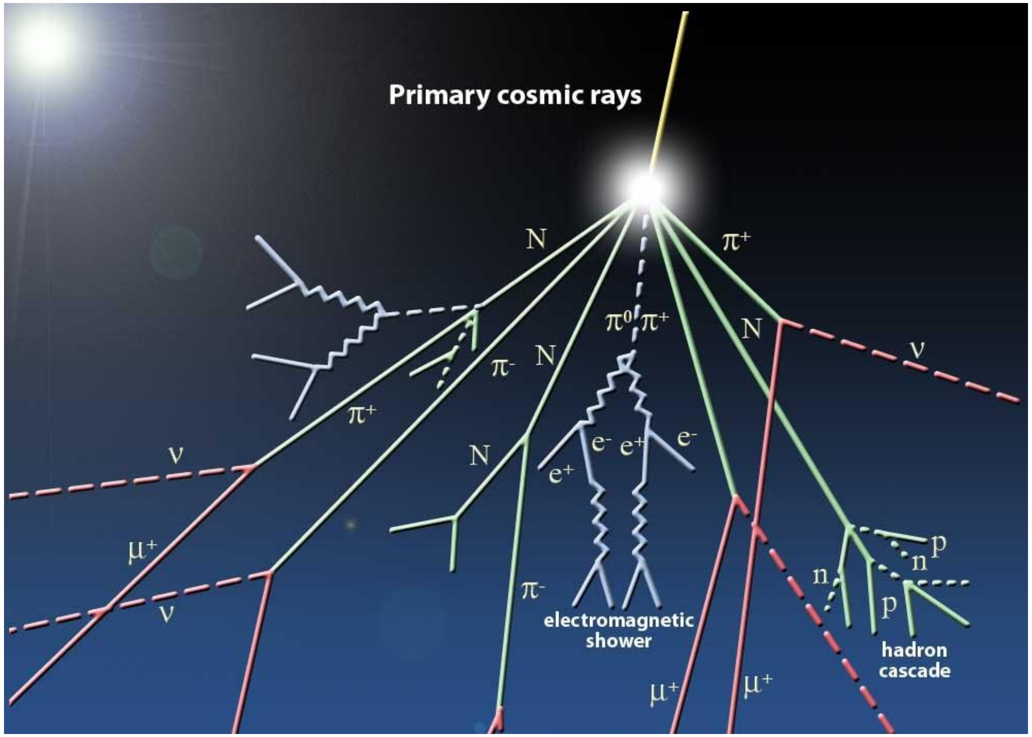
Low Background Measurements and Techniques

Ian Lawson

2023 CAP Congress
UNB, Fredericton, NB
June 21, 2023



Courtesy of Physics Open Labs

Effect of Overburden
(Why go underground)

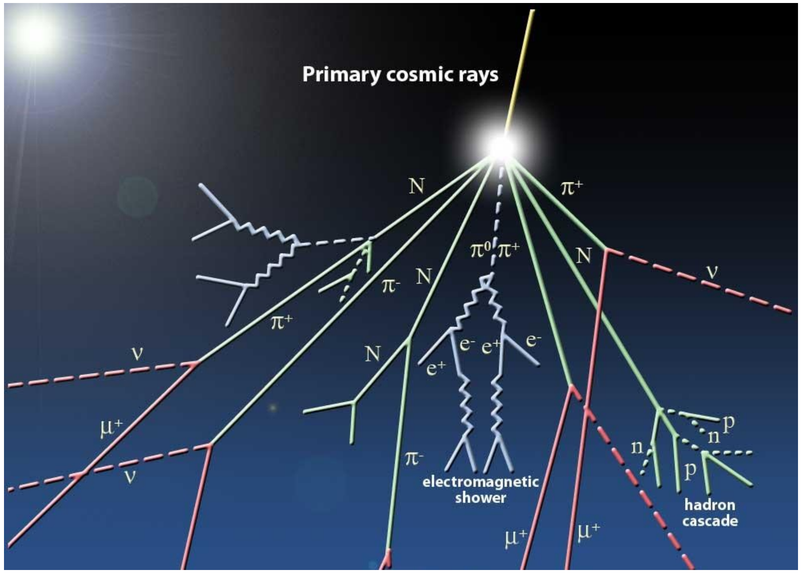
Deep underground facilities provide significant rock overburden and commensurate reduction in cosmic ray flux, and cosmic ray-spallation induced products (neutrons)

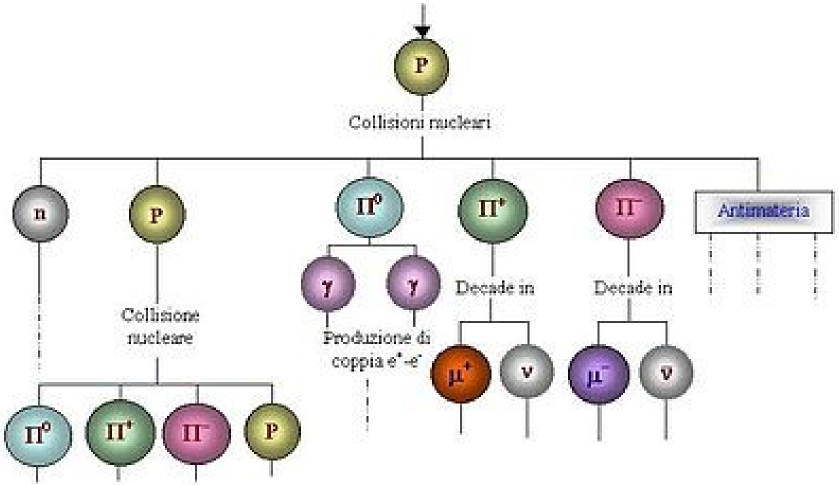
Muons can be veto'd in anti-coincidence shields; however, secondary products may be an issue

Cosmogenics may require underground material production or purification
- May also contribute to backgrounds (e.g. ^{11}C)

Muon flux depends on
- Overburden
- overburden profile
- seasonal effects

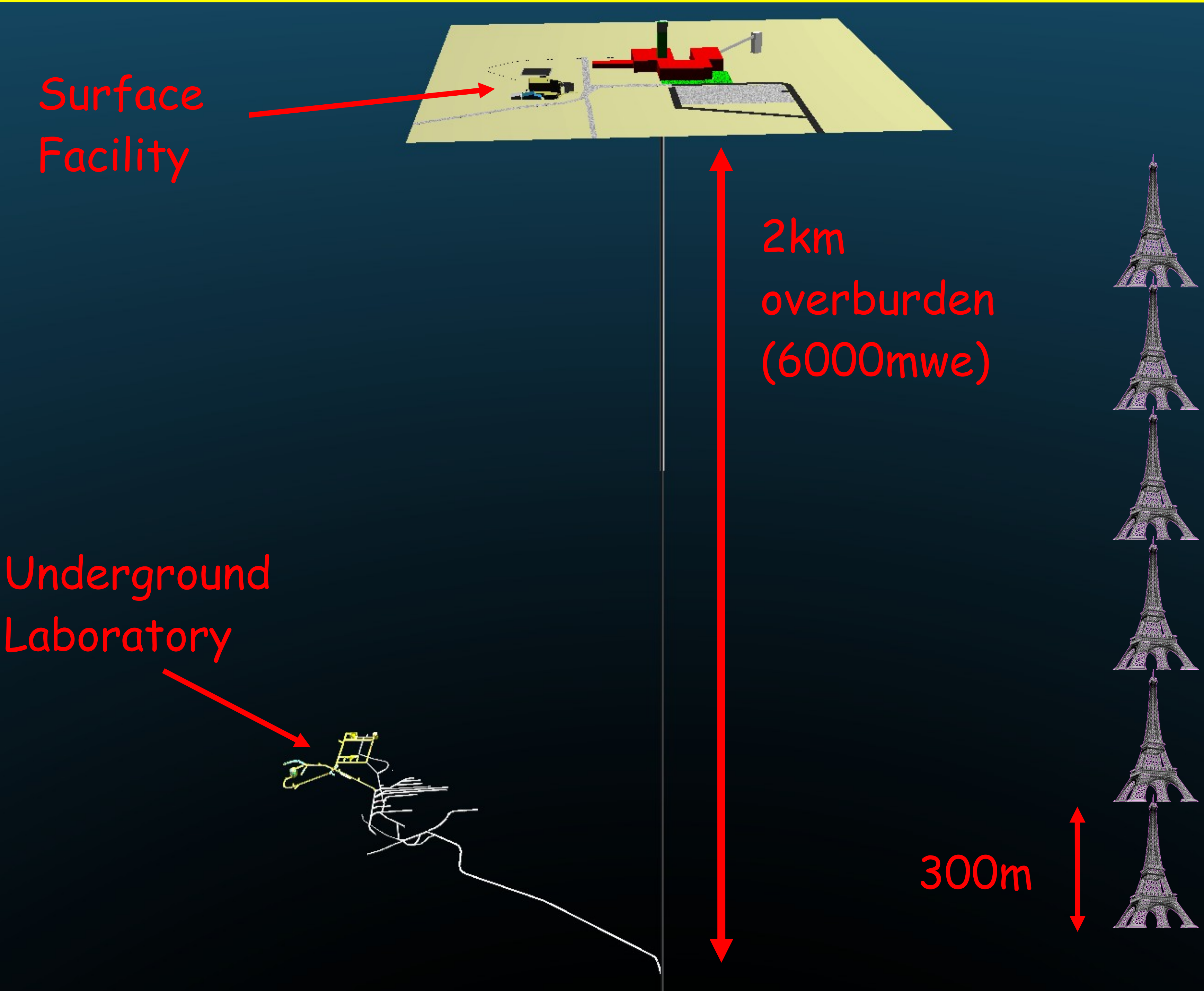
With all of these backgrounds present, there are several methods to measure them and these will be described.





Open Physics Lab

SNOLAB



Surface Facility

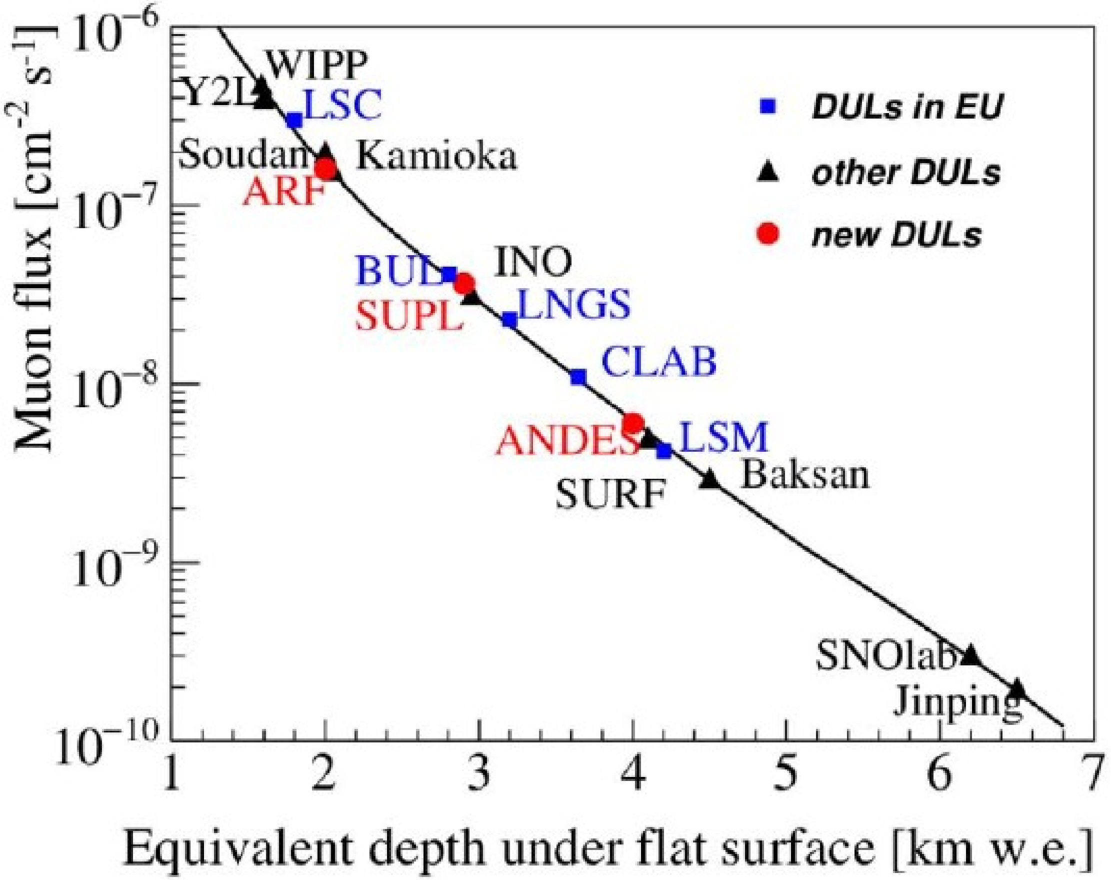
2km overburden (6000mwe)

Underground Laboratory

300m

Muon Supression

- 2 km overburden
- 6000 mwe
- Muon flux: 0.27 muons/m/day



Aldo Ianni 2020 J. Phys.: Conf. Ser. 1342 012003Aldo Ianni 2020 J. Phys.: Conf. Ser. 1342 012003

SNOLAB - Rock Properties

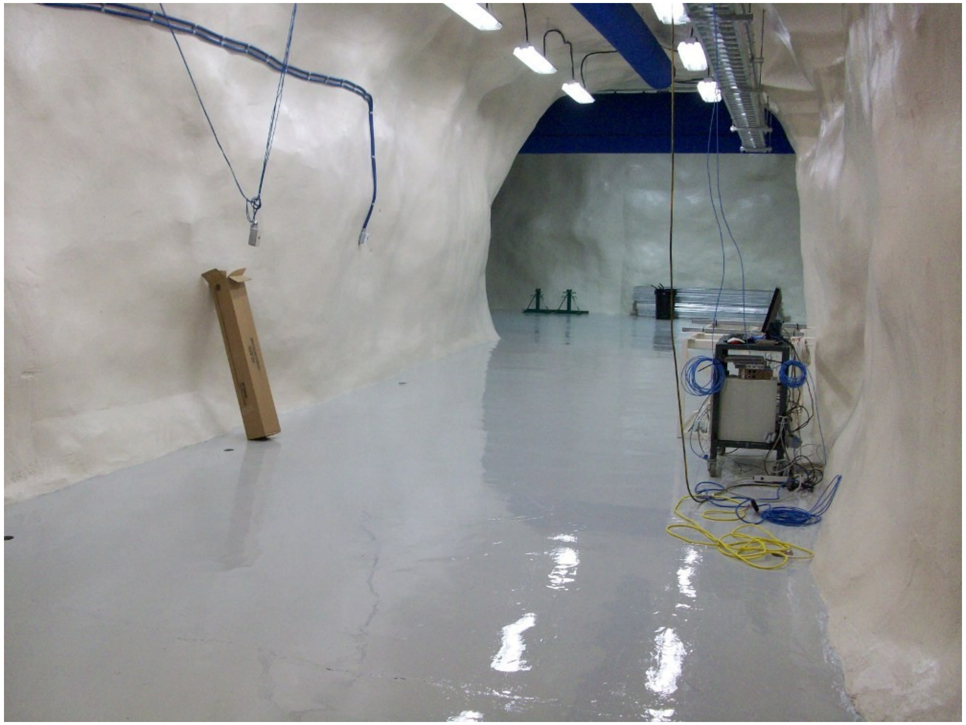
- Analysed using ICP-MS, ICP-AES and XRF
- Gamma Counted with HPGe
- Norite: The same as new lab areas
- Shotcrete: New areas slightly higher for Uranium and more than 2x for Thorium

	Norite Rock	Shotcrete/Concrete
O	47 %	48 %
Si	27 %	28 %
Fe	6.5 %	2.5 %
Al	6 %	6 %
Mg	6 %	1 %
Ca	3.5 %	10 %
Na	1.7 %	2 %
K	1 %	1.7 %
Ti	0.3 %	0.2 %

Norite Density: 2.88 g/cm^3

SNOLAB - Rock Properties

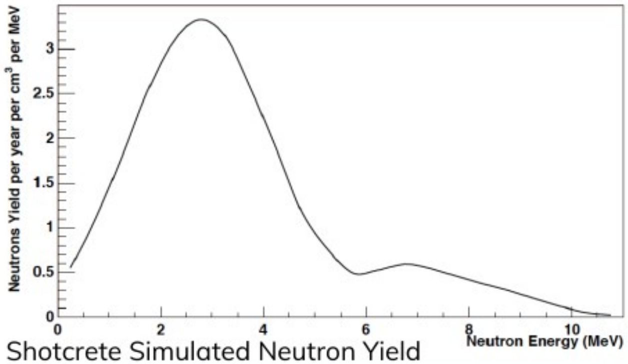
Isotope	Norite Rock		Shotcrete	
	Concentration	Neutron Production (n/yr/cm³)	Concentration	Neutron Production (n/yr/cm³)
^{232}Th	5.10 ppm	8.13	2.4 ppm	0.99
^{238}U	1.10 ppm	3.51	1.2 ppm	1.05
Spontaneous Fission ^{238}U		1.19		1.03
Total		12.83		3.07



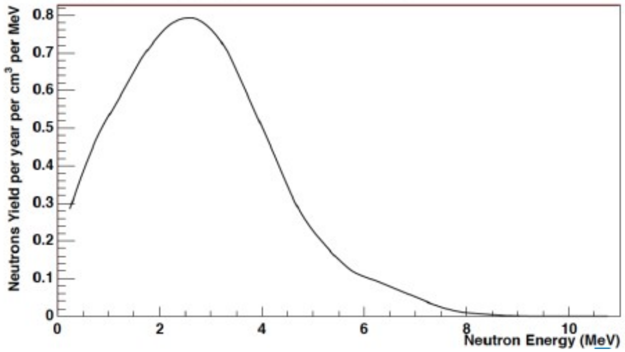
SNOLAB - Rock Properties

Isotope	Norite Rock		Shotcrete	
	Concentration	Neutron Production (n/yr/cm^3)	Concentration	Neutron Production (n/yr/cm^3)
^{232}Th	5.10 ppm	8.13	2.4 ppm	0.99
^{238}U	1.10 ppm	3.51	1.2 ppm	1.05
Spontaneous Fission ^{238}U		1.19		1.03
Total		12.83		3.07

Norite Rock Simulated Neutron Yield



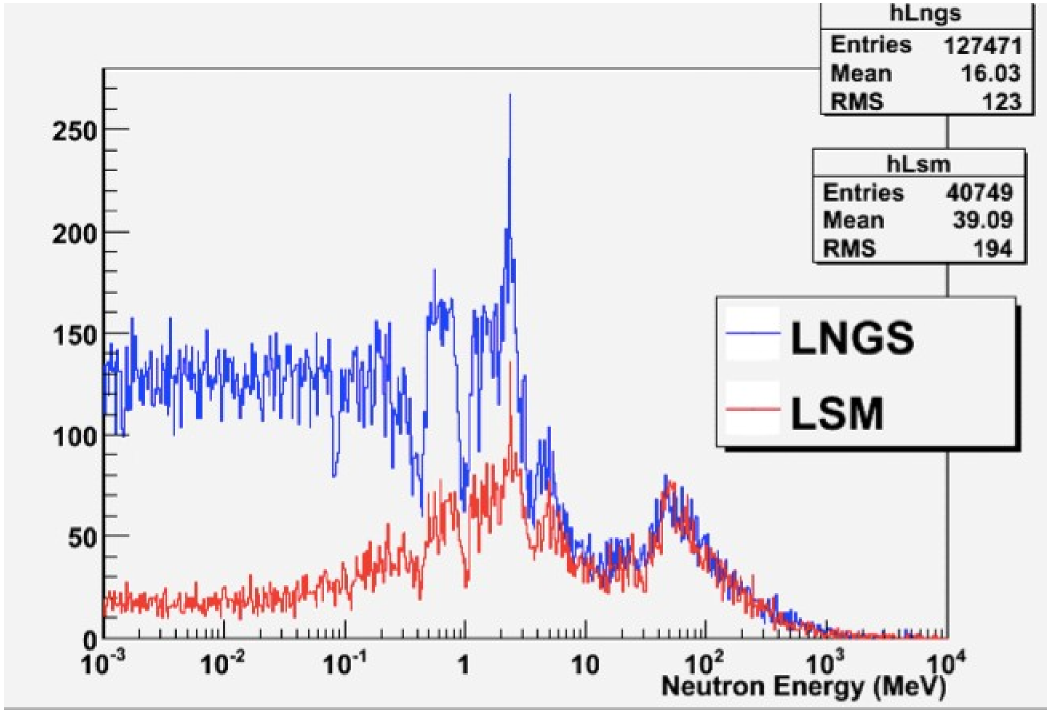
Shotcrete Simulated Neutron Yield



Neutron production estimates were obtained from SOURCES-4C and used as input in GEANT4

- 90%: (α,n) on light elements
- 10%: ^{238}U spontaneous fission
- Measurements from SNO area (1999):
- Thermal Flux: 4144 +- 50 +- 105 neutrons / m^2 / day
- Estimated Fast Neutron Flux: 4000 neutrons / m^2 / day

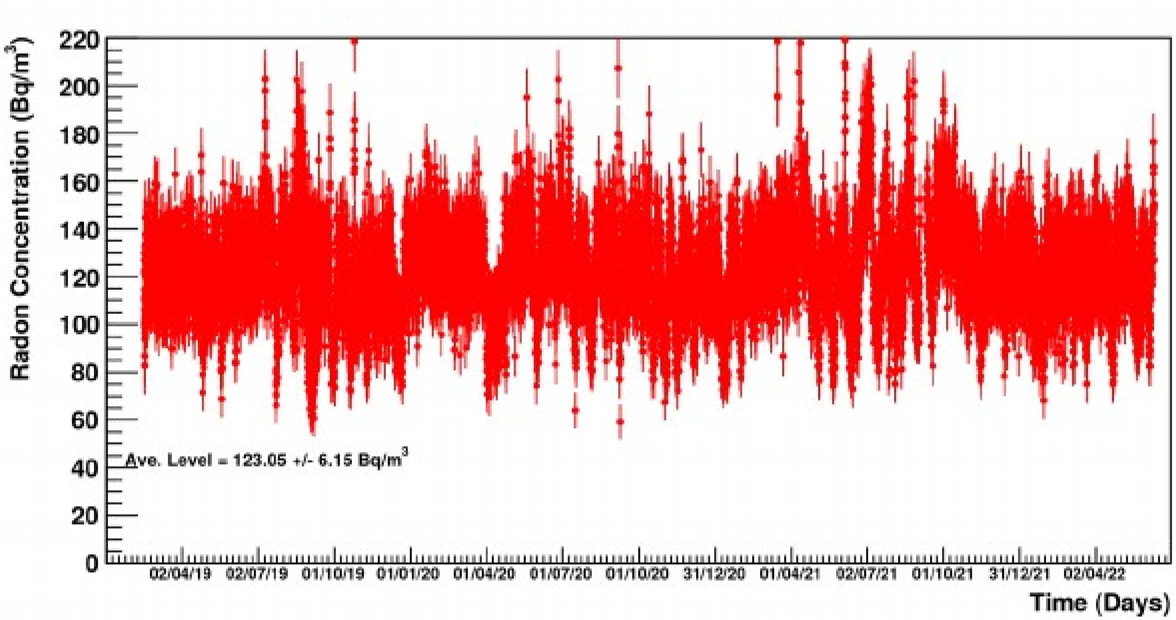
Measured Neutron Backgrounds
(LNGS & LSM)



Spectrum in laboratory depends on local geology (rock composition)

- both for fast and thermal neutrons
- U/Th + moderators
- muons + moderators
- small levels of high neutron cross-section contaminants make a big difference

Radon Levels



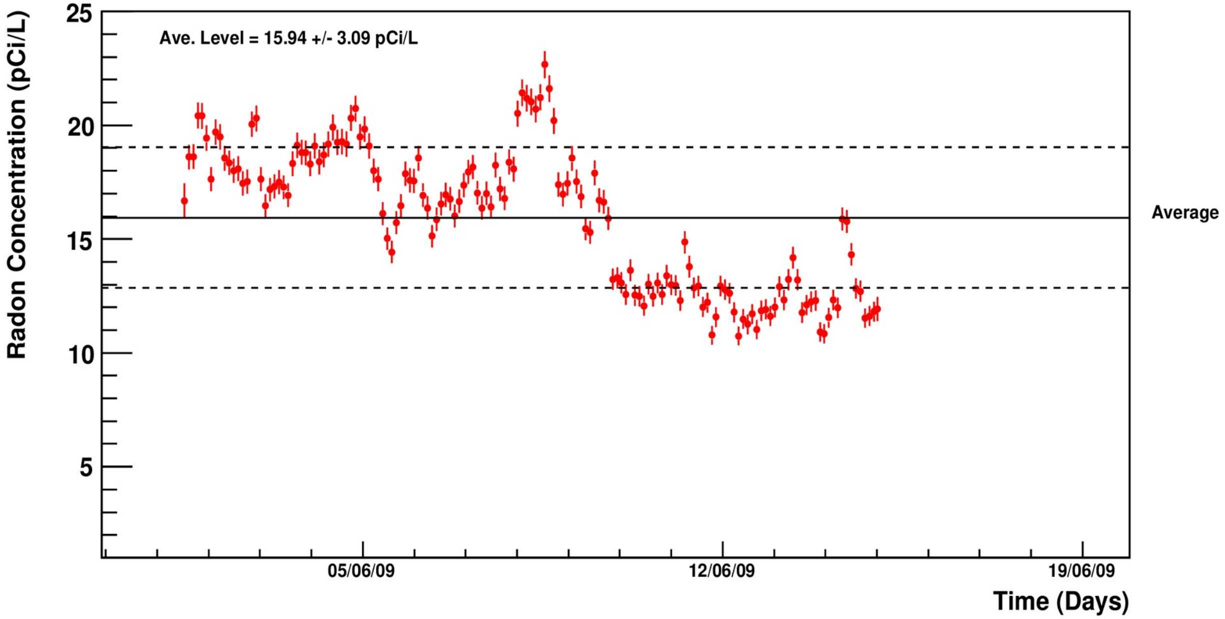
Average radon levels (with air ciruclation operational:

123.1 +- 6.2 Bq/m^3

Average radon levels without air circulation:

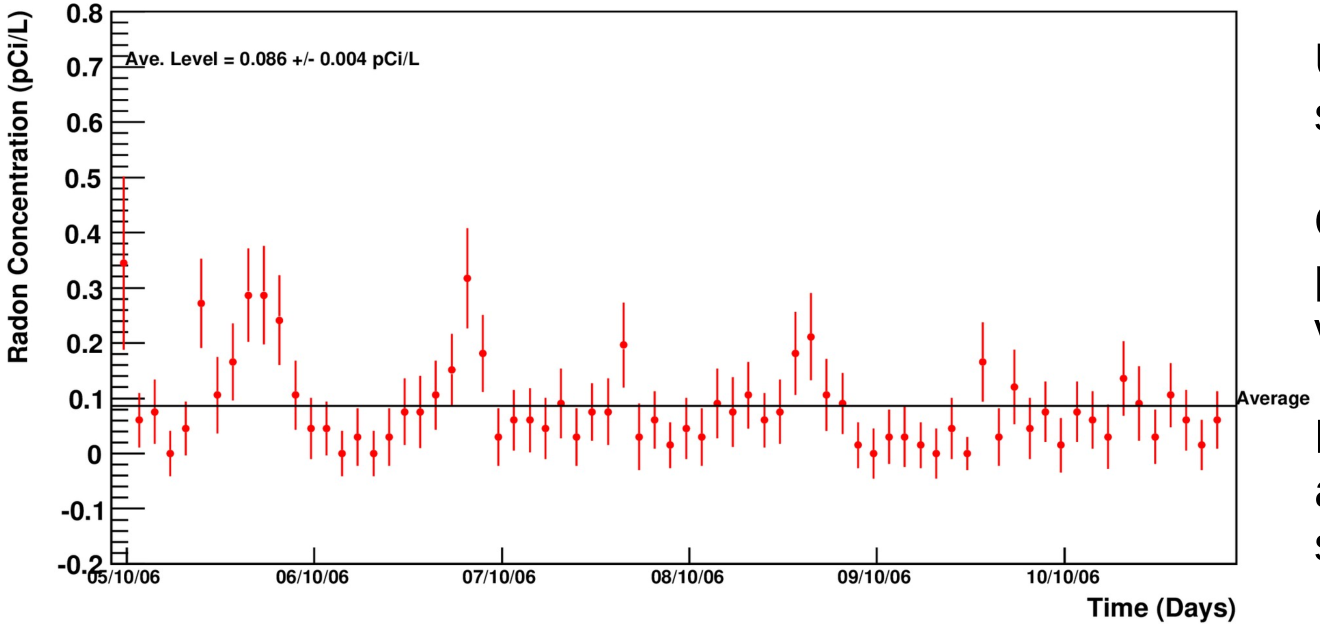
589.8 +- 114.3 Bq/m^3.

radoninstrument.com



Reducing Radon Levels

Use compressed air supplied from surface



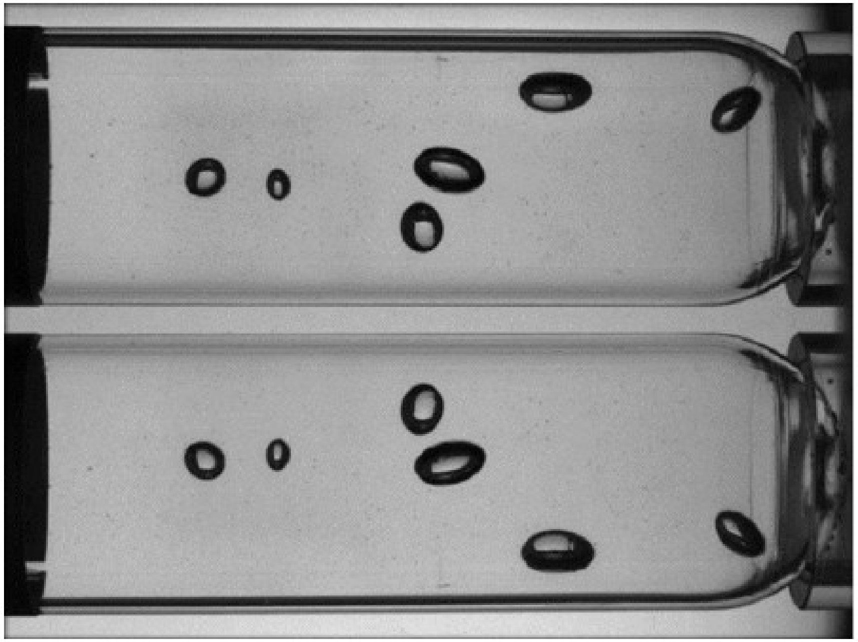
Use compressed air supplied from surface: 3.18 +- 0.15 Bq/m^3

One can also use nitrogen gas to purge radon from small/medium volumes: 2.06-4.41 Bq/m^3

Even better results can be achieved using radon scrubbing systems

Use liquid nitrogen boil-off gas

Neutron Measurements



- Direct measurement of the neutron spectrum will be useful
  - Simulations
  - Experiment Shield design
  - Data Analysis
- Low expected rate means long counting times

- Bubble Detector Spectrometer (BDS)
- The BDS is generally used nuclear research institutions, nuclear utilities and medical accelerator installations
- Previous use by space agencies
- Manufactured by Bubble Technology Industries for neutron spectrometry
- Superheated liquid in an elastic polymer gel
- When droplets are struck by neutrons, small gas bubbles are formed that remain fixed and can be counted
- Not sensitive to gammas
- Isotropic angular response
- Six thresholds: 10, 100, 600, 1000, 2500 and 10000 keV

*Ing, H., Noulty R., McLean T.D. (1997). Bubble Detectors- A Maturing Technology. Radiation Measurements 1(27). 1-11. doi:10.1016/S1350-4487(96)00156-4â

Mitigating Neutron Backgrounds

PICO-2L/SENSEI shield, showing water tank shielding stack, pressure carts, DAQ racks.

Tanks are 50 cm thick, combining water and polypropylene.

DAMIC CCD-based dark matter detector, focus on low mass WIMPS.

Shielding consists of 16 inches of polyethylene sheeting

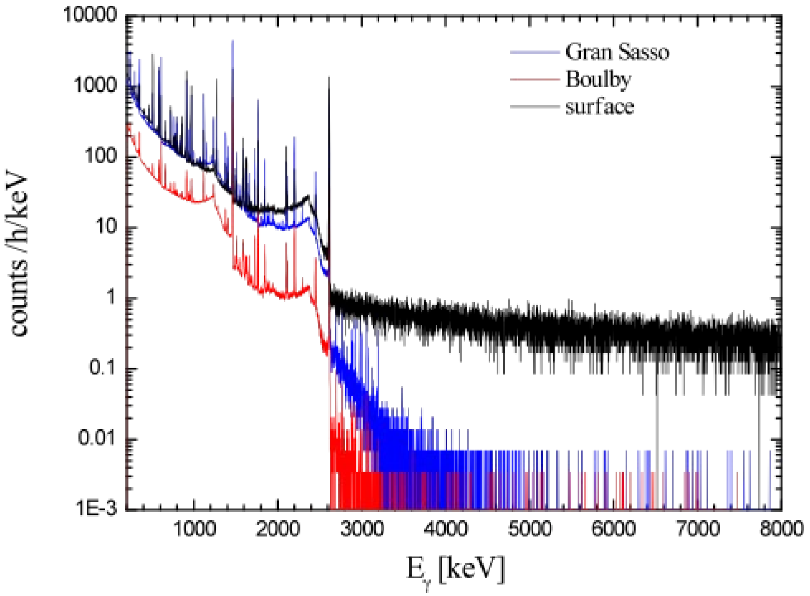
Gamma-ray Backgrounds

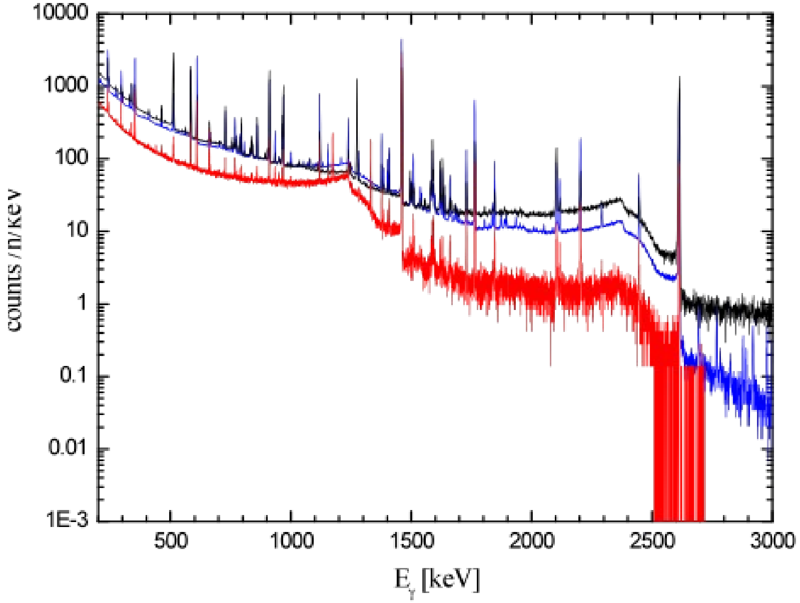
Reduction in γ-ray background at higher energies from c.r. and neutron reduction

- important for nuclear astrophysics dedicated beam experiments, and some $0\nu\beta\beta$ isotopes

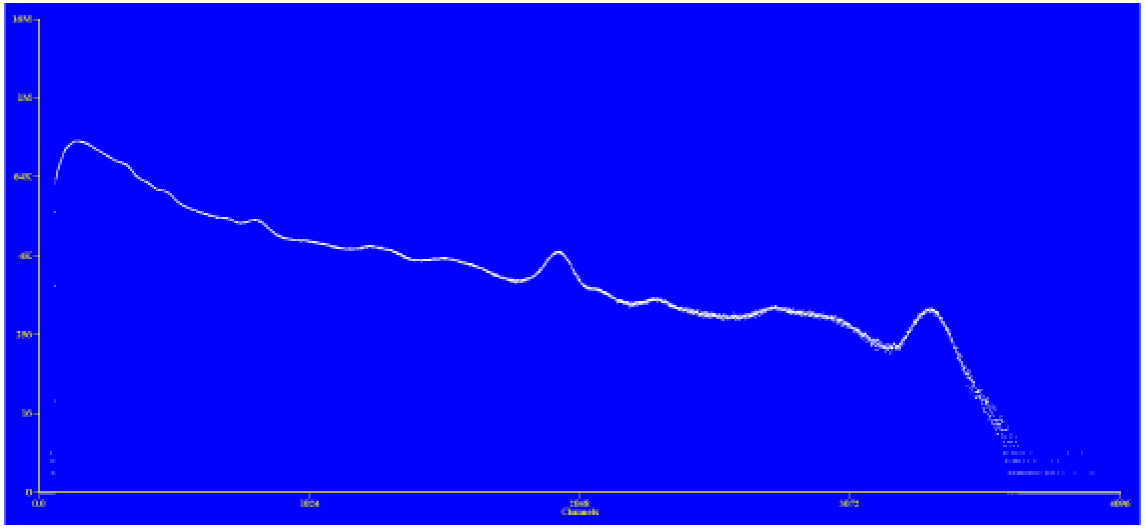
Below 3.5MeV dependent on local geology and rock material

- Boulby (red)
- Gran Sasso (blue)
- surface (black)





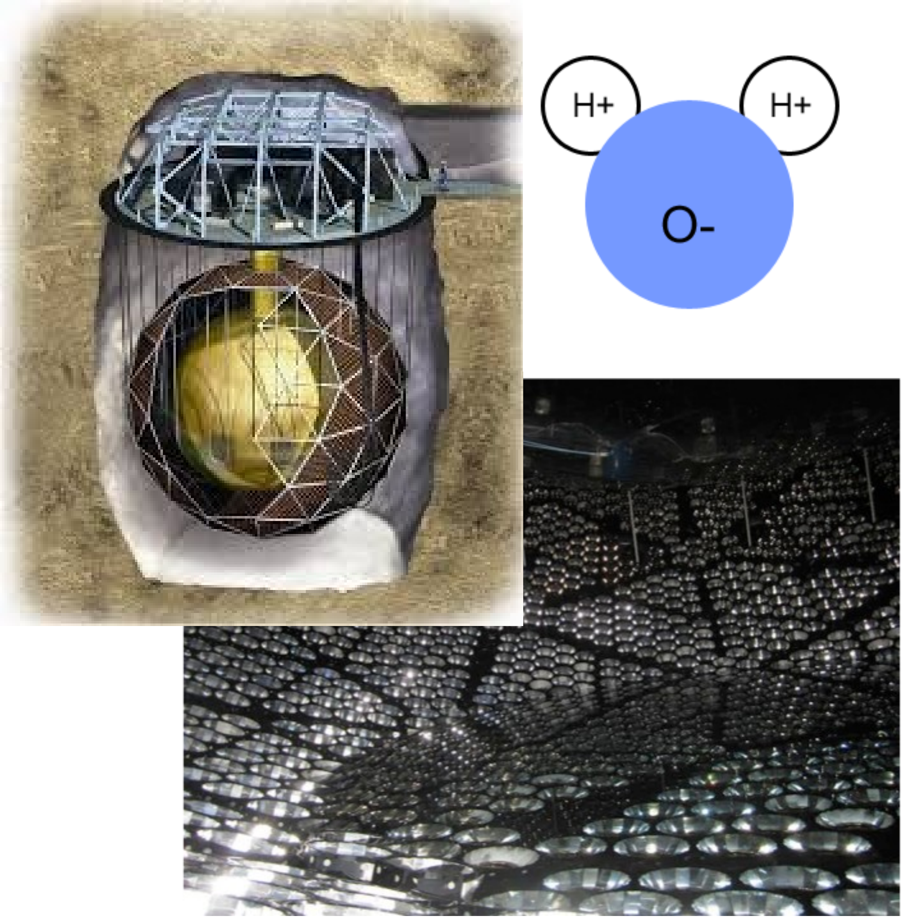
Gamma-ray Backgrounds



Sample of raw data from one of the small NaI crystal after 7.4 days

- Detailed gamma spectra below 3 MeV in different areas of the laboratory is of interest
- This spectra depends on the rock composition and materials, so it varies within the lab
- We have two 1.5 x 1.5 inch NaI(Tl) crystal and MCAs
- Currently measuring internal backgrounds
- A lab survey will be completed to generate spectra for areas of interest in the lab

Mitigating γ-ray Backgrounds



Water shielding at appropriate thickness

Lead shielding at appropriate thickness

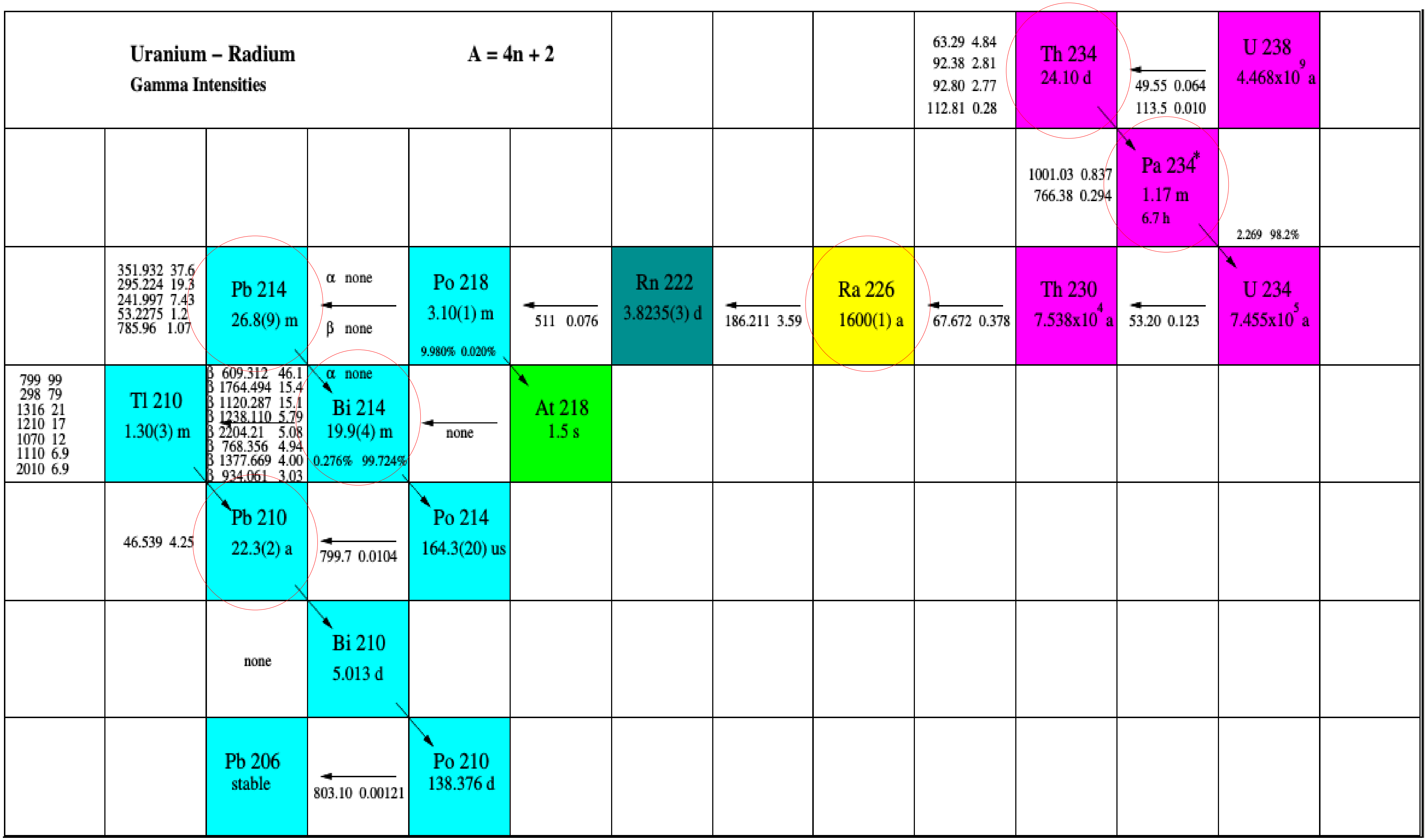
Techniques to Measure These Backgrounds

(Primarily U/Th decay chains and K)

Measurement Method	Background Detected	Sensitivity (for U/Th)
•Ge spectrometry	γ emitting nuclides	10-100 µBq/kg
•Rn emanation assay	^{226}Ra, ^{228}Th	0.1-10 µBq/kg
•Neutron activation	primordial parents	0.01 µBq/kg
•Liquid scintillation counting	α,β emitting nuclides	1 mBq/kg
•Mass spectrometry (ICP-MS; AMS)	primordial parents	1-100 µBq/kg
•Graphite furnace AAS	primordial parents	1-1000 µBq/kg
•Röntgen Excitation Analysis	primordial parents	10 mBq/kg
•α spectrometry	^{210}Po, α emitting nuclides	1 mBq/kg

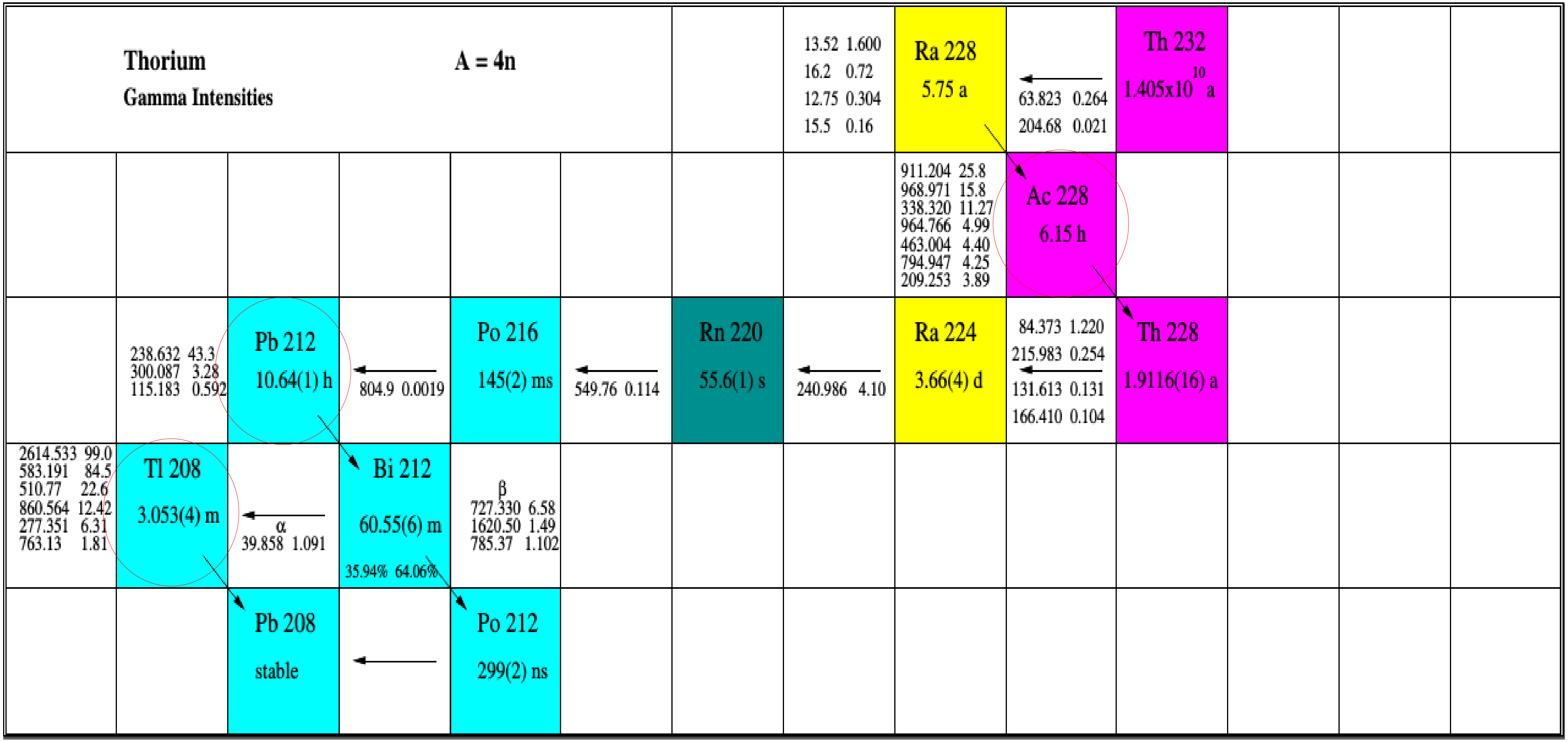
To reach these sensitivities, samples may have to count for several months

Uranium Decay 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	2.269 98.2%	
	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 9.980% 0.020%	← 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 β 934.061 3.03	α none 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									

Thorium Decay Chain



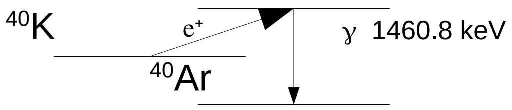
Thorium A = 4n **Gamma Intensities**							13.52 1.600 16.2 0.72 12.75 0.304 15.5 0.16	Ra 228 5.75 a	← 63.823 0.264 204.68 0.021	Th 232 1.405×10^{10} a			
								911.204 25.8 968.971 15.8 338.320 11.27 964.766 4.99 463.004 4.40 794.947 4.25 209.253 3.89	Ac 228 6.15 h				
	238.632 43.3 300.087 3.28 115.183 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									

Other Interesting Isotopes

Usually Present:

- ^{40}K

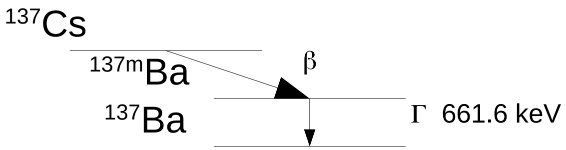
  1460.83 keV



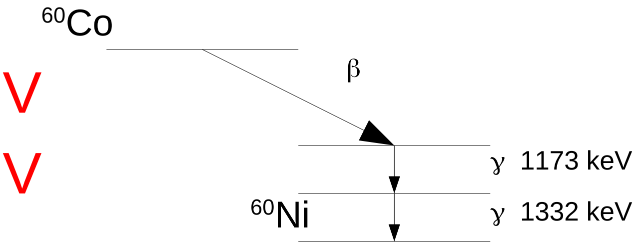
- ^{137}Cs

  661.66 keV

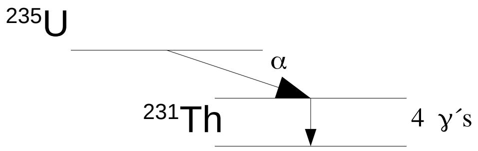
  (from fallout)



- ^{60}Co
  - 1173.2 keV
  - 1332.5 keV



- ^{235}U
  - 143.76 keV
  - 163.33 keV
  - 185.22 keV
  - 205.31 keV



Occasionally Present:

• ^{54}Mn at 834.85 keV	Observed in Stainless Steel
• ^{7}Be at 477.60 keV	Observed in Carbon based materials, due to neutron activation, samples are particularly affected after long flights.
• ^{138}La and ^{176}Lu	Observed in rare earth samples such as Nd or Gd.

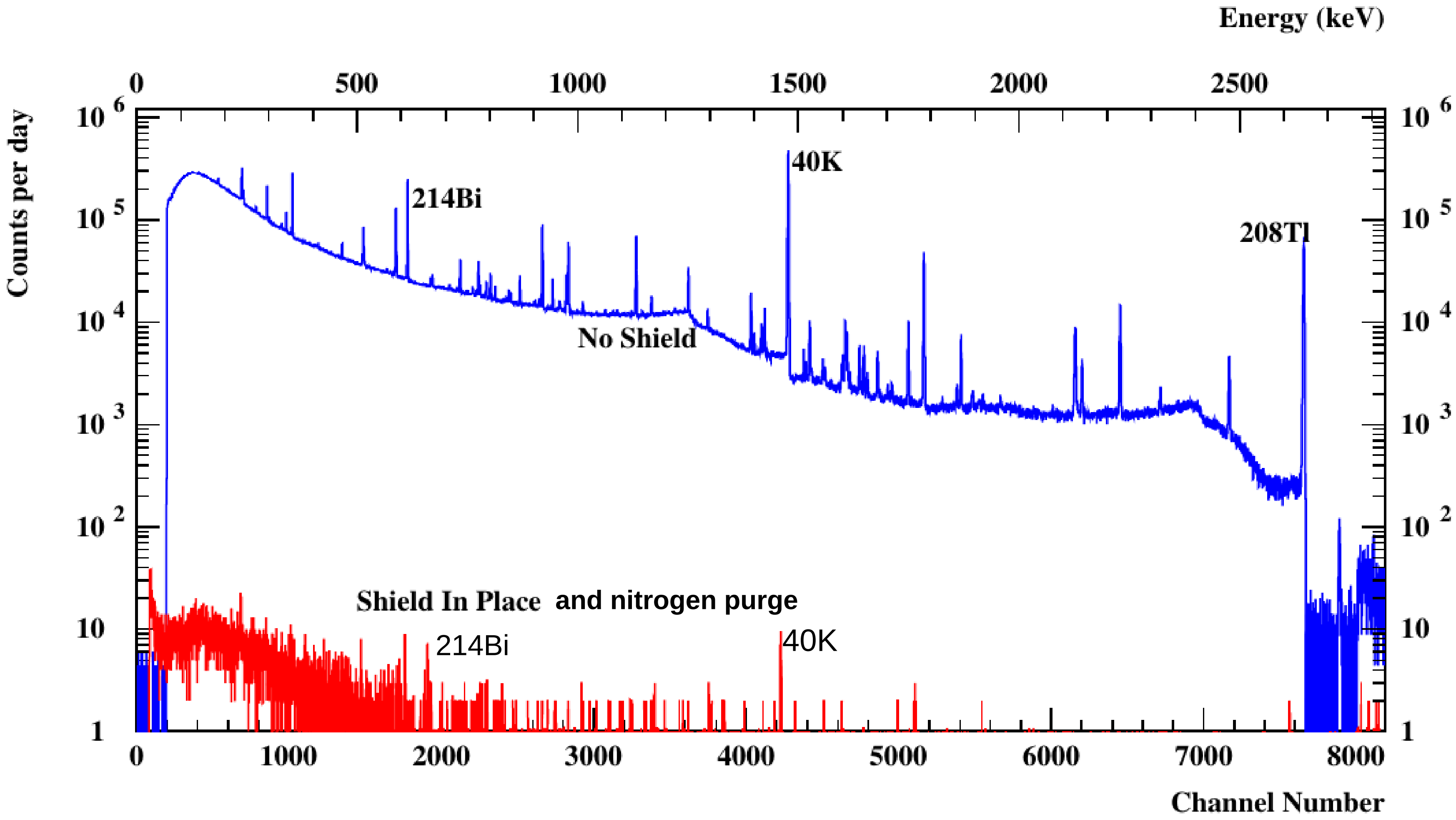
Ge Spectrometry

SNOLAB PGT HPGe Counter

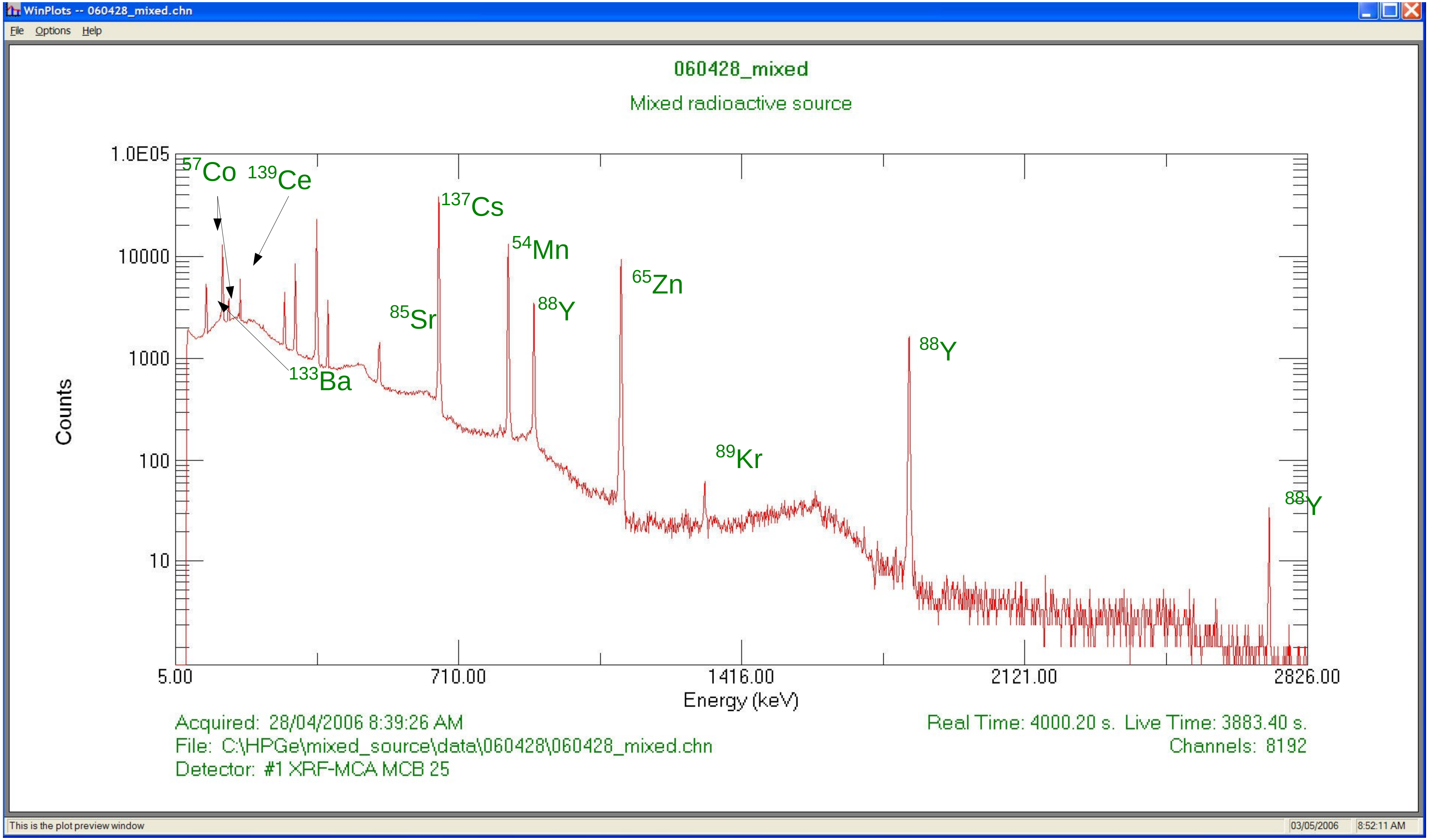
Standard 1 L geometry
Max: 4 L, if all of the
chamber is used.

Unshielded and Shielded Spectra

(PGT Coax Detector)



Calibration Spectrum



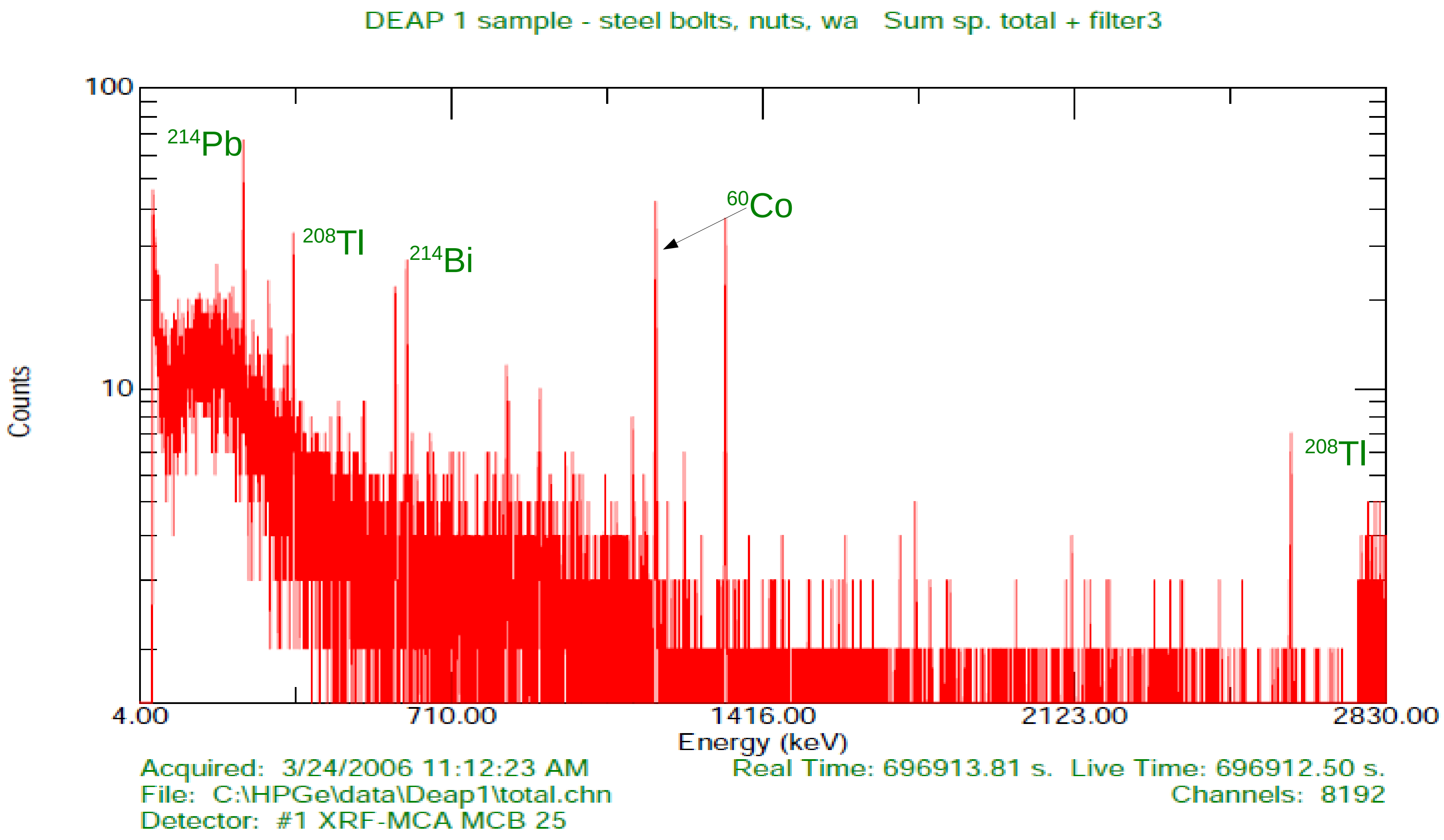
060428_mixed

Mixed radioactive source

Acquired: 28/04/2006 8:39:26 AM
File: C:\HPGe\mixed_source\data\060428\060428_mixed.chn
Detector: #1 XRF-MCA MCB 25

Real Time: 4000.20 s. Live Time: 3883.40 s.
Channels: 8192

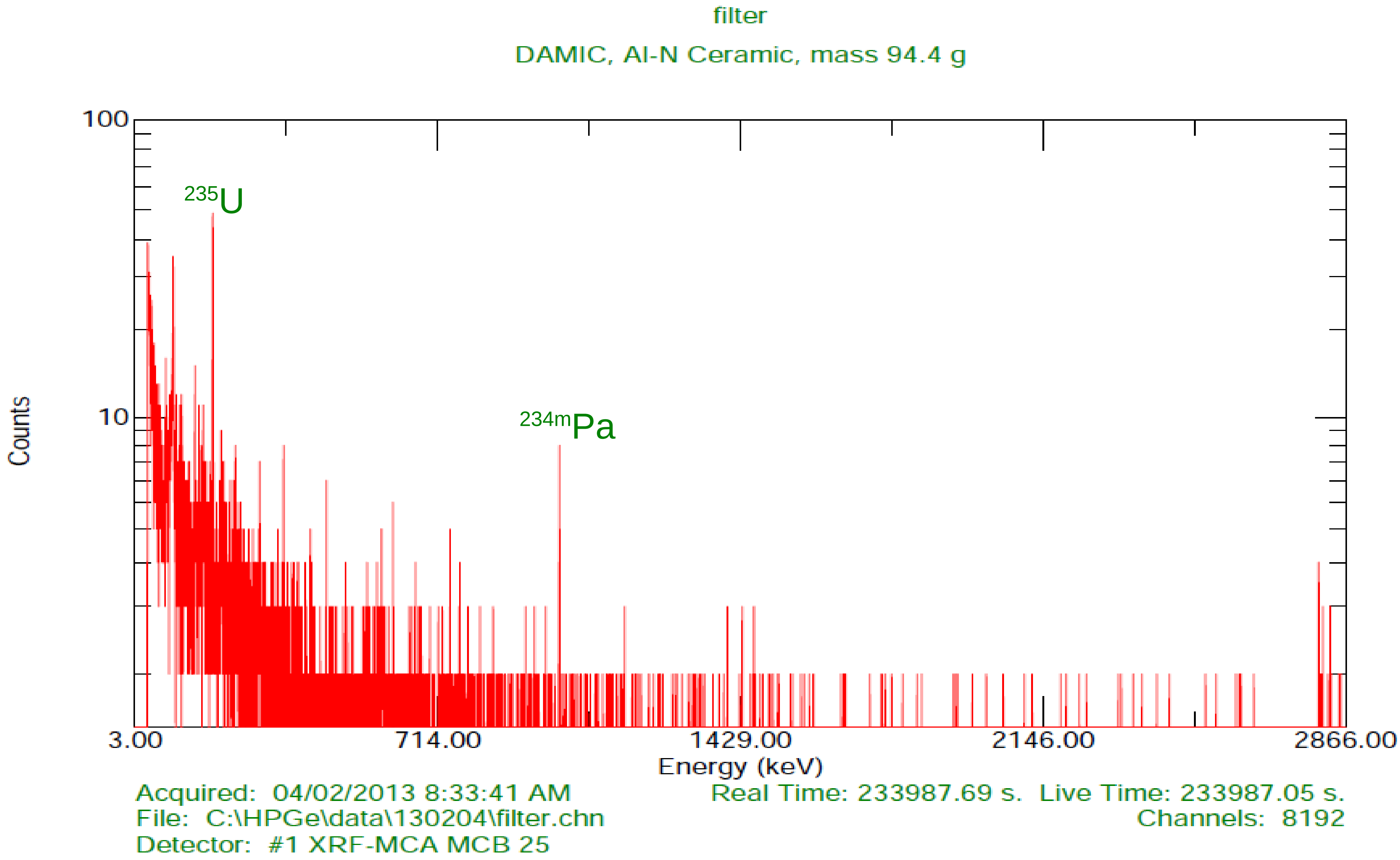
Typical Stainless Steel Spectrum



Acquired: 3/24/2006 11:12:23 AM
File: C:\HPGe\data\Deap1\total.chn
Detector: #1 XRF-MCA MCB 25

Real Time: 696913.81 s. Live Time: 696912.50 s.
Channels: 8192

Ceramic Spectrum



filter

DAMIC, Al-N Ceramic, mass 94.4 g

Acquired: 04/02/2013 8:33:41 AM
File: C:\HPGe\data\130204\filter.chn
Detector: #1 XRF-MCA MCB 25

Real Time: 233987.69 s. Live Time: 233987.05 s.
Channels: 8192

Gamma Counter Sensitivities

Isotope	SNOLAB Gamma Counter 1 (mBq) PGT	SNOLAB Gamma Counter 2 (mBq) Well	SNOLAB Gamma Counter 3 (mBq) Lively	SNOLAB Gamma Counter 4 (mBq) VdA	SNOLAB Gamma Counter 5 (mBq) Gopher
^{238}U	0.11 mBq	0.02 mBq	0.05 mBq	0.09 mBq	0.17 mBq
^{235}U	0.16 mBq	0.01 mBq	0.02 mBq	0.06 mBq	0.08 mBq
^{232}Th	0.10 mBq	0.02 mBq	0.06 mBq	0.08 mBq	0.21 mBq
^{40}K	1.42 mBq	0.92 mBq	0.45 mBq	1.22 mBq	1.01 mBq
^{60}Co	0.04 mBq	0.03 mBq	0.02 mBq	0.02 mBq	0.04 mBq
^{137}Cs	0.13 mBq	0.02 mBq	0.02 mBq	0.05 mBq	0.08 mBq
^{54}Mn	0.043 mBq	0.033 mBq	0.021 mBq	0.034 mBq	0.044 mBq
^{210}Pb	N/A	0.55 mBq	31.53 mBq	7.71 mBq	16.49 mBq

Dual Detector

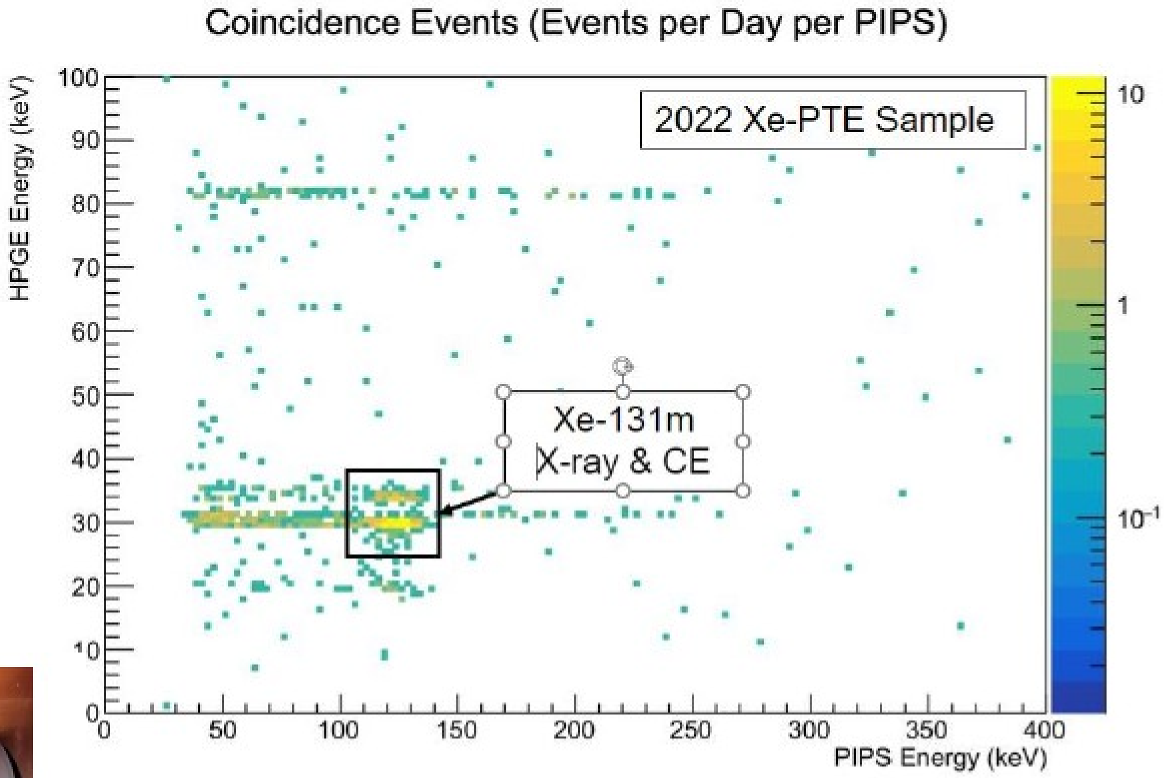
Comprehensive Test Ban Treaty Detector

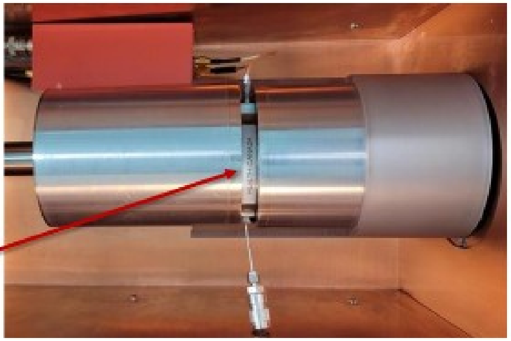
- Comprehensive Test Ban Treaty Detector
  Health Canada's radionuclide laboratory CAL05
- Two Broad Energy Germanium (BeGe) Detectors
- Coincidence events between the two detectors

Dual Detector

Beta-gamma coincidence detection

- Atmospheric radioxenon monitoring
- A PIPSBOX detector was added
- Two thin passivated implanted planar silicon wafers
- Beta Detector
- Gas samples are placed in the detector
- Coincidence of Beta-Gamma

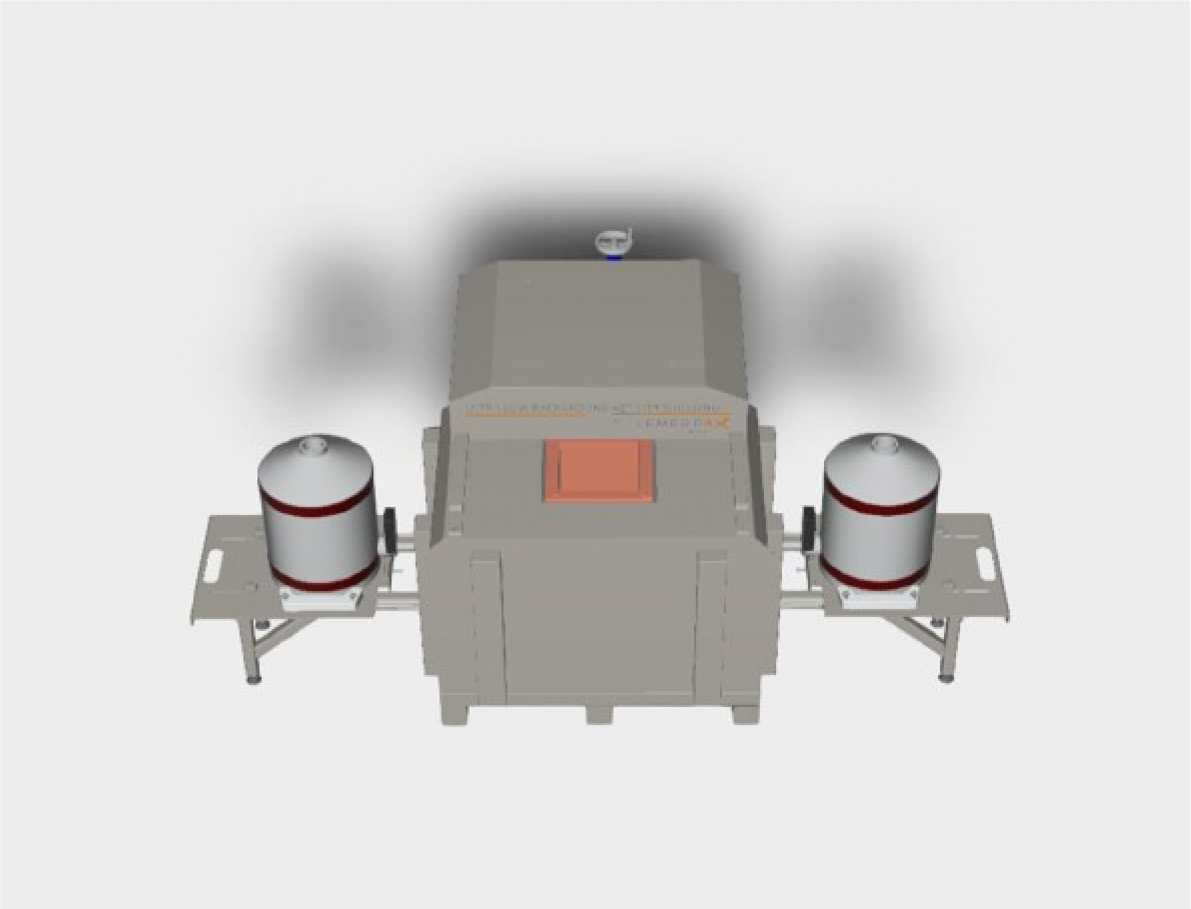




Dual Detector

Future Work

- Permanent Shielding is being manufactured
- Working on measuring backgrounds
- Measure detector efficiencies and verify the GEANT4 modelling of the detectors
- Conduct coincidence studies
- Detection and measurement of radioactive noble gas signals at significantly lower concentrations than currently achievable



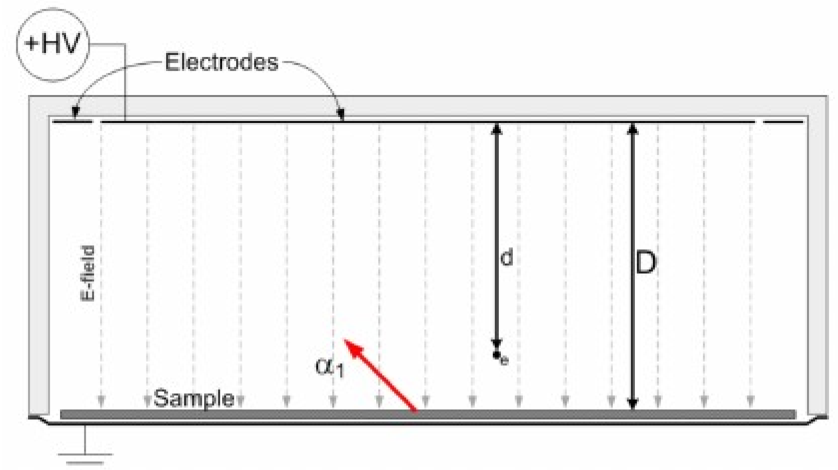
Alpha Counting

Model: XIA Ultra-Lo 1800

Argon gas drift chamber for Alpha rate measurement

Uses electronic amplification rather than gas amplifiication

”Background Free” measurements



Alpha Counting

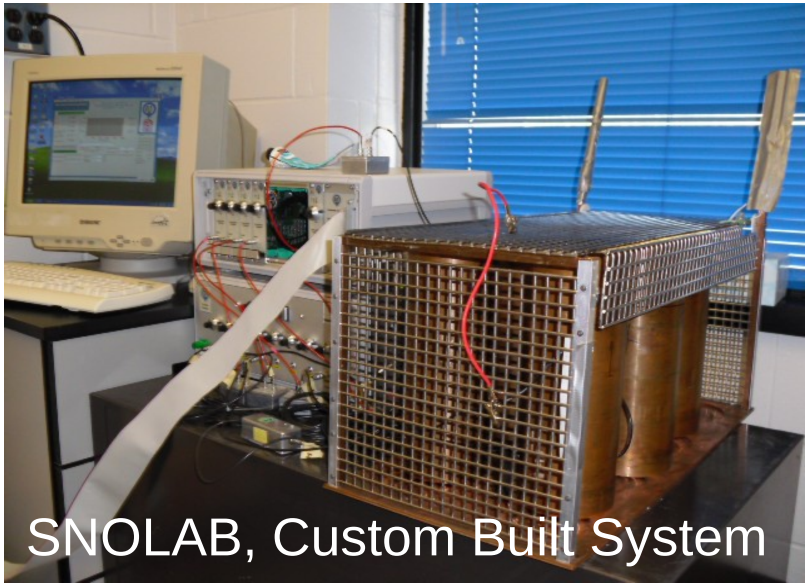
- Activities as low as 6 +/- 1 x 10^{-4} alphas/cm^2/hour = 180 +/- 30 nBq/cm^2 have been measured.
- Small residual background due to radon and cosmic rays slipping through cuts.
- Available for assays.
- Large (30 x 30 cm or more), thin (<1cm), conductive materials are best.
- Count region: 1800cm^2 and 707cm2 circular Maximum sample weight: 9kg, Maximum sample thickness: 6.3mm

Inductively Coupled Plasma - Mass Spectromety

- Agilent 8900 ICP-QQQ advanced application model (triple quadrupole ICP-MS)
- System will be run in SNOLAB's surface clean labs
- Used for elemental analysis at trace detection levels.
- Our aim is to achieve sub-ppt detection of a variety of elemental analytes in samples
- Our first effort will be an ultra-low detection method for UPW monitoring
- Current key analytes of interest for ICP-MS at SNOLAB are currently: U, Th, K, Pb
- We will also be using the instrument to perform isotopic ratio analysis

Agilent 8900 ICP-QQQ
Example of ICP-MS at SNOLAB

Alpha Beta (BiPo) Counting System


SNOLAB, Custom Built System

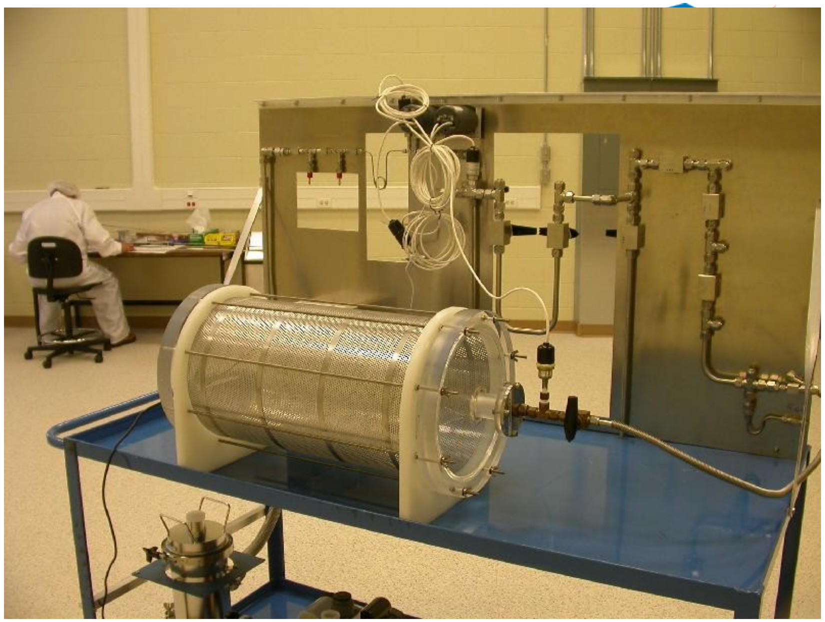

Ortec MPC-1000-GFW Commercial System

Transparent liquid scintillator vials optically coupled to 2” PMTs.

The technique is combination of pulse shape discrimination and coincidence counting for identifying BiPo events.

Sensitivity for ^{238}U and ^{232}Th is ~1 mBq assuming that the chains are in equilibrium.

Radon Emanation



Emanation: Radon atoms formed from the decay of radium escape from the decaying isotopes and into the spaces between the isotopes.

Transport: Diffusion and advective flow cause the movement of the radon atoms through the sample to the surface.

Exhalation: Radon atoms that have been transported to the surface and then exhaled to the surface.

Samples generally placed in a chamber to allow the radium to decay for several half-lives and then radium daughters are accumulated and counted to give the rate in Bq/m^2/s or Bq/kg/s

Sample	Rate (Bq/m^2/s	References
Shotcrete	1.7-4.2 mBq/m^2	J. Bigu and E.D. Hallman SNO-STR-92-064
Copper Foil	1.2-1.7 μBq/m^2	G. Zuzel, H. Simgen, Applied Radiation and Isotopes, Volume 67, Issue 5, May 2009, 889.
Stainless Steel	4.6-10.2 μBq/m^2	G. Zuzel, H. Simgen, Radon Emanation measurements, GERDA General Meeting, July 11, 2007
Silicon Rubber	196 mBq/m^2	Zuzel, G., AIP Conference Proceedings, Vol. 785, pp. 142-149.

SNOLAB Surface Radon Emanation Chamber

A new board with one emanation chamber is fully built and currently in use for material screening

Plan to add additional emanation chambers

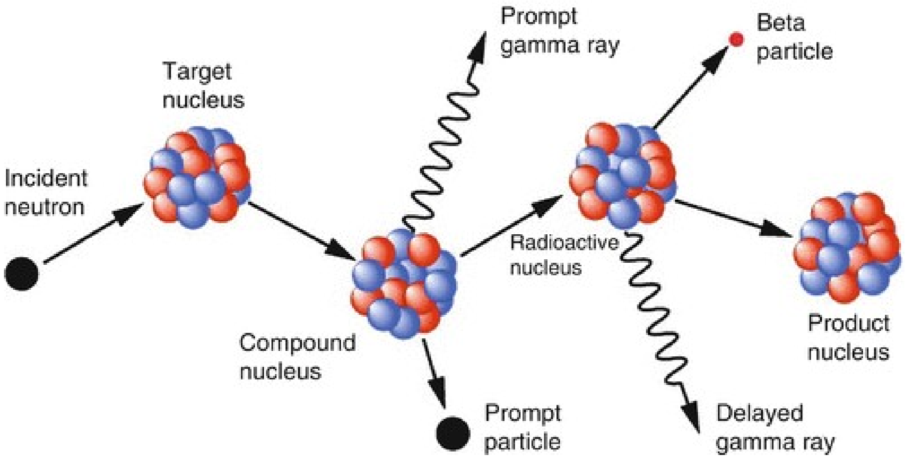
Neutron Activation

Sample is activated with neutrons causing its components to form radioactive isotopes.

Main advantage is that the sample does not need to be destroyed.

Sample can then be counted using usual methods such as Ge spectrometry.

Main drawback is that the sample may remain radioactive for quite some time and there are limited opportunities to irradiate samples as suitable activation reactors are declining.



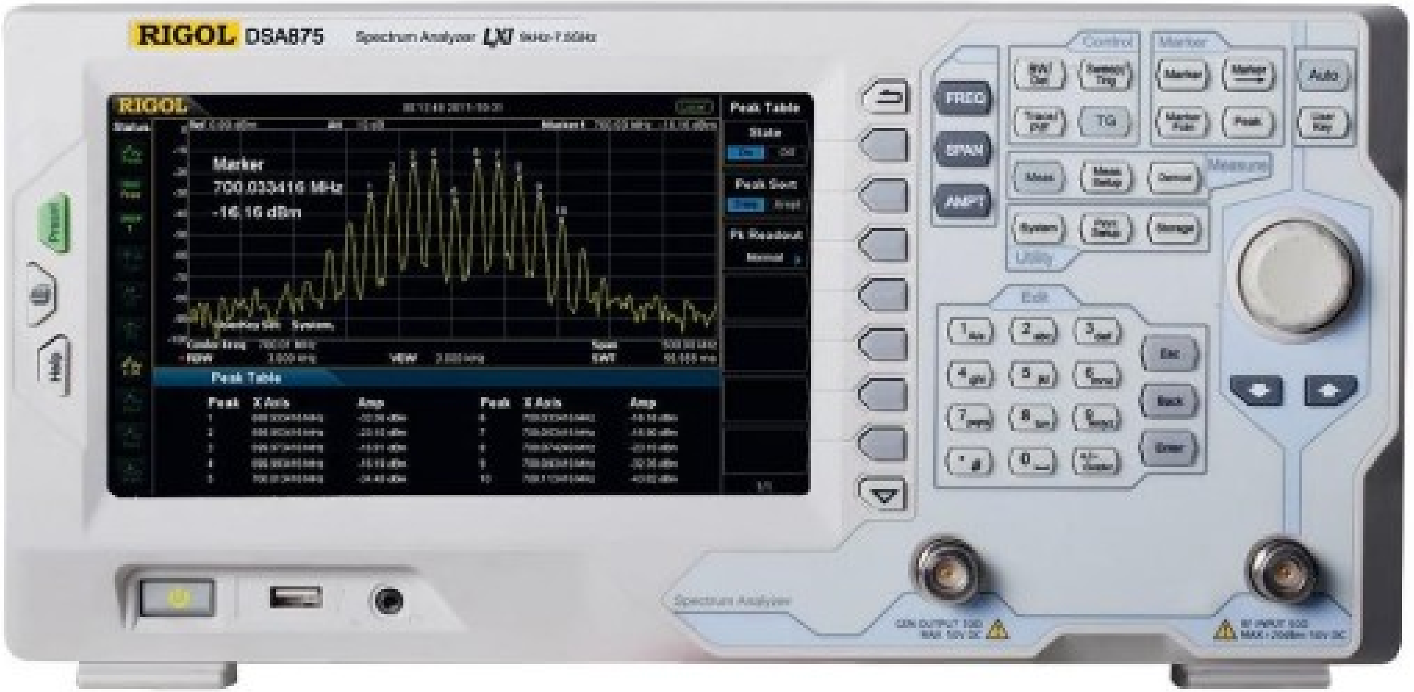
Röntgen Excitation Analysis

X-ray fluorescence of a sample after being bombarded with high-energy X-rays or gamma rays.

Used for elemental analysis and chemical analysis, used generally for metals, glass, building materials, etc…

For low background experiments, for example, it can be used to measure surface contamination by observing any presence of heavy elements such as iron, calcium and zinc which can be found in mine dust.

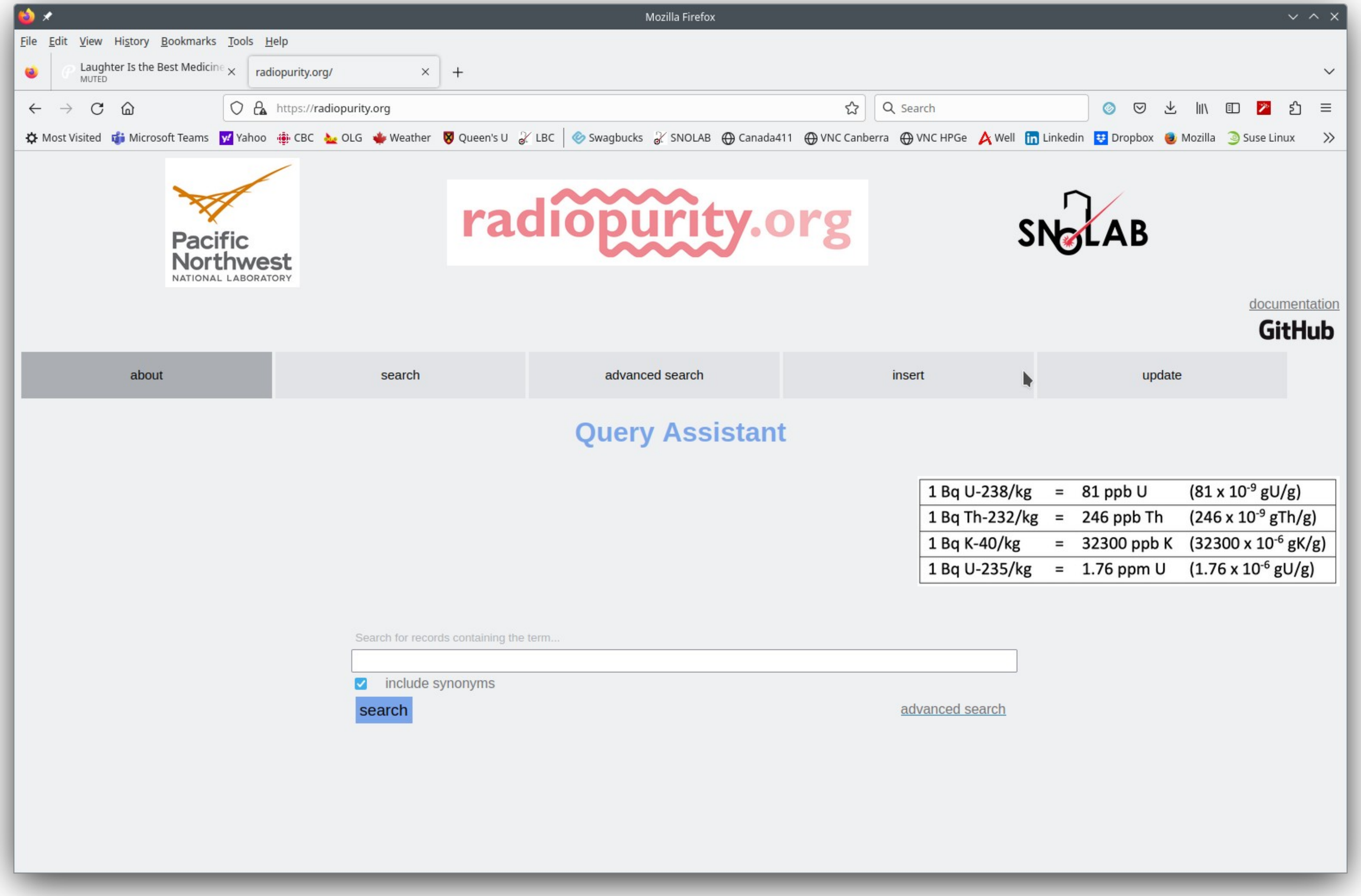
Catalogue of EMI Signatures



Spectrum Analyzer with a 9 kHz - 7.5 GHz frequency range

Survey and catalogue sources of electrical noise in the lab

Material Assay Database



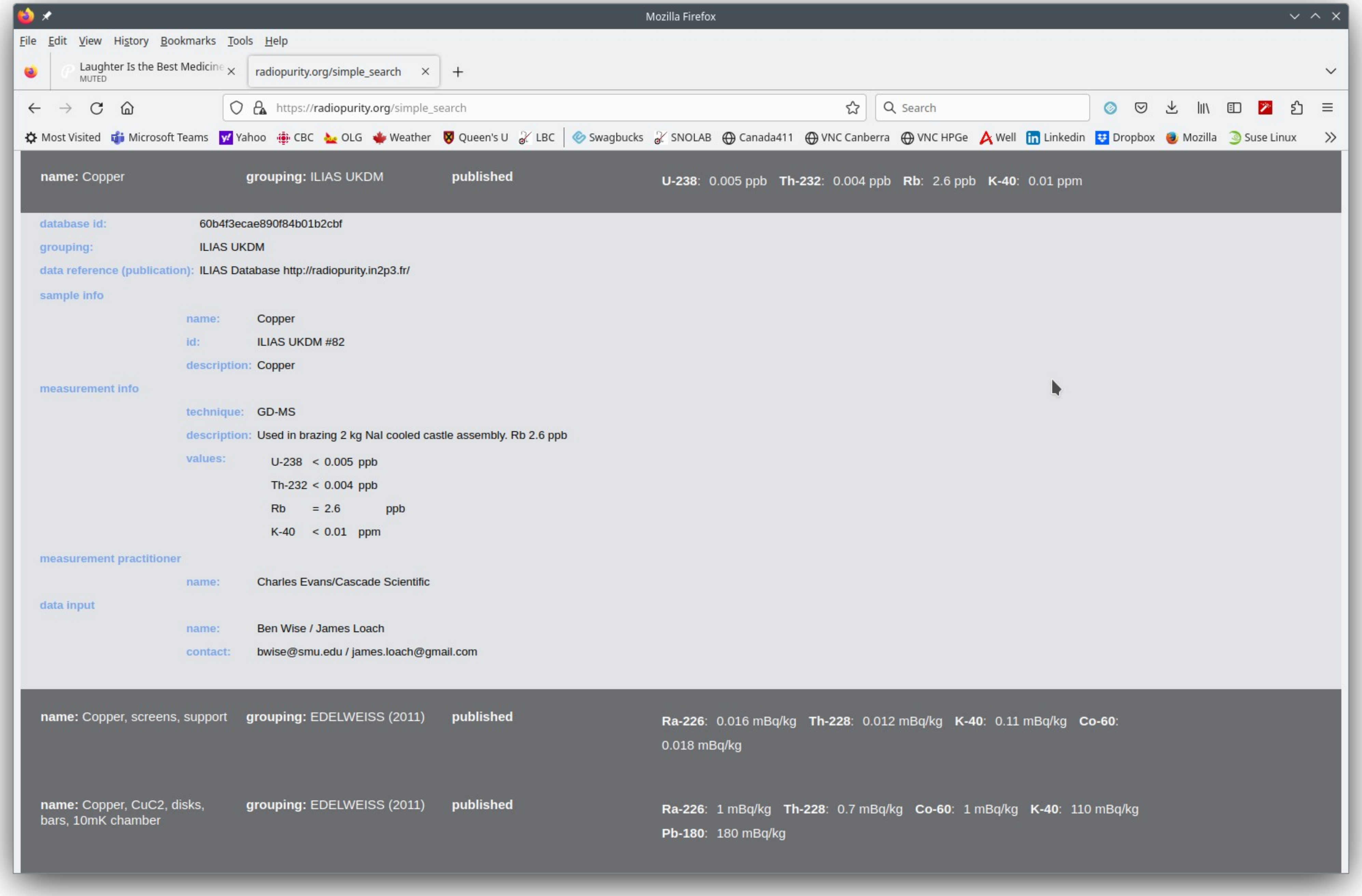
Query Assistant

1 Bq U-238/kg	=	81 ppb U	(81 x 10^{-9} gU/g)
1 Bq Th-232/kg	=	246 ppb Th	(246 x 10^{-9} gTh/g)
1 Bq K-40/kg	=	32300 ppb K	(32300 x 10^{-6} gK/g)
1 Bq U-235/kg	=	1.76 ppm U	(1.76 x 10^{-6} gU/g)

Search for records containing the term...

- The Assay and Acquisition of Radiopure Materials (AARM) Collaboration originally developed the Community Material Assay Database radiopurity.org.
- The database is hosted at SNOLAB.
- Contains published results and non-published results with permission of the experiment

Material Assay Database (radiopurity.org)



name: Copper **grouping:** ILIAS UKDM **published** **U-238**: 0.005 ppb **Th-232**: 0.004 ppb **Rb**: 2.6 ppb **K-40**: 0.01 ppm

database id: 60b4f3ecae890f84b01b2cbf
grouping: ILIAS UKDM
data reference (publication): ILIAS Database http://radiopurity.in2p3.fr/

sample info
name: Copper
id: ILIAS UKDM #82
description: Copper

measurement info
technique: GD-MS
description: Used in brazing 2 kg NaI cooled castle assembly. Rb 2.6 ppb
values:

U-238	<	0.005	ppb
Th-232	<	0.004	ppb
Rb	=	2.6	ppb
K-40	<	0.01	ppm

measurement practitioner
name: Charles Evans/Cascade Scientific

data input
name: Ben Wise / James Loach
contact: bwise@smu.edu / james.loach@gmail.com

name: Copper, screens, support **grouping:** EDELWEISS (2011) **published** **Ra-226**: 0.016 mBq/kg **Th-228**: 0.012 mBq/kg **K-40**: 0.11 mBq/kg **Co-60**: 0.018 mBq/kg

name: Copper, CuC2, disks, bars, 10mK chamber **grouping:** EDELWEISS (2011) **published** **Ra-226**: 1 mBq/kg **Th-228**: 0.7 mBq/kg **Co-60**: 1 mBq/kg **K-40**: 110 mBq/kg **Pb-180**: 180 mBq/kg

Summary

- There are many different techniques to measure radioactive backgrounds.

- The technique can depend on several factors:
  - upon its size,
  - whether or not the sample itself is to be used in the experiment
  - can the sample be sacrificed, etc…

- Sometimes a sample can be counted using multiple methods
  - Ge spectrometry to measure the sample bulk
  - α spectrometry to measure the sample surface

- SNOLAB is embarking on a program to better understand the underground background environment.

- Background database requires greater involvement with the community to include data from a much larger set of experiments.

SNOLAB Low Background Team

- SNOLAB, Sudbury
  - L. Anselmo, D. Chauhan, B. Cleveland, J. Farine, N. Fatemighomi, J. Hall, I. Lawson, S. Luoma, T. Sonley and Students
- CTBT radionuclide laboratory CAL05 - Dual CTBT Detector
  - Health Canada
  - Adrian Botti, Pawel Mekarski, Marc Bean, Colin Vant and Kurt Ungar
- UNAM group
  - Institute of Physics, UNAM, Mexico - Background Gamma and Neutron Measurements
  - Lead: Eric Vázquez-Jáuregui
- University of Michigan – Vibration Studies
  - Bjoern Penning and Sam Venetianer