2023/05/11

Gamma Ray Counting for Low Background Experiments

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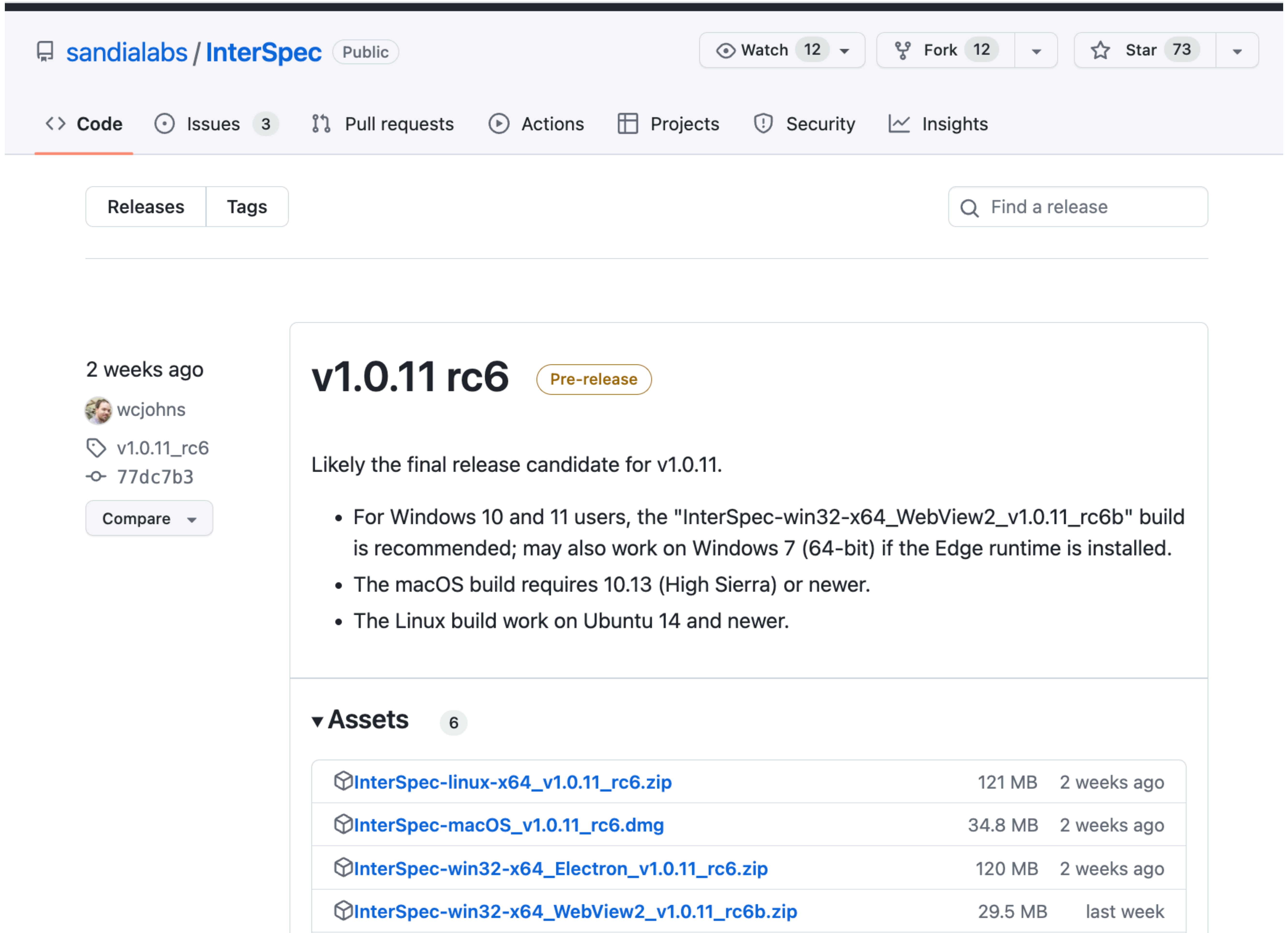
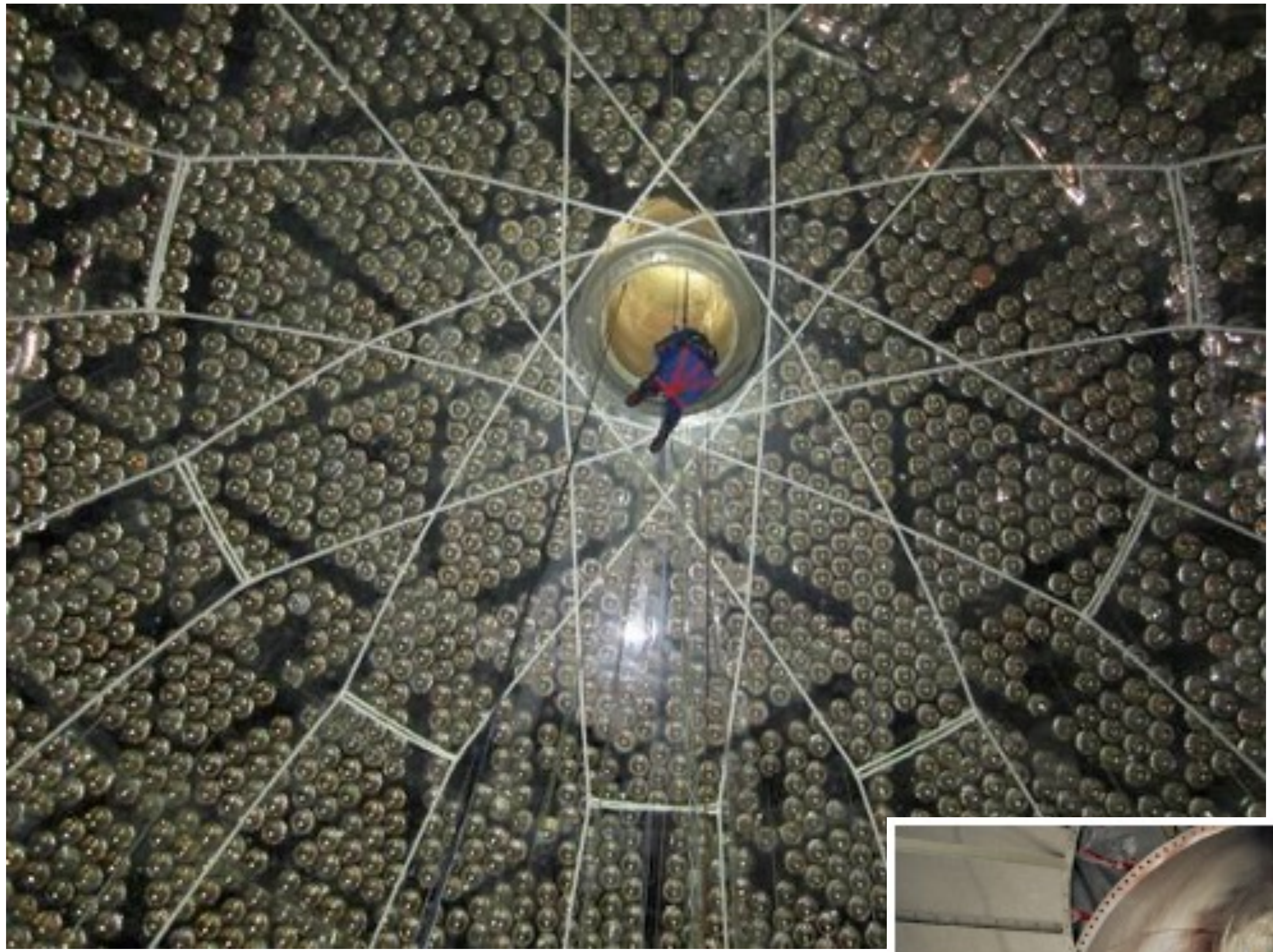
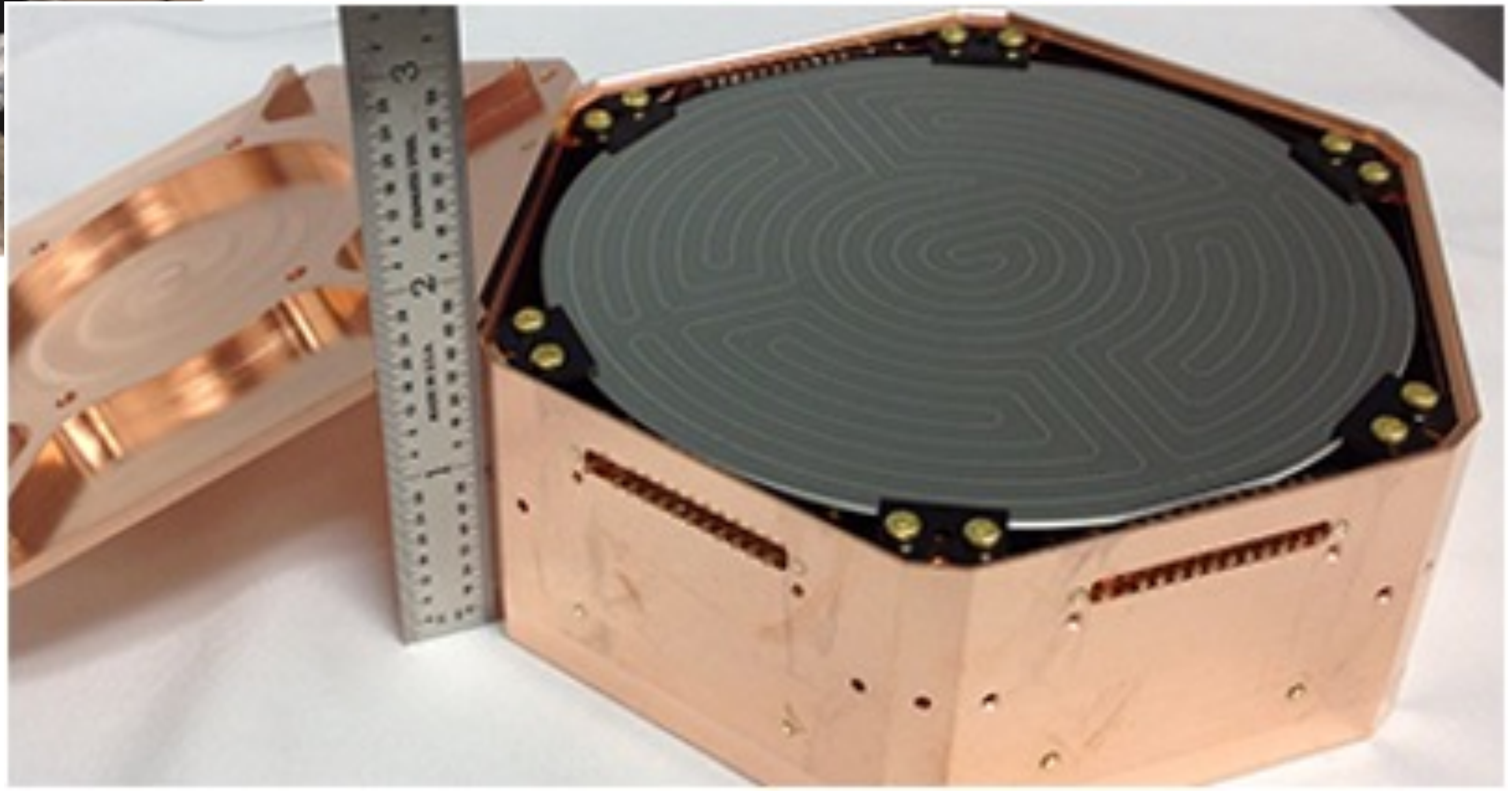
SNOLAB Staff Scientist

InterSpec Gamma Ray Software



- https://github.com/sandialabs/interspec/releases
- Please download and install the appropriate version for your OS.





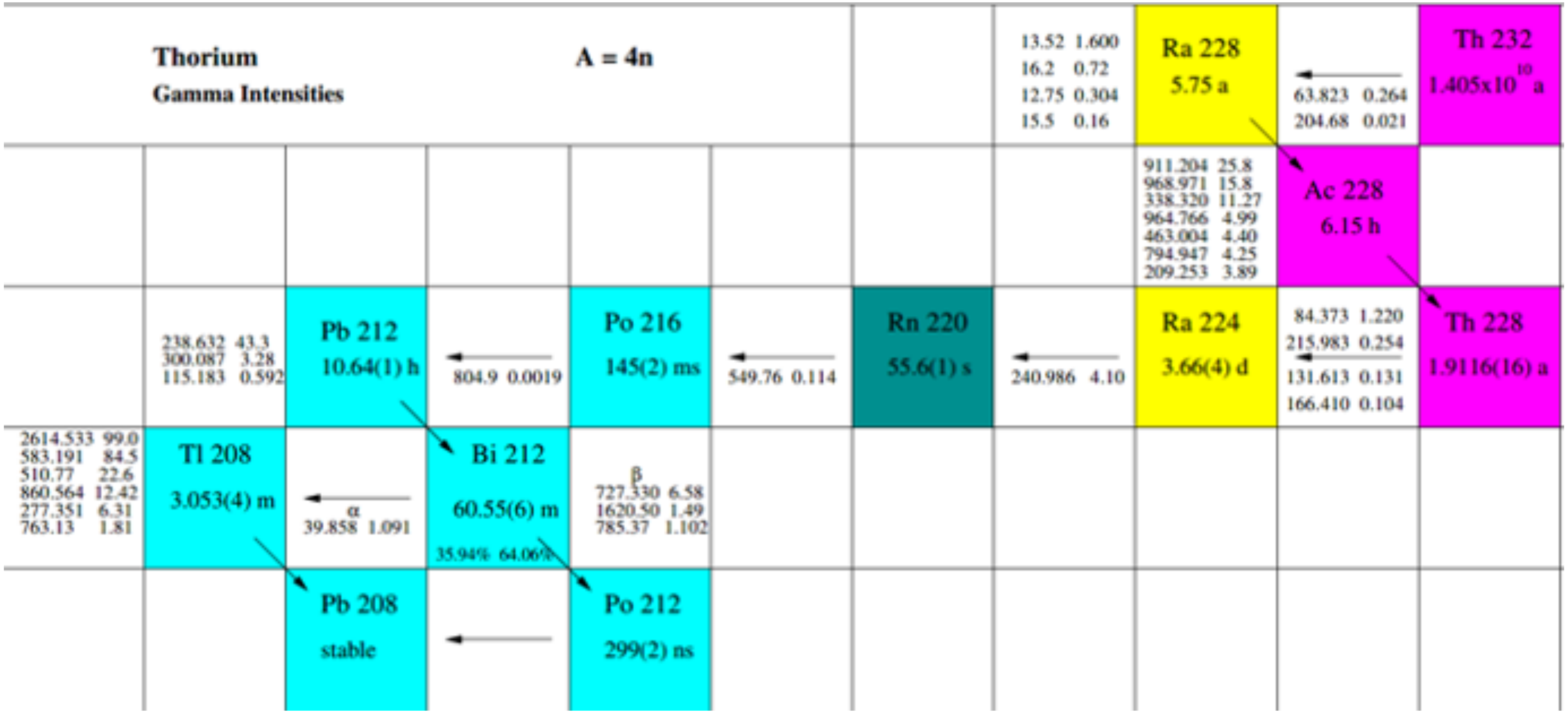
Example Radioactivity Levels

- ^{14}C: 1 ppt of natural Carbon
- ^{40}K: 120 ppm of natural Potassium
- ^{238}U: to 10 ppm in rocks and soil
- ^{232}Th: to 10 ppm in rocks and soil
- Thoriated welding rods: 1-4% ^{232}Th
- Screened low-background materials: <1 ppb U, Th
- Rn gas:
  - 1 to 100 Bq/m^3 on surface
  - ~3 Bq/m^3 in Sudbury
  - ~130 Bq/m^3 at SNOLAB

Sources of Radioactive Backgrounds

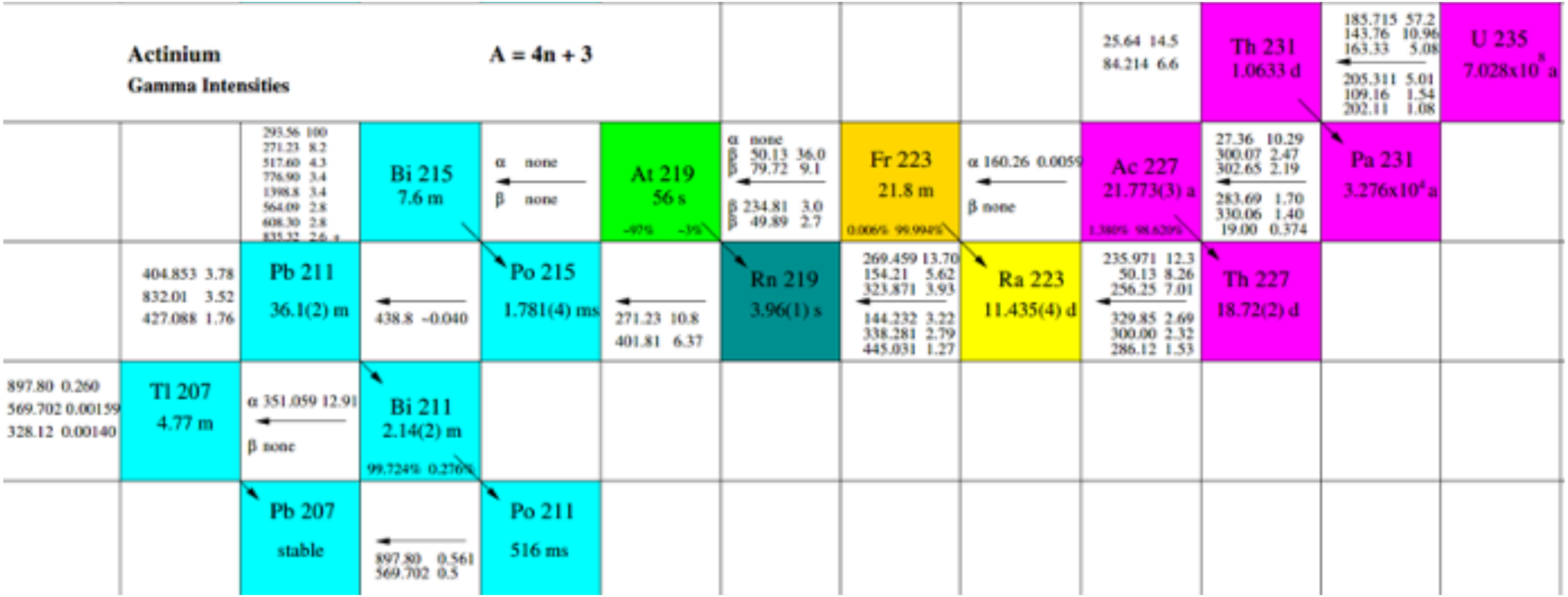
- Nearly stable isotopes
  - ^{238}U – 4.5 x 10^9 years
  - ^{232}Th – 1.4 x 10^{10} years
  - ^{235}U – 7 x 10^8 years
  - ^{40}K – 1.3 x 10^9 years
- Activated isotopes
  - ^{14}C – 5,700 years
  - ^{39}Ar – 270 years
  - ^{7}Be – 53 days
- Daughter isotopes
  - ^{210}Pb – 22 years
  - ^{208}Tl – 3 minutes
  - ^{228}Ac – 6.2 hours
- Gaseous daughter isotopes
  - ^{220}Rn – 56 seconds
  - ^{222}Rn – 3.8 days
  - ^{4}He – stable
- Fission products
  - ^{137}Cs – 30 years
  - ^{131}I – 8 days
- Man-made isotopes
  - ^{60}Co – 5.3 years
  - ^{3}H – 12 years
  - ^{18}F – 110 minutes

^{232}Th Chain



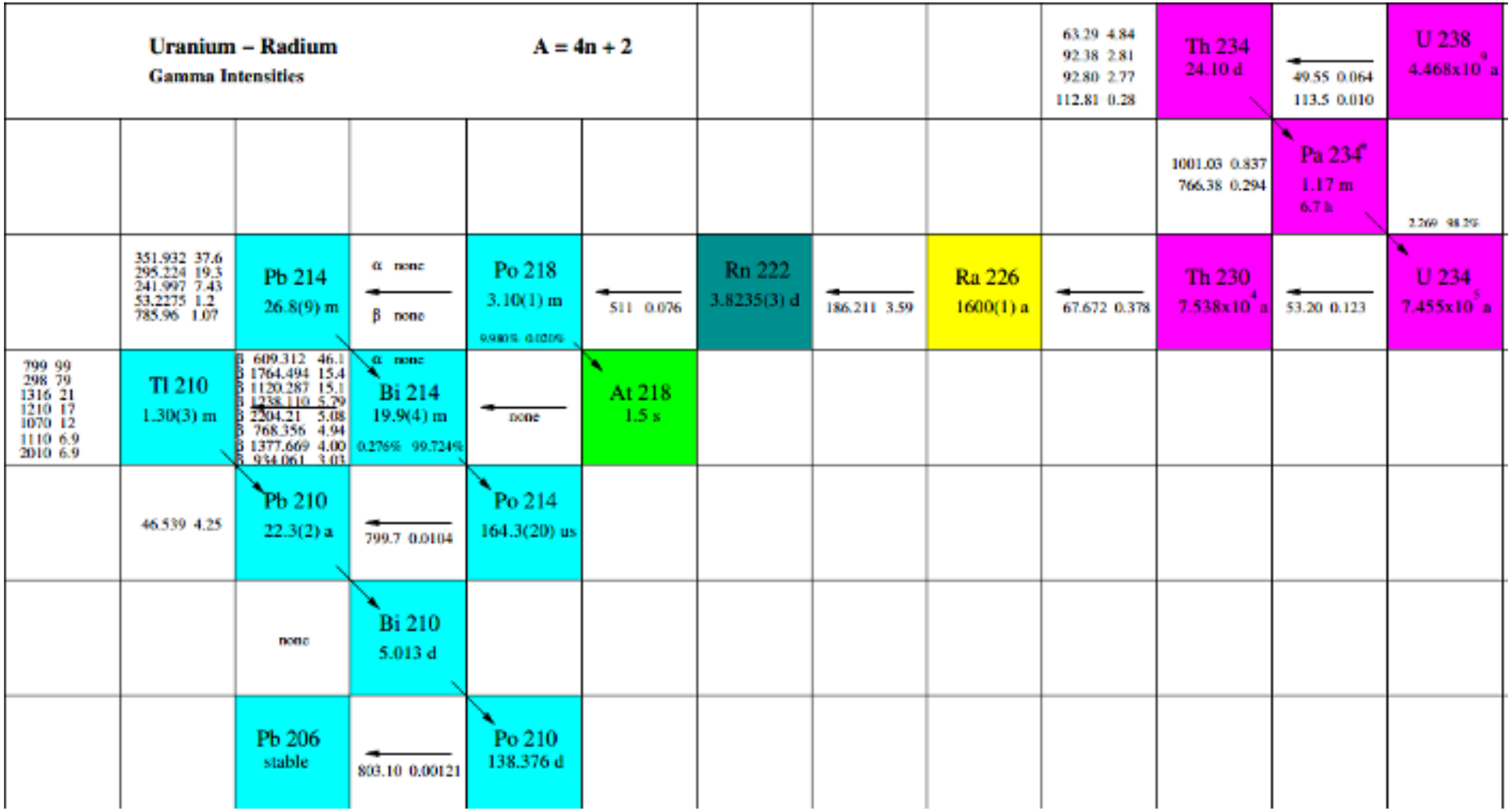
Thorium
Gamma Intensities
A = 4n
13.52 1.600
16.2 0.72
12.75 0.304
15.5 0.16
Ra 228
5.75 a
63.823 0.264
204.68 0.021
Th 232
1.405x10^10 a
911.204 25.8
968.971 15.8
338.320 11.27
964.766 4.99
463.004 4.40
794.947 4.25
209.253 3.89
Ac 228
6.15 h
238.632 43.3
300.087 3.28
115.183 0.592
Pb 212
10.64(1) h
804.9 0.0019
Po 216
145(2) ms
549.76 0.114
Rn 220
55.6(1) s
240.986 4.10
Ra 224
3.66(4) d
84.373 1.220
215.983 0.254
131.613 0.131
166.410 0.104
Th 228
1.9116(16) a
2614.533 99.0
583.191 84.5
510.77 22.6
860.564 12.42
277.351 6.31
763.13 1.81
Tl 208
3.053(4) m
α
39.858 1.091
Bi 212
60.55(6) m
35.94% 64.06%
β
727.330 6.58
1620.50 1.49
785.37 1.102
Pb 208
stable
Po 212
299(2) ns

^{235}U Chain



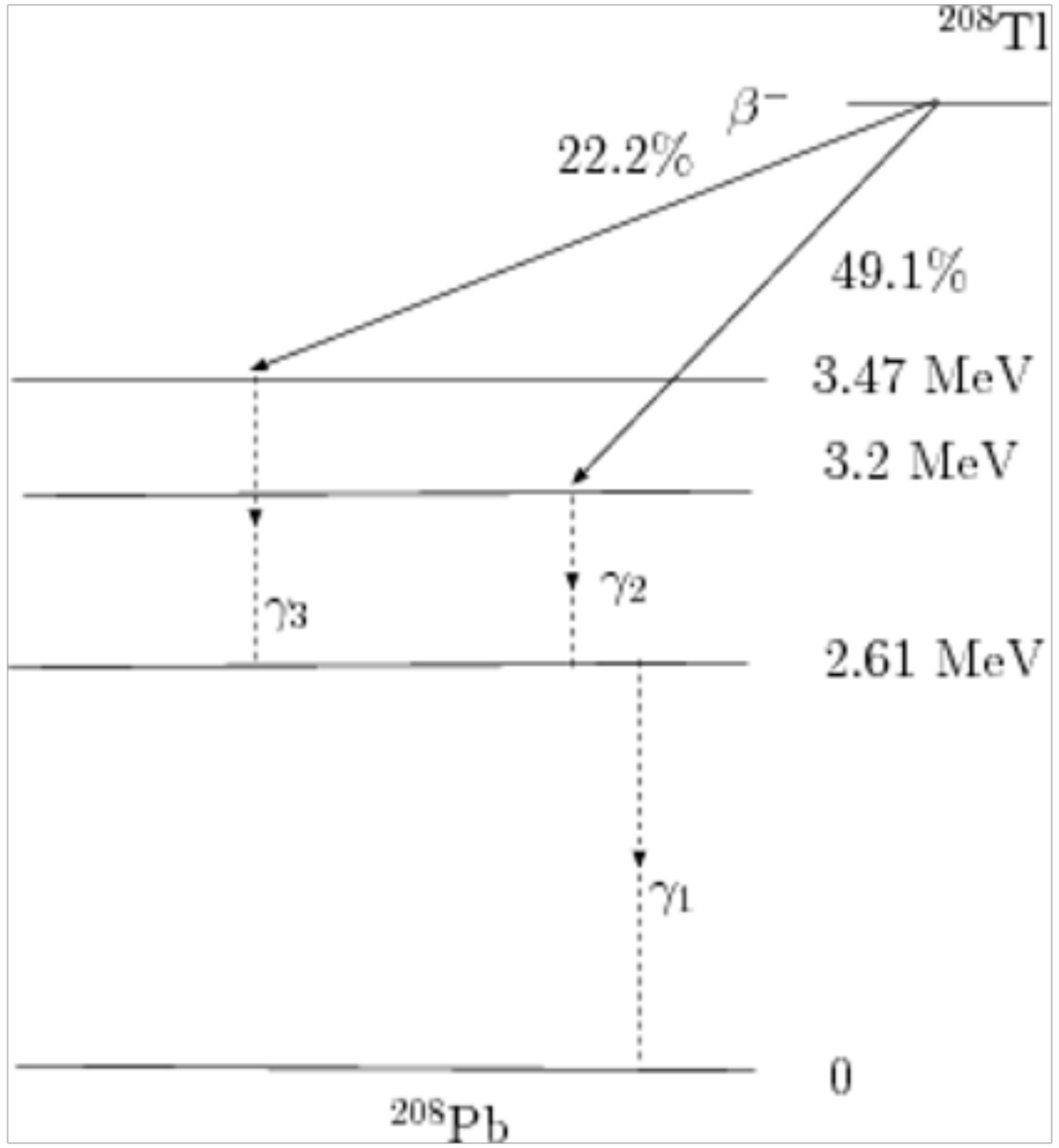
Actinium
Gamma Intensities
A = 4n + 3
25.64 14.5
84.214 6.6
Th 231
1.0633 d
185.715 57.2
143.76 10.96
163.33 5.08
205.311 5.01
109.16 1.54
202.11 1.08
U 235
7.028x10^8 a
293.56 100
271.23 8.2
517.60 4.3
776.90 3.4
1398.8 3.4
564.09 2.8
608.30 2.8
835.32 2.6
Bi 215
7.6 m
α none
β none
At 219
56 s
~97% ~3%
α none
β 50.13 36.0
β 79.72 9.1
β 234.81 3.0
β 49.89 2.7
Fr 223
21.8 m
0.006% 99.994%
α 160.26 0.0059
β none
Ac 227
21.773(3) a
1.380% 98.620%
27.36 10.29
300.07 2.47
302.65 2.19
283.69 1.70
330.06 1.40
19.00 0.374
Pa 231
3.276x10^4 a
404.853 3.78
832.01 3.52
427.088 1.76
Pb 211
36.1(2) m
438.8 ~0.040
Po 215
1.781(4) ms
271.23 10.8
401.81 6.37
Rn 219
3.96(1) s
269.459 13.70
154.21 5.62
323.871 3.93
144.232 3.22
338.281 2.79
445.031 1.27
Ra 223
11.435(4) d
235.971 12.3
50.13 8.26
256.25 7.01
329.85 2.69
300.00 2.32
286.12 1.53
Th 227
18.72(2) d
897.80 0.260
569.702 0.00159
328.12 0.00140
Tl 207
4.77 m
α 351.059 12.91
β none
Bi 211
2.14(2) m
99.724% 0.276%
Pb 207
stable
897.80 0.561
569.702 0.5
Po 211
516 ms

^{238}U Chain



Uranium – Radium
Gamma Intensities
A = 4n + 2
63.29 4.84
92.38 2.81
92.80 2.77
112.81 0.28
Th 234
24.10 d
49.55 0.064
113.5 0.010
U 238
4.468x10^9 a
1001.03 0.837
766.38 0.294
Pa 234
1.17 m
6.7 h
351.932 37.6
295.224 19.3
241.997 7.43
53.2275 1.2
785.96 1.07
Pb 214
26.8(9) m
α none
β none
Po 218
3.10(1) m
511 0.076
Rn 222
3.8235(3) d
186.211 3.59
Ra 226
1600(1) a
67.672 0.378
Th 230
7.538x10^4 a
53.20 0.123
U 234
7.455x10^5 a
799 99
298 79
1316 21
1210 17
1070 12
1110 6.9
2010 6.9
Tl 210
1.30(3) m
β 609.312 46.1
β 1764.494 15.4
β 1120.287 15.1
β 1238.110 5.79
β 2204.21 5.08
β 768.356 4.94
β 1377.669 4.00
Bi 214
19.9(4) m
0.276% 99.724%
none
At 218
1.5 s
46.539 4.25
Pb 210
22.3(2) a
799.7 0.0104
Po 214
164.3(20) us
none
Bi 210
5.013 d
Pb 206
stable
803.10 0.00121
Po 210
138.376 d

Gamma Ray Generation

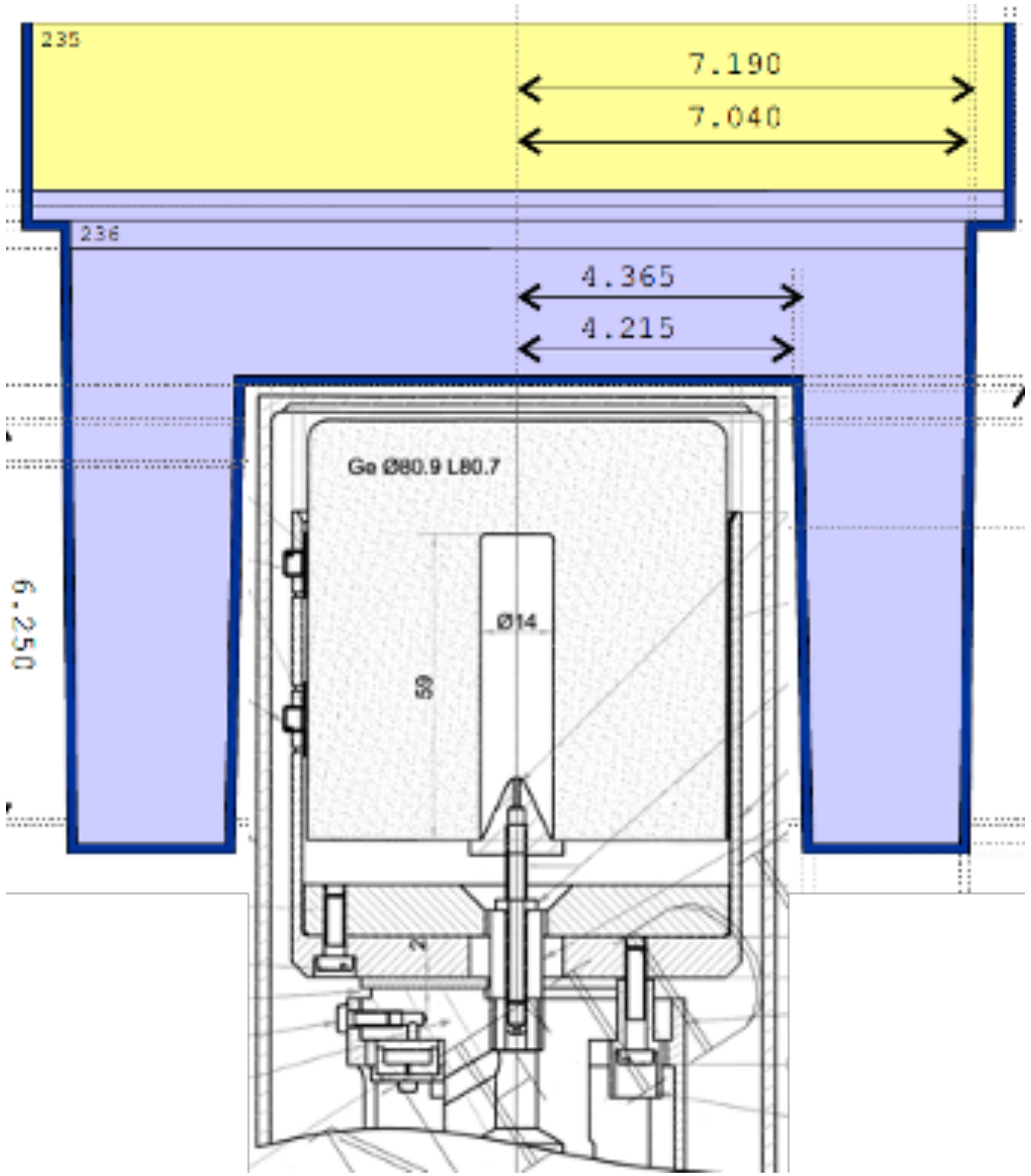


Gammas from ^{208}Tl (3.053 m 4)

Eg (keV)	Ig (%)	Decay mode
211.40 *15*	0.178 *20*	b⁻
233.36 *15*	0.307 *20*	b⁻
252.61 *10*	0.69 *4*	b⁻
277.351 *10*	6.31 *9*	b⁻
277.72		b⁻
485.95 *15*	0.050 *5*	b⁻
510.77 *10*	22.6 *3*	b⁻
583.191 *2*	84.5 *7*	b⁻
1381.1 *5*	0.007 *3*	b⁻
1647.5 *7*	0.0020 *10*	b⁻
1744.0 *7*	0.0020 *10*	b⁻
2614.533 *13*	99	b⁻

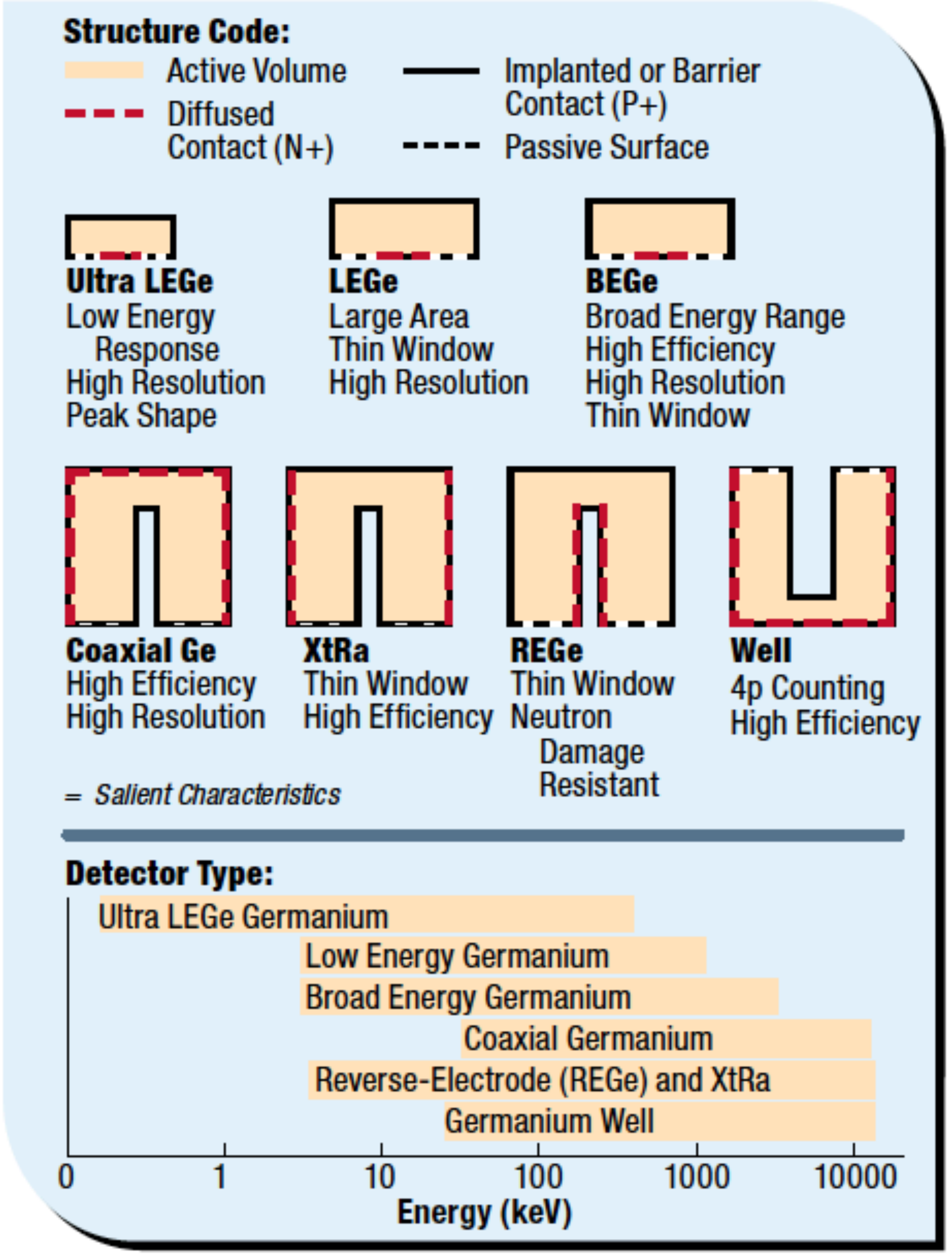
Lund/LBNL Nuclear Data
http://nucleardata.nuclear.lu.se/toi/

Gamma Ray Detection

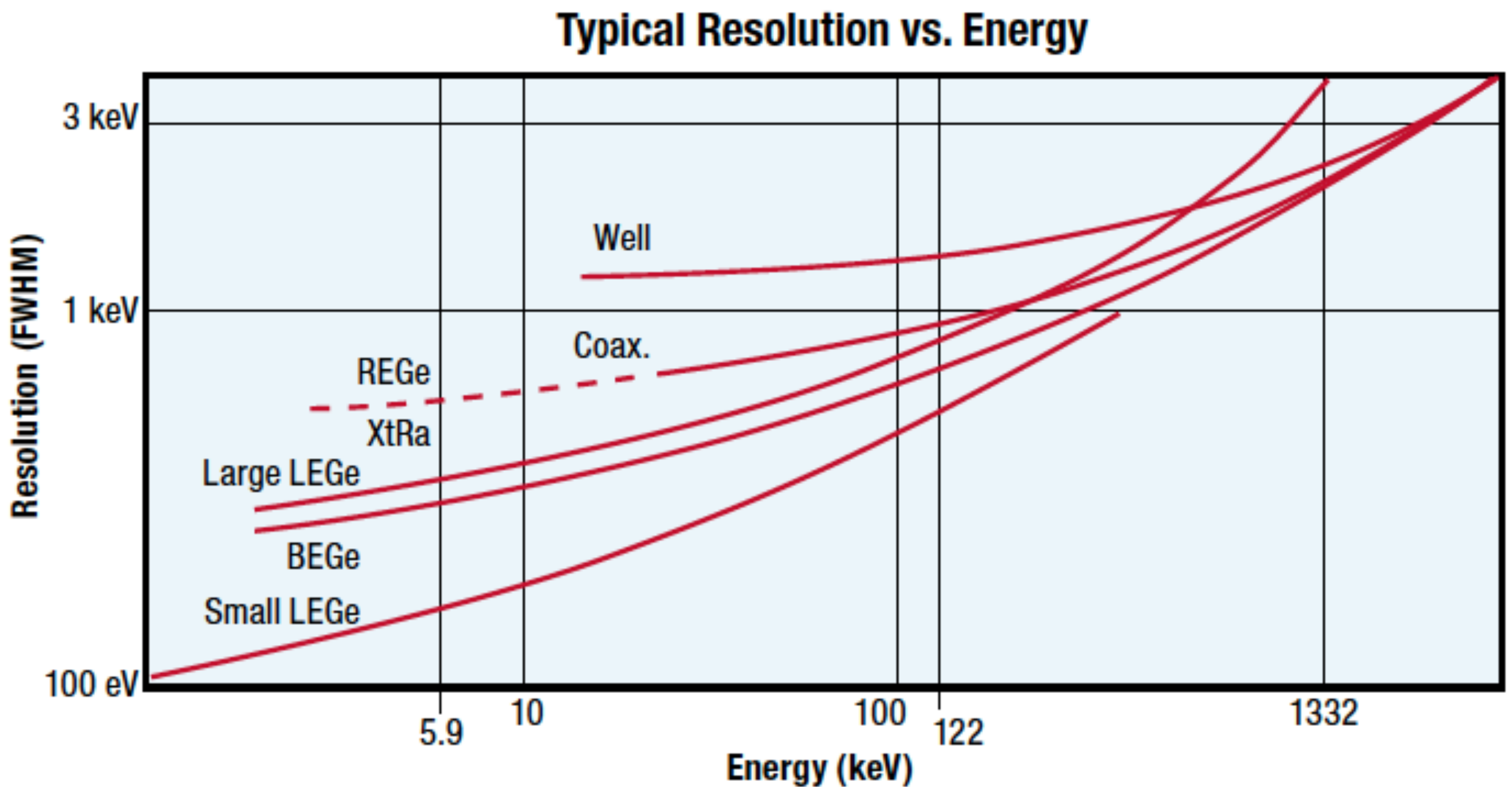


- High-purity germanium crystal detectors: Semiconductor Diodes
- Incoming gammas create holes/e- which are drifted to n/p electrodes for read-out
- Shielded with low-activity copper and lead

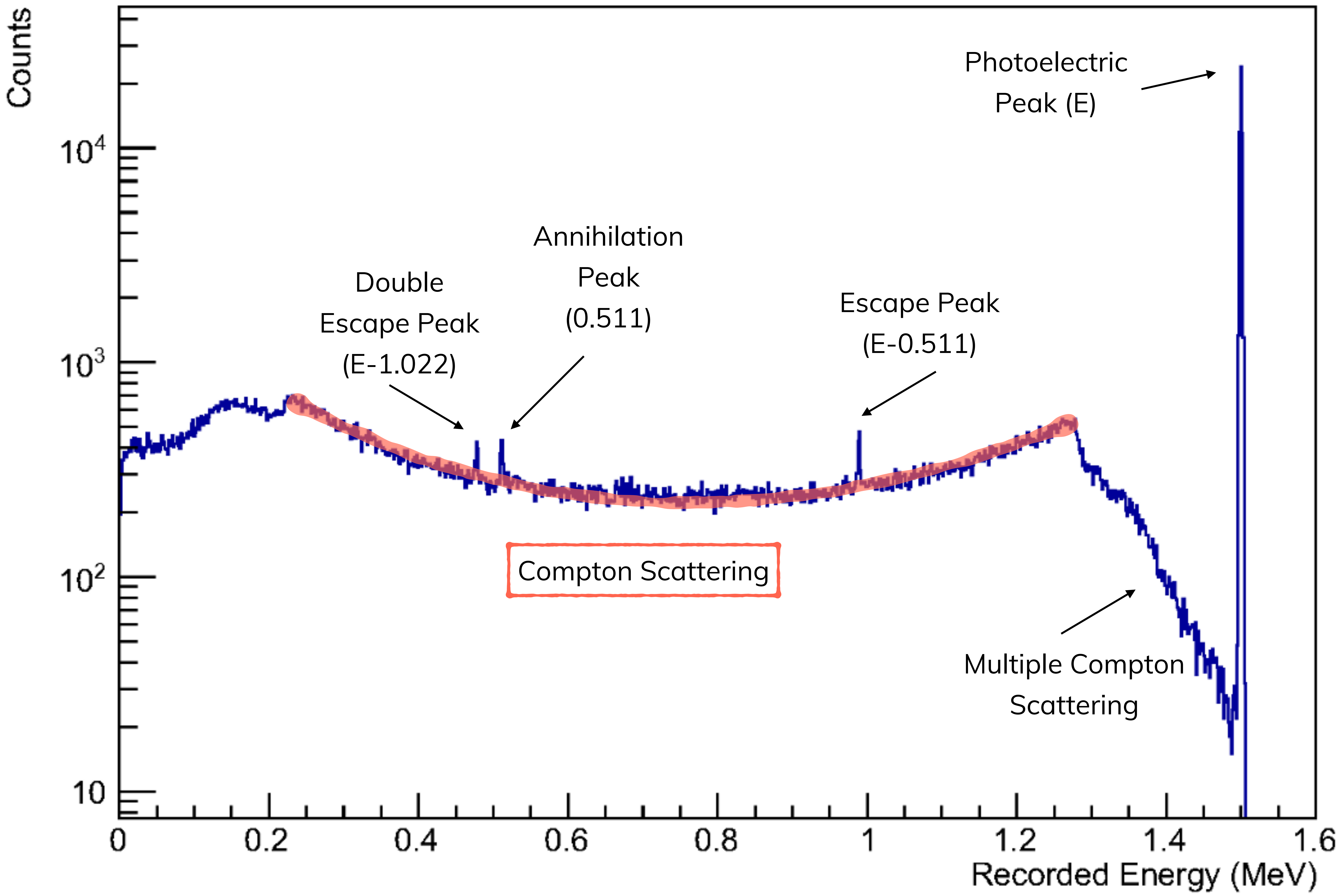
Germanium Detector Function



- Detectors must be cooled to reduce the thermal generation of charge carriers
- Liquid nitrogen, which has a temperature of 77 K is the common cooling medium
- Detector is mounted in a vacuum chamber, which is attached to or inserted into an LN_2 Dewar.



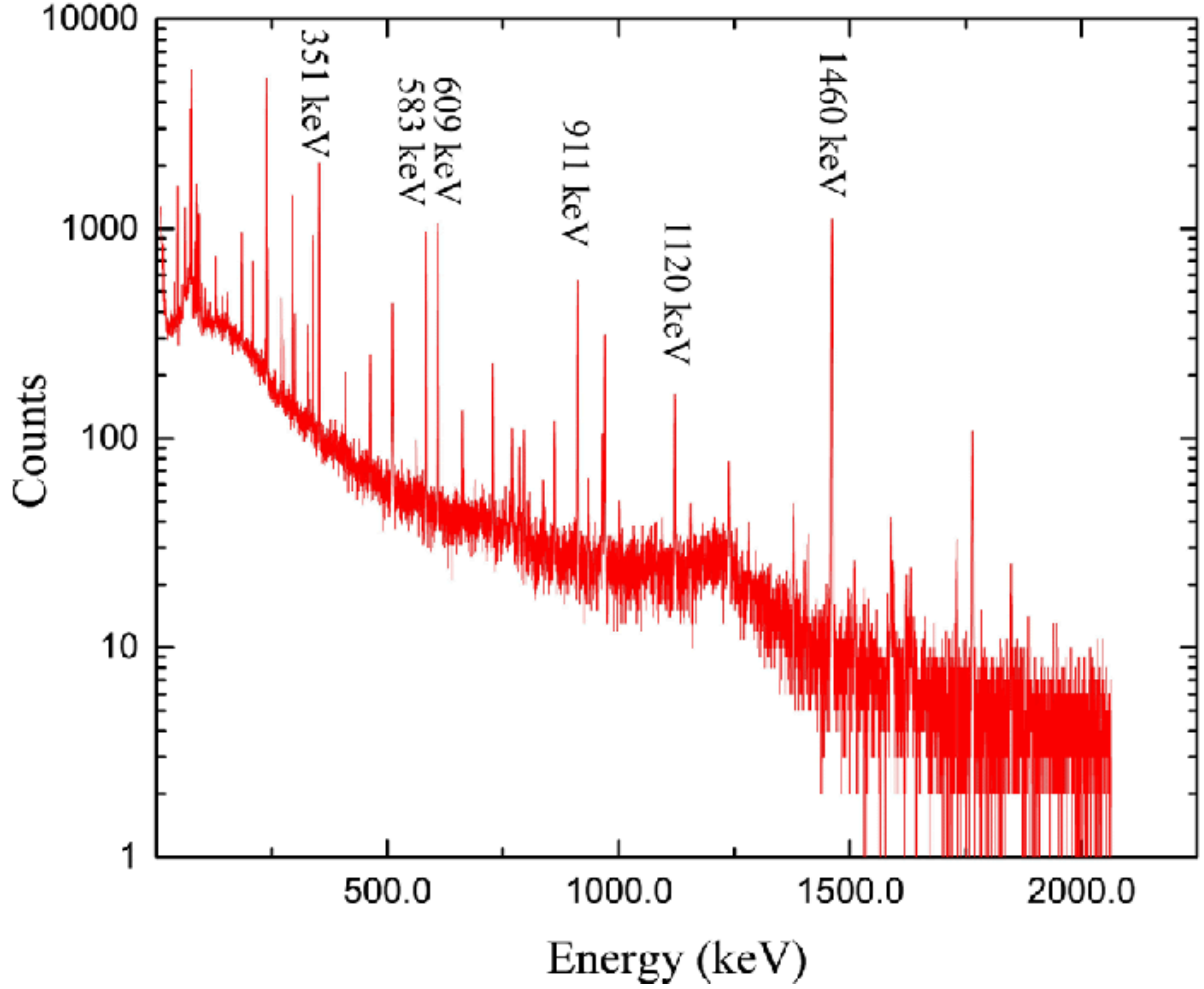
Simulation of 1.5 MeV Gamma Rays



- Line widths are usually set by the resolution of the detector.
- Germanium detectors have resolutions of 1 to 3 keV.

Analysis Method

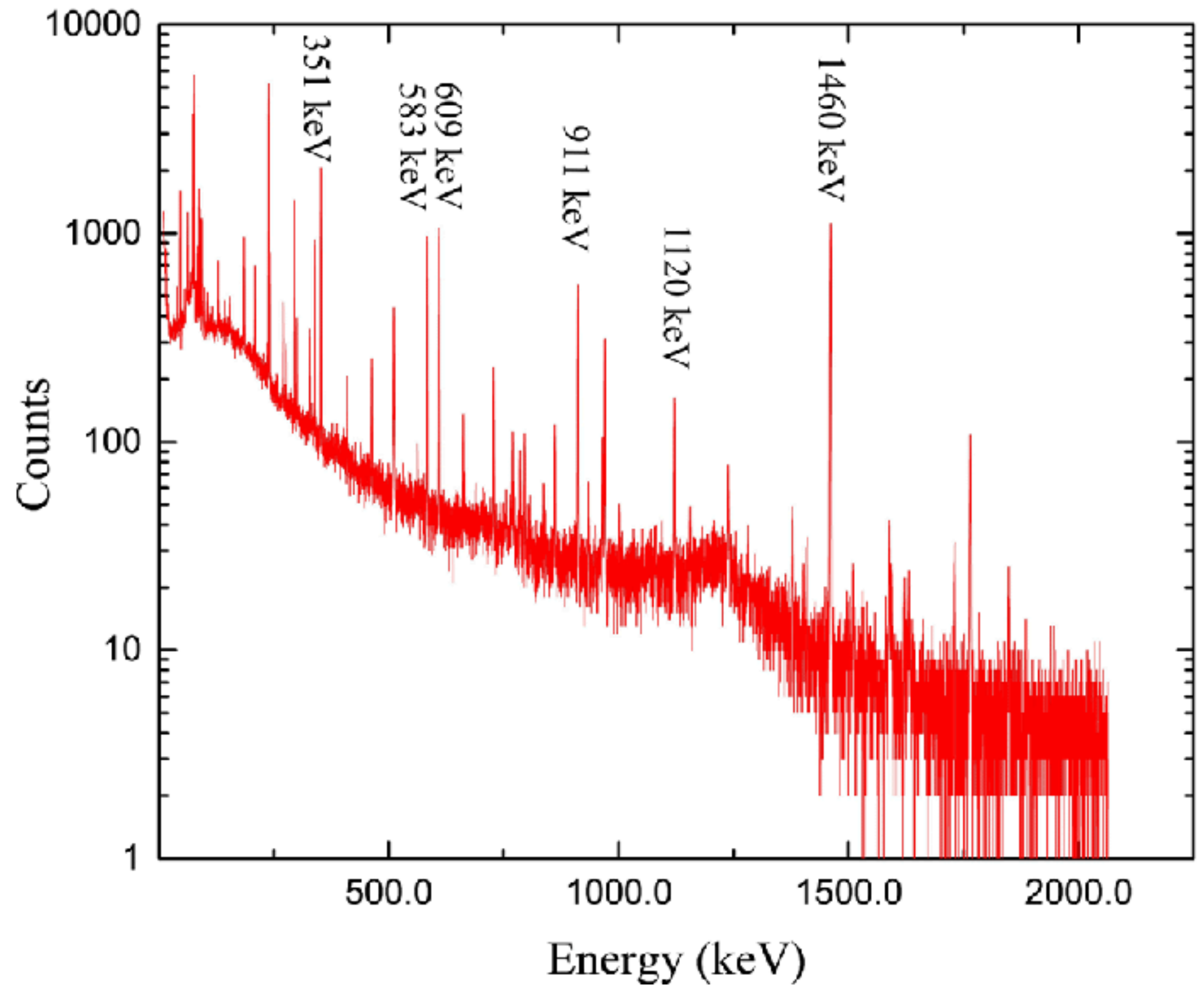
- Focus only on photoelectric peak
- Calculate number of observed events in peak
- Convert to activity for that isotope



Analysis Method

$$N = \Omega \cdot \epsilon \cdot \frac{Ig}{100} \cdot M \cdot t \cdot A$$

- N = Number of Counts
- Ω = Solid Angle factor (from Simulations)
- ϵ = Photoelectric peak efficiency (from Simulations)
- Ig = Branch Probability (from Lund database)
- M = Sample mass
- t = Data acquisition time
- A = Activity (units such as Bq/kg)



Analysis Goals

$$N = \Omega \cdot \epsilon \cdot \frac{Ig}{100} \cdot M \cdot t \cdot A$$

- What radioactive elements are present in your samples?
- What is the activity (with uncertainty) of each of these elements?
- Are these activities consistent with other measurements?
- Are there any decay chains present?
- Are the elements in the chains in equilibrium?
- Or have certain elements been concentrated or diluted?
- What are the dominant uncertainties in your analysis?

https://www.snolab.ca/~tjsonley/CAPSS2023/

CAPSS 2023 Gamma Ray Counting Exercise

Interspec Software

Each group need a copy of Interspec on one of their computers.
Windows link
Mac link
Linux link
The download website is here

Data Files

Download all of the data files in a .zip file
The unzipped data is here if you have trouble unzipping the main file.

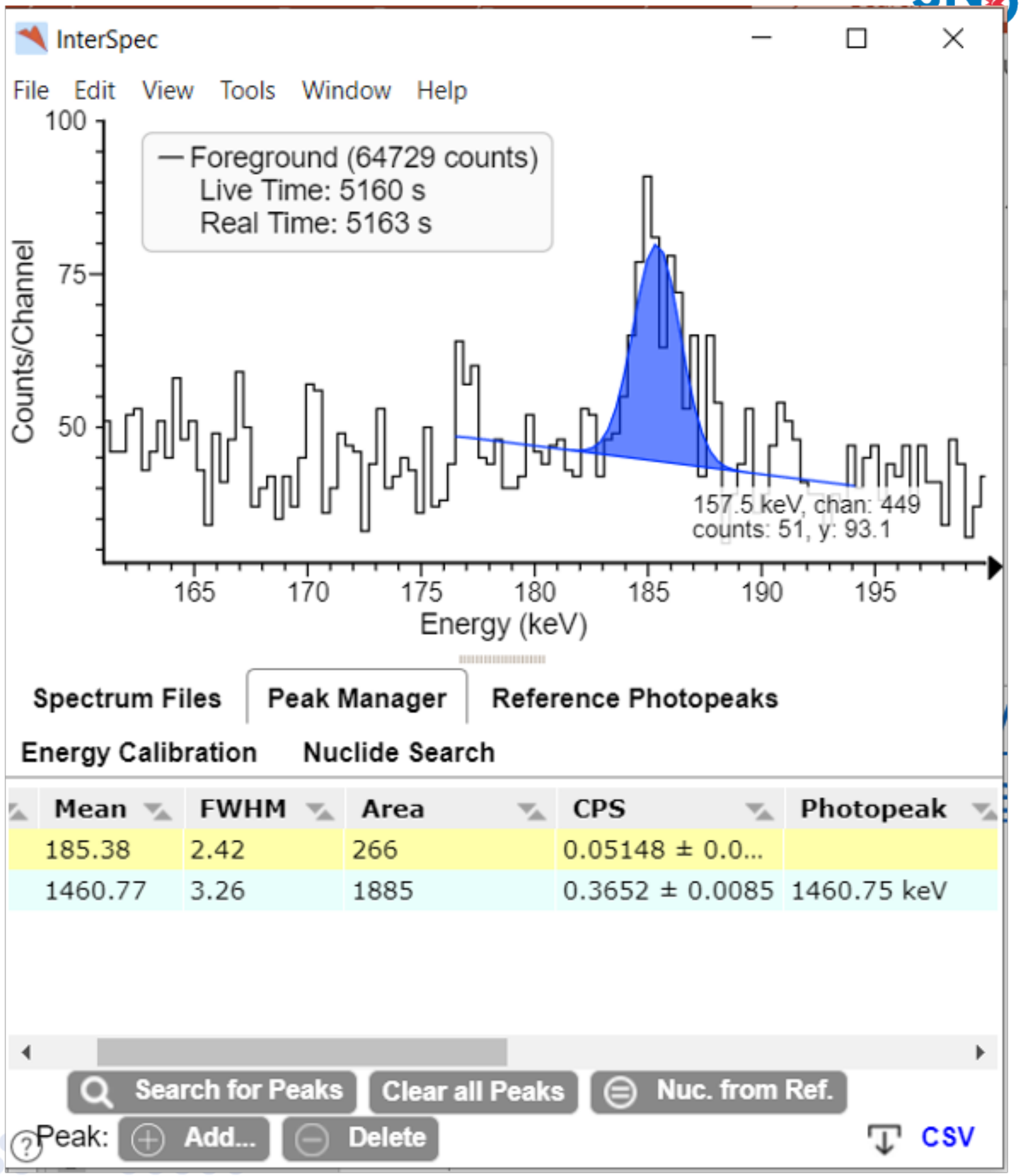
Python

We will be using python to perform part of the analysis.
There is a simple python interface using "Jupyter Notebooks" in your web browser available at https://jupyter.org/try-jupyter/lab/
Follow that link, then use the file browser to upload all of the files in the "PythonFitting" directory.
Then open CAPSS2023Notebook.ipynb.

Now, highlight each of the cells in order and click the "play" button above to execute the code.
The first box should take 30 seconds or so to run, but the others should be fast.
You will see the marker in front of the box go from [] before hitting play,
to [*] while the code is running,
to [1] or [2] when the code has finished.
You can change any of the lines and rerun that cell to see how it changes the output.

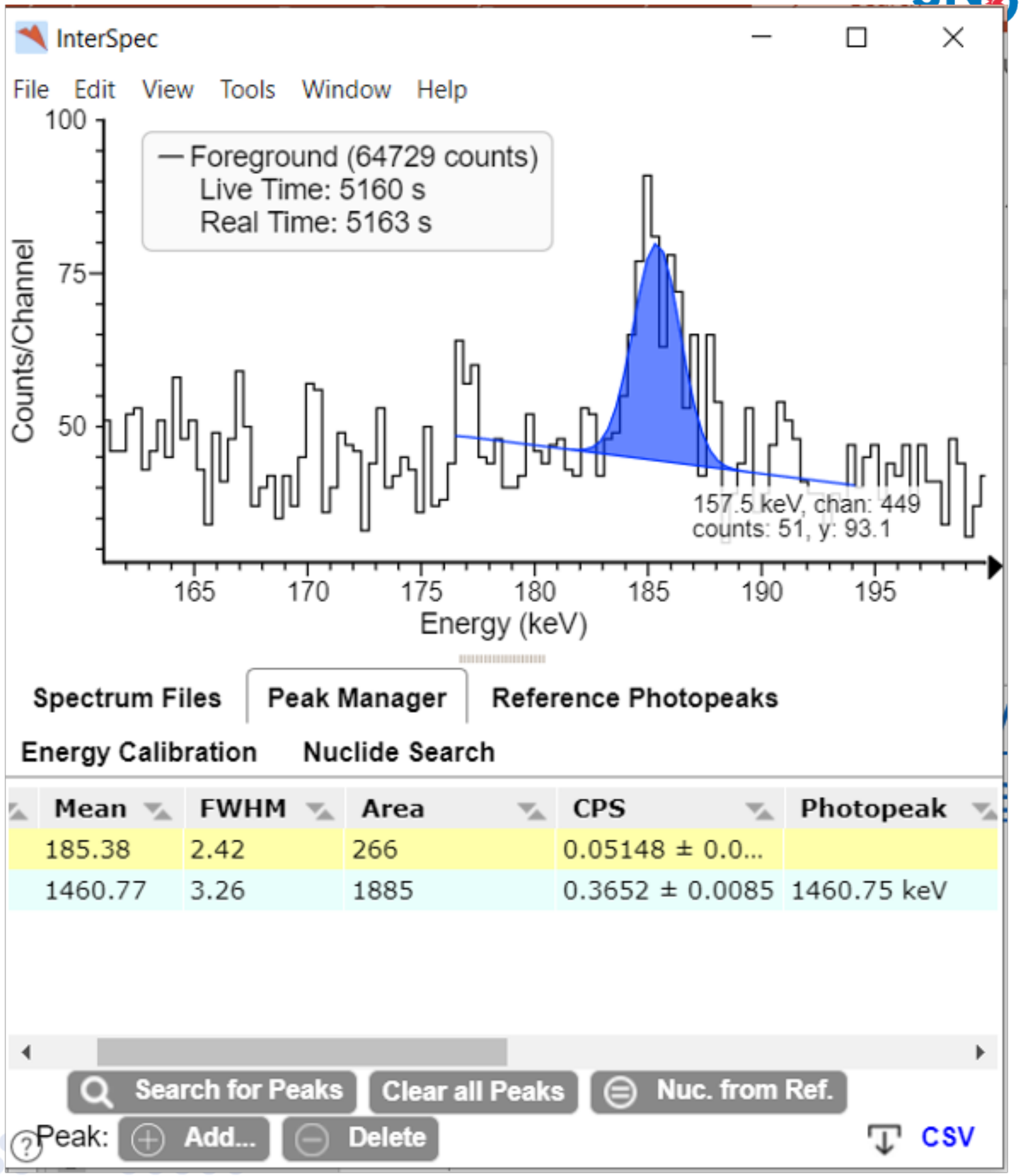
InterSpec

- https://github.com/sandialabs/interspec/releases
- Can open many data formats
- Automatic Peak Fitting
- Automatic Background Subtraction
- Library of Gamma Ray Nuclides



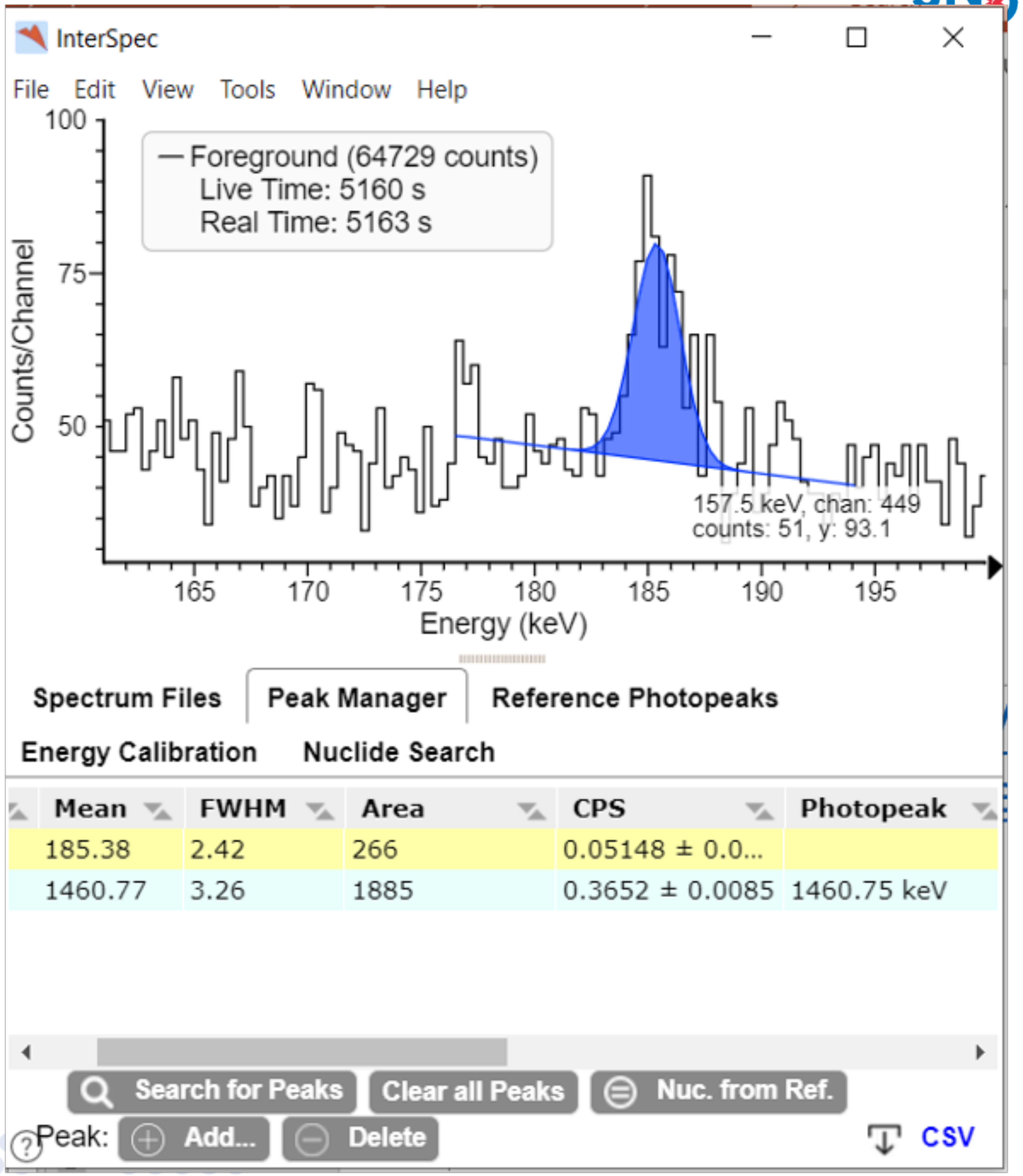
InterSpec

- Open the Rain_Water.chn file
- View -> Chart Options -> Linear Y-Scale
- Zoom in by dragging right
- Zoom out by dragging left
- Double-click on a peak to fit it
- Details show up in the bottom peak manager
- Right-click on a peak to refit
- Library of Gamma Ray Nuclides



InterSpec

- Use Nuclide Search tab to identify peaks
  - Click on peak to automatically fill energy
  - Search for decays with high “Rel B.R.” = Relative Branching Ratio
  - InterSpec will sometimes list multiple “Parents” for the same decay. Just choose one.

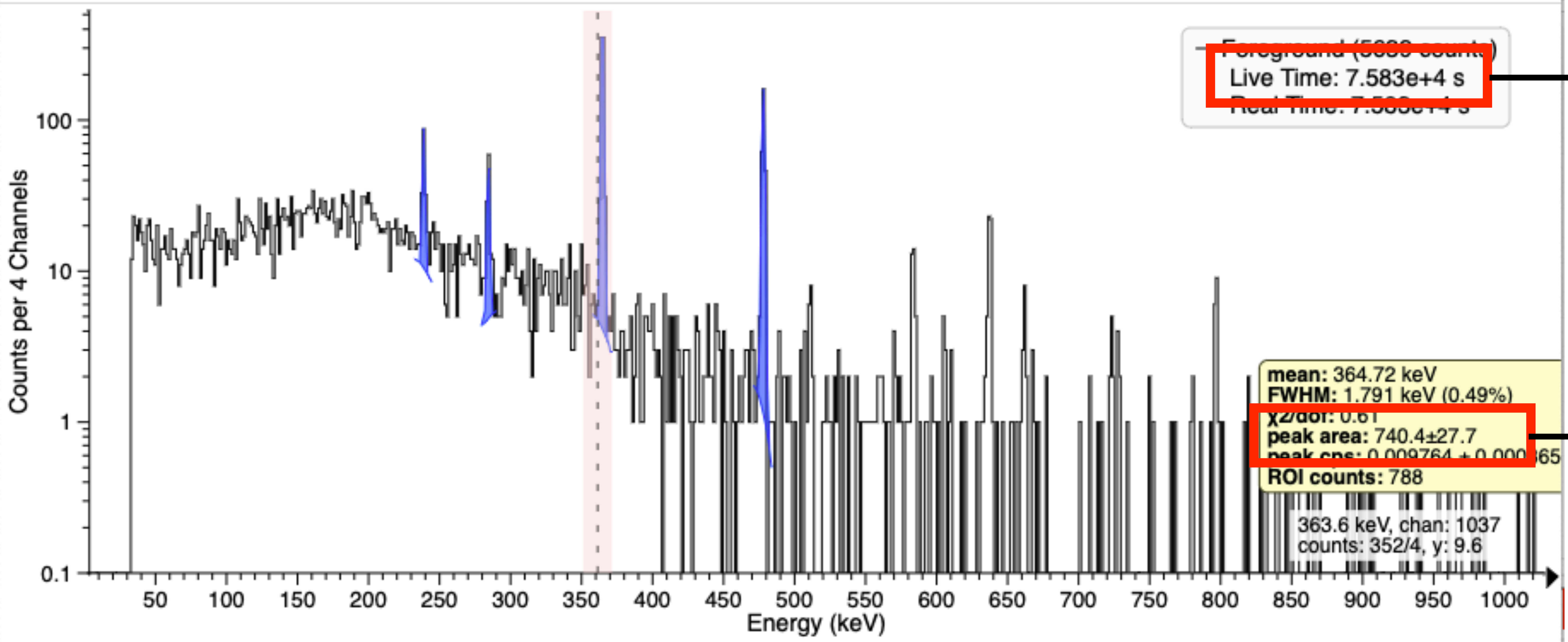


InterSpec Parameters (1)

$$N = \Omega \cdot \epsilon \cdot \frac{Ig}{100} \cdot M \cdot t \cdot A$$

SNOLAB

InterSpec



t=Time of sample taking

N = Peak Area

Spectrum Files | Peak Manager | Reference Photopeaks | Energy Calibration | Nuclide Search

Energy 361.349 +/- 10 keV

Parent	Energy (keV)	Diff.	Rel. B.R.	Profile	Decay
Gd159	363.54	2.19	1.00	0.95	Gd159→Tb159
I131	364.49	3.14	1.00	0.90	I131→Xe131
Re181	360.70	0.65	0.35	0.18	Re181→W181
Ta183	353.99	7.36	0.42	-0.18	Ta183→W183
Ba133	356.02	5.33	1.00	-0.21	Ba133→Cs133
Pd103	357.45	3.90	0.32	-0.23	Pd103→Rh103
Au196	355.73	5.62	1.00	-0.25	Au196→Pt196
Re183	354.00	7.35	0.02	-0.32	Re183→W183
Md258	367.80	6.45	1.00	-0.32	Md258→Es254m

Gammas X-rays Reactions

Min. BR 0 Min. HL 6000 s

Energy &

Decay

InterSpec Parameters (2)

Spectrum Files | Peak Manager | Reference Photopeaks | Energy Calibration | **Nuclide Search**

Energy 361.349 +/- 10 keV

☑ Gammas ☑ X-rays ☐ Reactions

Min. BR 0 Min. HL 6000 s

Parent	Energy (keV)	Diff.	Rel. B.R.	Profile	Decay
Gd159	363.54	2.19	1.00	0.95	Gd159→Tb159
I131	$\boxed{364.49}$	3.14	1.00	0.90	$\boxed{\text{I131→Xe131}}$
Re181	360.70	0.65	0.35	0.18	Re181→W181
Ta183	353.99	7.36	0.42	-0.18	Ta183→W183
Ba133	356.02	5.33	1.00	-0.21	Ba133→Cs133
Pd103	357.45	3.90	0.32	-0.23	Pd103→Rh103
Au196	355.73	5.62	1.00	-0.25	Au196→Pt196
Re183	354.00	7.35	0.02	-0.32	Re183→W183
Md258	367.80	6.45	1.00	-0.32	Md258→Es254m

From File Info:
M = 856.9 g

Energy & Decay give
Branch Probability

$$N = \Omega \cdot \epsilon \cdot \frac{Ig}{100} \cdot M \cdot t \cdot A$$

Gammas from ^{131}I (8.02070 d *11*)

Eg (keV)	Ig (%)	Decay mode
80.185 *2*	2.62 *3*	b^-
85.9 *2*	0.00009 *5*	b^-
163.930 *8*		b^-
177.214 *2*	0.270 *3*	b^-
232.18 *15*	0.0032 *4*	b^-
272.498 *17*	0.0578 *11*	b^-
284.305 *5*	6.14 *5*	b^-
295.8 *2*	0.0018 *8*	b^-
302.4 *2*	0.0047 *6*	b^-
318.088 *16*	0.0776 *16*	b^-
324.651 *25*	0.0212 *25*	b^-
325.789 *4*	0.274 *21*	b^-
358.4 *2*	0.016 *6*	b^-
364.489 *5*	81.7 *6*	b^-
404.814 *4*	0.0547 *16*	b^-
503.004 *4*	0.360 *3*	b^-
636.989 *4*	7.17 *9*	b^-
642.719 *5*	0.217 *4*	b^-
722.911 *5*	1.773 *25*	b^-

Simulation Parameters

$$N = \Omega \cdot \epsilon \cdot \frac{Ig}{100} \cdot M \cdot t \cdot A$$

- The product ($\Omega \cdot \epsilon$) is calculated by simulation
- https://www.snolab.ca/~tjsonley/CAPSS2023/

Python

We will be using python to perform part of the analysis.
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to [*] while the code is running,
to [1] or [2] when the code has finished.
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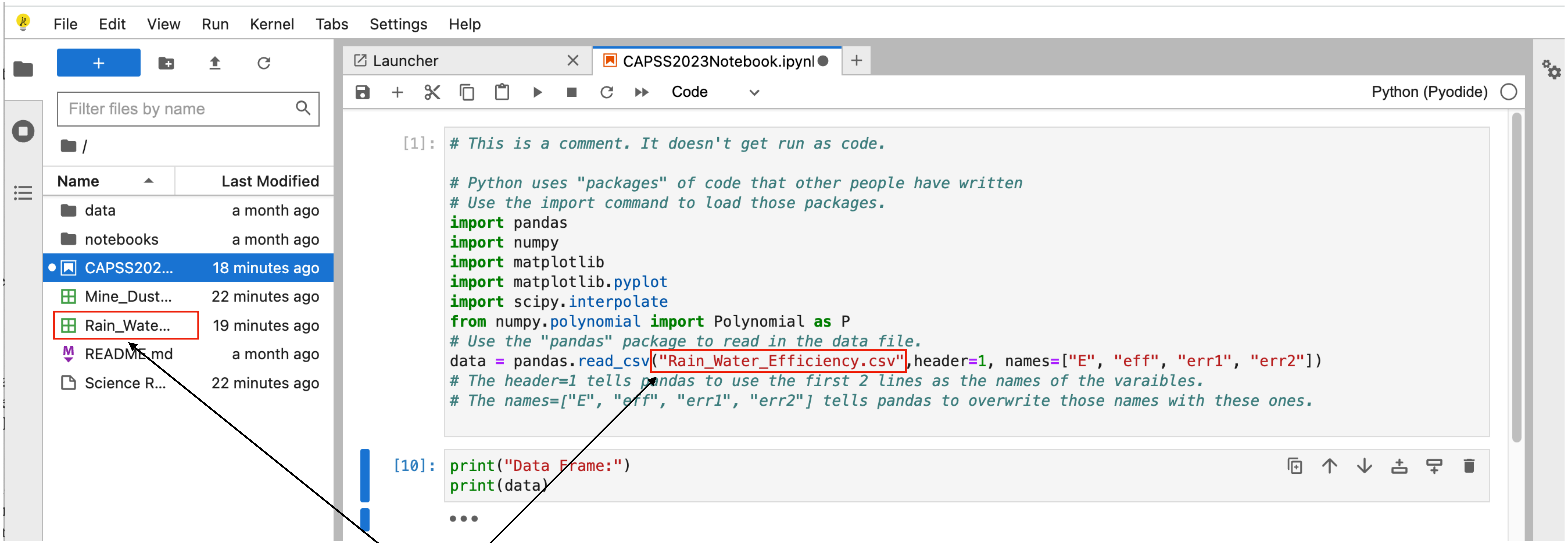
Simulation Parameters

$$N = \Omega \cdot \epsilon \cdot \frac{Ig}{100} \cdot M \cdot t \cdot A$$



- Change the input Efficiency file to the one for the data you are analyzing
- Go through the notebook and find the efficiency at the energy of the given peak
- Repeat for every peak!

Analysis Goals

$$N = \Omega \cdot \epsilon \cdot \frac{Ig}{100} \cdot M \cdot t \cdot A$$

- What radioactive elements are present in your samples?
- What is the activity (with uncertainty) of each of these elements?
- Are these activities consistent with other measurements?
- Are there any decay chains present?
- Are the elements in the chains in equilibrium?
- Or have certain elements been concentrated or diluted?
- What are the dominant uncertainties in your analysis?

Error Propagation

$$F = f(a, b)$$

$$\sigma_F^2 = \left(\frac{\partial F}{\partial a} \cdot \sigma_a\right)^2 + \left(\frac{\partial F}{\partial b} \cdot \sigma_b\right)^2$$

$$F = \frac{ab}{c}$$

$$\sigma_f^2 = F^2\left(\frac{\sigma_a^2}{a^2} + \frac{\sigma_b^2}{b^2} + \frac{\sigma_c^2}{c^2}\right)$$

Measurement precision is given by $\frac{\sigma_f}{F}$:

Error Comparisons

$$\frac{\sigma_f^2}{F^2} = \left(\frac{\partial F}{\partial a} \cdot \frac{\sigma_a}{F}\right)^2 + \left(\frac{\partial F}{\partial b} \cdot \frac{\sigma_b}{F}\right)^2$$

Error Source	Uncertainty (%)
Uncertainty on Counts	10.2
Detection Efficiency	5
Branching Ratio	1
Sample Mass	0.1
Livetime	0.001
Total	11.4

- Usually summarized in an Error Table
- Since they are added in quadrature, only the largest ones matter.
- e.g. “Uncertainty on Counts” contributes 80% of the total

Error Rules of Thumb

Measurement precision is given by $\frac{\sigma_f}{F}$:

$$\frac{\sigma_f^2}{F^2} = \left(\frac{\partial F}{\partial a} \cdot \frac{\sigma_a}{F}\right)^2 + \left(\frac{\partial F}{\partial b} \cdot \frac{\sigma_b}{F}\right)^2$$

- Dominant Uncertainties
  - > 1/3 of max uncertainty
  - These must be addressed to improve the measurement
  - Papers and reports must describe how these were estimated
- Secondary Uncertainties
  - 1/3 to 1/10 of max uncertainty
  - These could become dominant in an improved measurement
  - Reports should describe the general method used to estimate them (repeated measurements, simulations, etc.)
- Negligible Uncertainties
  - < 1/10 of max uncertainty
  - They must go in the error table
  - Reports should spend less than 1 sentence describing them.