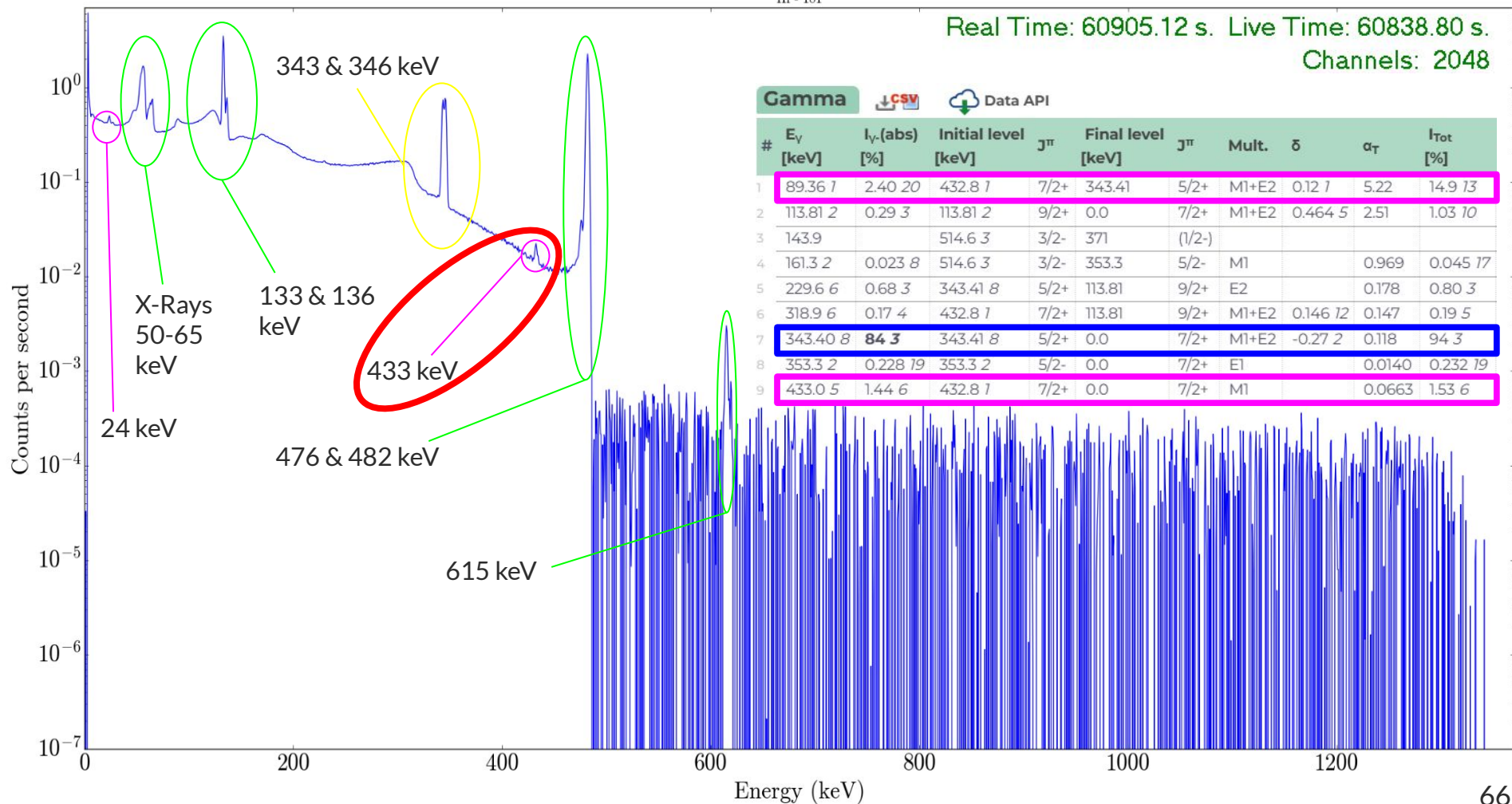
#	E_γ [keV]	$I_\gamma(\text{abs})$ [%]	Initial level [keV]	J^π	Final level [keV]	J^π	Mult.	δ	α_T	I_{Tot} [%]	Comments
1	89.36 1	2.40 20	432.8 1	7/2+	343.41	5/2+	M1+E2	0.12 1	5.22	14.9 13	
2	113.81 2	0.29 3	113.81 2	9/2+	0.0	7/2+	M1+E2	0.464 5	2.51	1.03 10	
3	143.9		514.6 3	3/2-	371	(1/2-)					
4	161.3 2	0.023 8	514.6 3	3/2-	353.3	5/2-	M1		0.969	0.045 17	
5	229.6 6	0.68 3	343.41 8	5/2+	113.81	9/2+	E2		0.178	0.80 3	
6	318.9 6	0.17 4	432.8 1	7/2+	113.81	9/2+	M1+E2	0.146 12	0.147	0.19 5	
7	343.40 8	84 3	343.41 8	5/2+	0.0	7/2+	M1+E2	-0.27 2	0.118	94 3	
8	353.3 2	0.228 19	353.3 2	5/2-	0.0	7/2+	E1		0.0140	0.232 19	
9	433.0 5	1.44 6	432.8 1	7/2+	0.0	7/2+	M1		0.0663	1.53 6	



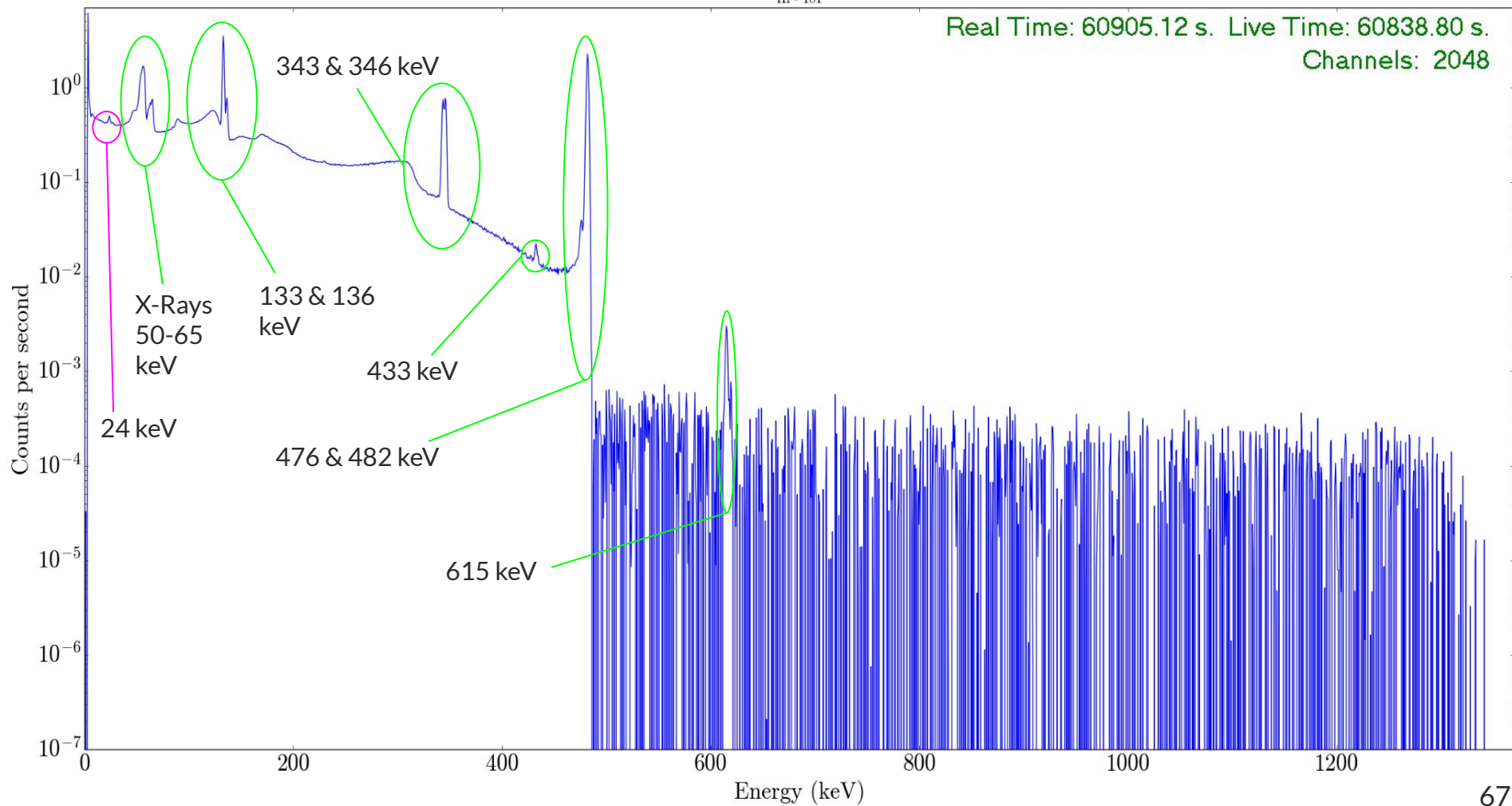
Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



Real Time: 60905.12 s. Live Time: 60838.80 s.
Channels: 2048



Isotope	Energy (keV)	Literature (keV)	Relative size (%)
Hf-181	133.051 ± 0.053	133.021 ± 0.019	100.00
Hf-181	482.058 ± 0.572	482.18 ± 0.09	74.73
Hf-181	345.939 ± 0.025	345.93 ± 0.06	22.17
Hf-175	343.422 ± 0.025	343.4 ± 0.08	19.95
Hf-181	136.350 ± 0.111	136.26 ± 0.018	8.15
??????	23.451 ± 0.083	?????	2.70
Hf-181	475.886 ± 0.051	475.99 ± 0.09	0.89
Hf-175	432.851 ± 0.128	433 ± 0.5	0.26
Hf-181	615.194 ± 0.088	615.17 ± 0.11	0.09

Summary

All lines are expected except for the peak at 24 keV.

Activated zirconium is not detectable in the hafnium samples.

Thank you!

nEXO  BNL



**NSERC
CRSNG**



McGill
UNIVERSITY

Ethan.coulthard@mail.mcgill.ca

Appendix



Why are we looking for $0\nu\beta\beta$

Neutrinos being Majorana particles, along with seesaw mechanics, could explain their extremely small mass.

$0\nu\beta\beta$ would push physics beyond the standard model, allowing for the study of new physics.

Violates lepton number conservation, pointing toward leptogenesis.

Expected half life of 10^{25-26} years

McMasters Reactor

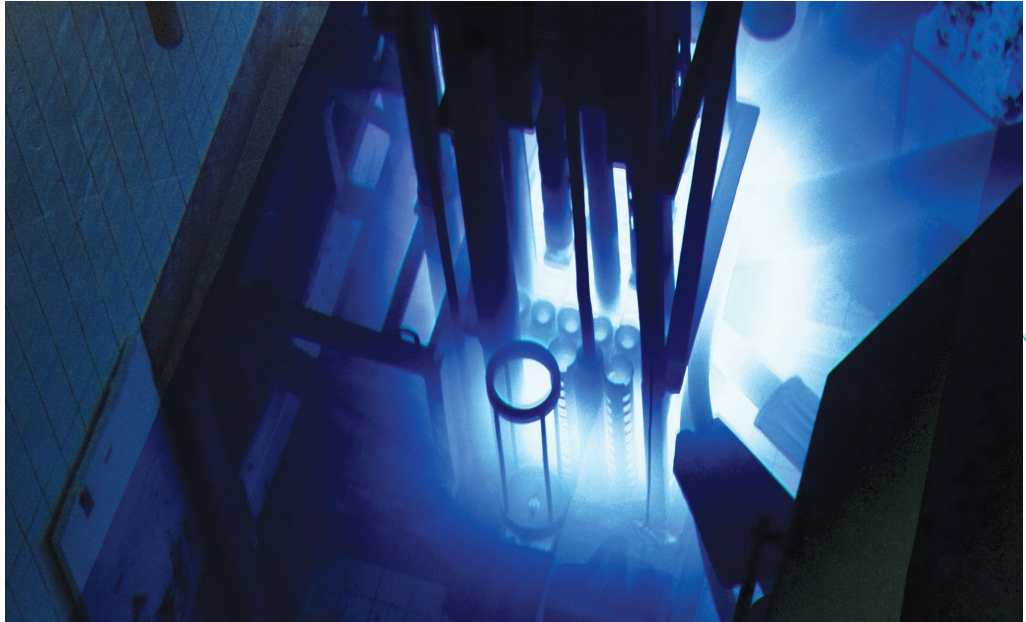
Built in 1959

Operates at 3 MW
(Max of 5 MW)

$1e14$ neutrons per
square cm

Really cool

Tours from 09:00 to 16:30 on Weekdays



McMasters Neutron Spectrum

J. ATANACKOVIC ET AL.

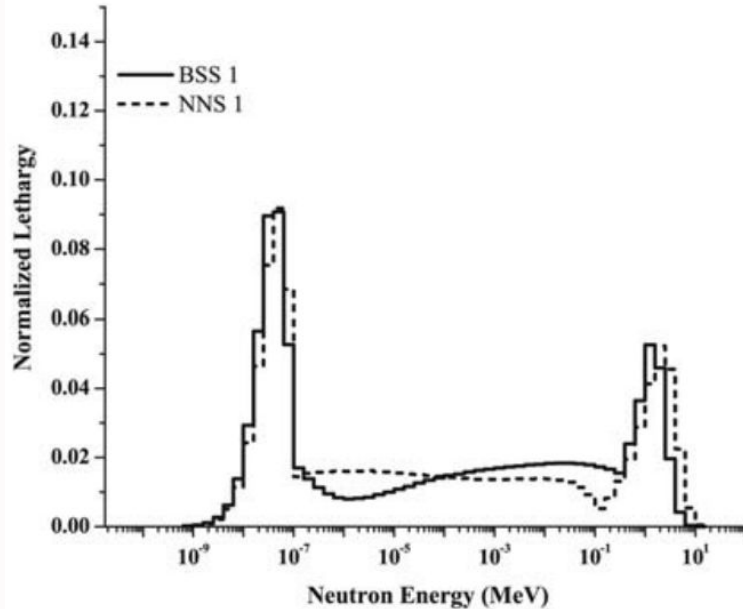


Figure 4. BSS and NNS spectra at MNR position 1.

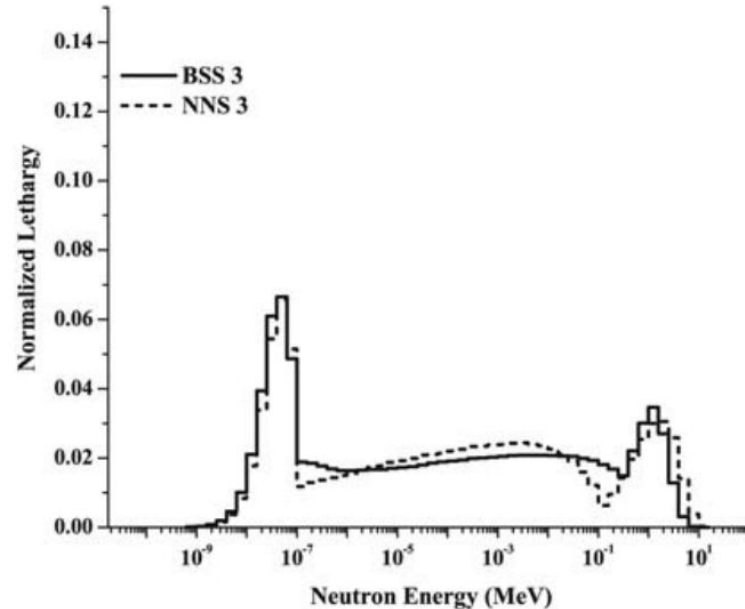
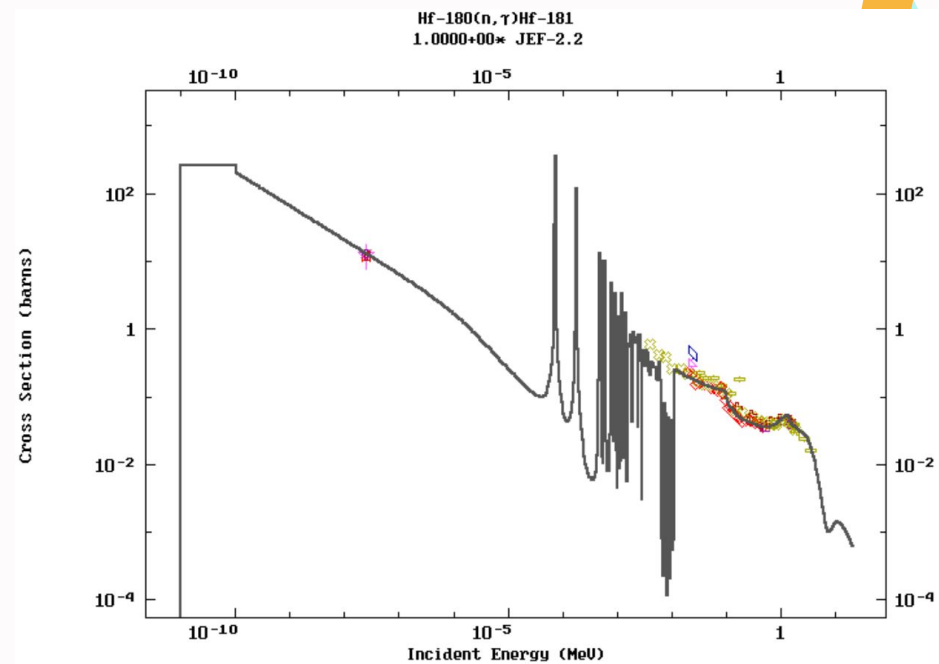
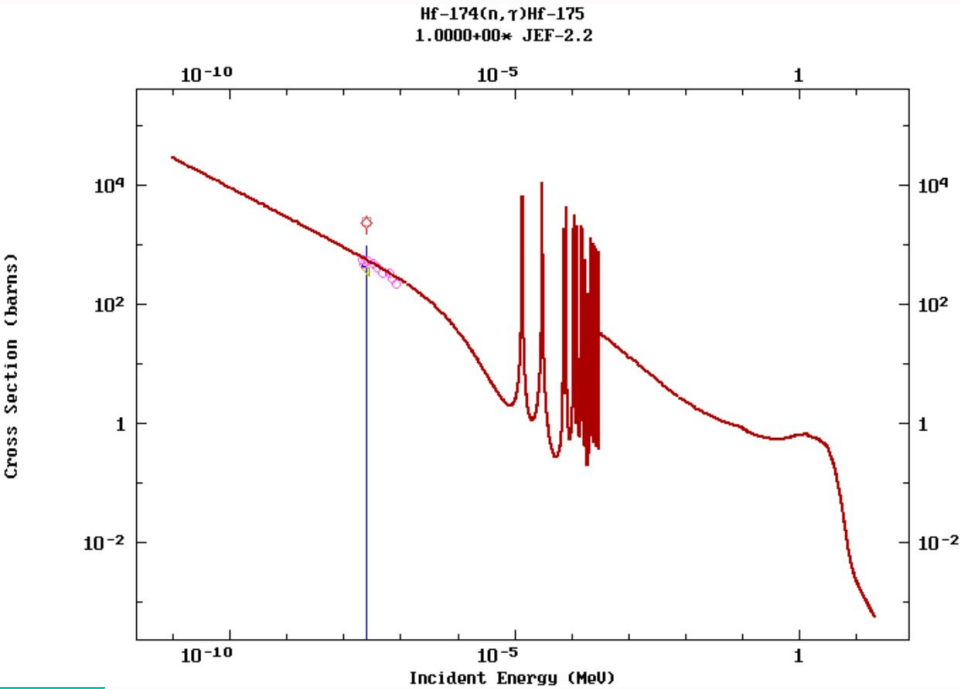


Figure 6. BSS and NNS spectra at MNR position 3.

Neutron Cross Section



Neutron Cross Section

Cross Section (barns)

