The University Of Sheffield.

Gadolinium Radiopurity Assay Programme for Super-Kamiokande

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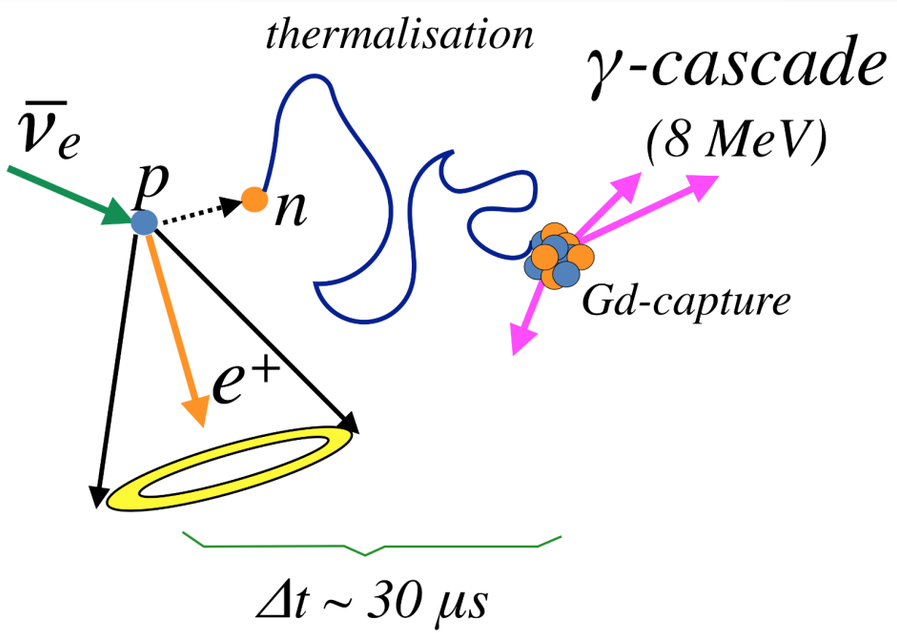
Gadolinium in Water Cherenkov Detectors

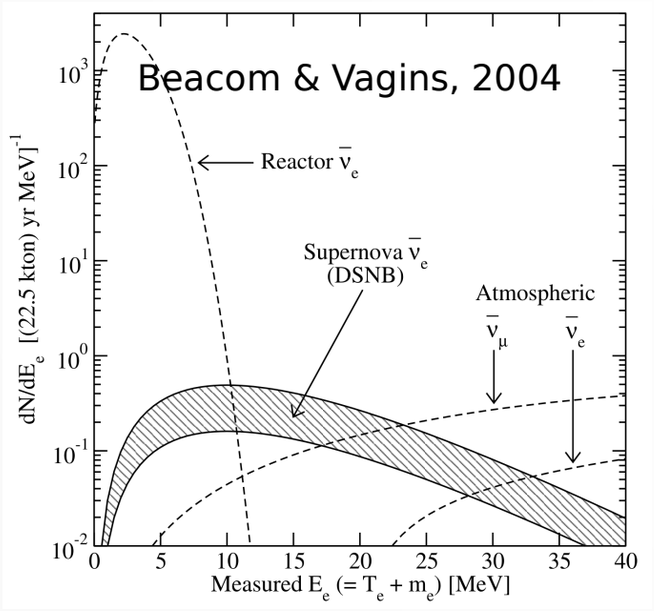
Why?

- Neutron capture cross-section on Gd: 48800 b.
- Tag neutrons from IBD by low energy $\bar{\nu}$s (1.8 → 100 MeV).
- Discern $\nu+n\rightarrow p+e^-$ from $\bar{\nu}+p\rightarrow n+e^+$ CCQE scattering.

Gd-doping (theoretically) allows:

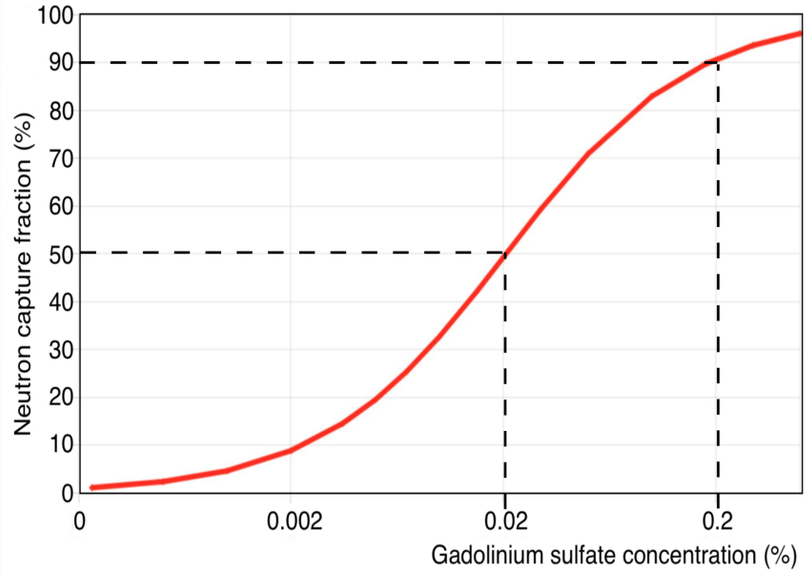
- Diffuse Supernova Background (DSNB) $\bar{\nu}$ discovery.
- Supernova Early Warning, Si Burning.
- Proton Decay veto.
- Moderate benefits to other ν oscillation physics.





SK-Gd Project

- $Gd_2(SO_4)_3$ soluble, non-corrosive, and does not affect water transparency.
- EGADS: R&D established feasibility of water systems, purification and Gd loading/removal.
- 0.2% loading of SK, beginning 2018.



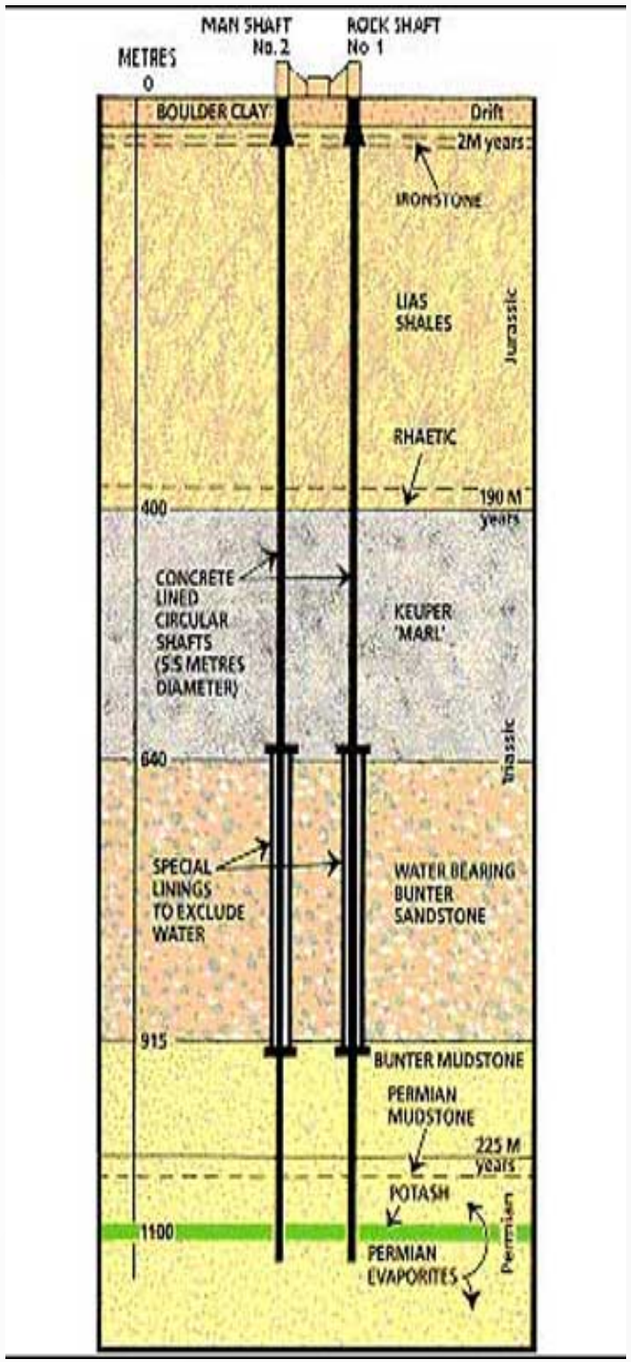
Impact of Gd Radioactivity on Physics

- Natural earth radiological backgrounds in $Gd_2(SO_4)_3$ present throughout SK FV.
- Neutron tagging w/ Gd removes many backgrounds, but adds new irreducible sources:
  - ^{238}U spontaneous fission, mimics IBD,
  - H.E. β-decays ($Q_\beta > 2$ MeV), mimics solar ν elastic scattering,
  - (α,n) interaction + solar ν candidate, mimics IBD.
- Need to reduce natural backgrounds in $Gd_2(SO_4)_3$,
  - During processing of raw Gd ore,
  - Anion exchange resin.

Radioactive chain	Part of the chain	SRN (mBq/kg)	Solar ν (mBq/kg)
^{238}U	^{238}U	< 5	-
	^{226}Ra	-	< 0.5
^{232}Th	^{228}Ra	-	< 0.05
	^{228}Th	-	< 0.05
^{235}U	^{235}U	-	< 3
	^{227}Ac / ^{227}Th	-	< 3

Boulby Mine and Lab

- Working potash (KCl) mine on coast of N. York Moors.
- STFC Lab located 1100m underground (2805 m.w.e.).
- Low cosmic muon, radon, and natural radioactive backgrounds in the lab.
  - U, 67 ppb, – Rn, <3 Bqm^{-3},
  - Th, 125 ppb, – Low γ, n.
  - Exception: High ^{40}K from potash.
- Site of experiments:
  - DRIFT-IId,
  - ULB Ge Materials Screening,
  - Muon tomography for CCS,
  - Environmental gamma spec,
  - Astrobiology,
  - Space Exploration Tech. Dev.,
  - Life in low background radiation.

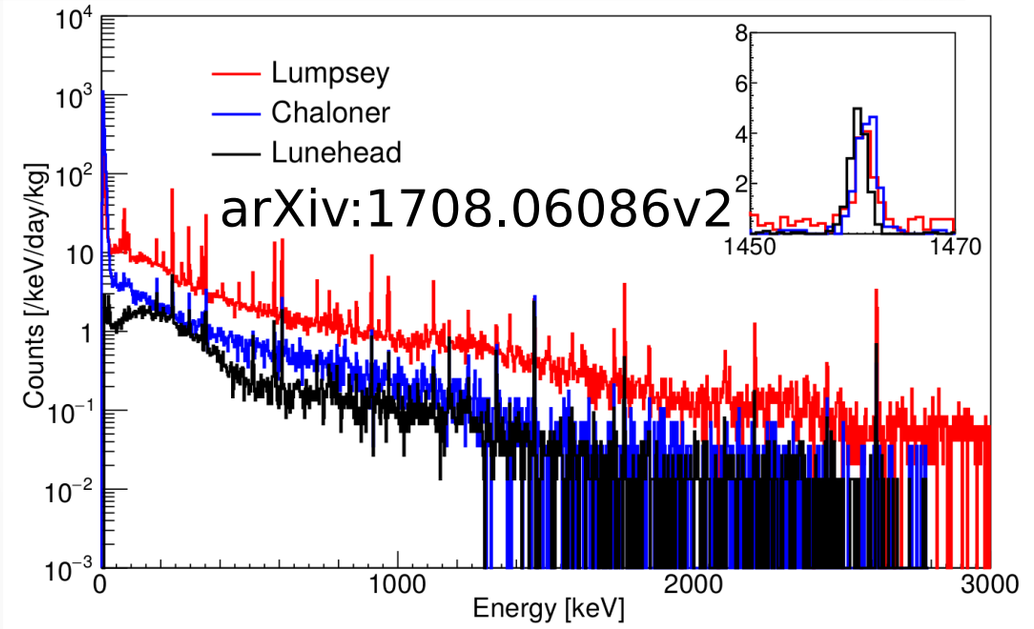


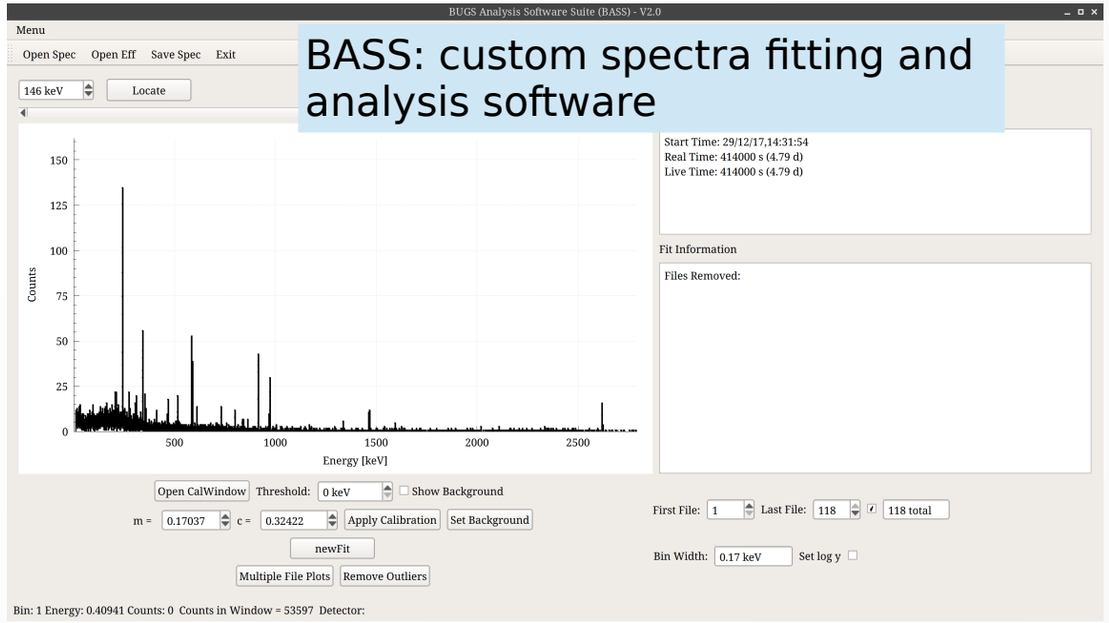
Boulby Underground Germanium Suite (BUGS)

- ISO class 1000 clean room.
- 6 HPGe detectors in operation:

Chaloner	BEGe	0.8 kg	48% rel. eff.
Lumpsey	SAGe-Well	1.5 kg	69% rel. eff.
Lunehead	p-type Coax	2.0 kg	92% rel. eff.
Roseberry	BEGe	0.9 kg	58% rel. eff.
Merrybent	p-type Coax	2.0 kg	112% rel. eff.
Belmont	p-type Coax	3.2 kg	171% rel. eff.

New Extra-ULB

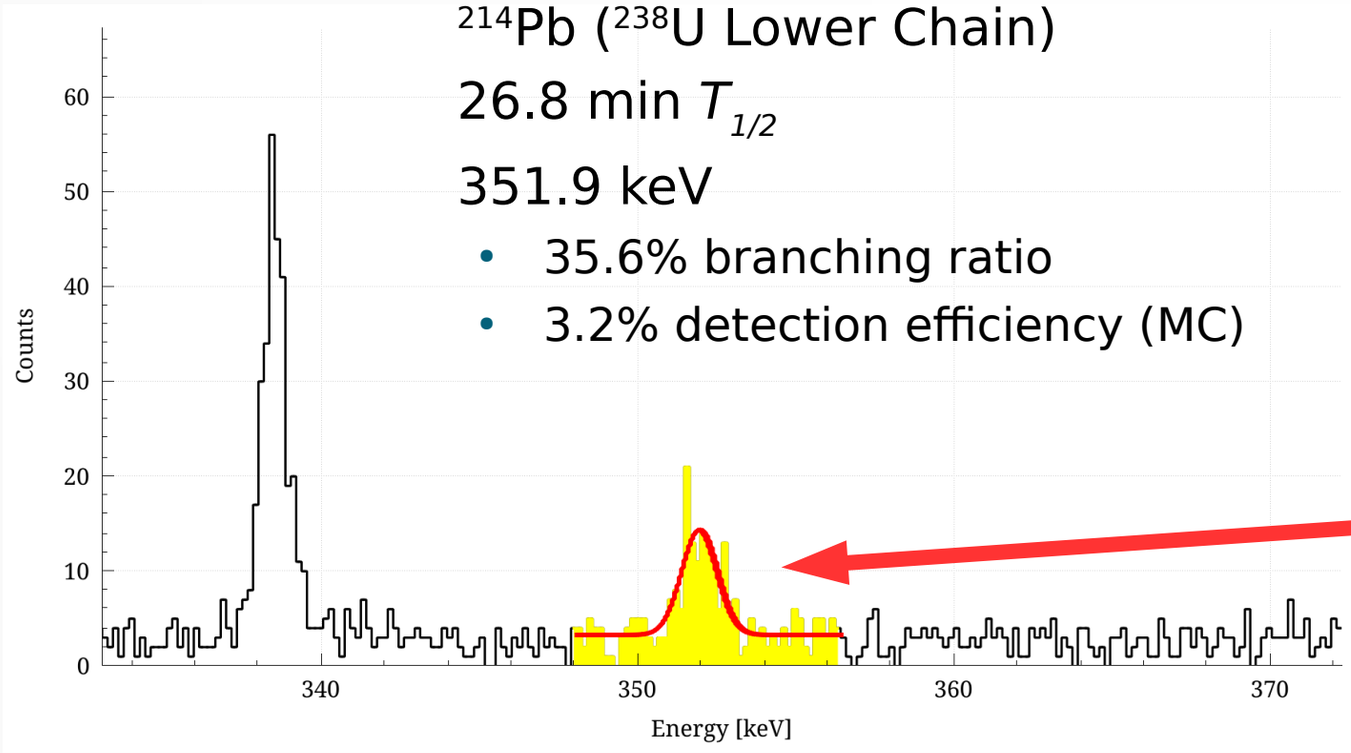




BASS: custom spectra fitting and analysis software

Uranium-238

- 2.4 kg sample of $Gd_2(SO_4)_3$ measured on Lunehead.
- Sample measured for 4.92 days.
- Background measured for 7.85 days, w/o sample.

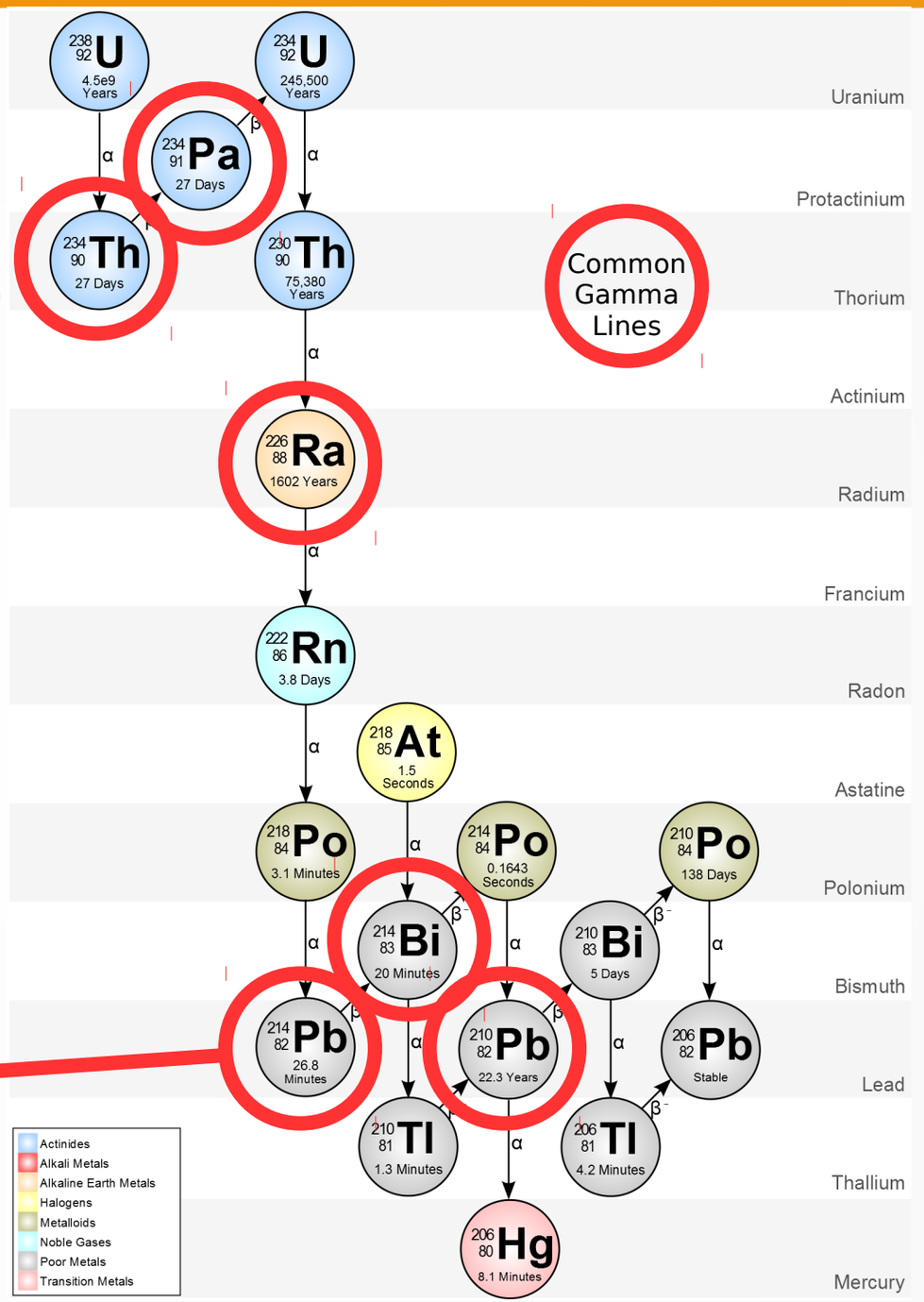


^{214}Pb (^{238}U Lower Chain)

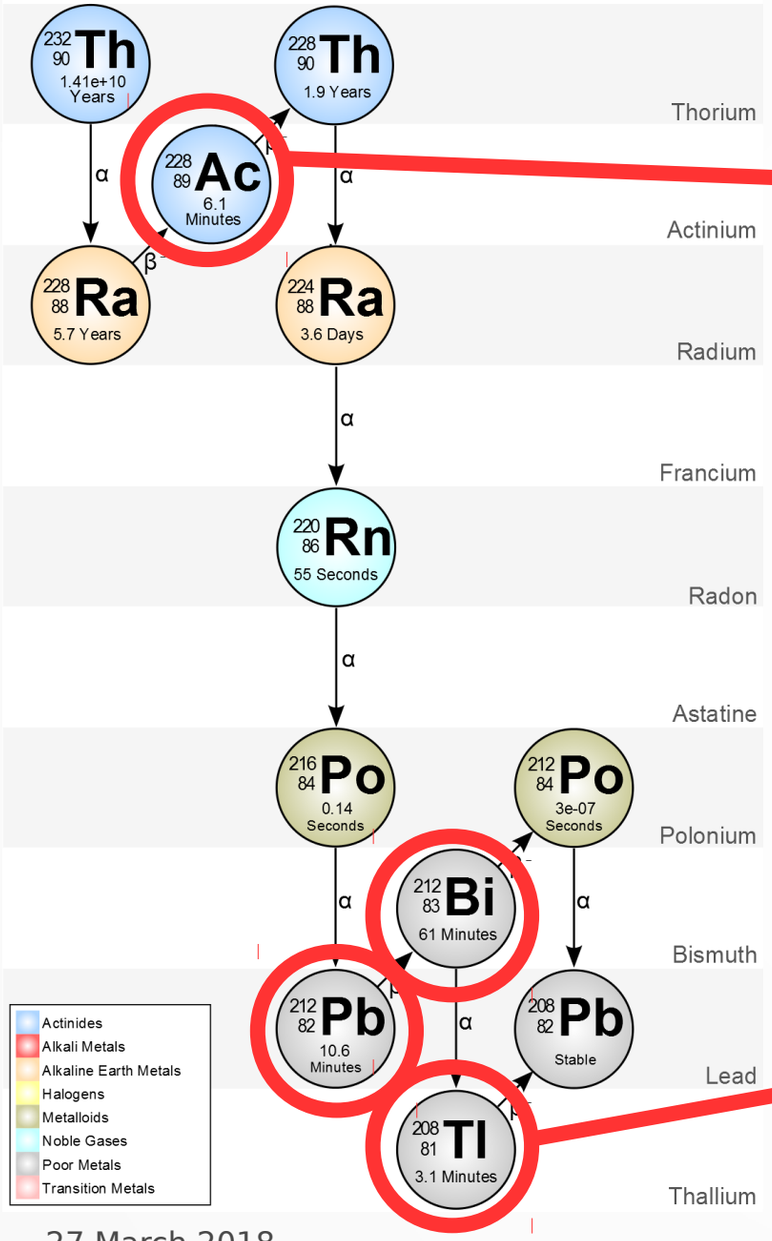
26.8 min $T_{1/2}$

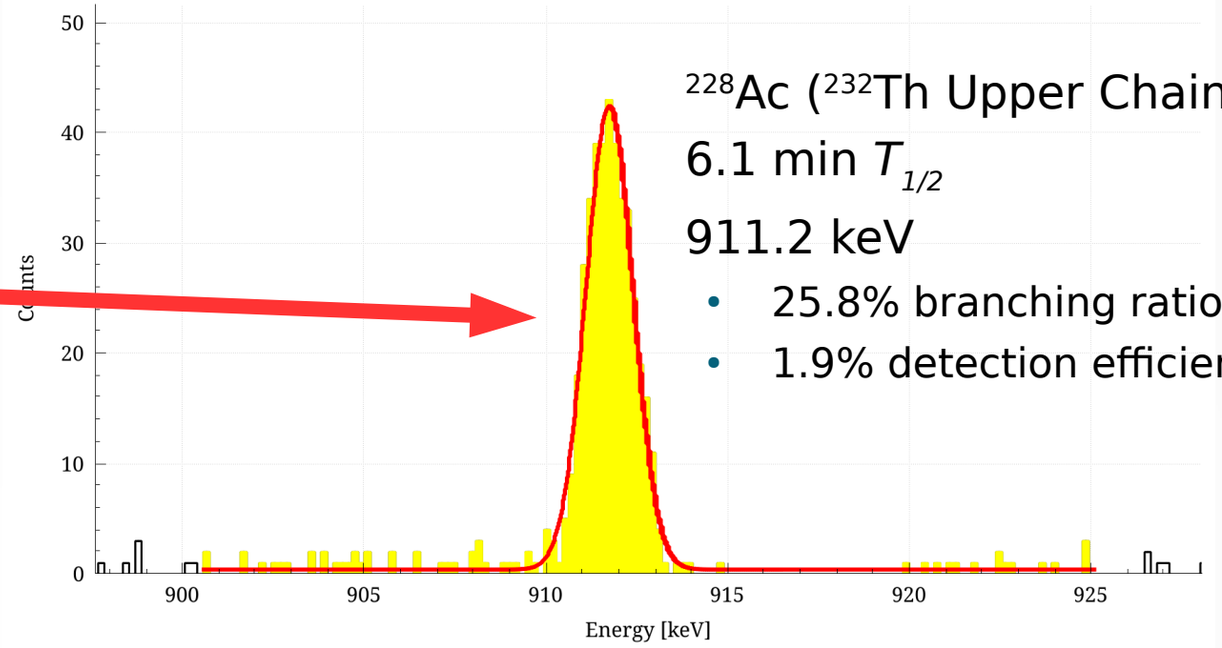
351.9 keV

- 35.6% branching ratio
- 3.2% detection efficiency (MC)



Thorium-232



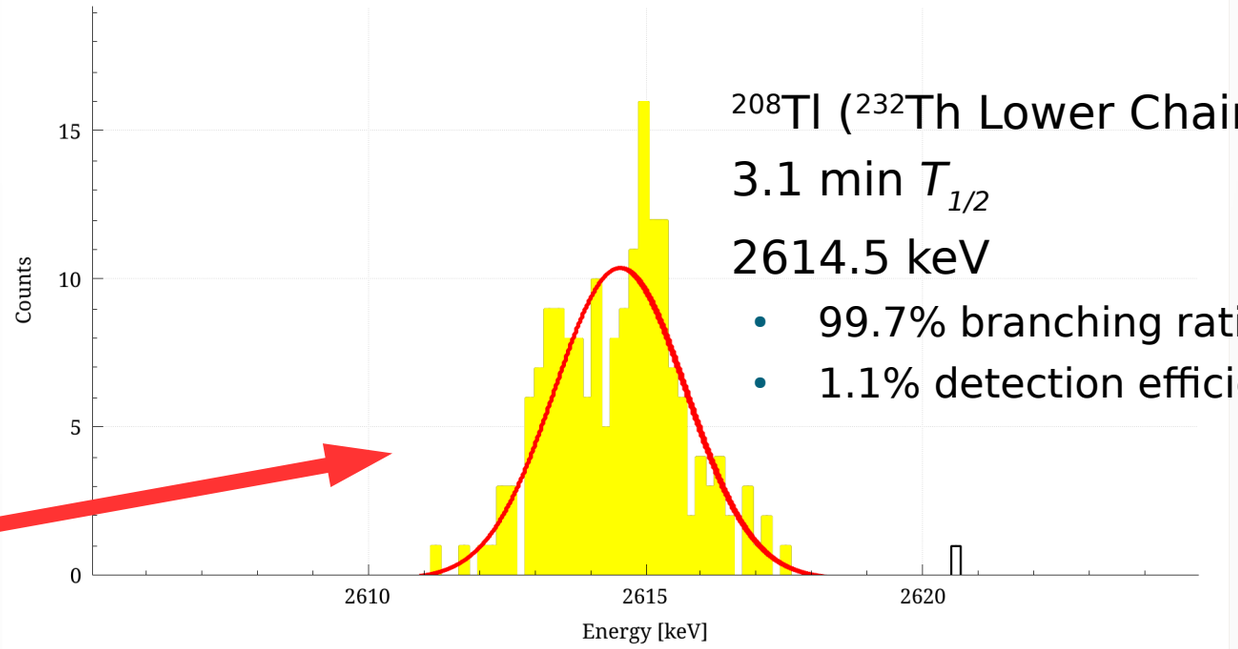


^{228}Ac (^{232}Th Upper Chain)

6.1 min $T_{1/2}$

911.2 keV

- 25.8% branching ratio
- 1.9% detection efficiency (MC)



^{208}Tl (^{232}Th Lower Chain)

3.1 min $T_{1/2}$

2614.5 keV

- 99.7% branching ratio
- 1.1% detection efficiency (MC)

Other Interesting Isotopes

- No evidence of ^{235}U activity in sample.
- Other isotopes present:
  - ^{60}Co, common impurity in copper (part of the detector shielding) due to activation,
  - ^{40}K, from rock walls, primordial,
  - ^{176}Lu, primordial.

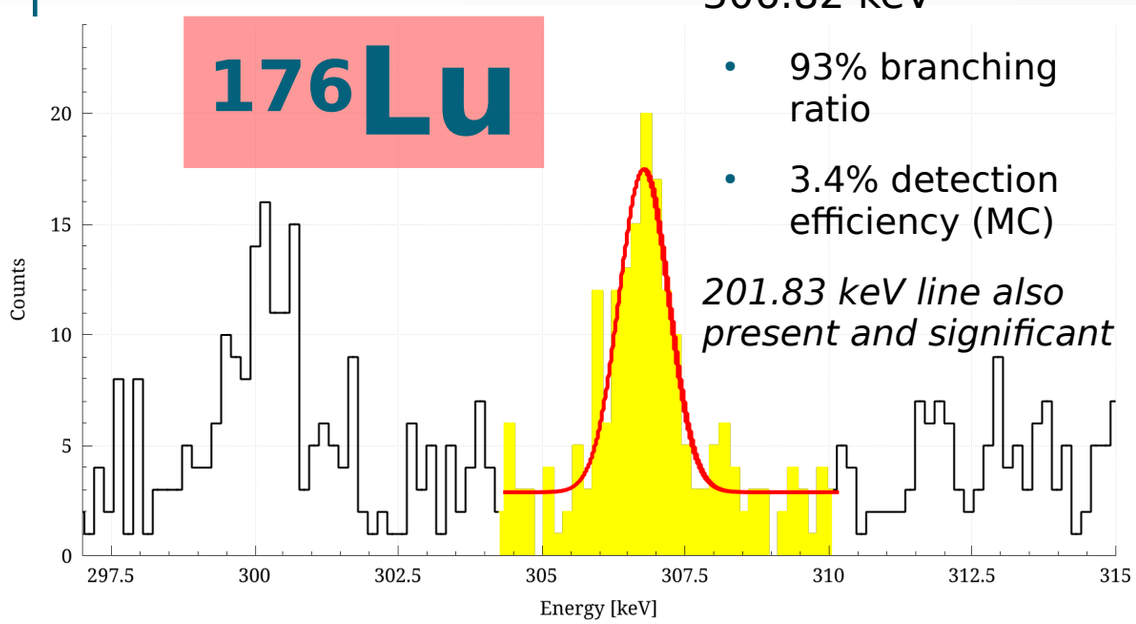
$^{176}Lu \rightarrow {}^{176}Hf$

306.82 keV

^{176}Lu

- 93% branching ratio
- 3.4% detection efficiency (MC)

201.83 keV line also present and significant



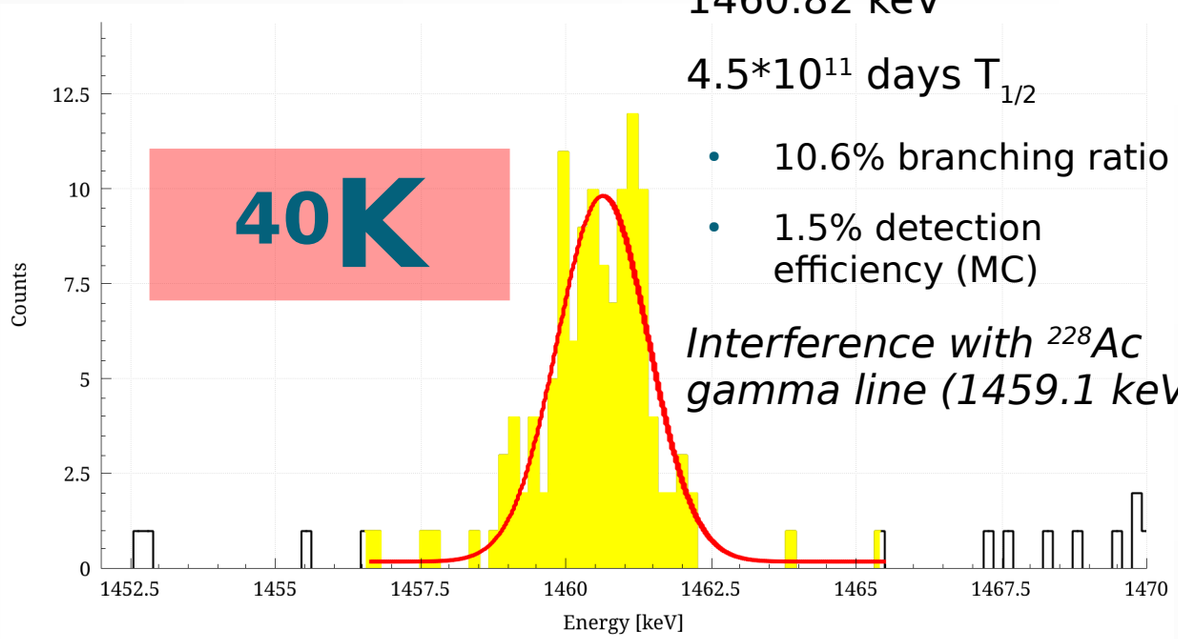
1460.82 keV

$4.5*10^{11}$ days $T_{1/2}$

^{40}K

- 10.6% branching ratio
- 1.5% detection efficiency (MC)

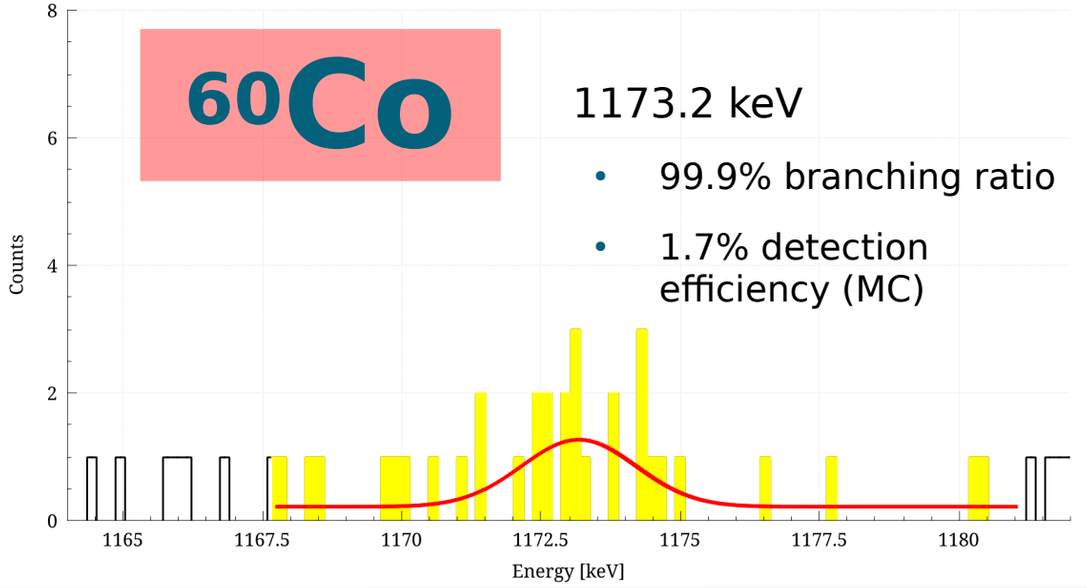
Interference with ^{228}Ac gamma line (1459.1 keV)



^{60}Co

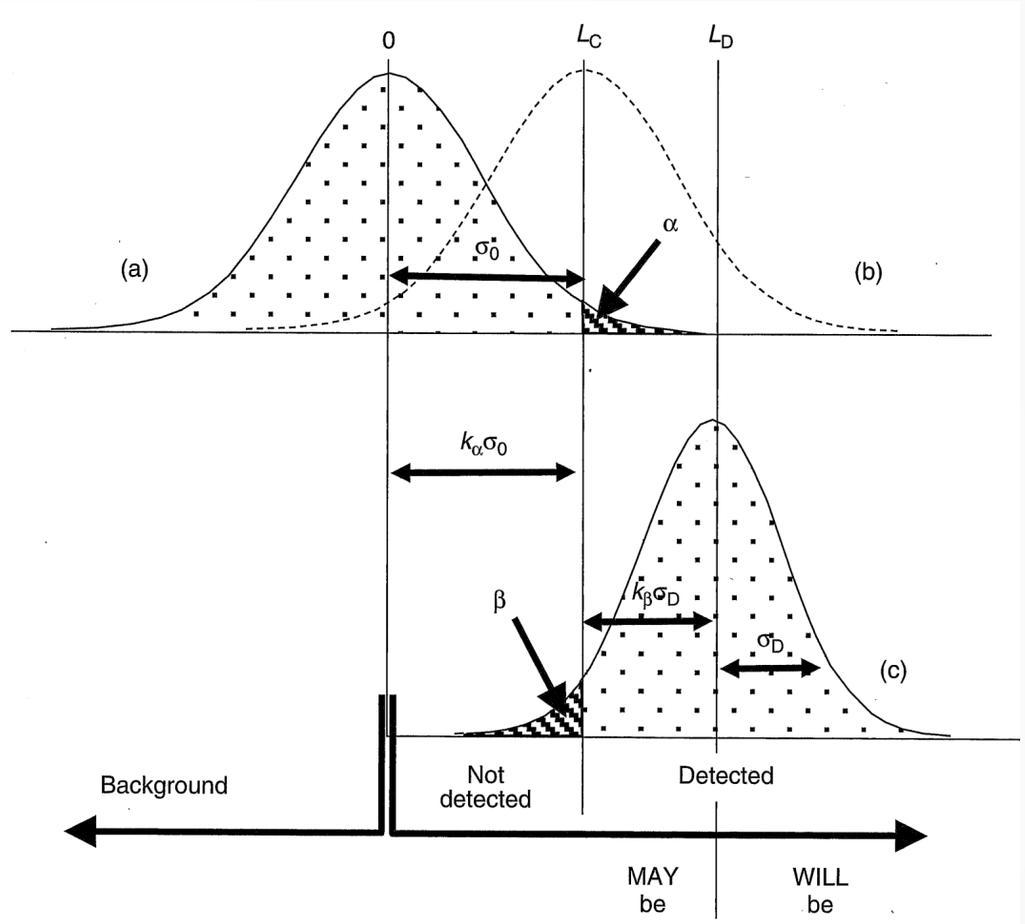
1173.2 keV

- 99.9% branching ratio
- 1.7% detection efficiency (MC)



Total Activity

- Net count rate, $N = C/\Delta t_C - B/\Delta t_B$.
- Critical Limit: *"Is the net count significant (i.e. $N > k_\alpha \sigma_0$)?"*
- Upper Limit: *"Given that this count is not statistically significant, what is the maximum statistically reasonable count?"*
- Activity = Net count rate / (sample mass * live time * det. efficiency * branching ratio).
- Uncertainties → Poisson statistics.
- Total activity in each decay chain: average all individual gamma line activities, weighted by branching ratio.



Glimore, Practical Gamma Ray Spectrometry, 2nd ed., 2008.

For $Gd_2(SO_4)_3$ sample on Lunehead:

- **^{238}U: 1.79 +/- 1.71 mBq/kg,**
- **^{232}Th: 48 +/- 17 mBq/kg,**
- **^{235}U: <4 mBq/kg,**
- **^{40}K: <39 mBq/kg,**
- **^{60}Co: <0.43 mBq/kg,**
- **^{176}Lu: 2.5 +/- 1.8 mBq/kg.**

Screening Programme Status

- Three samples measured at Boulby for SK-Gd.
- Many samples measured at Canfranc Lab in Spain.
- *Repeated measurements on identical samples at both labs are consistent.*
- SK-Gd radiopurity requirements for supply $Gd_2(SO_4)_3$ met.
- Further radiopurity monitoring of other detector components (e.g. resin, sealant, PMT glass, etc.) ongoing.
- Huge effort upcoming to screen full delivery of SK-Gd $Gd_2(SO_4)_3$, 100 tons of material!

Units are mBq/Kg; limits are at 95% CL

Chain	Main subchain isotope	GSF-1710-NYC-170901	GSF-1710-NYC-170902
^{238}U	^{238}U	< 9.7	< 12
	^{226}Ra	< 0.19	< 0.21
^{232}Th	^{228}Ra	< 0.24	< 0.26
	^{228}Th	< 0.28	< 0.31
^{235}U	^{235}U	< 0.35	< 0.41
	^{227}Ac/^{227}Th	< 1.7	< 1.4
	^{40}K	< 0.8	< 1.0
	^{138}La	< 0.09 <115 ppb La	< 0.05 <61 ppb La
	^{176}Lu	0.13± 0.03 2.5 ppb Lu	0.11± 0.04 2.1 ppb Lu
	^{134}Cs	< 0.08	< 0.06
	^{137}Cs	< 0.13	< 0.10

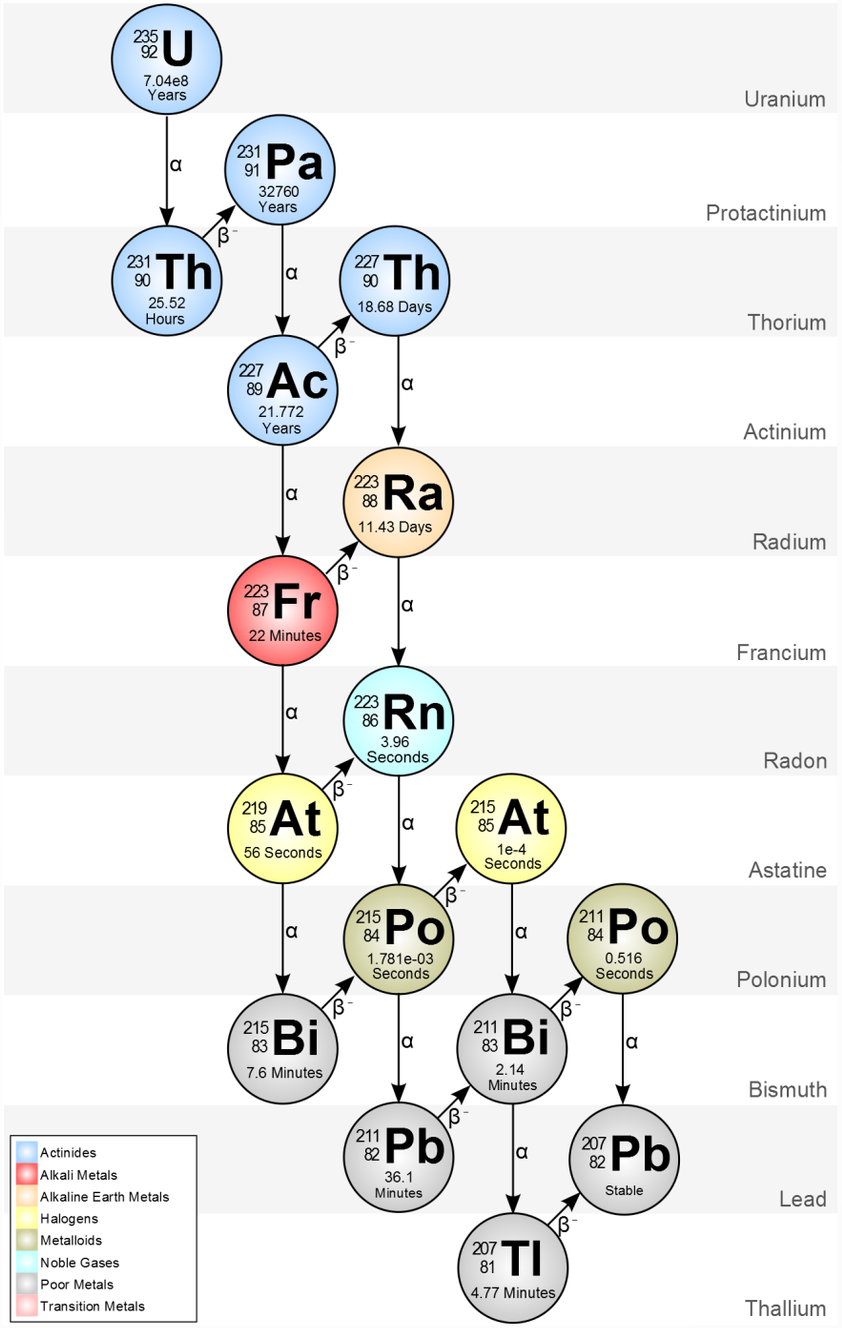
		Specific activity (mBq/kg) - isotope	ppb	Specific activity (mBq/kg) - isotope	ppb	Specific activity (mBq/kg) - isotope	ppb
Isotope	Abundance	GSF-1604-MLC-1		GSF-1604-MLC-2		GOX-1510-MLC-1	
238-U	0.993	33 ± 7	3 ± 1	< 35	< 3	1198 ± 225	97 ± 18
232-Th	1.000	118 ± 4	29 ± 1	95 ± 3	23 ± 1	254 ± 19	62 ± 5
235-U	0.007	1.0 ± 0.5	2 ± 1	5 ± 1	8 ± 2	n/a	n/a
176-Lu	0.026	14 ± 6	286 ± 119	3 ± 2	51 ± 40	n/a	n/a
60-Co		< 0.5	trace	< 0.5	trace	n/a	n/a
40-K	0.000	< 21	< 677	< 17	< 511	<322	<10382

Canfranc

Boulby

Backup

Uranium-235


235 92 U 7.04e8 Years
231 91 Pa 32760 Years
231 90 Th 25.52 Hours
227 90 Th 18.68 Days
227 89 Ac 21.772 Years
223 88 Ra 11.43 Days
223 87 Fr 22 Minutes
223 86 Rn 3.96 Seconds
219 85 At 56 Seconds
215 85 At 1e-4 Seconds
215 84 Po 1.781e-03 Seconds
211 84 Po 0.516 Seconds
215 83 Bi 7.6 Minutes
211 83 Bi 2.14 Minutes
211 82 Pb 36.1 Minutes
207 82 Pb Stable
207 81 Tl 4.77 Minutes
α
β⁻
Uranium
Protactinium
Thorium
Actinium
Radium
Francium
Radon
Astatine
Polonium
Bismuth
Lead
Thallium
Actinides
Alkali Metals
Alkaline Earth Metals
Halogens
Metalloids
Noble Gases
Poor Metals
Transition Metals