The 3rd INFN School on Underground Physics

Material Screening

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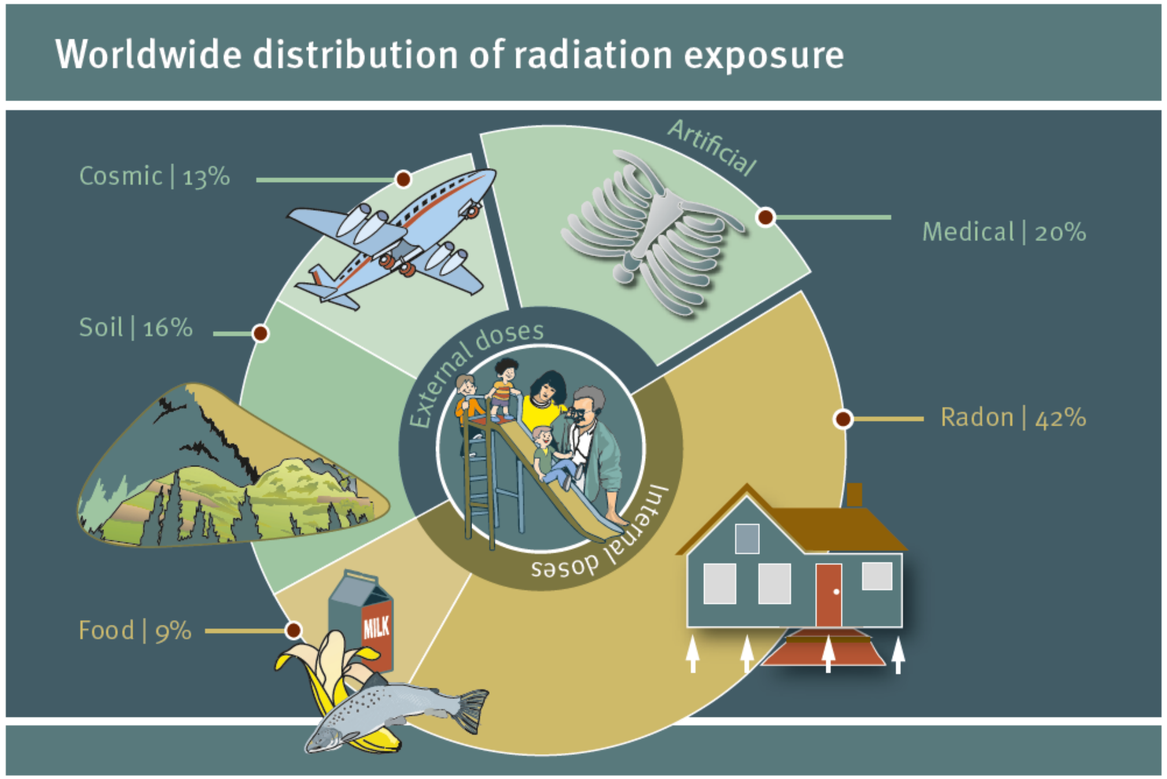
Outline

- Sources of radioactive background
- The strategies for background reduction
- The main techniques for material screening:
  - ✦ Gamma spectroscopy with HPGe detectors
  - ✦ Neutron activation analysis
  - ✦ Inorganic mass spectrometry
  - ✦ Alpha spectroscopy
  - ✦ “Custom” techniques

Radioactivity is all around us

Sources of human radiation exposure
Average contributions in Italy:

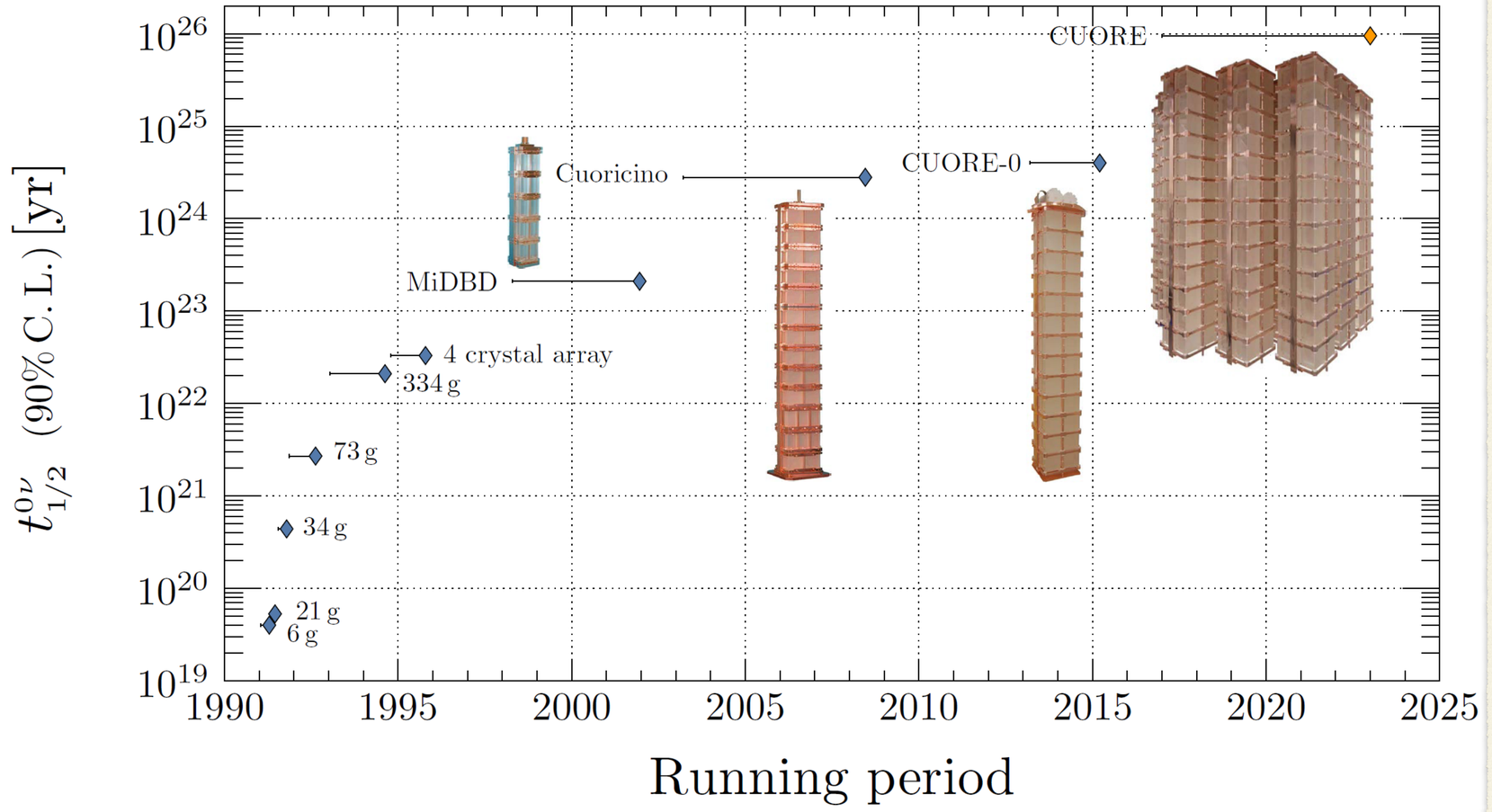
- Natural radiation (~80%)
  - Radon gas: 1.5 – 2.5 mSv/y
  - Cosmic radiation: 0.3 – 0.5 mSv/y
  - Terrestrial radiation: 0.3 – 0.4 mSv/y
  - Internal radiation: 0.2 mSv/y
- Artificial radiation (~20%)
  - Medical procedures: 0.5 – 1.2 mSv/y
  - Other sources: negligible

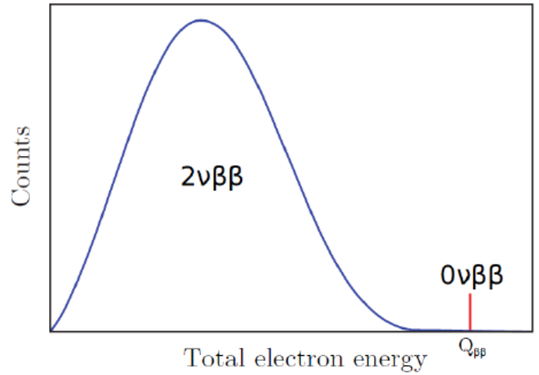


➡ Total Average Annual Radiation Exposure in Italy: ~ 3 – 4 mSv/y

A case study - $0\nu\beta\beta$ decay search

The CUORE experiment with cryogenic detectors





Experimental sensitivity: (for bkg ≠ 0)

$$S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{i.a.}{A}\sqrt{\frac{M\,t_{meas}}{\Delta E \cdot bkg}}$$

ε	detector efficiency	**ΔE**	FWHM resolution
i.a.	$0\nu\beta\beta$ isotope abundance	**M**	total active mass
A	atomic mass	t_{meas}	measuring time

bkg background @ ROI in counts/keV/kg/y

A case study - $0\nu\beta\beta$ decay search

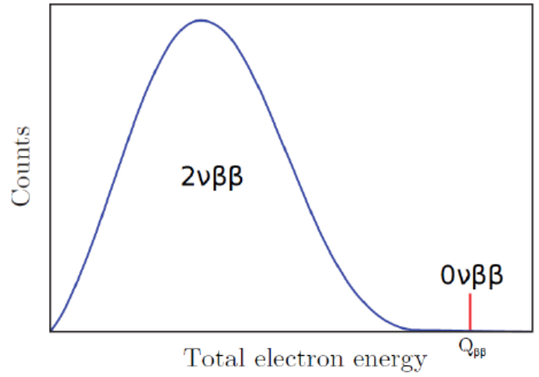
Planned and future experiments

Ultimately, for bkg = 0:

$$S^{0\nu}(\tau_{1/2}) \propto \frac{\epsilon\, i.a.}{A} M t_{meas}$$

sensitivity increases linearly with mass and measuring time

This is what the experiments aim at



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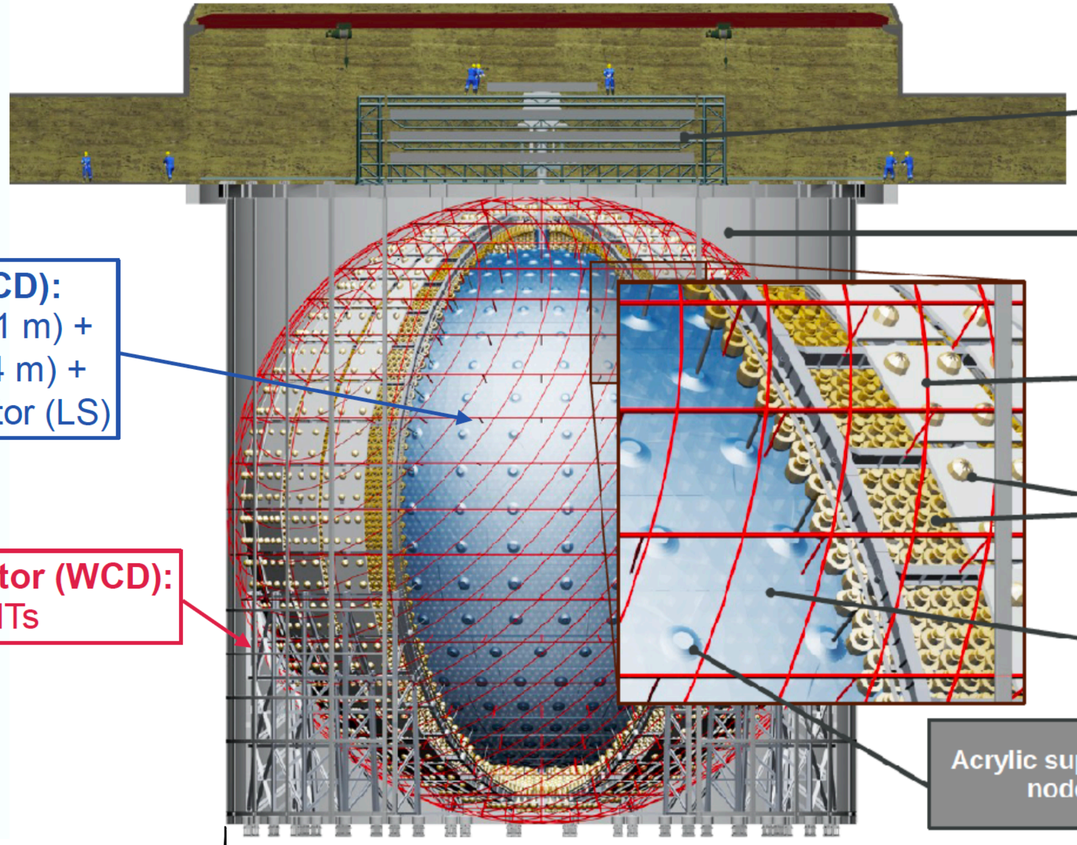
- **ε** detector efficiency
- **ΔE** FWHM resolution
- **i.a.** $0\nu\beta\beta$ isotope abundance
- **M** total active mass
- **A** atomic mass
- $\mathbf{t_{meas}}$ measuring time
- **bkg** background @ ROI in counts/keV/kg/y

A case study - measurement of ν oscillations

The JUNO experiment to determine the neutrino mass ordering



Central Detector (CD):
Steel structure (⌀ 40.1 m) +
Acrylic vessel (⌀ 35.4 m) +
20 kton Liquid Scintillator (LS)

Water Cherenkov Detector (WCD):
2400 20-inch PMTs

Top tracker and calibration house

Top Tracker (TT):
3 plastic scintillator layers

Water pool

Pool's dimensions
- height: 44 m
- diameter: 43.5 m
- water depth: 43.5 m

Earth magnetic field compensation coils

Photo-multiplier tubes

Light read-out:
17612 20-inch PMTs
25600 3-inch PMTs

Acrylic spherical vessel filled with liquid scintillator

Acrylic supporting nodes

47 events/day expected
→ bkg control is mandatory!

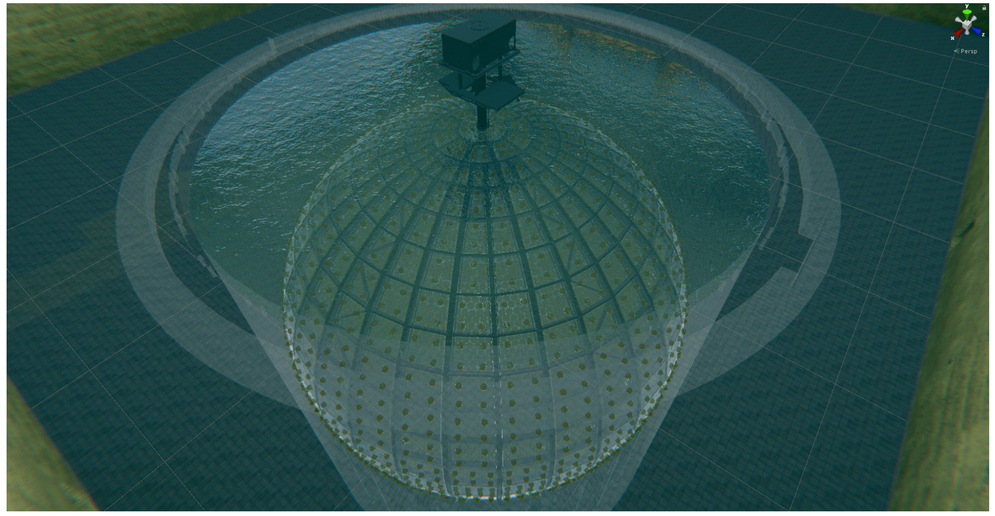
Experiment	Daya Bay	BOREXINO	KamLAND	JUNO
LS mass	20 ton	~ 300 ton	~ 1 kton	20 kton
Coverage	~ 12%	~ 34%	~ 34%	~ 78%
Energy resolution	~ 8% /√E	~ 5% /√E	~ 6% /√E	~ 3% /√E
Light yield	~ 160 p.e. /MeV	~ 500 p.e. /MeV	~ 250 p.e. /MeV	> 1345 p.e. /MeV

A case study - JUNO radiopurity requirements

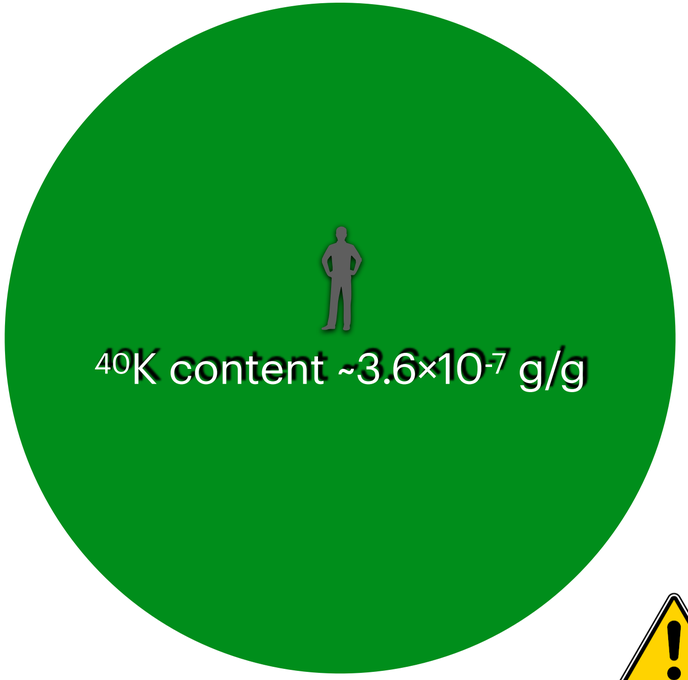
for the liquid scintillator (20 kton of mass)

Minimum requirements for LS:

- $^{238}U/^{232}Th < 10^{-15}$ g/g
- $^{40}K < 10^{-16}$ g/g



mass ~70 kg



JUNO LS
^{40}K content < 10^{-16} g/g

illustrative only!
not to scale!

Sources of radioactivity

of particular concern for neutrino and dark matter experiments

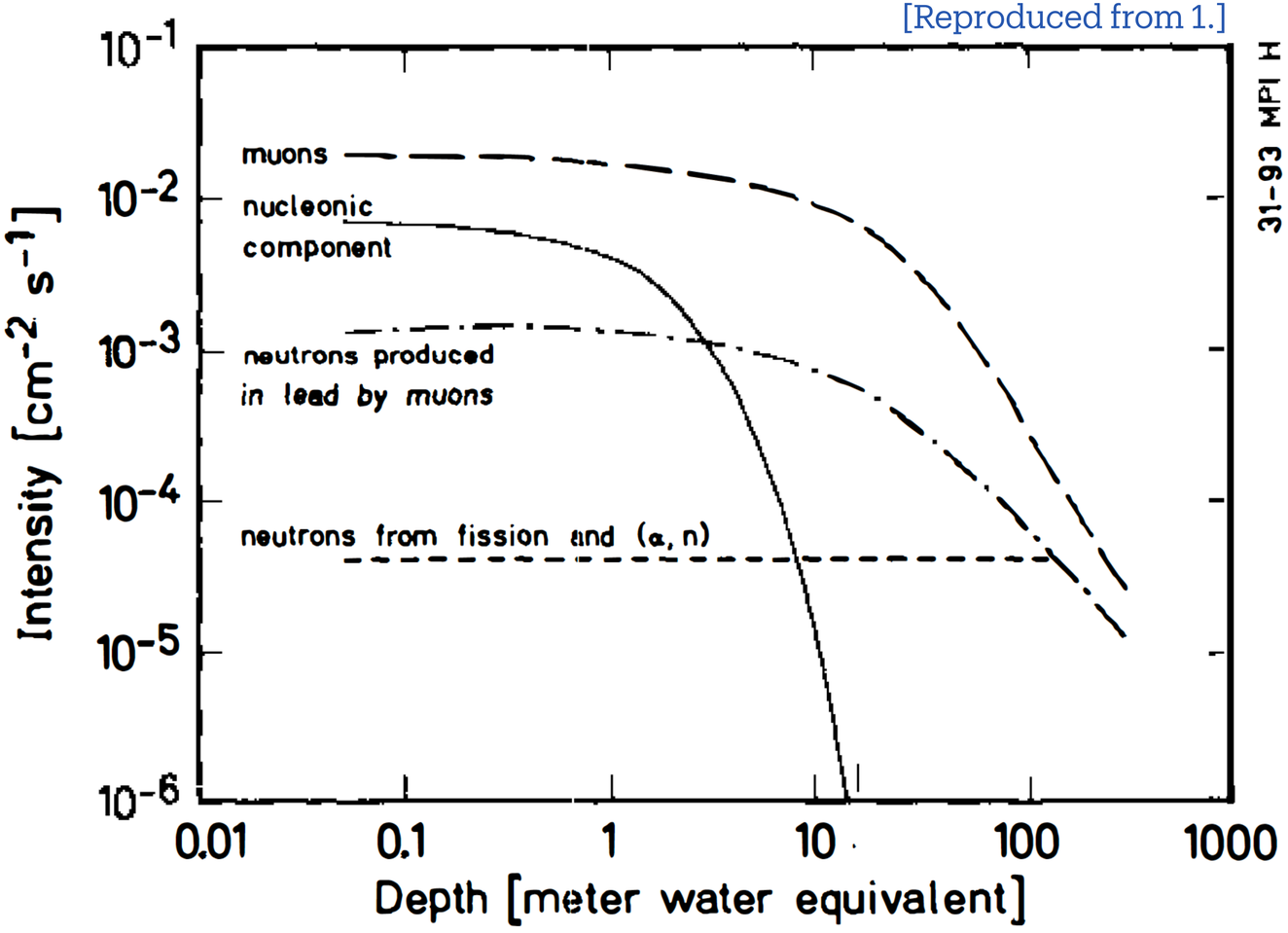
- Natural long lived radionuclides ^{238}U and ^{232}Th - with their decay chains at secular equilibrium - and ^{40}K
- Natural medium lived radionuclides ^{226}Ra, $^{210}Pb/^{210}Bi$, ^{210}Po when secular equilibrium is broken in ^{238}U chain
- Gaseous nuclides ^{222}Rn, ^{85}Kr, ...
- Artificial (anthropogenic, man-made) radionuclides ^{60}Co, ^{137}Cs, ^{3}H, ^{14}C, ^{90}Sr, ...
- Cosmic rays
- Cosmogenic activated nuclides

Cosmic rays

Primary and secondary components

- Primary cosmic rays: protons (90%), alphas (9%), heavier nuclei (1%)
- Secondary particles produced by interaction with atmosphere: neutrons, electrons, neutrinos, protons, muons, pions
- Muons and neutrons are of great concern in low background experiments

[Reproduced from 1.]



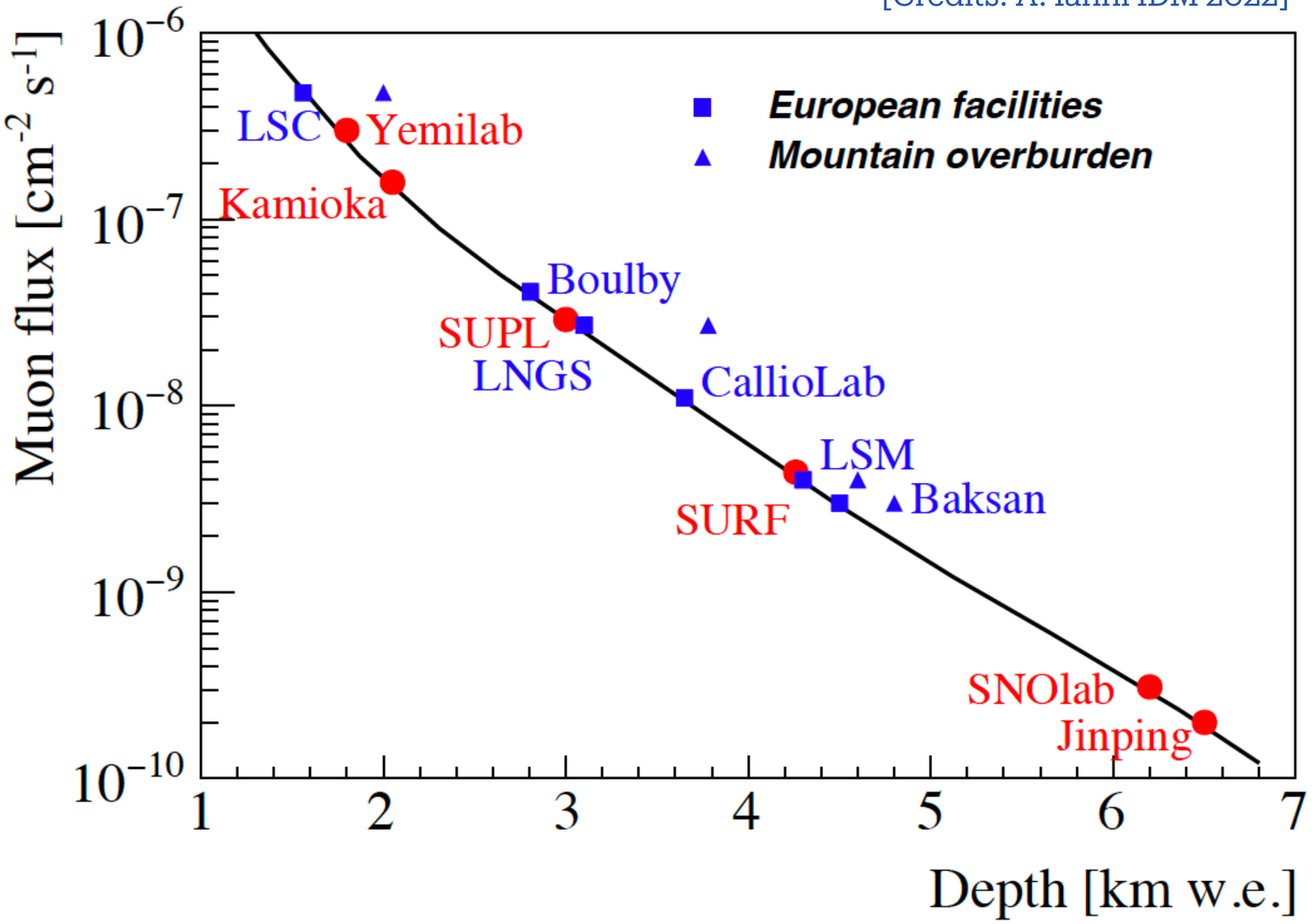
Meter of water equivalent (m.w.e.) *represents the thickness of water that would provide the same level of shielding as the given material*

Cosmic rays

Muon attenuation in underground laboratories

- Muon flux at sea level:
  ~ 10^{-2} cm^{-2} s^{-1}
- The energy spectrum of muons is shifted towards higher energies with increasing depth:
  ~ 4 GeV at sea level
  ~ 270 GeV at LNGS
- Muon spallation products could be difficult to tag: neutrons are of most concern

[Credits: A. Ianni IDM 2022]



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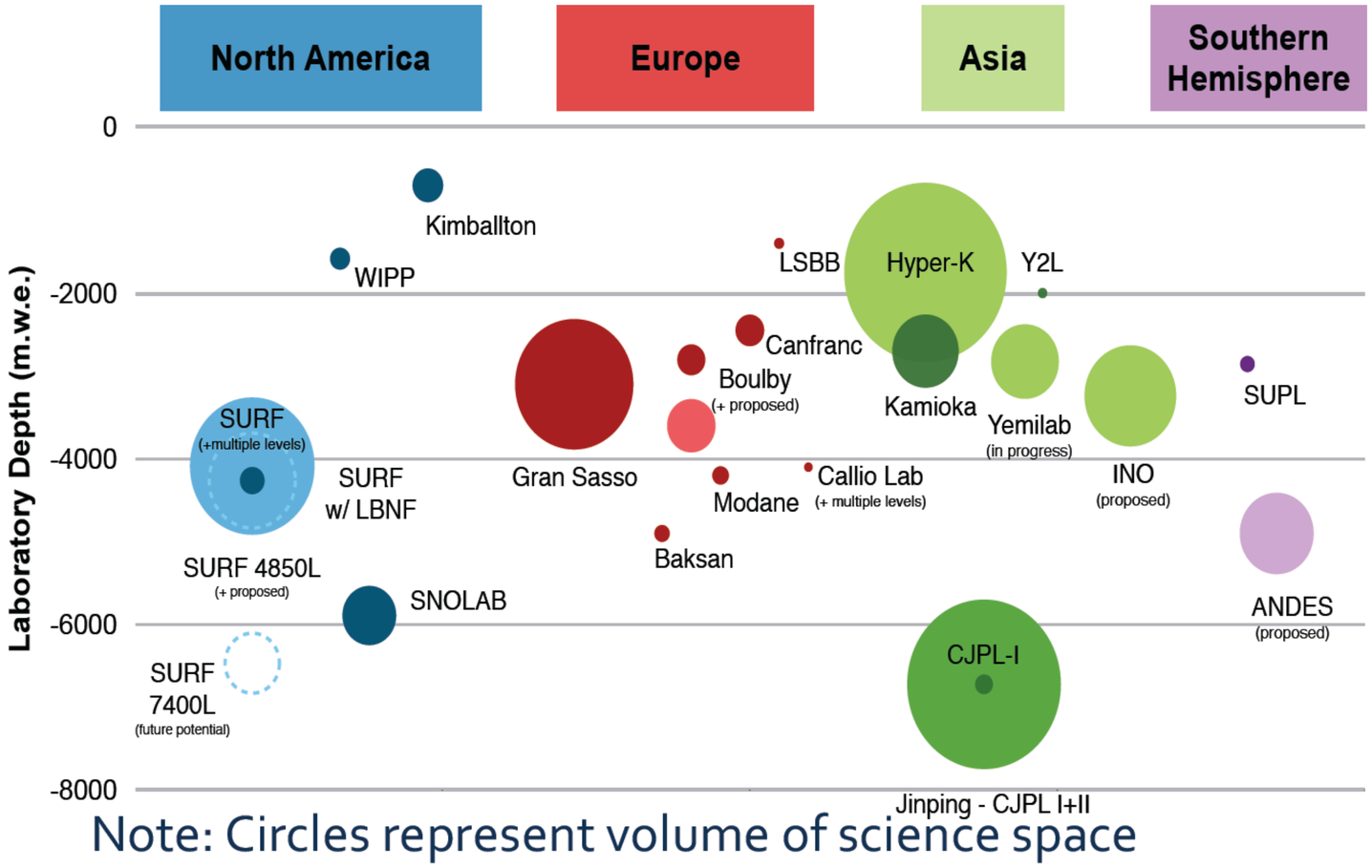


Neutron production underground

from natural radioactivity: (α,n) reactions and spontaneous fission

[Reproduced from 2.]

Type of rock	U (ppm)	Th (ppm)	U(α, n)	Th(α, n)	Fission	Total yield
	Concentration (ppm)		(neutrons/g/y)			
Granite	5	11	7.85	7.755	2.33	17.9
Limestone	1	1	0.64	0.285	0.467	1.4
Sandstone	1	1	0.837	0.38	0.467	1.7
Granite A	1.32	7.79	2.24	5.92	0.62	8.8
Granite B	6.25	4.59	10.62	3.49	2.92	17.0
Granite C	1.83	4.38	3.11	3.33	0.85	7.3
Salt I	0.30	2.06	1.60	4.77	0.14	6.5
Salt II	0.13	1.80	4.17	0.69	0.06	4.9

Estimated neutron production from different types of rocks

- U/Th contaminations in the detector materials could also be a source of (α,n) reactions, e.g. natural contaminants in the liquid scintillator of JUNO: material control is crucial.

Cosmogenic activated nuclides

Radioisotope production

- Production of different radionuclides depending on the materials under consideration. This is of concern for all components of the experimental setup.
- e.g., Measured activated nuclides in copper:

[Applied Radiation and Isotopes 67 (2009) 750–754]

Cosmogenic production rates (PR) (saturation activity) and primordial radio- nuclide concentrations (activity) in Cu

Radionuclide	Half-life[a]	(Saturation) activity (μBq kg^{-1})		
		Exposed	Unexposed	Estimated[b]
Cosmogenic				
^{56}Co	77.236 d	230 ± 30		557
^{57}Co	271.80 d	1800 ± 400		2147
^{58}Co	70.83 d	1650 ± 90		3878
^{60}Co	5.271 a	2100 ± 190	< 10	2367
^{54}Mn	312.13 d	215 ± 21		791
^{59}Fe	44.495 d	455 ± 120		157
^{46}Sc	83.788 d	53 ± 18		93
^{48}V	15.9735 d	110 ± 40		
Primordial				
^{226}Ra (U)	1600 a	< 35	< 16	
^{228}Th (Th)	698.60 d	< 20	< 19	
^{40}K	1.265×10^9 a	< 110	< 88	

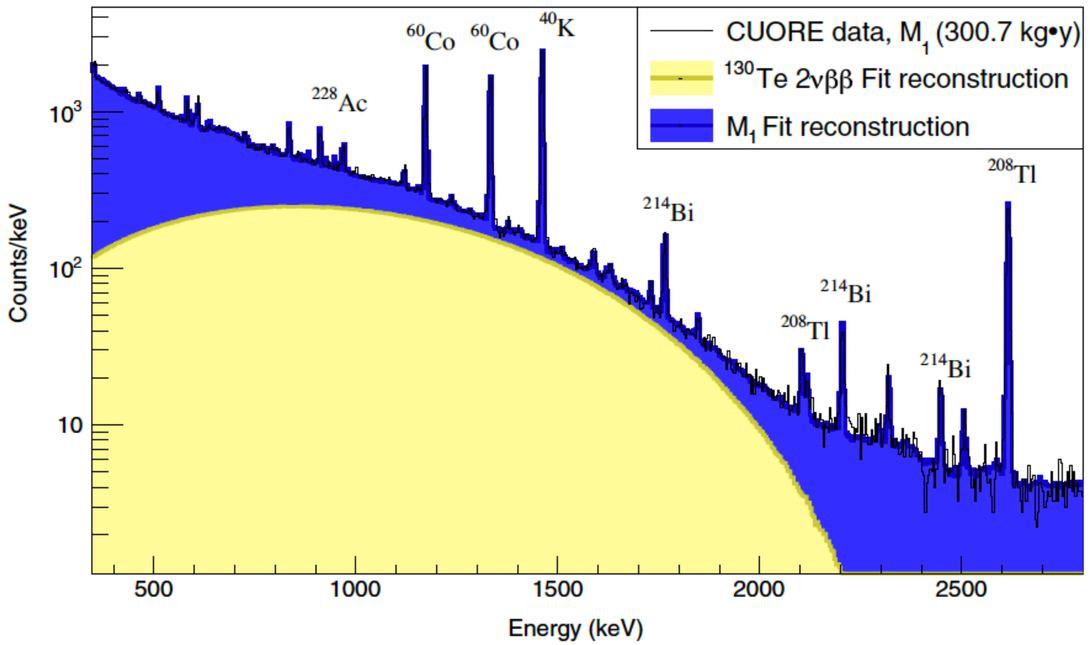
Anthropogenic radionuclides

Man-made radioactivity

- Radioactive isotopes occurring in the environment due to human activities
- They are mostly the results of nuclear weapons testing, nuclear accidents, and operation of nuclear power plants.
- The most dangerous nuclides depend on the particular experiment and on the environment, e.g. ^{108m}Ag for KamLAND-ZEN after the Fukushima accident.

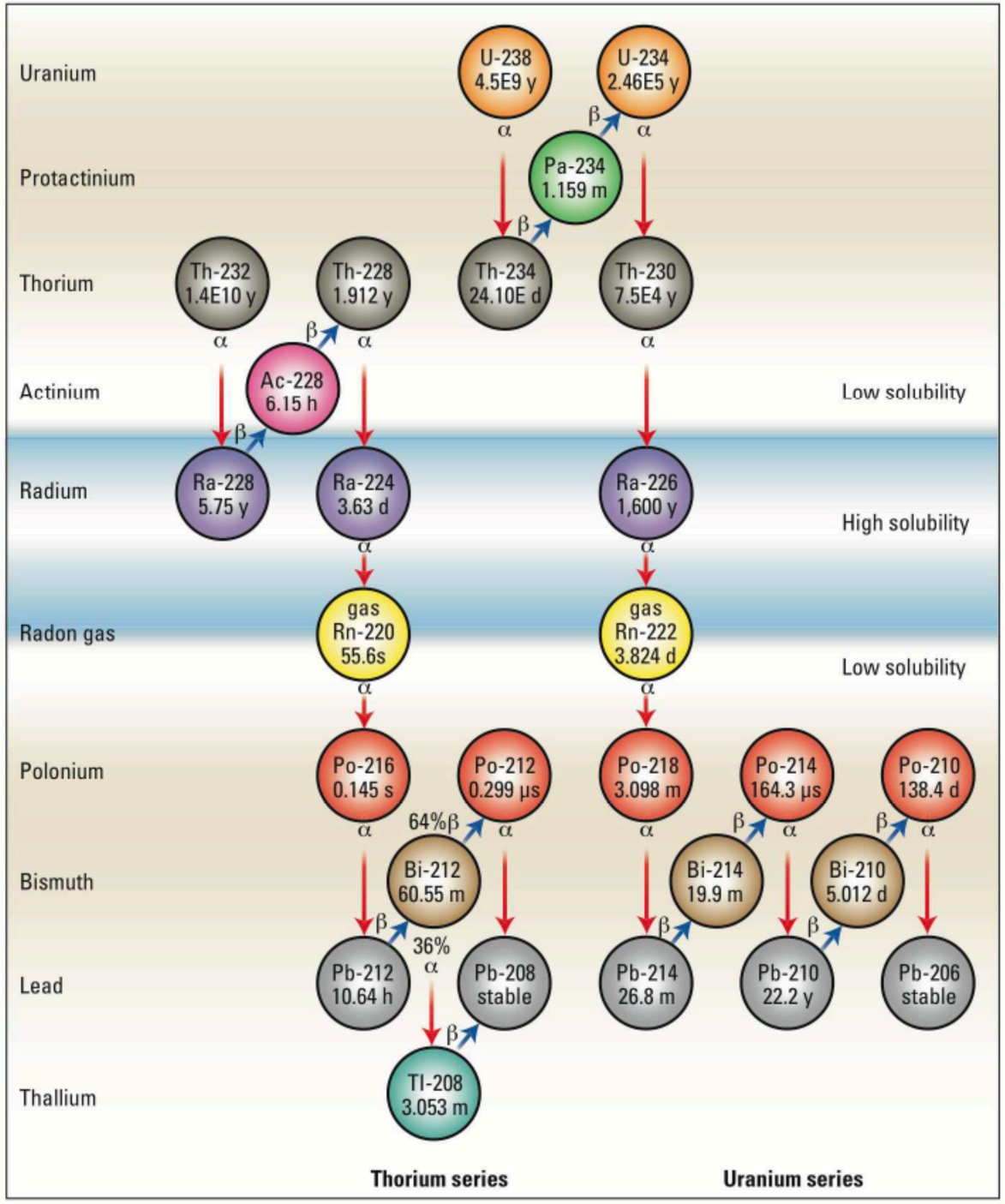
Very dangerous are the pure beta emitters like ^{90}Sr ($T_{1/2}$ = 28.9 y, Q=546 keV), e.g. for $2\nu\beta\beta$ studies.

[PRL 126 (2021) 171801]



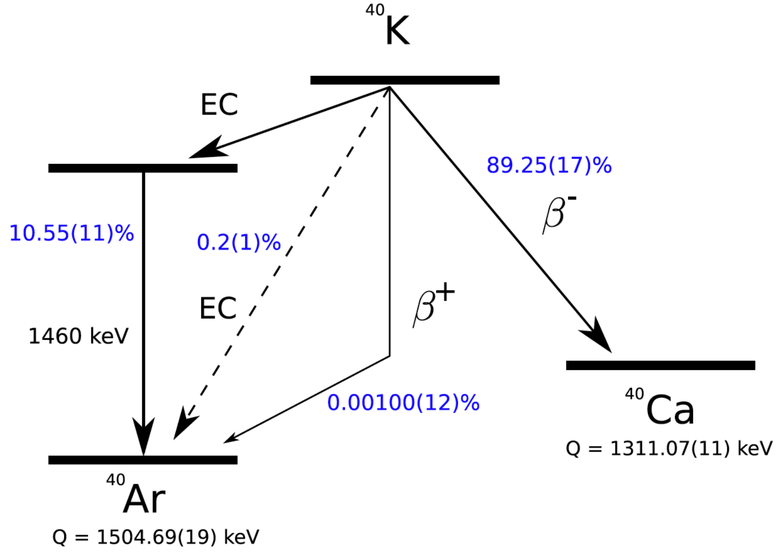
Natural radioactivity

^{238}U and ^{232}Th series:



^{40}K decay:

(^{40}K: i.a. = 0.0117%)



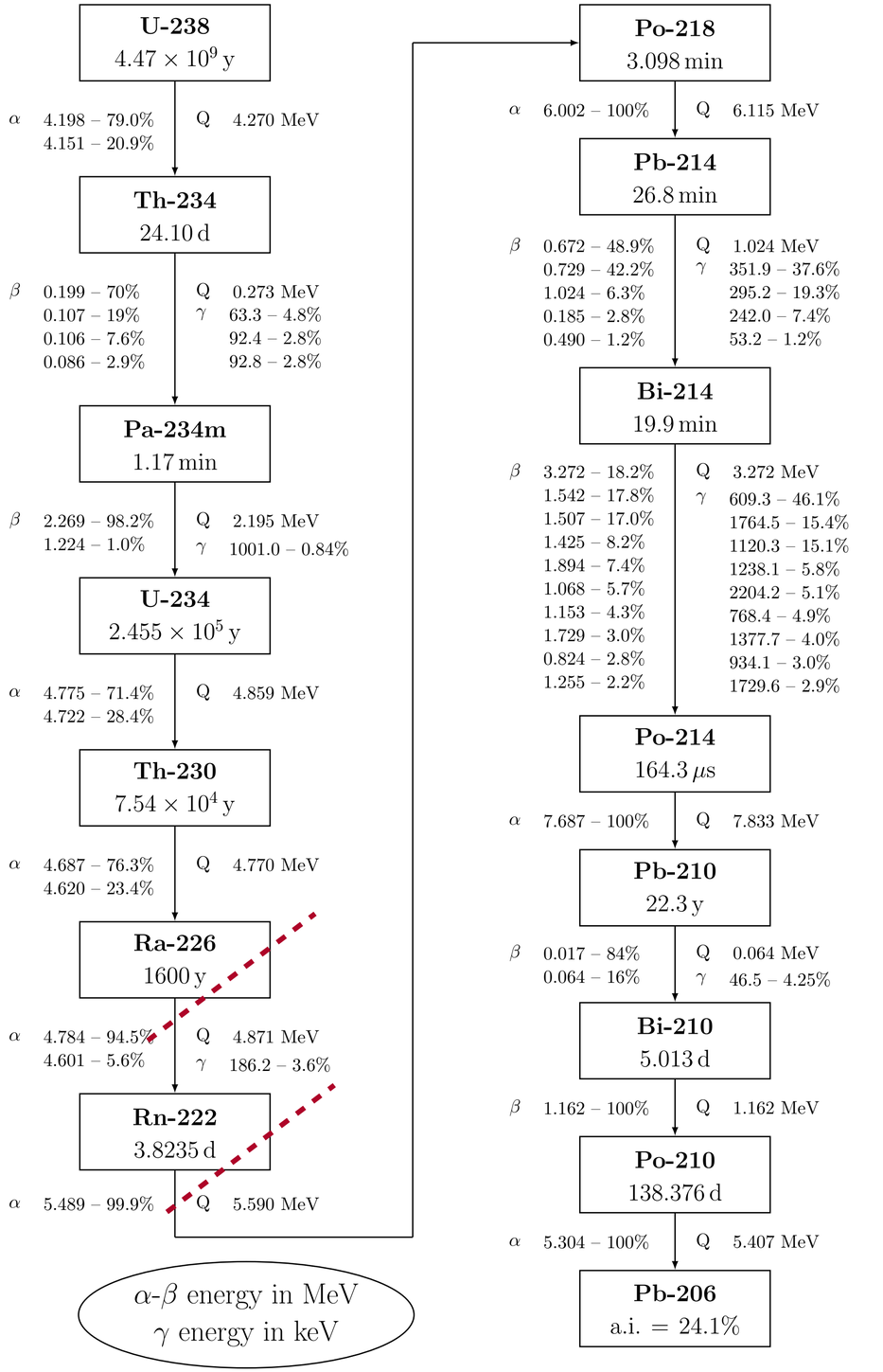
Average concentrations in the Earth's crust:

- ^{238}U ~ 36 Bq/kg
- ^{232}Th ~ 44 Bq/kg
- ^{40}K ~ 850 Bq/kg

Natural radioactivity

^{238}U series

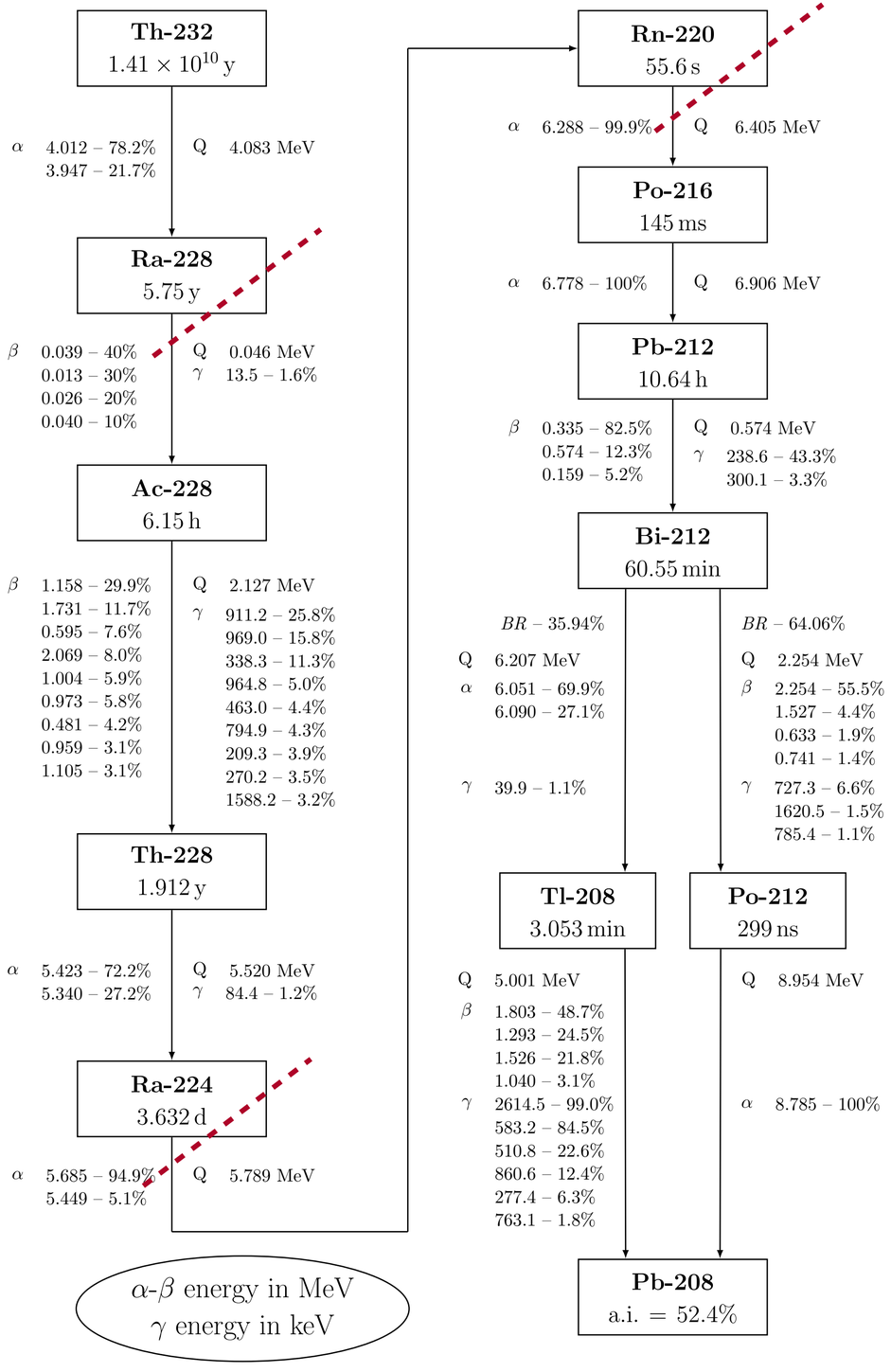
- ^{238}U: i.a. 99.3%
  half-life 4.5×10^{9} y
- Decay chain is rarely in secular equilibrium
- One of its daughters, ^{222}Rn, is responsible for most of the human radiation exposure. It is also one of the most insidious background sources.
- Radon decay is the origin of ^{210}Pb (^{210}Po) implantation on material surfaces.



Natural radioactivity

^{232}Th series

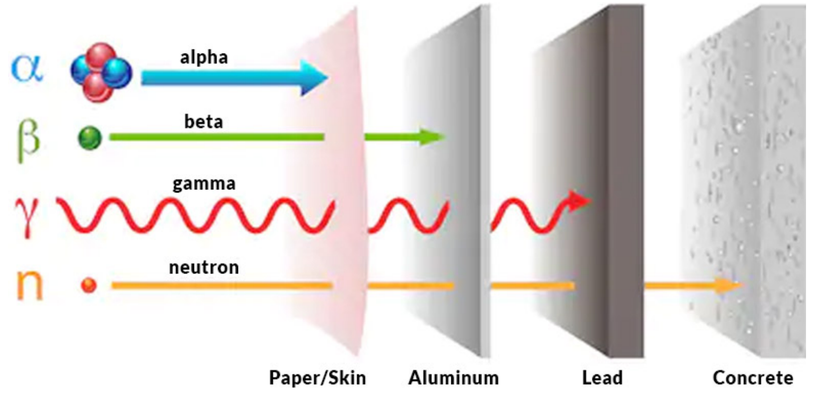
- ^{232}Th: i.a. 100%
  half-life 14×10^9 y
- The decay chain quickly reaches secular equilibrium, typically within approximately 30 years.
- The radon isotope in the thorium decay chain has a significantly shorter half-life compared to ^{222}Rn.



Background reduction

The everyday struggle of a low-background experimentalist

- Environmental radioactivity
- Contaminations in the shielding material
- Contaminations in the detector material
- Radon and its progenies
- Cosmic and cosmogenic background



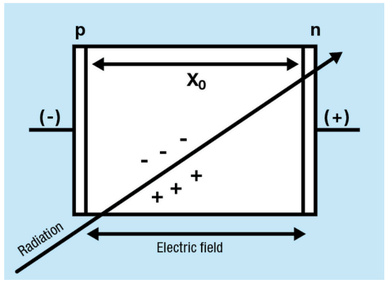
How to reach optimum background reduction?

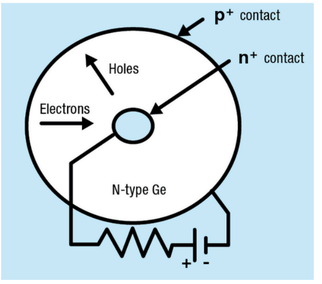
→ **Case study: HPGe spectroscopy**

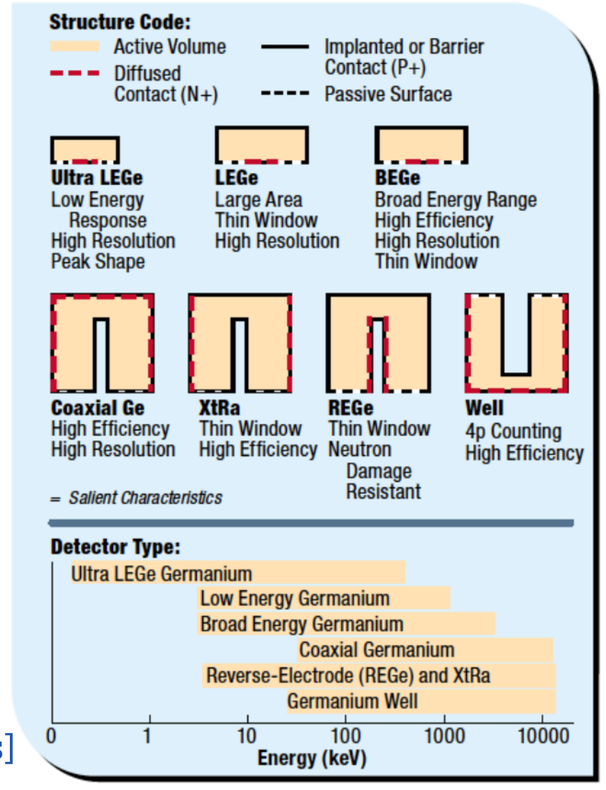
Low background γ-ray spectroscopy

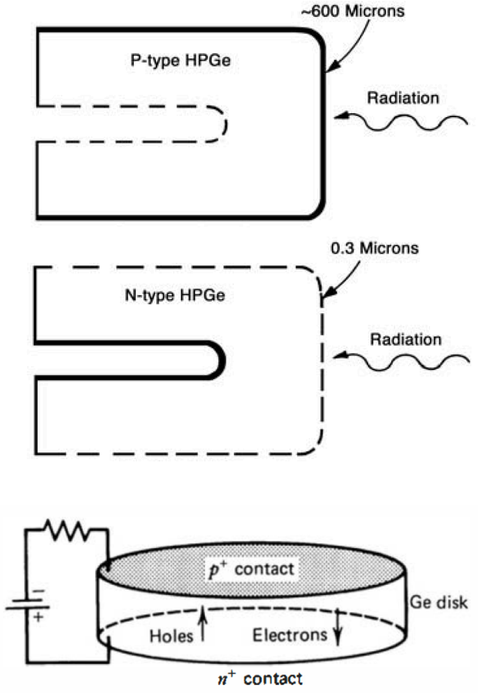
using High Purity Germanium detectors (HPGe)

- Semiconductor p-i-n diodes: under reverse bias an electric field extends across the intrinsic (depleted) region
- When photons interact within the depleted region, charge carriers are produced and swept by the electric field to the electrodes. The charge is proportional to the deposited energy
- Since germanium has a small band gap (—> superior energy resolution), the detector must be operated at 77°K to reduce leakage current









[credits: Mirion Technologies]

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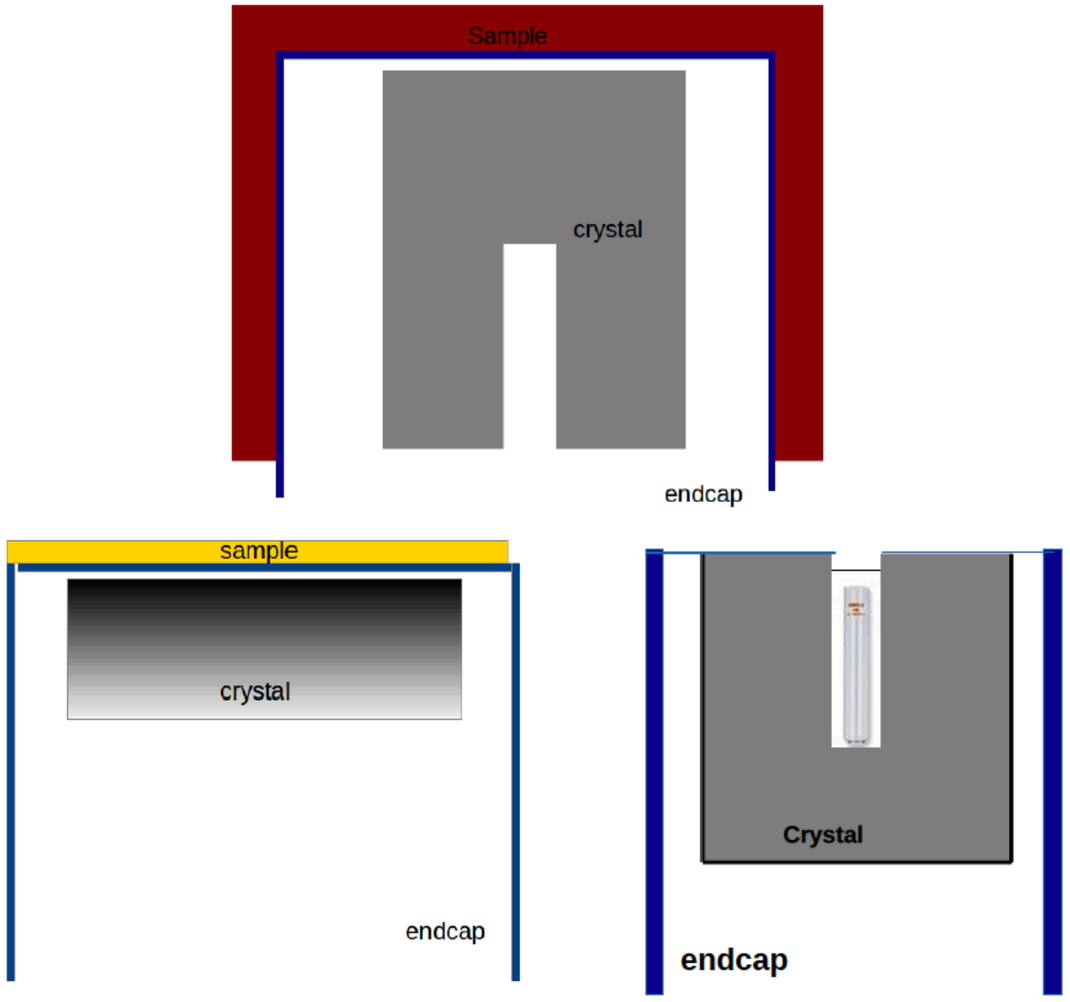
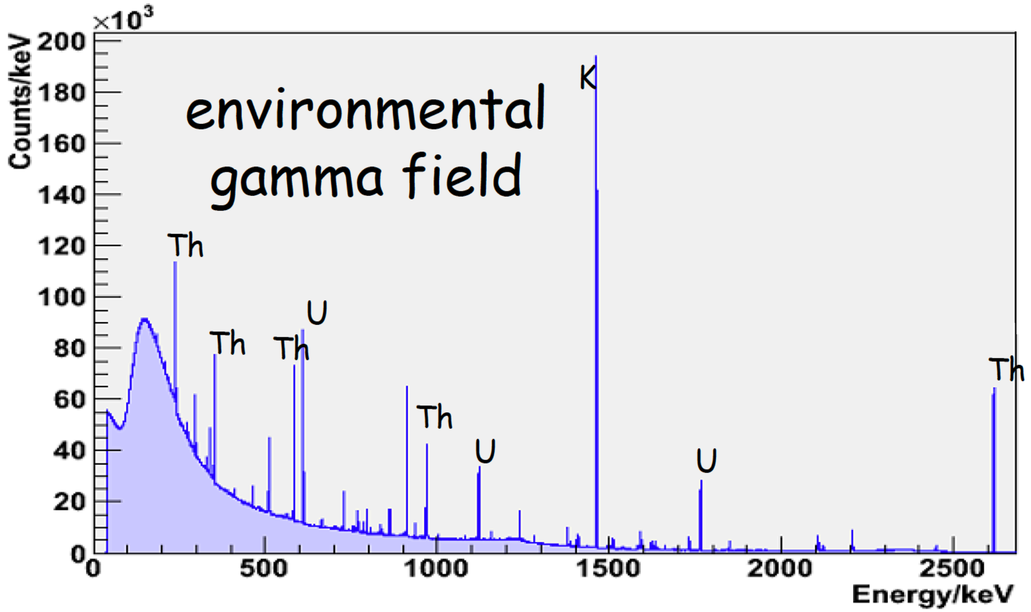


[credits: P. Loaiza]

Optimising a HPGe system

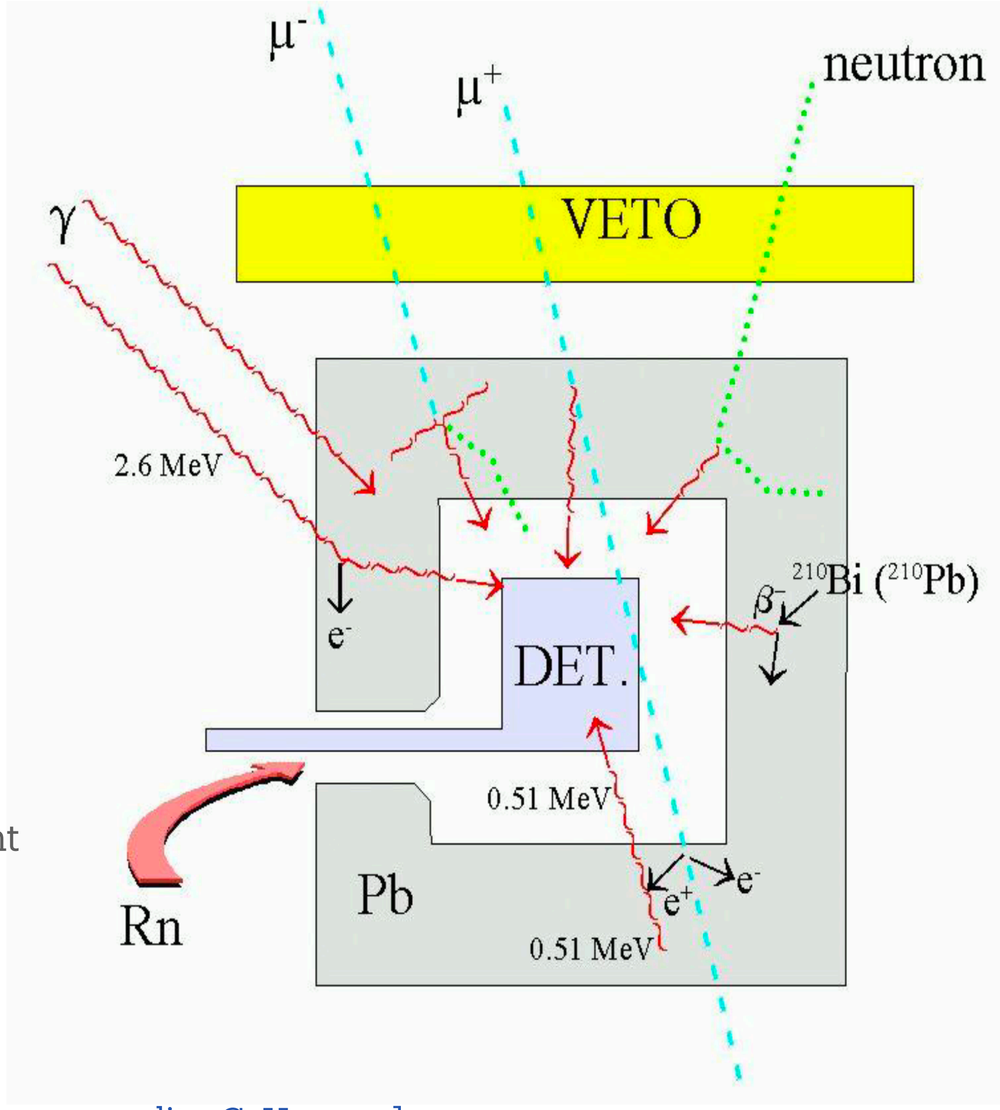
Reducing environmental, cosmic and cosmogenic background



- Passive background reduction:

  $I(x) = I_0 \exp(-\mu x)$ where μ [cm^{-1}] is the attenuation coefficient

- Pb (high Z) is usually a good choice



[image credits: G. Heusser]

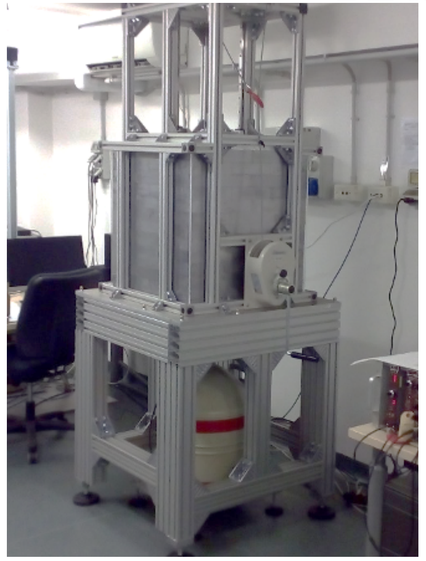
Shielding material radiopurity

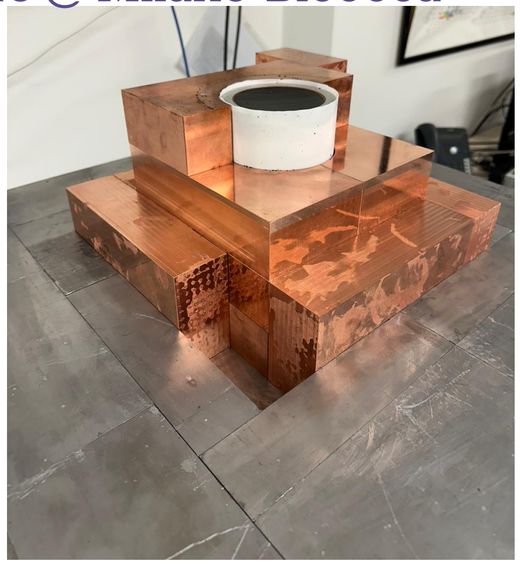
Composite shielding is usually used

material	activity [μBq/kg]				E-6 attenuation of 2.61 MeV γ
	^{226}Ra (U)	^{228}Th (Th)	^{40}K	various	
lead	≤ 29 a)	≤ 22 a)	270 a)	< 4x10^{3} ^{210}Pb b)	28.5 cm
copper	≤ 16 a)	9 c) ≤ 19 a)	≤ 88 a)	≤ 10 ^{60}Co a)	40.9 cm
steel	130 a)	≤ 40 a)	50 a)	140 ^{60}Co a)	46.2 cm
water	≤ 1*	0.04 d) 0.008 e)	≤ 2 d)		324 cm
liq. sc. (PC)	10^{-6} f)	≤ 10^{-6} f)	≤ 0.001 f)		373 cm
liq. nitrogen	≤ 0.3*			10^{-3} ^{39}Ar g) 0.04 ^{85}Kr g)	443 cm
liq. argon	≤ 7*			^{39}Ar: 10^{6} h) 6500 i)	276 cm
liq. xenon	<< 60 k)*			0.2 ^{85}Kr k)+	120 cm

a) GeMPI; b) bolometric Milano; c) Ge PNNL; d) ^{232}Th by ICP-MS Ispra; e) ^{232}Th by NAA TU München; f) ^{226}Ra + ^{228}Th by Bi-Po Borexino; g) Rare Gas MS MPI-K; h) atmospheric Ar, PC Bern, WARP; i) underground Ar, I. Xu et al. (DarkSide), j) Gerda; k) XENON100/1T ,+ Rare Gas MS MPI-K; * via ^{222}Rn MPI-K

BEGe @ Milano-Bicocca



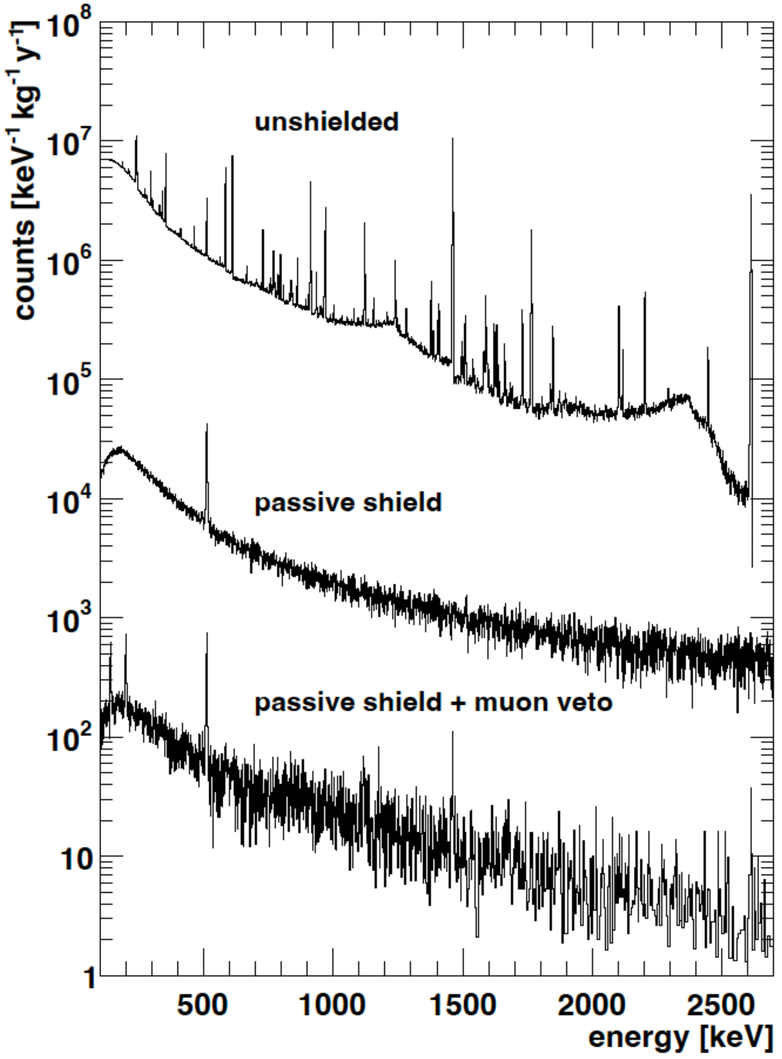


Roman lead

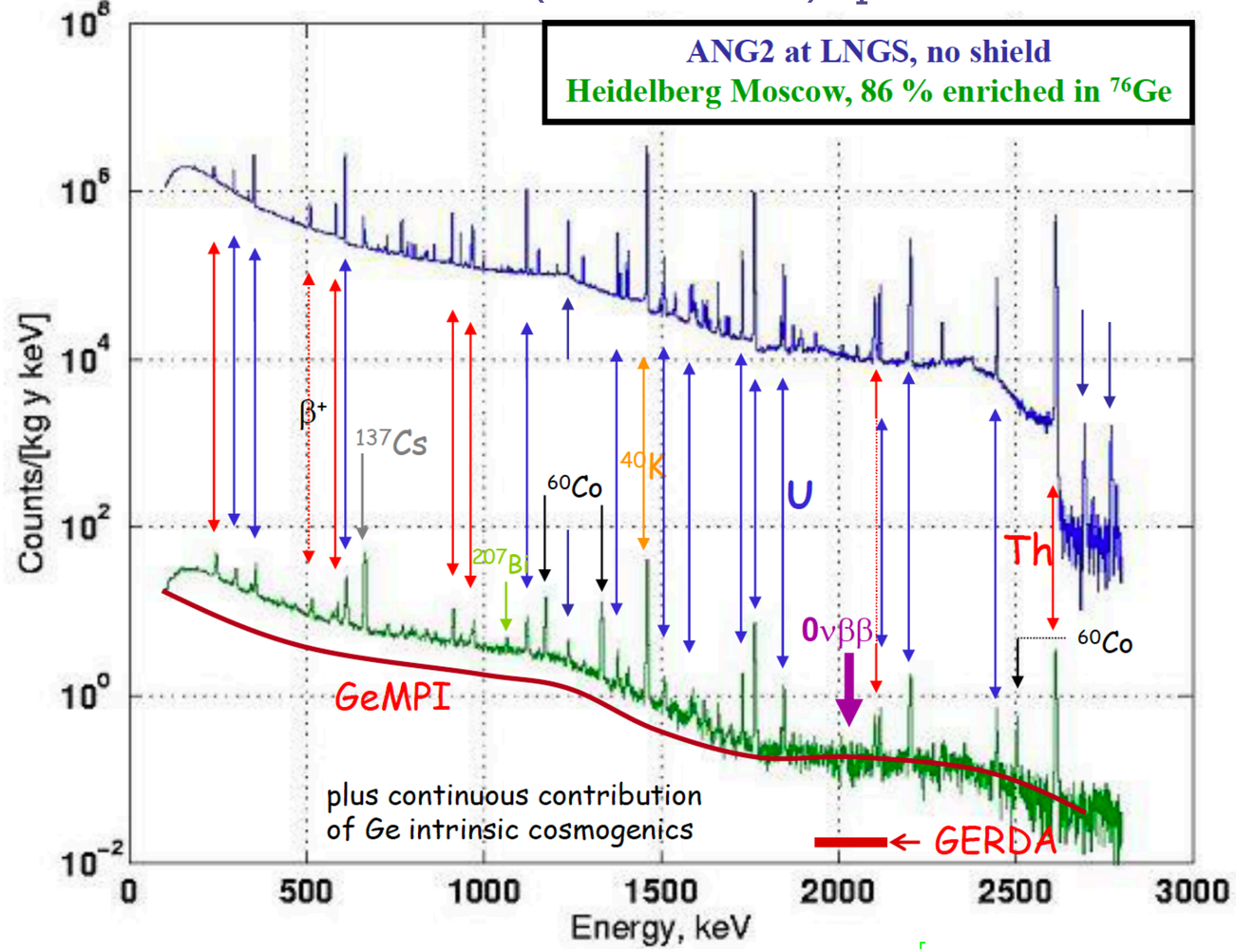
Optimising a HPGe system

Environmental background reduction by shielding

Near surface (15 m.w.e.) spectra



LNGS (3700 m.w.e.) spectra

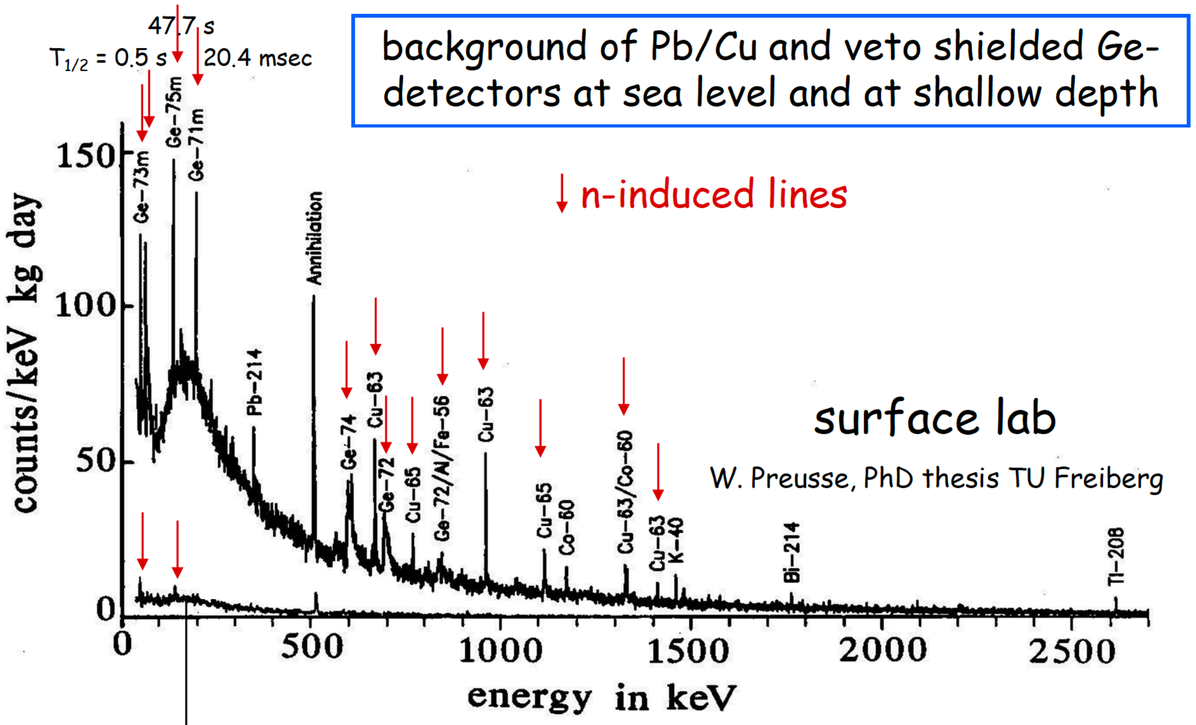


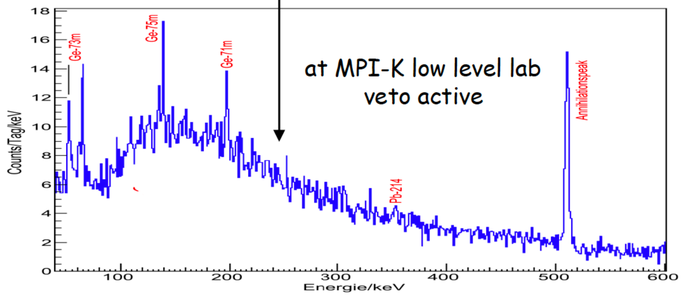
[credits: G. Heusser]

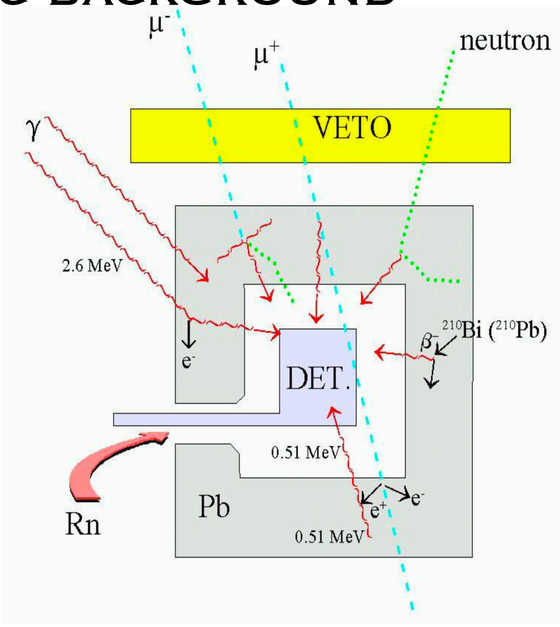
Optimising a HPGe system

Reducing environmental, cosmic and cosmogenic background

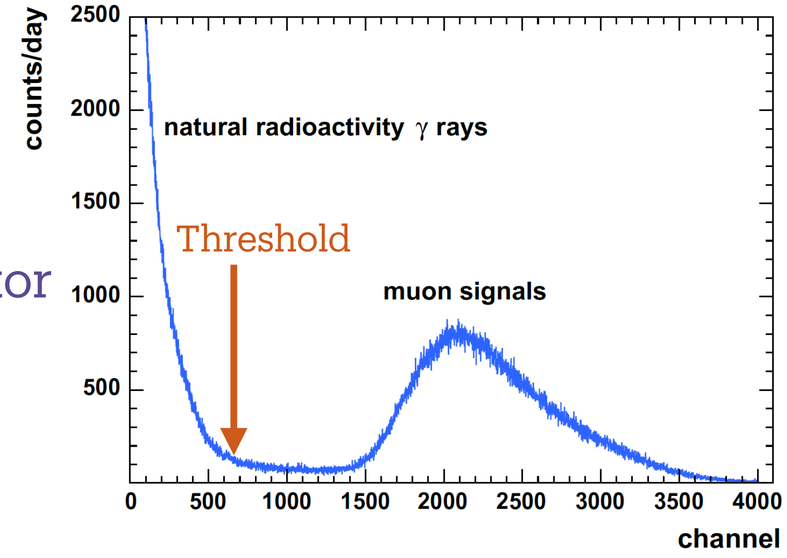
background of Pb/Cu and veto shielded Ge-detectors at sea level and at shallow depth







Typical plastic-scintillator spectrum



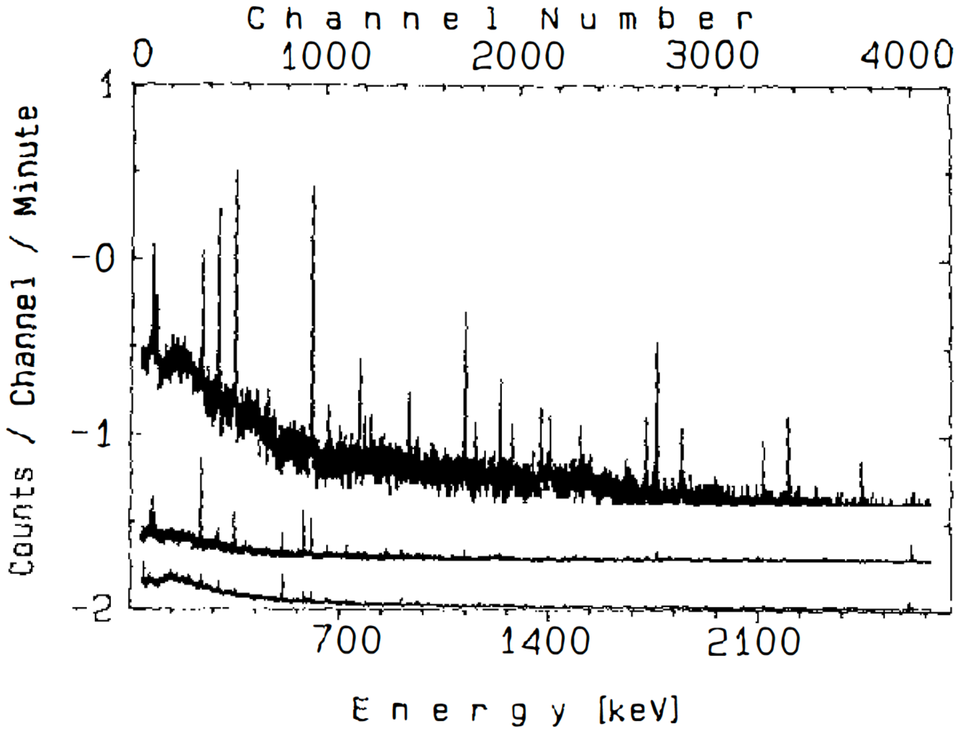
[credits: G. Heusser]

Optimising a HPGe system

Reducing environmental, cosmic and cosmogenic background

Ge γ-spectra of Rn progenies on a plastic foil at different time intervals after plate-out (after evacuating the sample chamber): the first 130 min (top); 200-1500 min (middle); 2-22 days (bottom)

[Reproduced from 1.]



To reduce Rn:

- Enclose the shielding and flush with nitrogen gas
- Pump the sample chamber

Optimising a HPGe system

GIOVE (Germanium Inner Outer VEto) at 15 m.w.e.

[EPJ C (2015) 75:531]

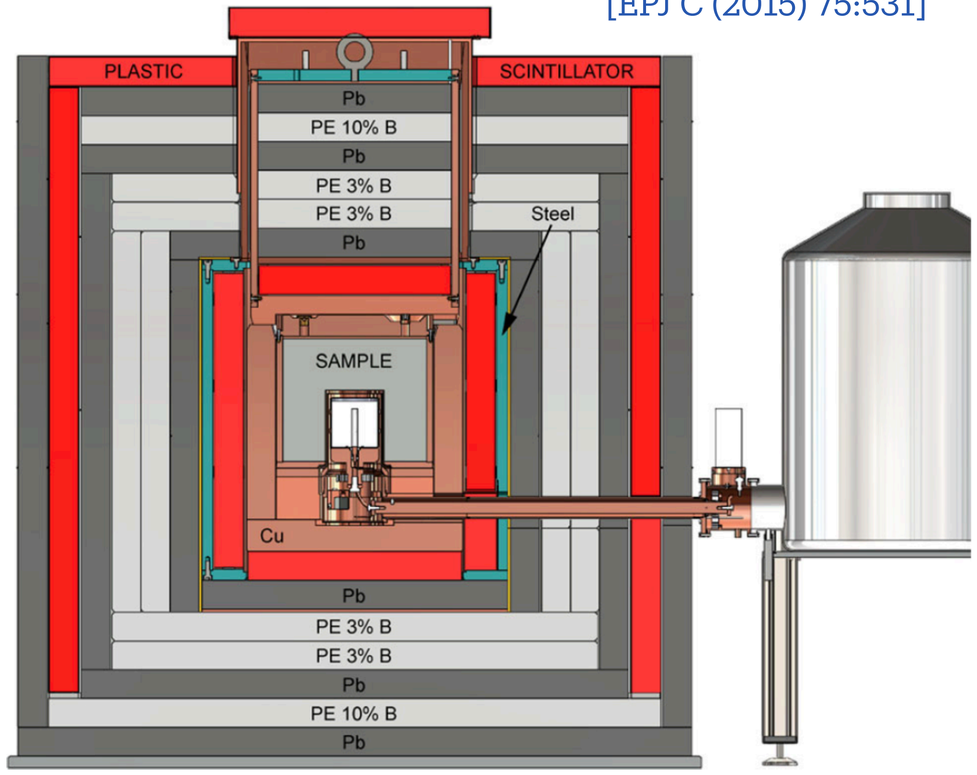
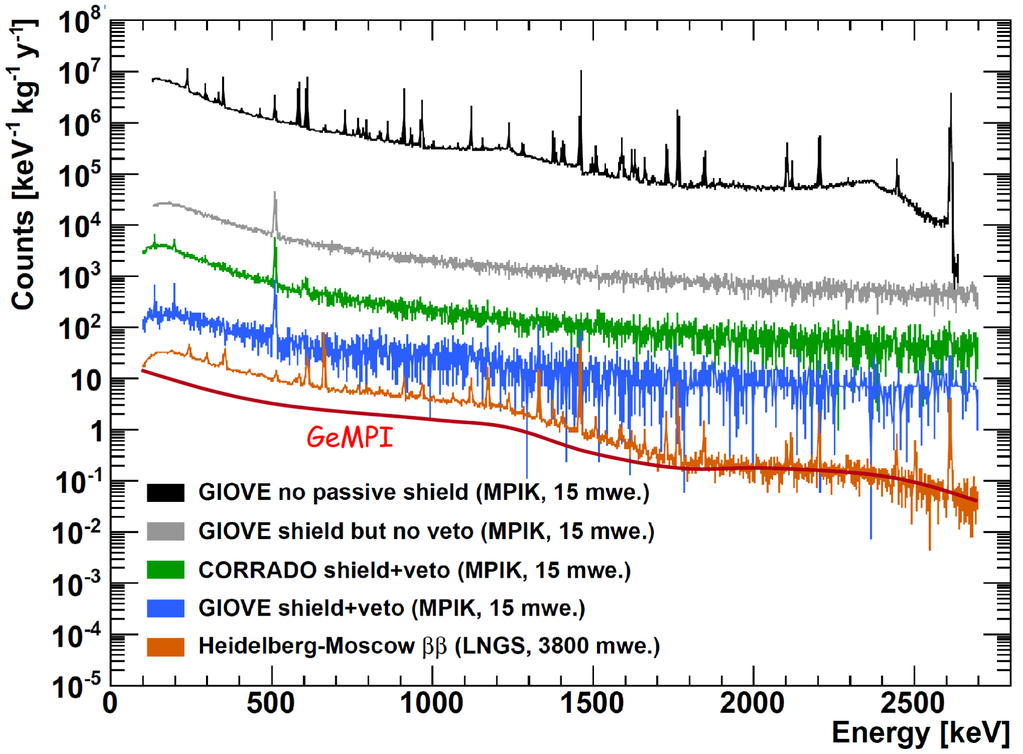


Fig. 1 Cut-away view of the GIOVE detector and shield. Different layers for radiation absorption (Pb, Cu), neutron moderation (PE) and active vetoing (*red colored areas*) form a shell structure to efficiently lower the background count rate in the central Ge crystal. More details provided in the text

Table 5 Integral count rates of low-background Ge spectrometers located in different underground sites. The values are normalized by the active mass (m_{act}) of the detectors. Among them, only GIOVE and Corrado are equipped with active muon veto systems. The sample chambers (SC) were empty during the measurement

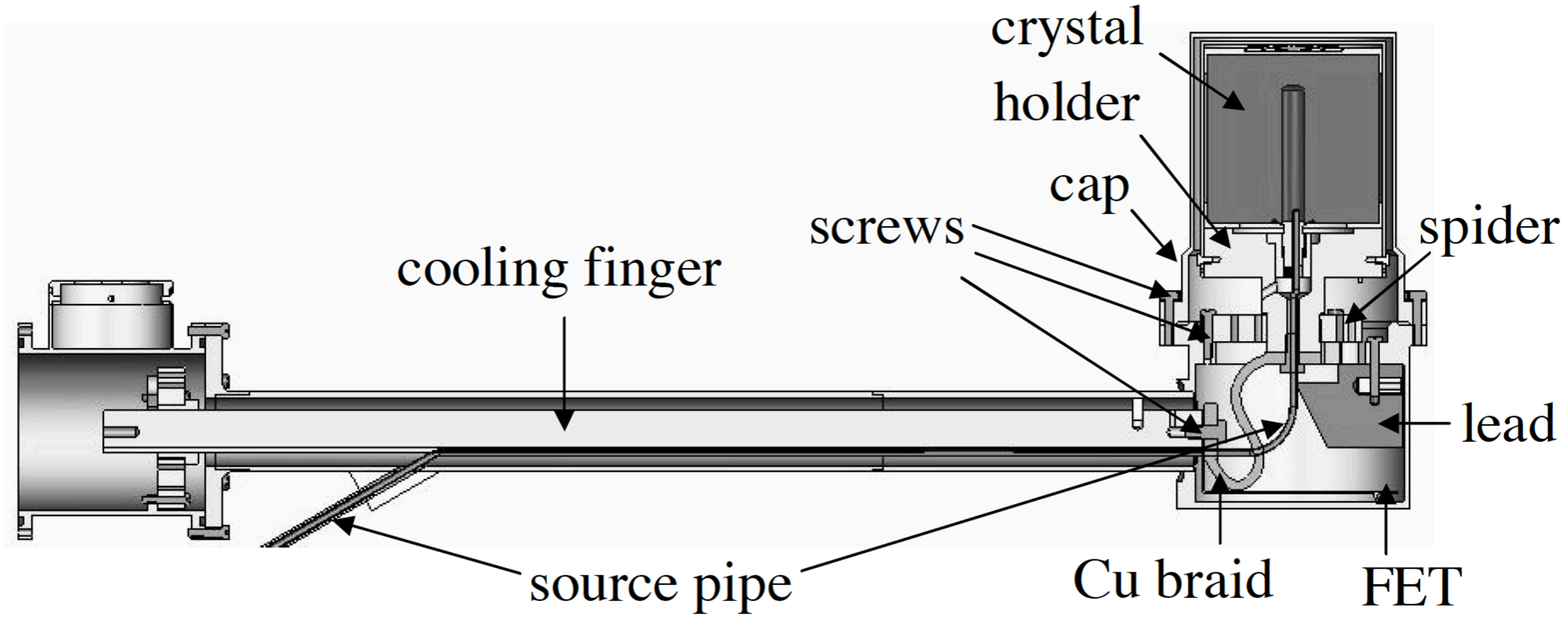
Detector	m_{act} (kg)	SC_{vol} (liter)	Location, depth (m w.e.)	μ flux reduction (comp. sea level)	Count rate in (40–2700) keV ($d^{-1}kg^{-1}$)
GIOVE	1.81	12.4	MPIK, 15	2−3	348 ± 3
Corrado	0.94	11	MPIK, 15	2−3	3661 ± 11
Ge-3	1.24	0.4	HADES, 500	5×10^3	394 ± 2
GeMPI	2.06	15	LNGS, 3800	10^6	66 ± 1



Optimising a HPGe system

Reducing background from detector material components

- Optimize design
- Select materials



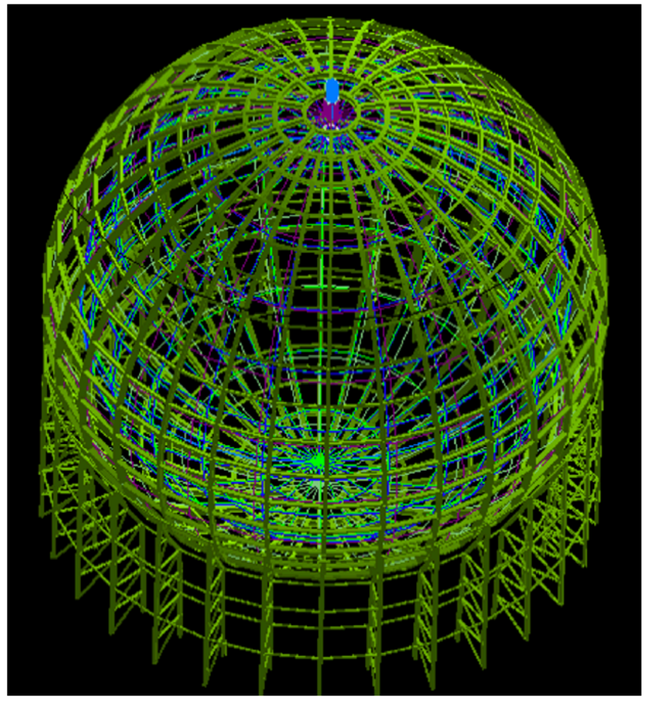
GeMPI detector at LNGS
[Heusser, Laubenstein]

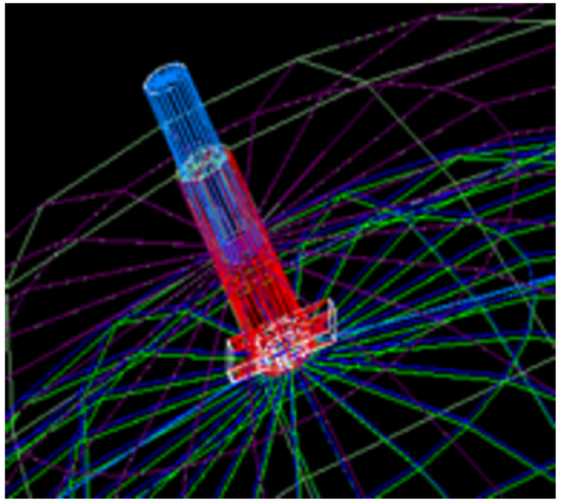
Background control in ν/DM experiments

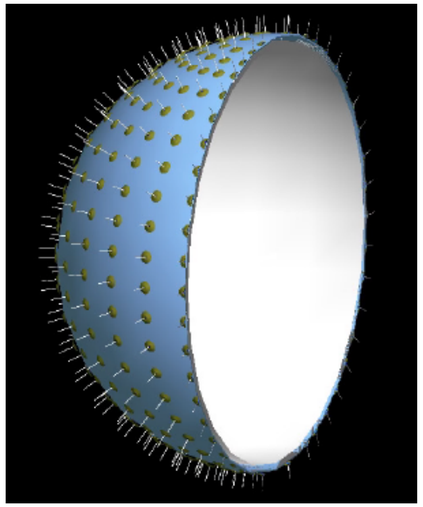
Example: the JUNO detector

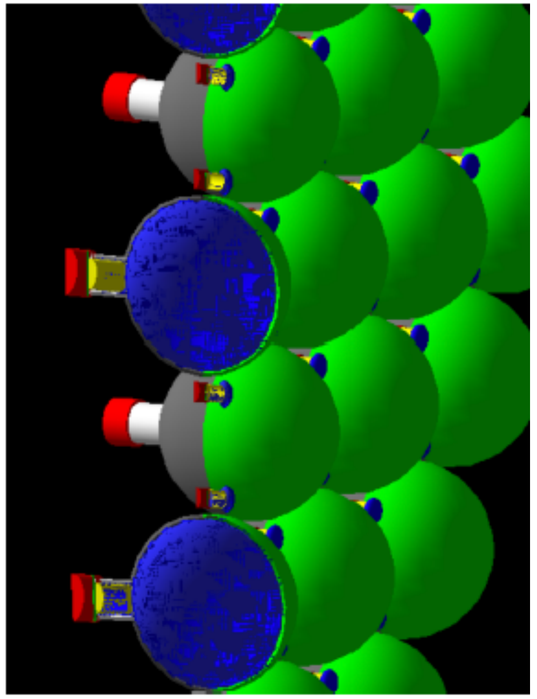
- Optimize design
- Select materials

Detailed Monte Carlo simulations of the experimental apparatus — with all materials included — are needed to build the expected **Background Budget** of the experiment







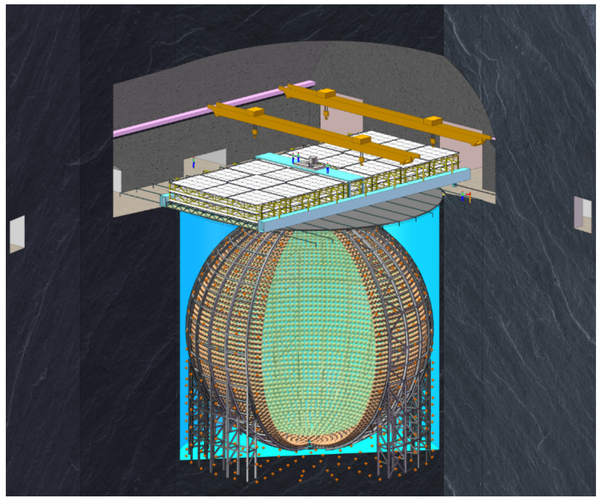


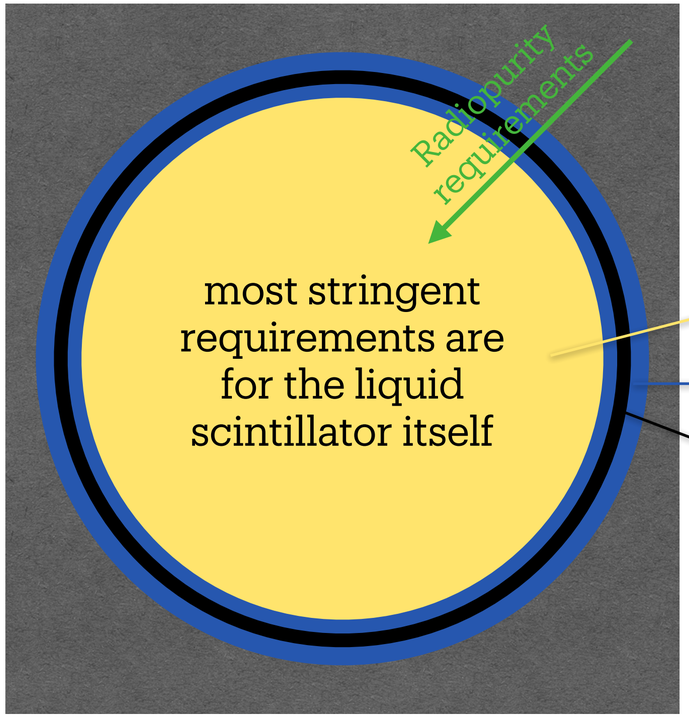
[JHEP 11 (2021) 102]

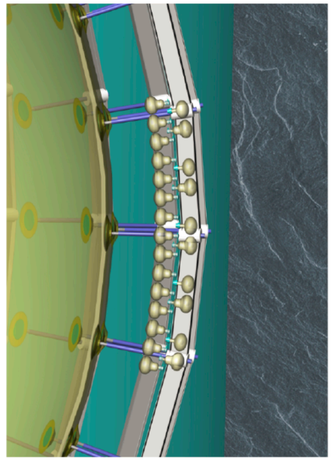
Background control in ν/DM experiments

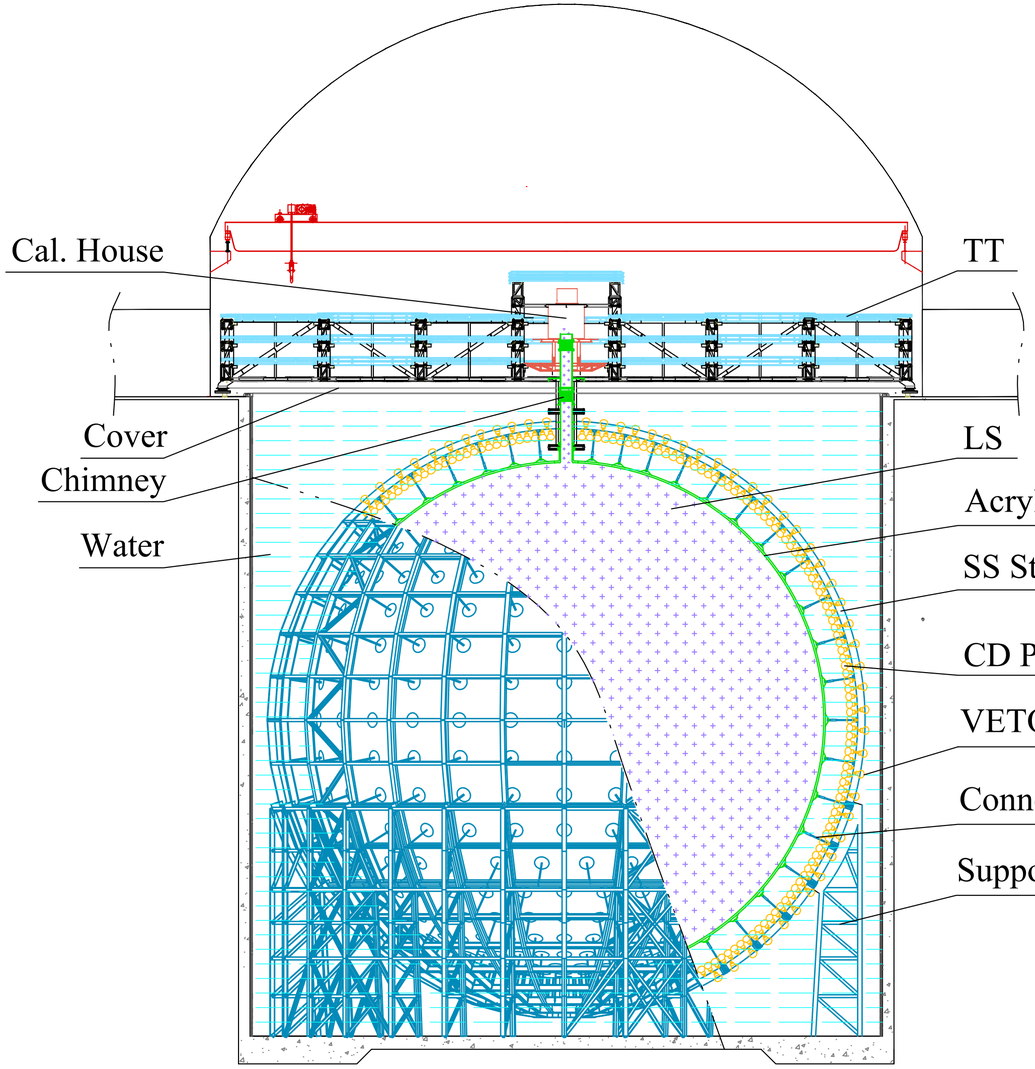
Example: the JUNO detector

- Optimize design
- Select materials





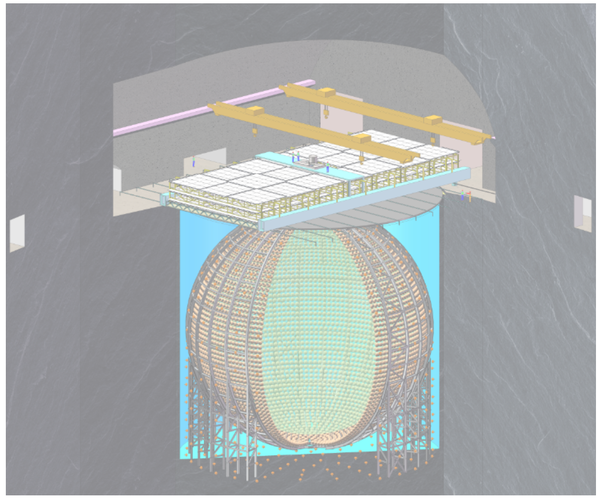


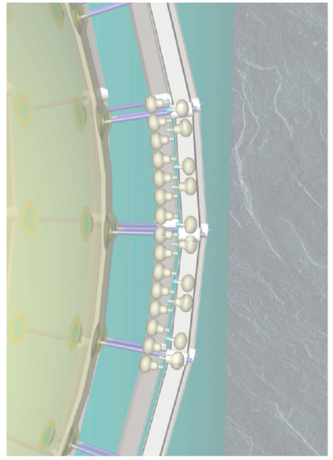


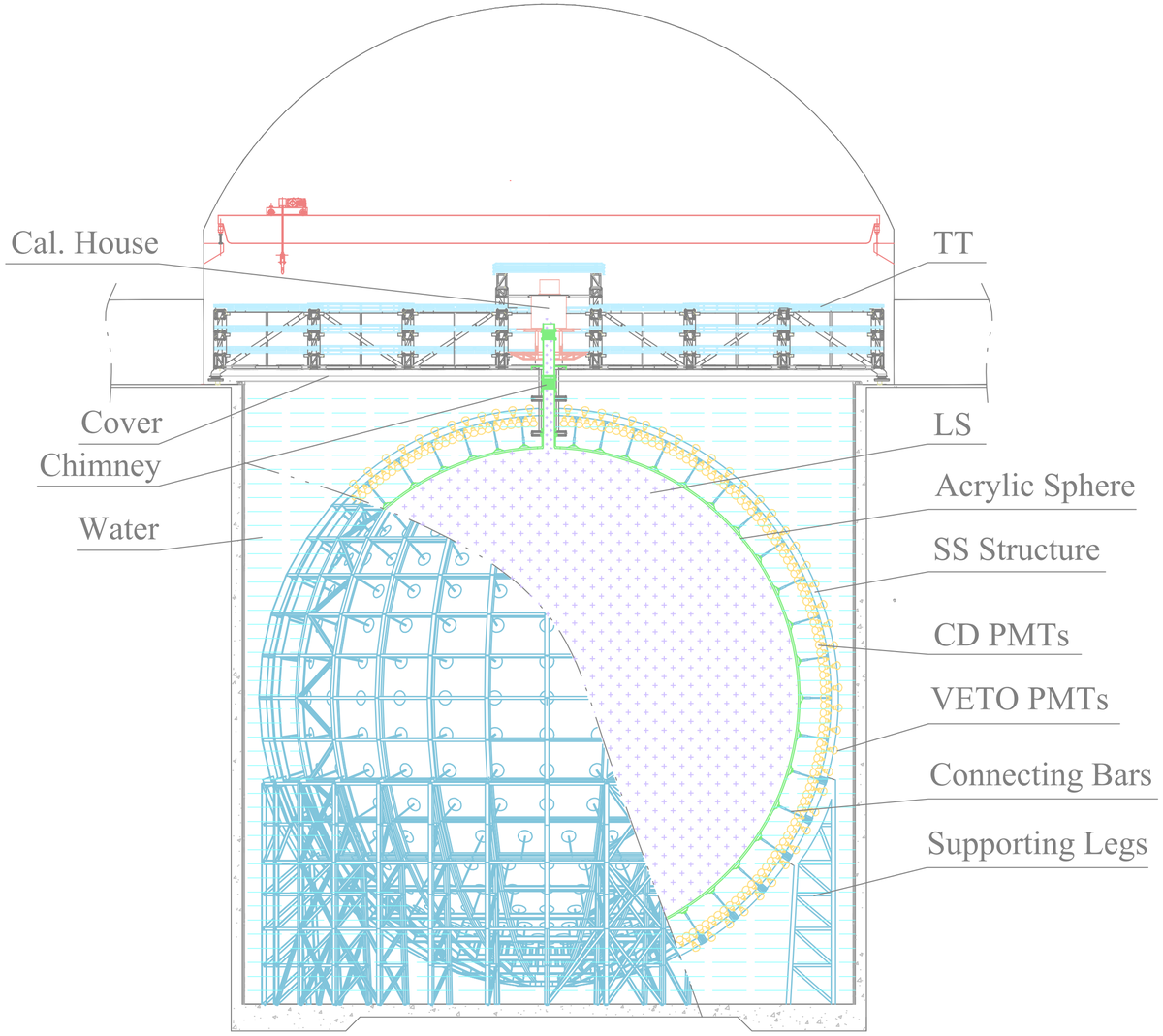
Background control in ν/DM experiments

Example: the JUNO detector

- Optimize design
- Select materials



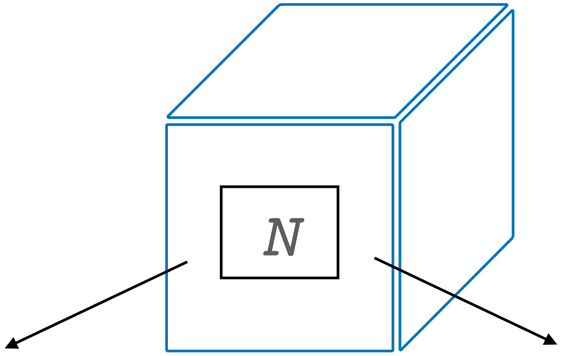




Measuring radioactivity

How to assess the concentration of a contaminant in a material

N = number of atoms of the radioactive species R with life-time $\tau = 1/\lambda$



Measuring time: Δt

Concentration measurement

$N(t)$

Activity measurement

$\lambda N(t)$

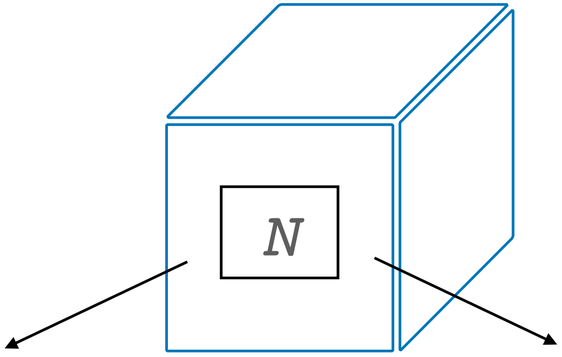
$N_{mis} = N(t) \simeq N(t + \Delta t)$ ← if $\tau \gg \Delta t$ → $N_{mis} = A(t) \cdot \Delta t$

$N(t) \neq N(t + \Delta t)$ ~~N_{mis}~~ ← if $\tau \lesssim \Delta t$ → $N_{mis} = N_0(1 - e^{-\lambda t})$

Measuring radioactivity

How to assess the concentration of a contaminant in a material

N = number of atoms of the radioactive species R with life-time $\tau = 1/\lambda$



Measuring time: Δt

Concentration measurement

$N(t)$

Activity measurement

$\lambda N(t)$

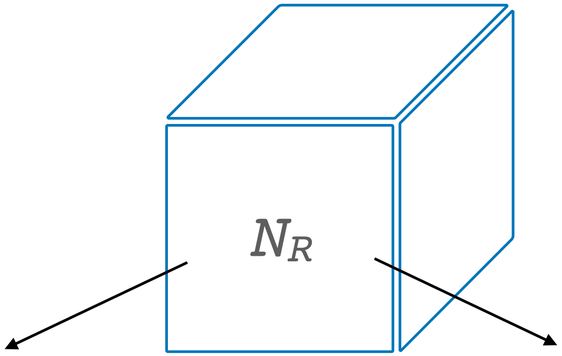
The decision between a concentration and an activity measurement depends on:

- the half-life of the radionuclide
- the measuring time
- the required sensitivity

Measuring radioactivity

How to assess the concentration of a contaminant in a material

Sample C containing radioactive species R



Mass concentration

$$C_R = \frac{m_R}{m_C} \quad \left[\frac{g}{g}\right]$$

Specific activity

$$A_S = \frac{A_R}{m_C} \quad \left[\frac{Bq}{kg}\right]$$

As (^{232}Th) = 4.07×10^6 $\left[\frac{Bq}{kg}\right]$ a.i.=100%

$\tau_{1/2}(^{232}\text{Th}) = 1.40\text{E}10$ y

As (^{238}U) = 1.24×10^7 $\left[\frac{Bq}{kg}\right]$ a.i.=99.28%

$\tau_{1/2}(^{238}\text{U}) = 4.47\text{E}9$ y

As (^{40}K) = 2.65×10^8 $\left[\frac{Bq}{kg}\right]$

$\tau_{1/2}(^{40}\text{K}) = 1.248\text{E}9$ y

As (^{nat}K) = 3.18×10^4 $\left[\frac{Bq}{kg}\right]$ a.i.(^{40}K)=0.012%

$\tau_{1/2}(^{40}\text{K}) = 1.248\text{E}9$ y

Mass concentration ⟷ Activity

conversions for the natural radioisotopes

^{232}Th $1\ [\mathrm{Bq/kg}] \leftrightarrow \dfrac{1}{4.07 \times 10^{6}}\ [\mathrm{g/g}] = 246\ \mathrm{ppb}$ ⟷ $1\ [\mathrm{ppb}] = 4.07\ [\mathrm{mBq/kg}]$

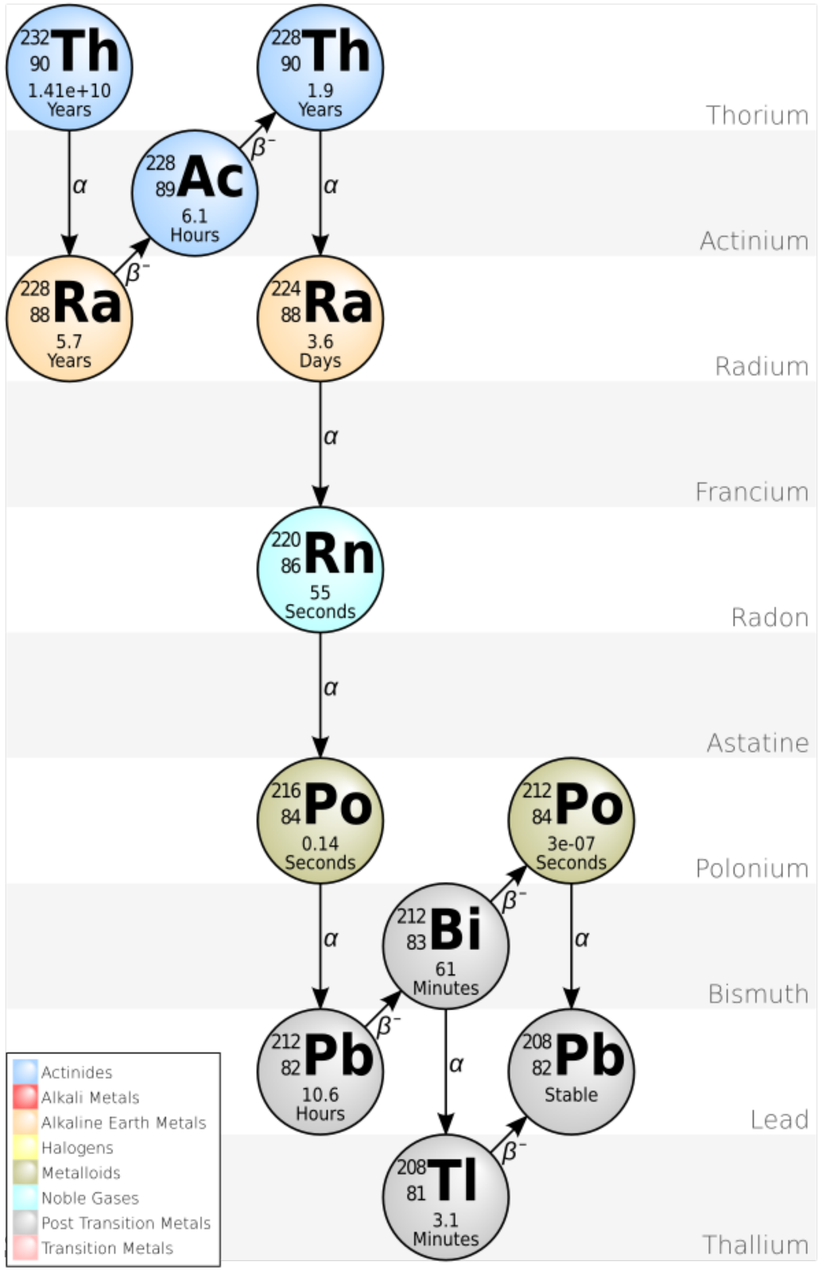
^{238}U $1\ [\mathrm{Bq/kg}] \leftrightarrow \dfrac{1}{1.24 \times 10^{7}}\ [\mathrm{g/g}] = 81\ \mathrm{ppb}$ ⟷ $1\ [\mathrm{ppb}] = 12.4\ [\mathrm{mBq/kg}]$

^{nat}K $1\ [\mathrm{Bq/kg}] \leftrightarrow \dfrac{1}{3.18 \times 10^{4}}\ [\mathrm{g/g}] = 31.5\ \mathrm{ppm}$ ⟷ $1\ [\mathrm{ppb}] = 31.8\ [\mu\mathrm{Bq/kg}]$

^{40}K $1\ [\mathrm{Bq/kg}] \leftrightarrow \dfrac{1}{2.65 \times 10^{8}}\ [\mathrm{g/g}] = 3.8\ \mathrm{ppb}$ ⟷ $1\ [\mathrm{ppb}] = 264.6\ [\mathrm{mBq/kg}]$

- 10^{-6} g/g = 1 ppm
- 10^{-9} g/g = 1 ppb
- 10^{-12} g/g = 1 ppt
- 10^{-15} g/g = 1 ppq

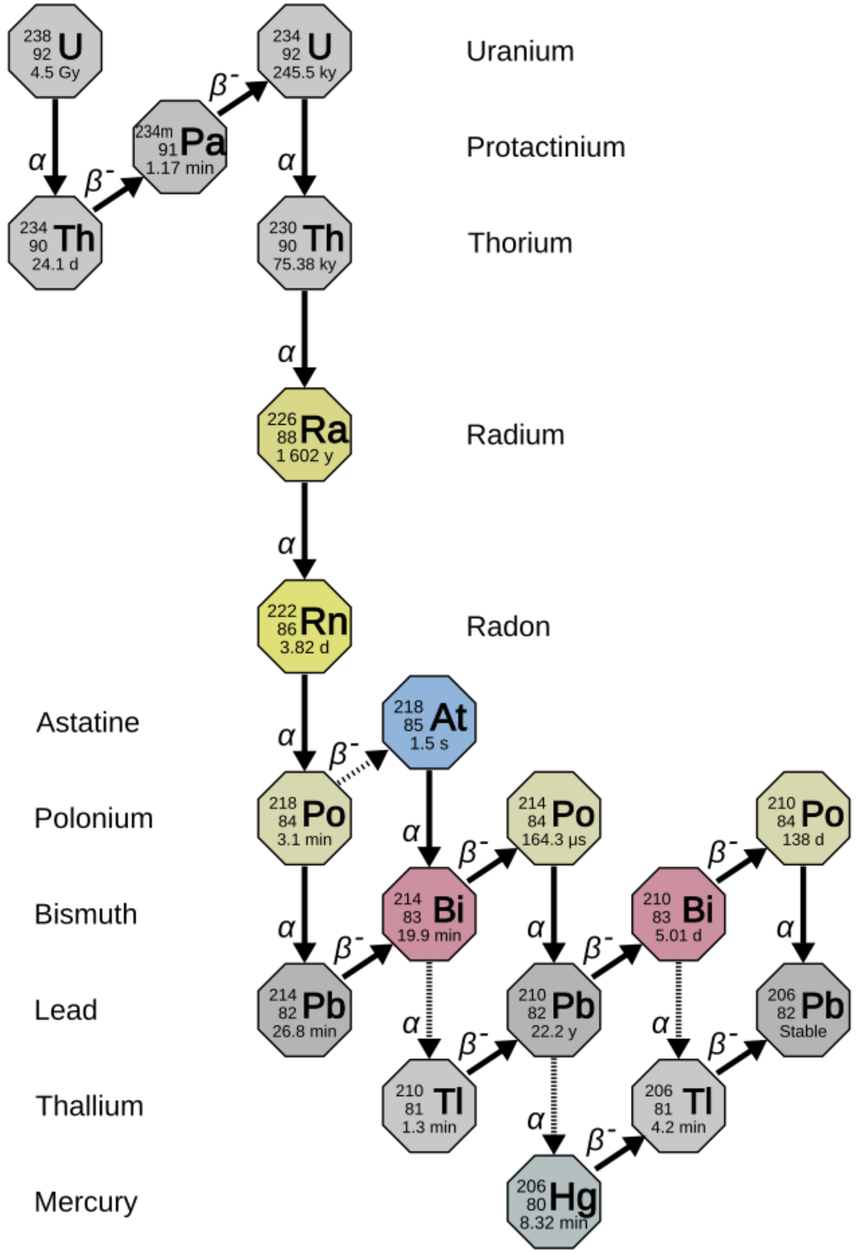
Concentration or Activity measurement ?



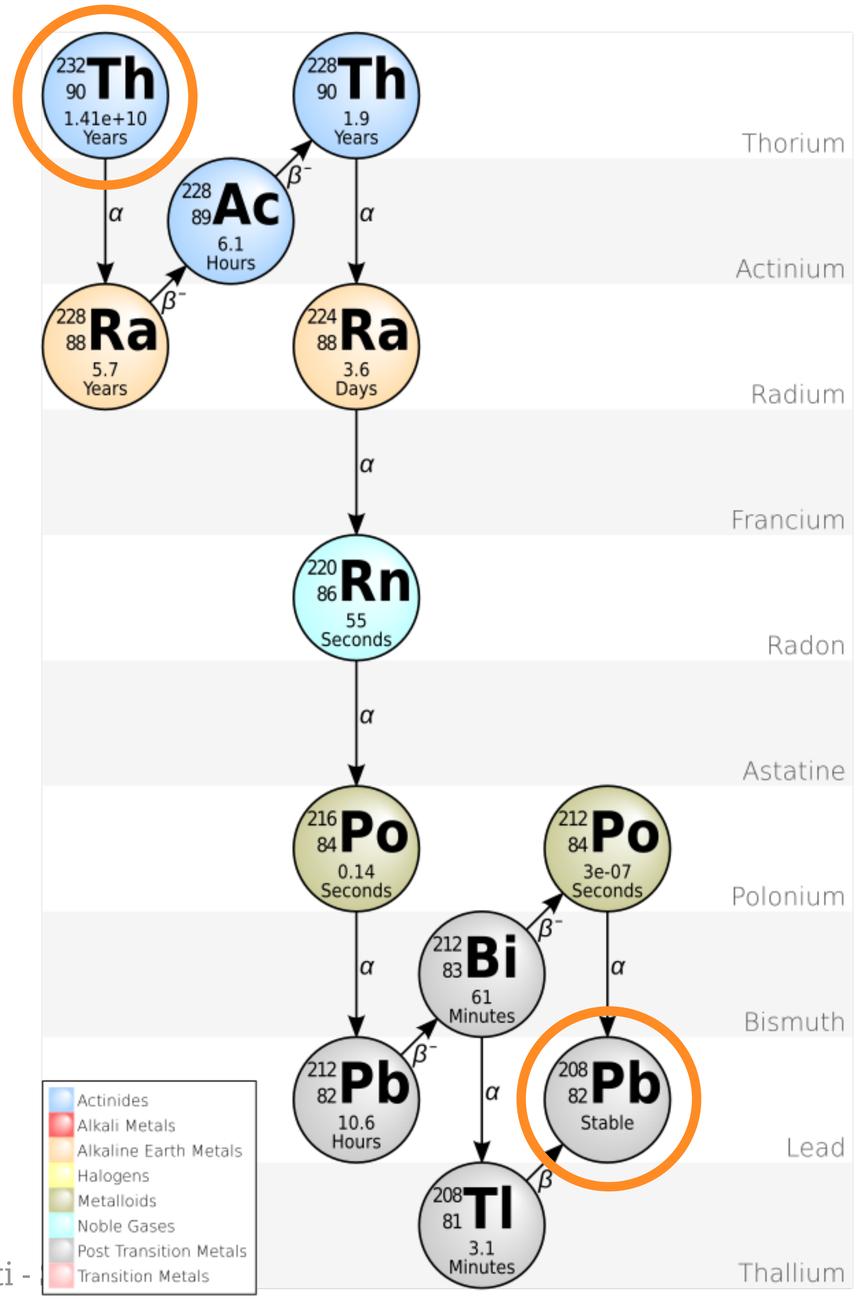
If secular equilibrium holds:

$$\lambda_1 N_1 = \lambda_2 N_2$$

$$N_1 = \frac{\tau_1}{\tau_2} N_2$$



Concentration or Activity measurement ?

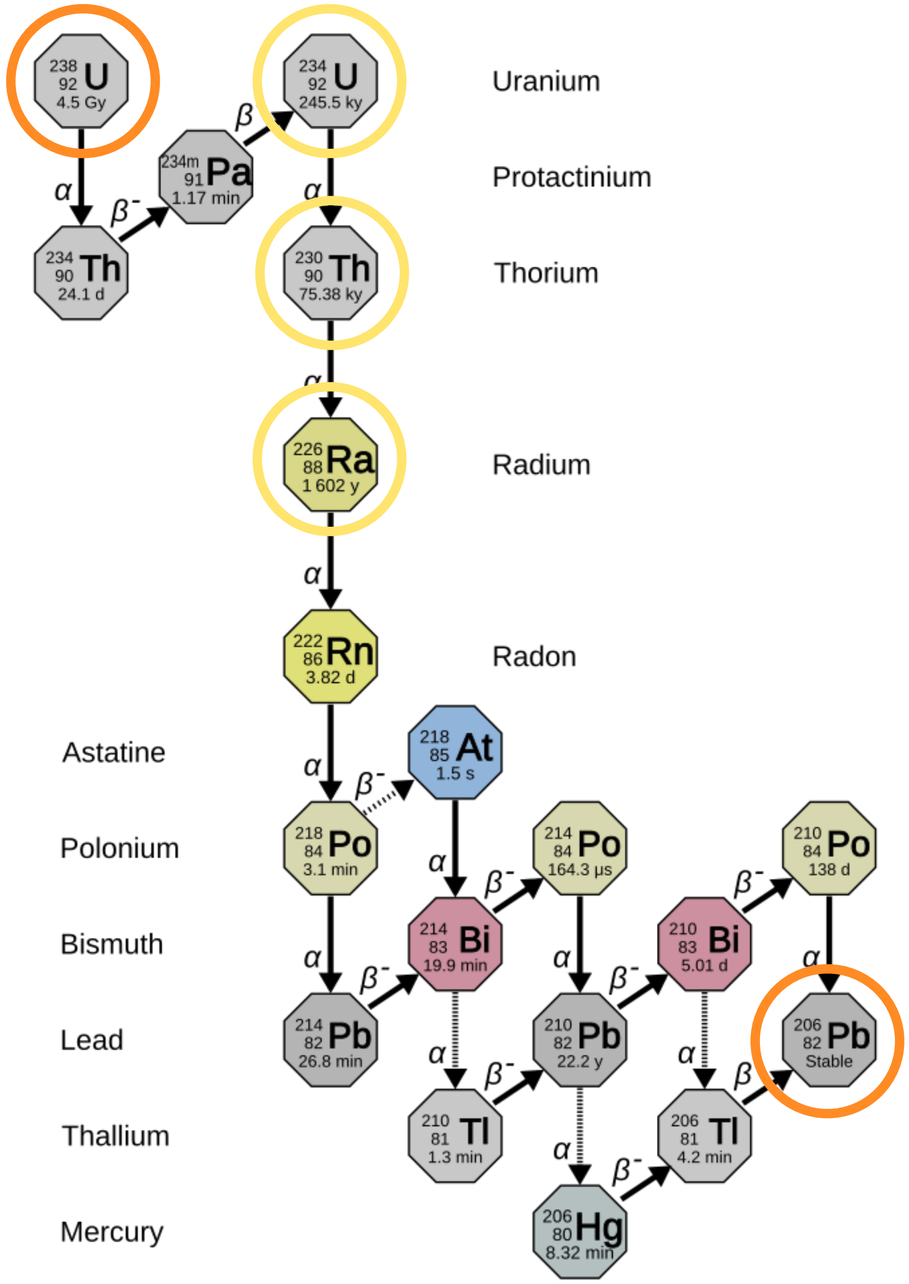


If secular equilibrium holds:

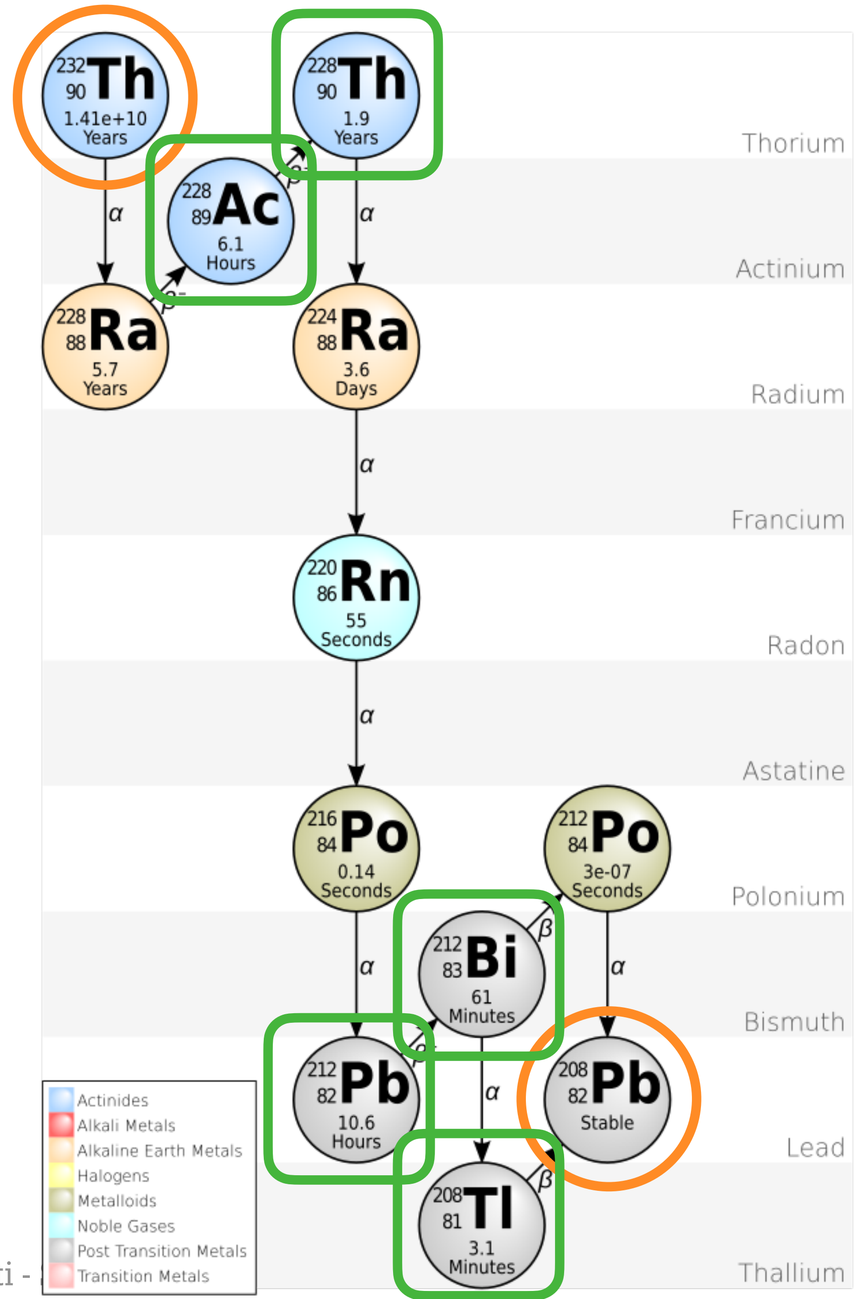
$$\lambda_1 N_1 = \lambda_2 N_2$$

$$N_1 = \frac{\tau_1}{\tau_2} N_2$$

c



Concentration or Activity measurement ?



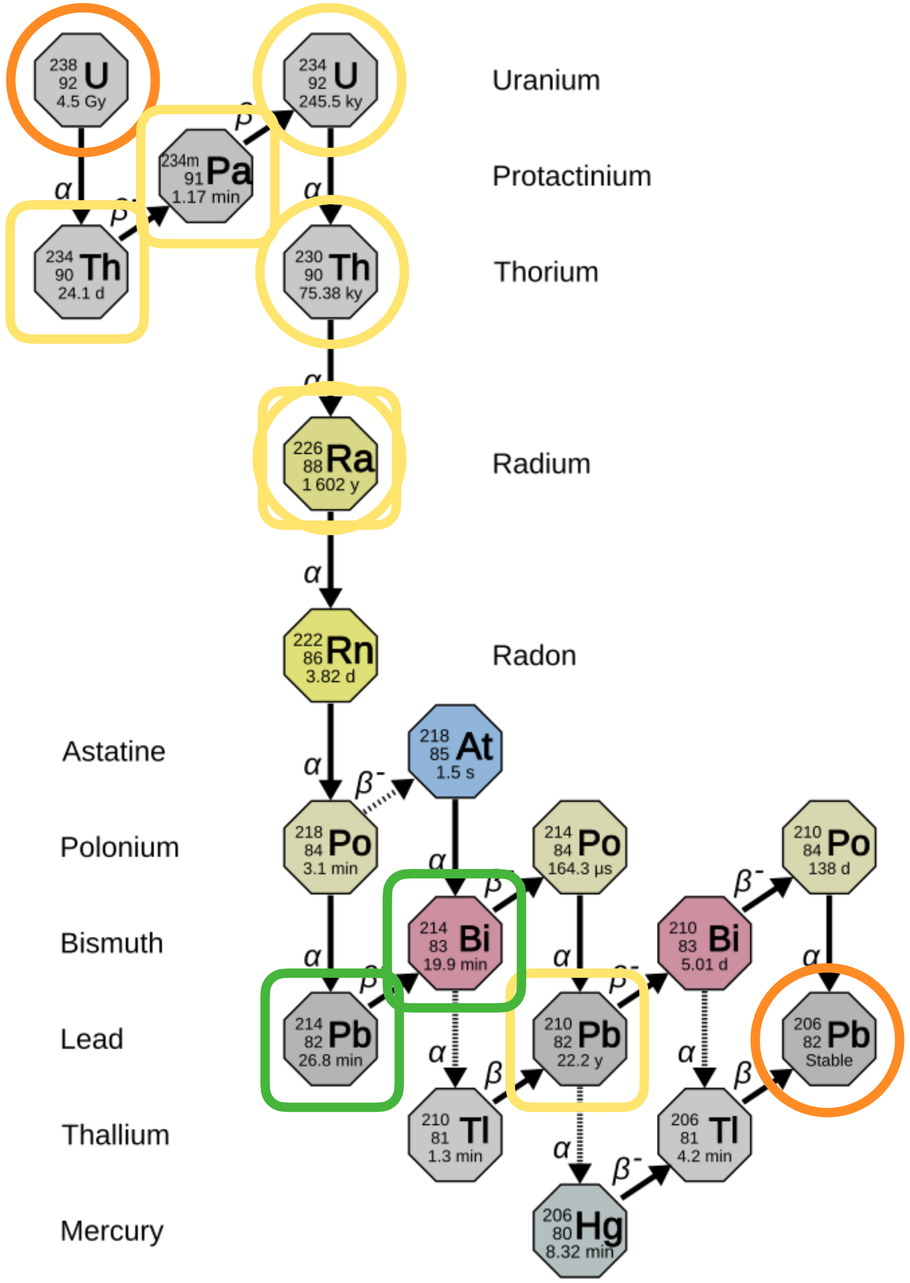
If secular equilibrium holds:

$$\lambda_1 N_1 = \lambda_2 N_2$$

$$N_1 = \frac{\tau_1}{\tau_2} N_2$$

C

A



Most popular techniques

U/Th sensitivity comparison

Technique	Application	U/Th sensitivity
Gamma Spectroscopy *	γ-emitters	10–100 μBq/kg
Alpha spectroscopy	210Po, α-emitters	< 1 μBq/cm^2
Neutron Activation Analysis	decay chain progenitors	0.01 μBq/kg
Mass spectrometry	decay chain progenitors	0.01 μBq/kg
Liquid Scintillators	α, β emitting nuclides	1 mBq/kg
Radon emanation measurements	226Ra, 228Th	0.1–10 μBq/kg

*Only gamma spectroscopy can give info on secular equilibrium breaks!

HPGe spectroscopy

Example of measurement results: JUNO acrylic sample

Sample:	**Acrylic**		
mass:	13.6 kg	Detector: GeMPI2, LNGS	
live time:	27 days	meas. start: May 2021	
	Activity		**Concentration**
Th-232:			
Ra-228	< 82 μBq/kg	⇔	< 2.0 E-11 g/g
Th-228	< 95 μBq/kg	⇔	< 2.3 E-11 g/g
U-238:			
Ra-226	< 47 μBq/kg	⇔	< 3.8 E-12 g/g
Th-234	< 3.8 mBq/kg	⇔	< 3.1 E-10 g/g
Pa-234m	< 0.67 mBq/kg	⇔	< 5.5 E-11 g/g
U-235:	< 0.12 mBq/kg	⇔	< 2.1 E-10 g/g
K-40:	< 0.34 mBq/kg	⇔	< 1.1 E-8 g/g
Cs-137:	< 33 μBq/kg		

Upper limits with k=1.645. Uncertainties are given with k=1 (approx. 68% CL)

[Courtesy of M. Laubenstein]

Ra-228 from Ac-228
Th-228 from Pb-212 & Bi-212 & Tl-208
Ra-226 from Pb-214 & Bi-214
U-235 from U-235 & Ra-226/Pb-214/Bi-124

HPGe spectroscopy

Example of measurement results: CUORE copper sample

Sample:	OFE Copper		
mass:	7.64 kg	Detector: GeMPI, LNGS	
live time:	37,5 days	meas. start: January 2009	
	Activity		**Concentration**
Th-232:			
Ra-228	< 0.12 mBq/kg	⇔	< 3.0 E-11 g/g
Th-228	< 64 μBq/kg	⇔	< 1.6 E-11 g/g
U-238:			
Ra-226	< 54 μBq/kg	⇔	< 4.3 E-12 g/g
Pa-234m	< 3.3 mBq/kg	⇔	< 2.6 E-10 g/g
U-235:	< 8.6 μBq/kg	⇔	< 1.5 E-10 g/g
K-40:	< 0.67 mBq/kg	⇔	< 2.2 E-8 g/g
Cs-137:	< 28 μBq/kg		

Pb-210:	< 1.4 Bq/kg		
Co-60:	< 24 μBq/kg	@	start of meas.
Co-57:	(0.27 ± 0.13) mBq/kg	@	start of meas.
Co-58:	(32 ± 14) μBq/kg	@	start of meas.
Mn-54:	(64 ± 19) μBq/kg	@	start of meas.

Ra-228 from Ac-228
Th-228 from Pb-212 & Bi-212 & Tl-208
Ra-226 from Ra-226 & Pb-214 & Bi-214
U-235 from U-235 & Ra-226/Pb-214/Bi-124
Pb-210 from Po-210

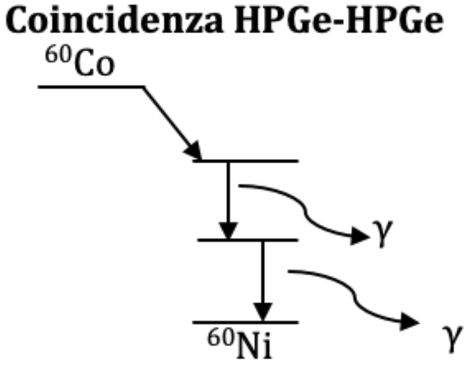
Upper limits with k=1.645. Uncertainties are given with k=1 (approx. 68% CL)

[Measured by M. Laubenstein]

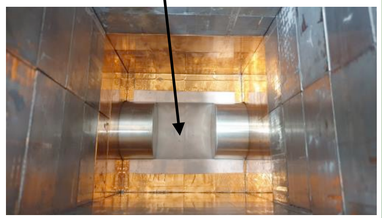
HPGe spectroscopy

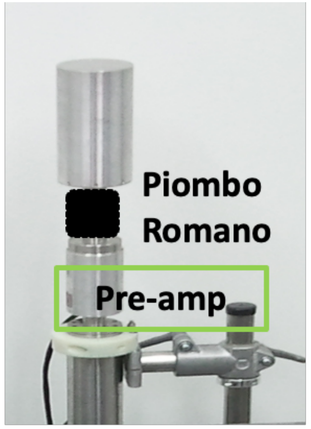
Above ground lab: coincidence configurations to increase sensitivity

	Copper	Acrylic
	5,4 kg	0,7 kg
Isotopo	MDA (mBq/kg)	MDA (mBq/kg)
^{232}Th chain	< 3	< 10
^{238}U chain	< 2	< 4
^{40}K	< 8	< 28
^{60}Co	< 1	< 3
^{137}Cs	< 1	< 3

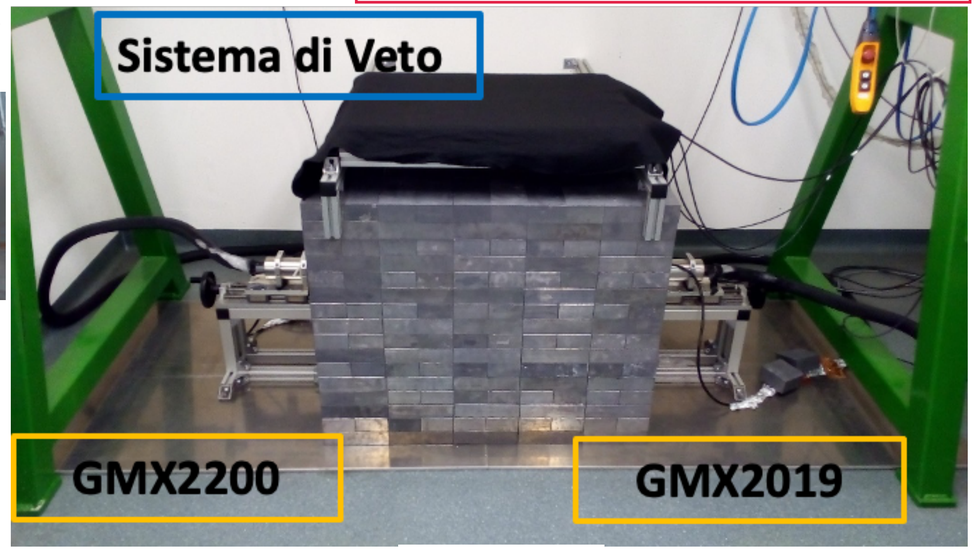


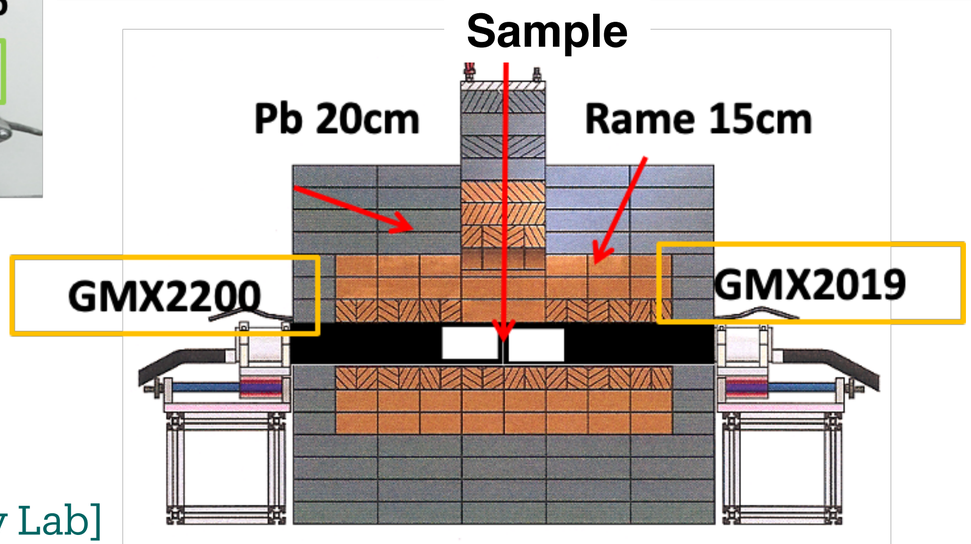
Alloggiamento campioni





GMX – γ-γ detector





2 × GMX:
n-type coaxial
En. 17-3200 keV
ε_{rel} 100%

[Milano-Bicocca Radioactivity Lab]

HPGe spectroscopy

Above ground lab: coincidence configurations to increase sensitivity

GeSpark

Table 3
MDA of the detector for the main nuclides in ^{238}U, ^{235}U and ^{232}Th chains and ^{60}Co, all with a sample mass of 100 g and a measurement time of 31 d. The MDA expressed in g/g is relative to the parent nuclide of the chain assuming secular equilibrium.

Chain	Nuclide (decay)	E_γ (keV)	ϵ·BR (%)	B	MDA (mBq/kg)	MDA (10^{-9}g/g)
^{238}U	^{226}Ra (α)	186	0.126	0	8.0	0.64
	^{214}Pb (β)	352	0.804	137	26	2.1
	^{214}Bi (β)	609	0.618	81	27	2.2
^{235}U	^{235}U (α)	143.7	0.503	5	9.7	0.12
	^{211}Bi (α)	351	0.286	2	12	0.15
	^{211}Pb (β)	405	0.074	102	252	3.2
^{232}Th	^{224}Ra (α)	241	0.108	0	9.4	2.3
	^{228}Ac (β)	911	0.290	58	49	12
	^{208}Tl (β)	583	0.429	100	43	11
	^{60}Co (β)	1173	0.843	40	14	$3.3 \cdot 10^{-10}$
		1332	0.757	38	15	$3.6 \cdot 10^{-10}$

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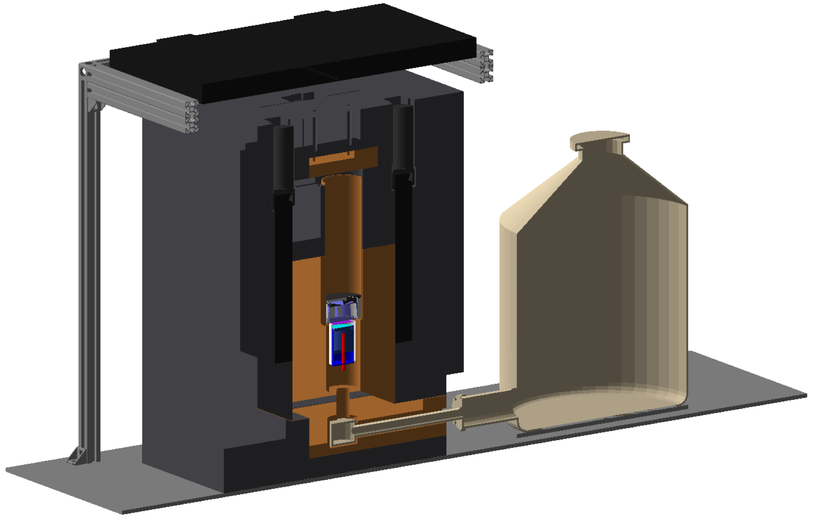
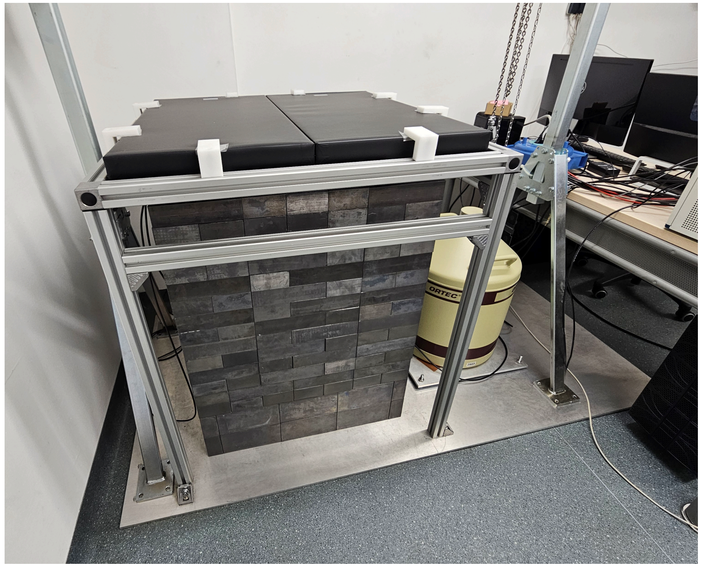




[Milano-Bicocca Radioactivity Lab]

HPGe spectroscopy

Pros and Cons for ultra-low background material screening

- Non destructive analysis
- No sample preparation required
- Sensitive to equilibrium breaking in the radioactive decay chains
- Very good detection sensitivities can be achieved

- Sizable sample masses are needed for high sensitivity
- Measuring times are long (~ several weeks) for high sensitivity
- Only sensitive to gamma emitters
- Accurate evaluation of the measurement efficiency is needed

Neutron activation analysis

A powerful technique for mass concentration measurement

Neutron activation analysis (NAA) is a very sensitive method for qualitative and quantitative determination of elements based on the measurement of characteristic radiation from radionuclides formed directly or indirectly by neutron irradiation of the material.

- The principle is very simple:

- Multi-element capability
- Sensitivity for many elements

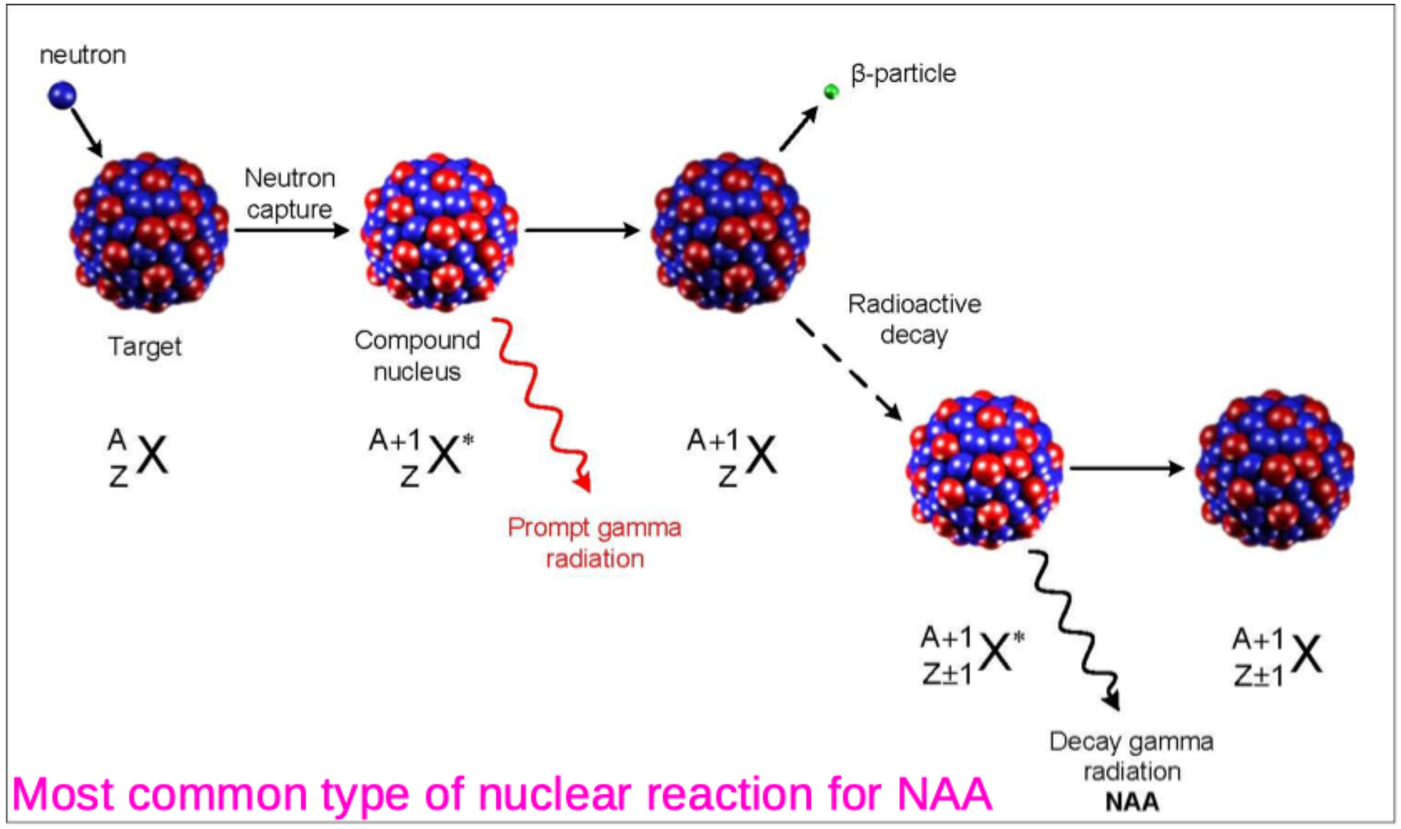
$$\mathrm{A}^{x} + \mathrm{n}^{1} \rightarrow \mathrm{A}^{1+x}$$

$$\mathrm{A}^{1+x} \rightarrow \mathrm{B} + \text{radiation}$$

to be measured

Neutron activation analysis

Basic principles

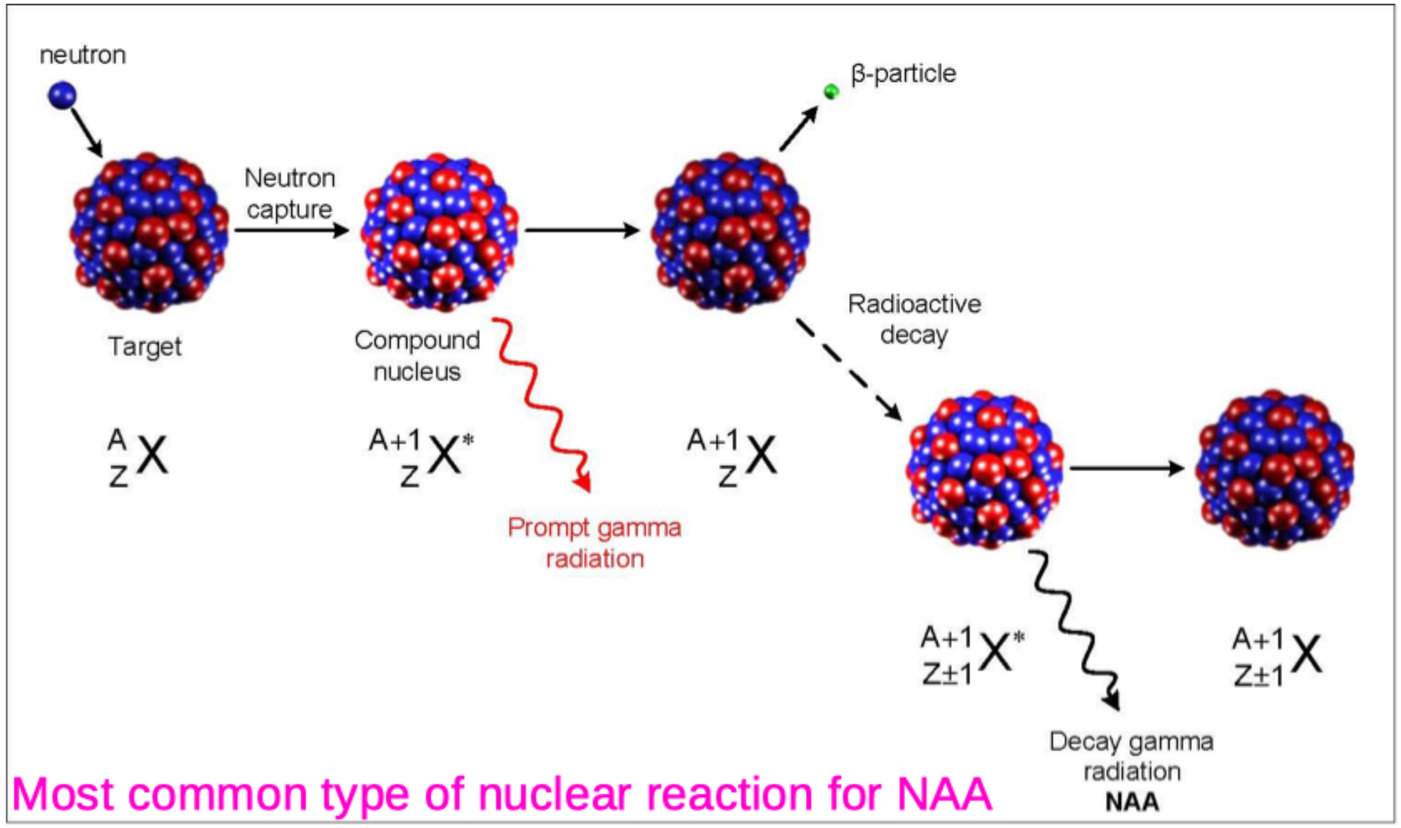


- A bombarding particle is absorbed by an atomic nucleus after a nuclear reaction.
- A compound nucleus is formed (highly excited, unstable nucleus).
- The compound nucleus de-excites, usually by ejecting a small particle and a product nucleus.

The particle may be an elementary particle (neutron, electron, proton), an alpha particle or a photon.
The product nucleus may be stable or radioactive.

Neutron activation analysis

Basic principles



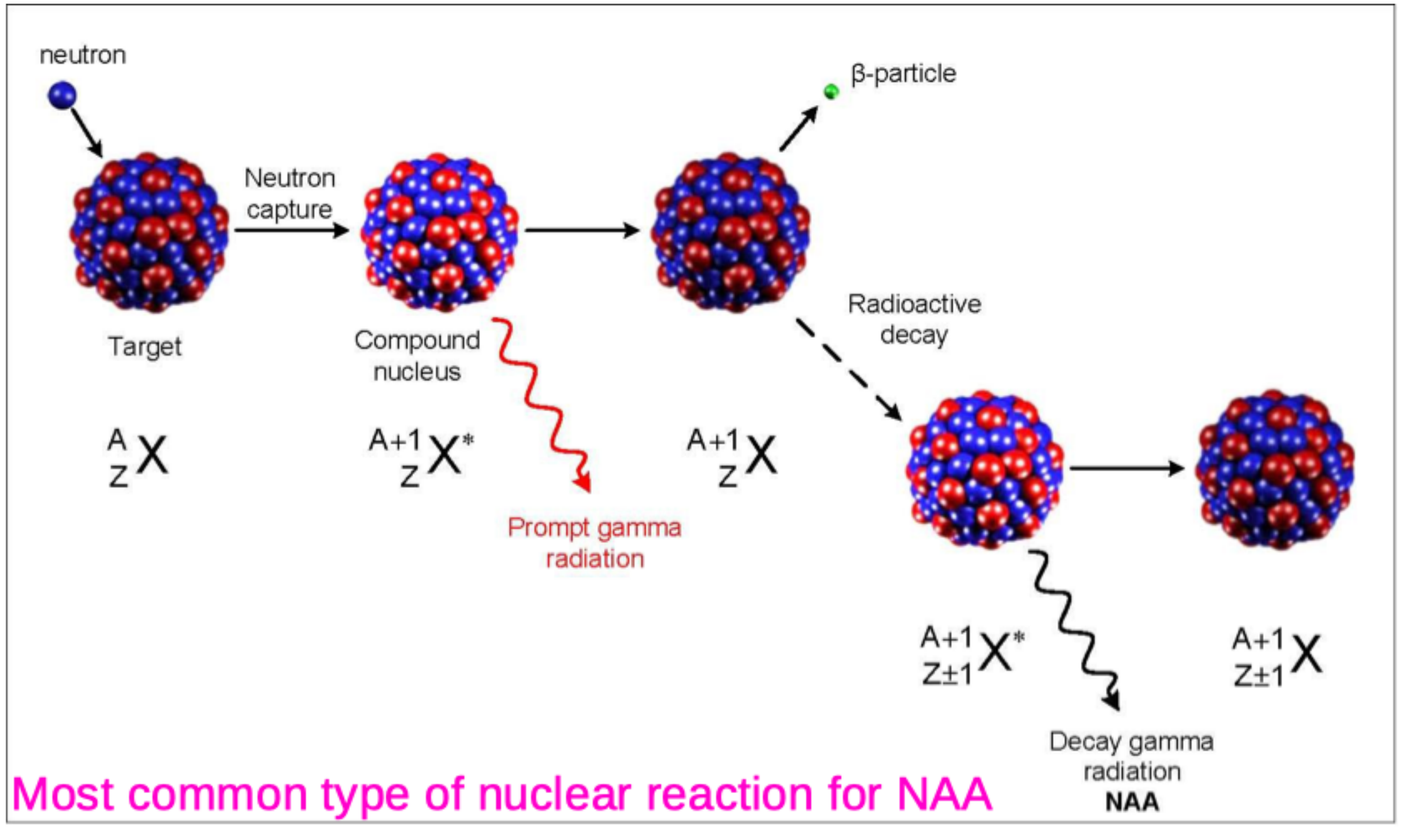
- A bombarding particle is absorbed by an atomic nucleus after a nuclear reaction.
- A compound nucleus is formed (highly excited, unstable nucleus).
- The compound nucleus de-excites, usually by ejecting a small particle and a product nucleus.

Prompt radiation emitted ~10^{-12} s after neutron capture.

Prompt gamma Analysis (PGA): measurement of γ rays during de-excitation of the compound nucleus after neutron capture

Neutron activation analysis

Basic principles



- A bombarding particle is absorbed by an atomic nucleus after a nuclear reaction.
- A compound nucleus is formed (highly excited, unstable nucleus).
- The compound nucleus de-excites, usually by ejecting a small particle and a product nucleus.

Commonly employed method in NAA.
It is useful for many types of elements that produce radioactive nuclei.
Measuring time and sensitivity depend on decay half-life.

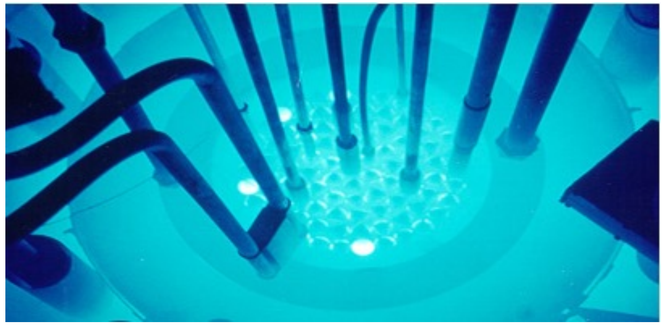
Delayed Gamma Neutron Activation Analysis (DGNAA):
measurement of γ rays emitted during the decay of the product nucleus after the capture reaction is stopped.

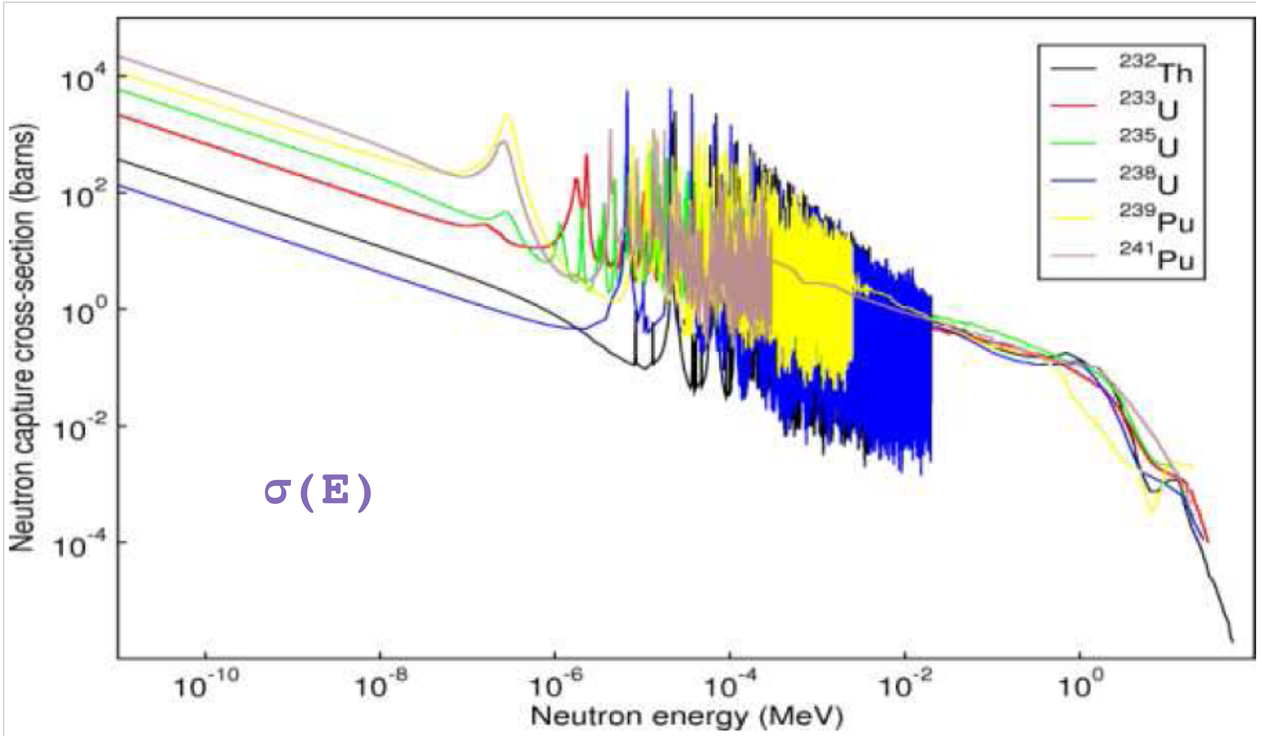
Neutron activation analysis

Neutron source: nuclear research reactors

Owing to the high neutron flux, nuclear research reactors operating in the power region of 20 kW — 10 MW, with maximum thermal neutron fluxes of 10^{11} — 10^{14} neutrons cm^{-2} s^{-1} are the most efficient neutron sources for high sensitivity activation analysis induced by epithermal and thermal neutrons.

Activation via (n, γ) reactions





Neutron capture cross section vs Energy for major actinides

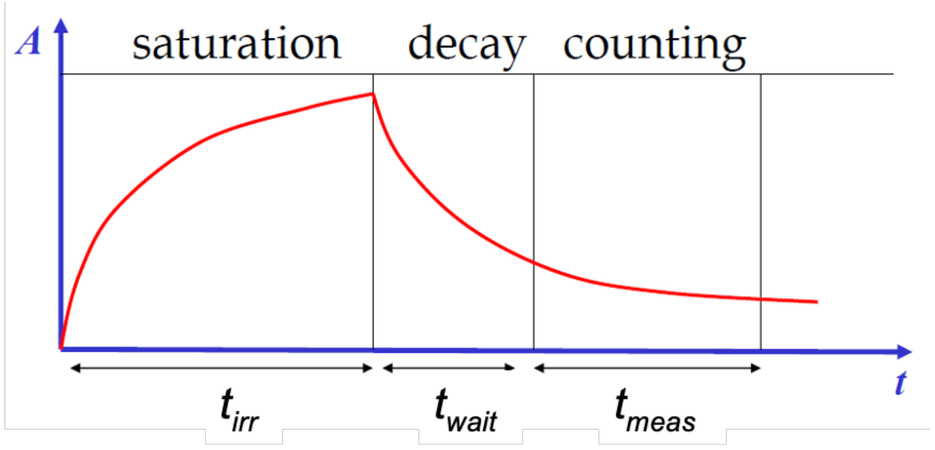
Neutron activation analysis

Key ingredients

$$^{A}X + n \longrightarrow {}^{A+1}X \xrightarrow{\beta^-} {}^{A+1}_{Z+1}Y + \gamma_{\text{cascade}}$$

Three key ingredients:

- High neutron flux
- High enough neutron capture cross section
- "Convenient" daughter nucleus (γ emission, half-life time)



Sensitivity depends on:

- type of material (short-lived activation products)
- neutron exposure time
- interferences in the matrix
- background in the region of the gamma emission

- care in the sample preparation is extremely important!
- the radiopurity of the sample container is also of concern!

NAA for ^{40}K, ^{232}Th, ^{238}U

The activation reactions

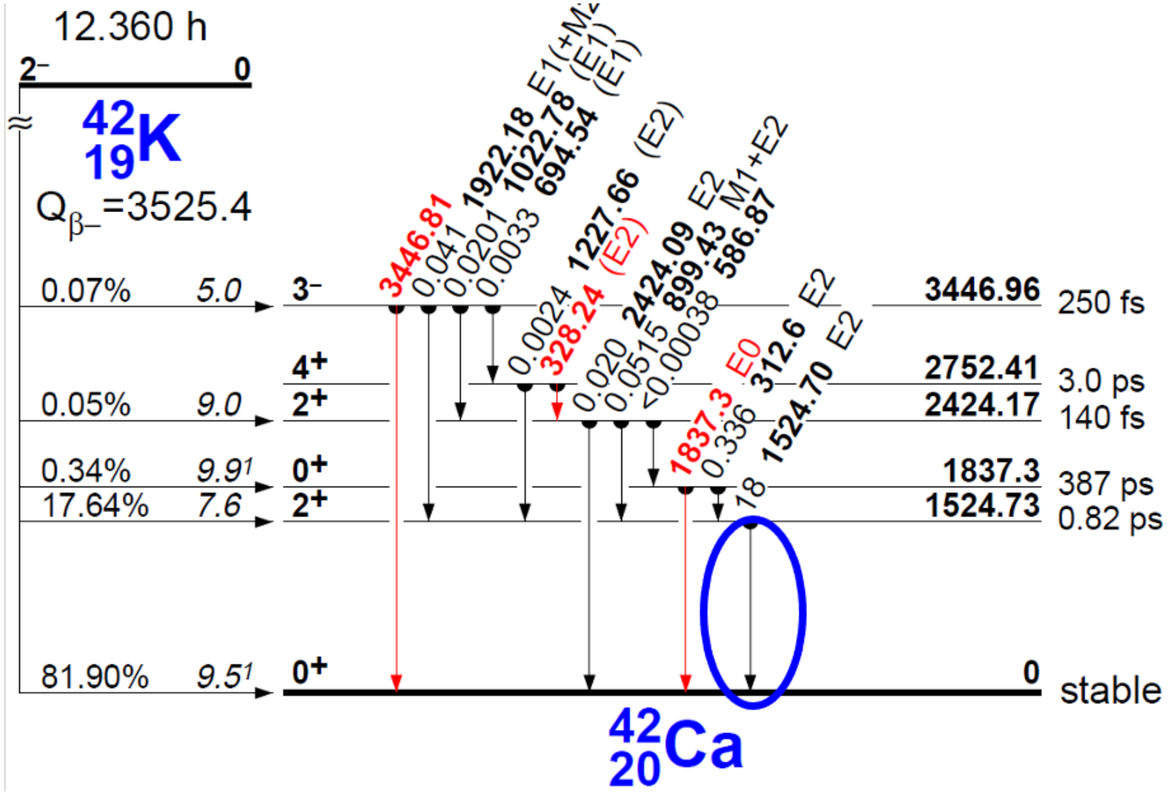
$n + {}^{41}K \longrightarrow {}^{42}K \xrightarrow{\beta^-,\ 12.36\ h} {}^{42}Ca$

$n + {}^{238}U \longrightarrow {}^{239}U \xrightarrow{\beta^-,\ 23.5\ m} {}^{239}Np \xrightarrow{\beta^-,\ 2.36\ d} {}^{239}Pu$

$n + {}^{232}Th \longrightarrow {}^{233}Th \xrightarrow{\beta^-,\ 22.3\ m} {}^{233}Pa \xrightarrow{\beta^-,\ 27.0\ d} {}^{233}U$

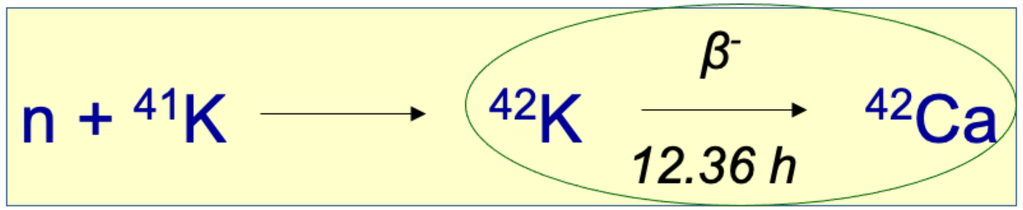
- ^{41}K isotopic abundance is 6.7%
- ^{40}K isotopic abundance is 0.01%

^{40}K concentration is calculated from ^{41}K one



NAA for ^{40}K, ^{232}Th, ^{238}U

The activation reactions



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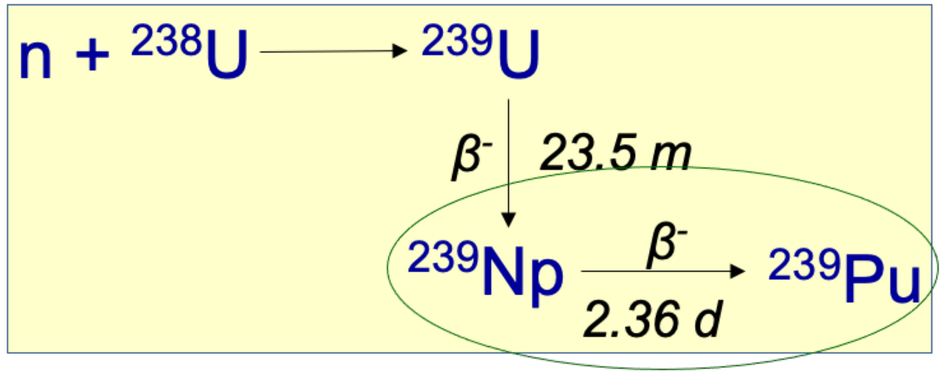
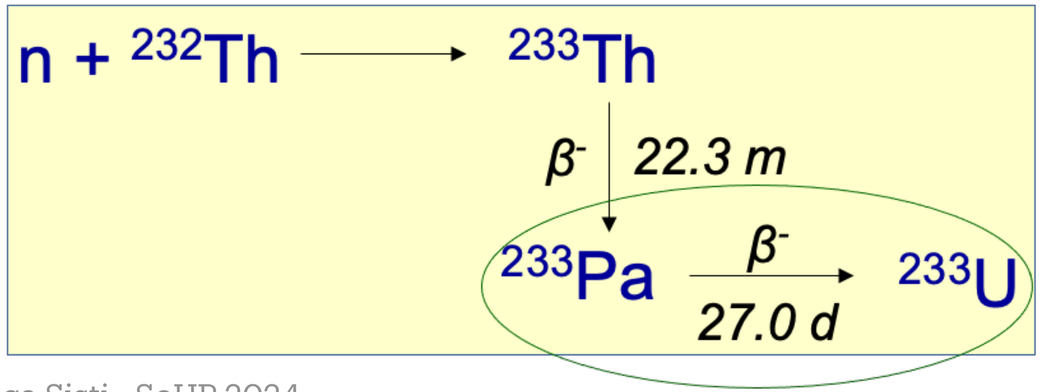
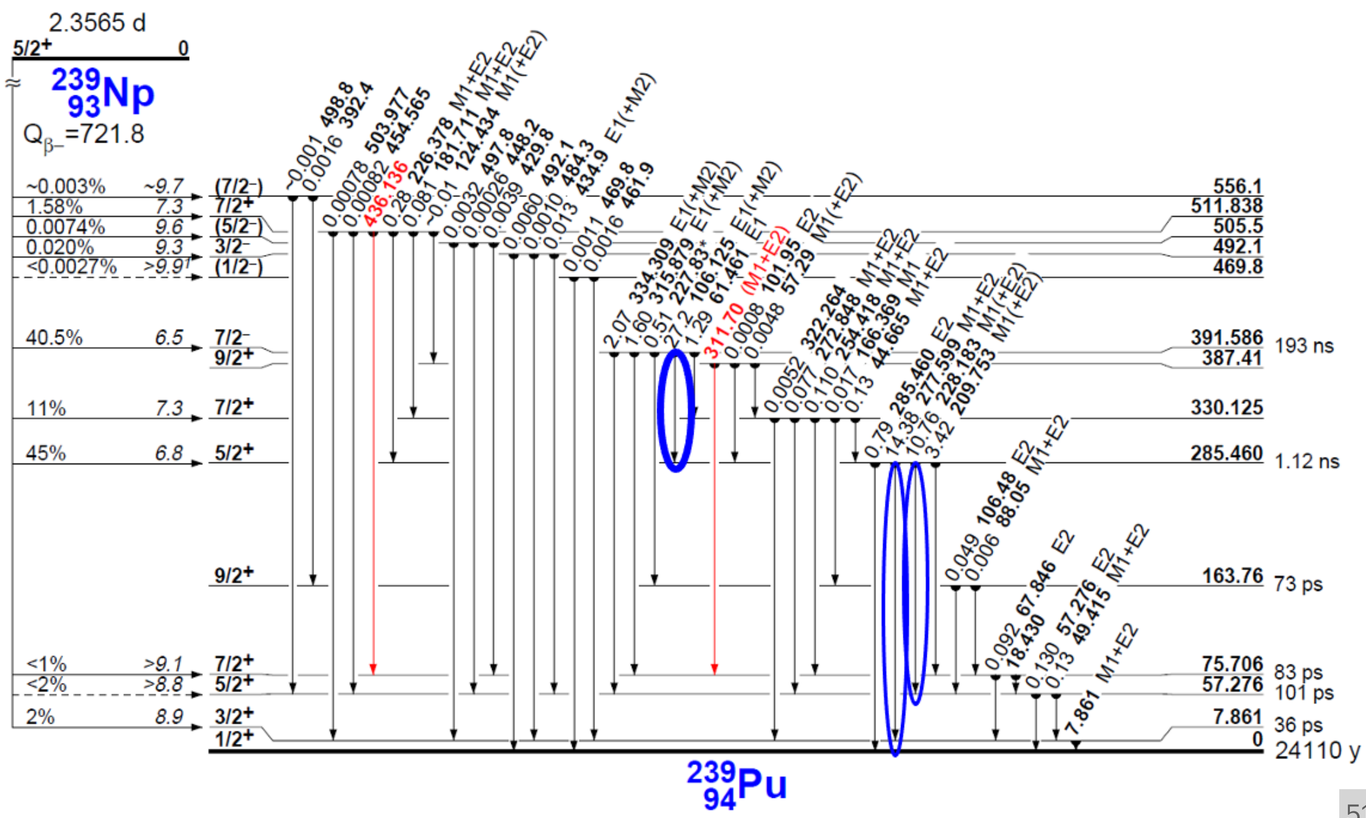
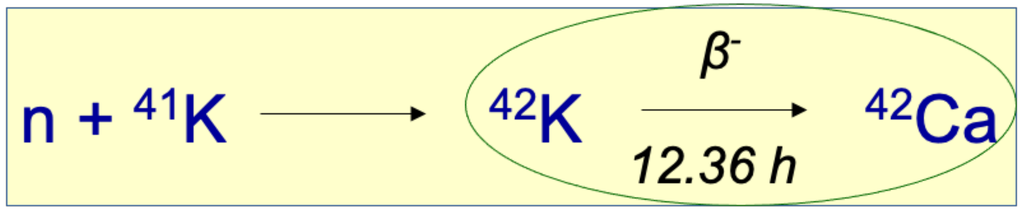






NAA for ^{40}K, ^{232}Th, ^{238}U

The activation reactions



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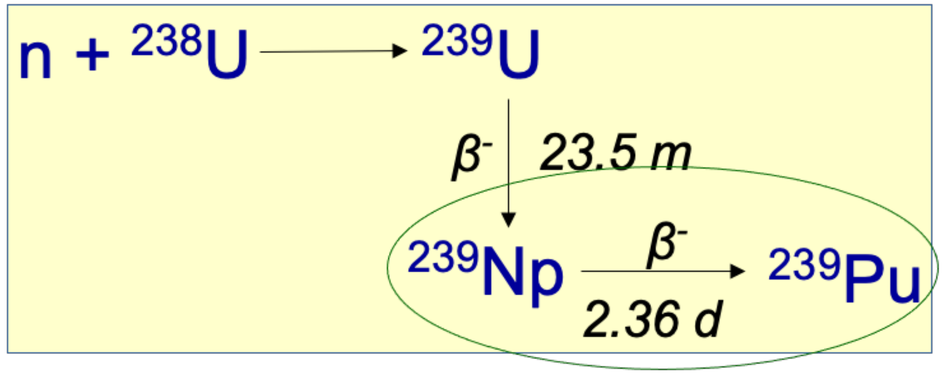
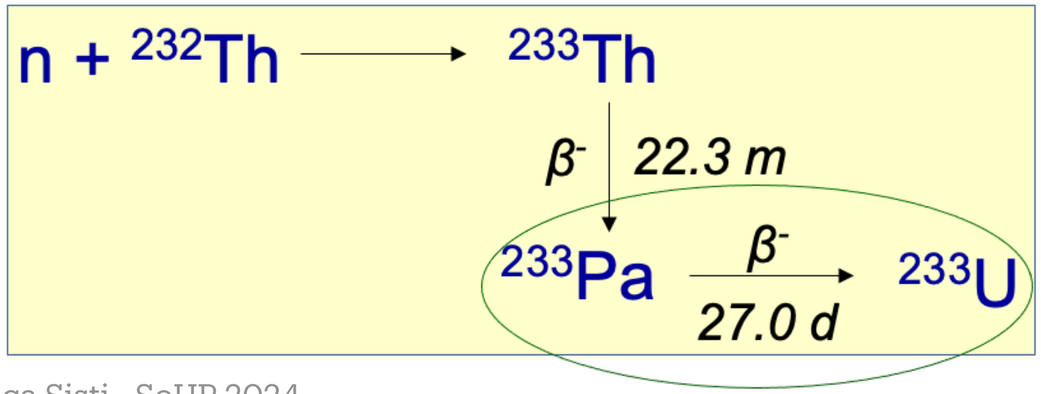
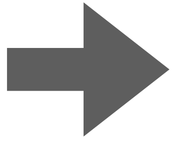
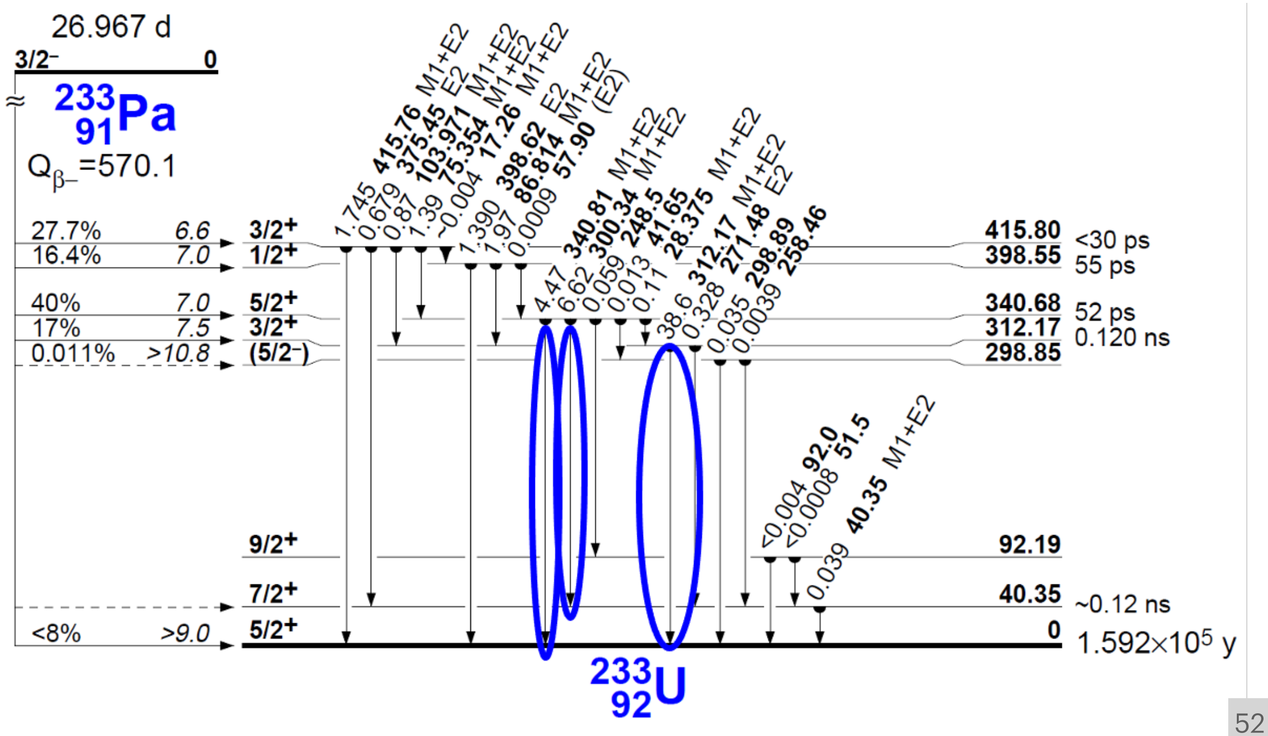








Neutron activation analysis

Activation rate

The number of radioisotopes that each second are created by neutron-induced reactions (the activation rate R) is related to the amount (N) of the original, stable (or long-lived) isotope in the sample:

$$R = \mathcal{N} \int \phi(E)\sigma(E)\mathrm{d}E$$

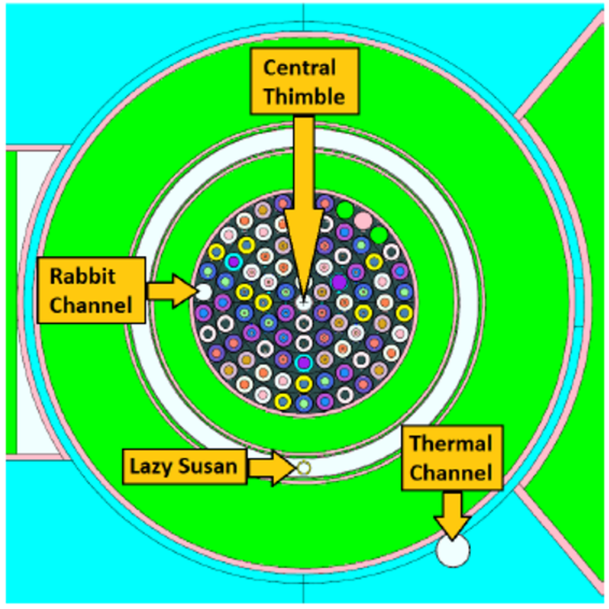
At the end of the irradiation, the amount (N) of the original, stable isotope in the sample is calculated via the counts measured with HPGe detectors in the gamma peaks following the decays of the activated isotope:

$$n_{\mathrm{dec}} = \frac{R}{\lambda}\left(1 - e^{-\lambda t_{\mathrm{irr}}}\right)e^{-\lambda t_{\mathrm{wait}}}\left(1 - e^{-\lambda t_{\mathrm{meas}}}\right)$$

Usually irradiation standards are used, containing the same elements to be traced in the sample with a known amount, to be independent of the neutron flux and effective activation cross section.

Neutron activation analysis

Examples of achievable sensitivities



Neutron irradiation:

TRIGA Mark II research reactor (250 kW) - Pavia, Italy

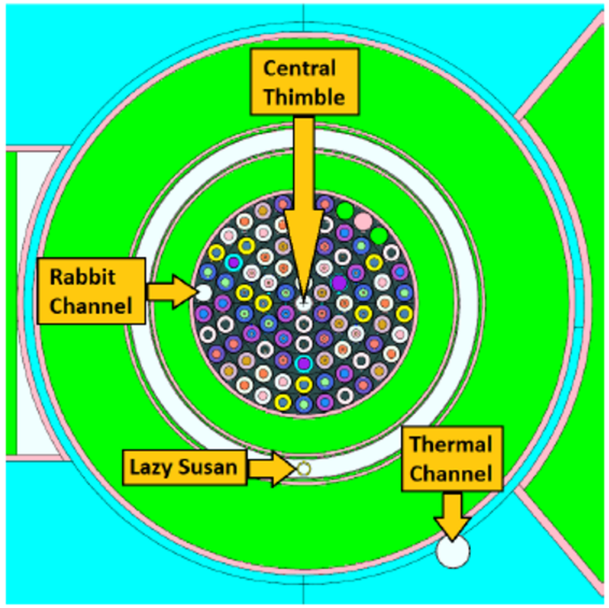
Acrylic samples

Contaminant concentration in an acrylic sample of 6 g

40K [ppt]	238U [ppt]	232Th [ppt]
0.09 ± 0.02	< 0.17	< 0.13

Neutron activation analysis

Examples of achievable sensitivities



Neutron irradiation:

TRIGA Mark II research reactor (250 kW) - Pavia, Italy

LAB samples

LAB sample

Detector	LAB Sample	Sample mass	^{238}U [g/g]	^{232}Th [g/g]
β-ϒ detector	Distillated	22g	<6·1E-14	<3·1E-13

Limit for the sentivity Limit @ 90% C.L.

Sample **mass is limited** at few tens of grams

Presence of interferences ^{82}**Br** and ^{24}**Na**

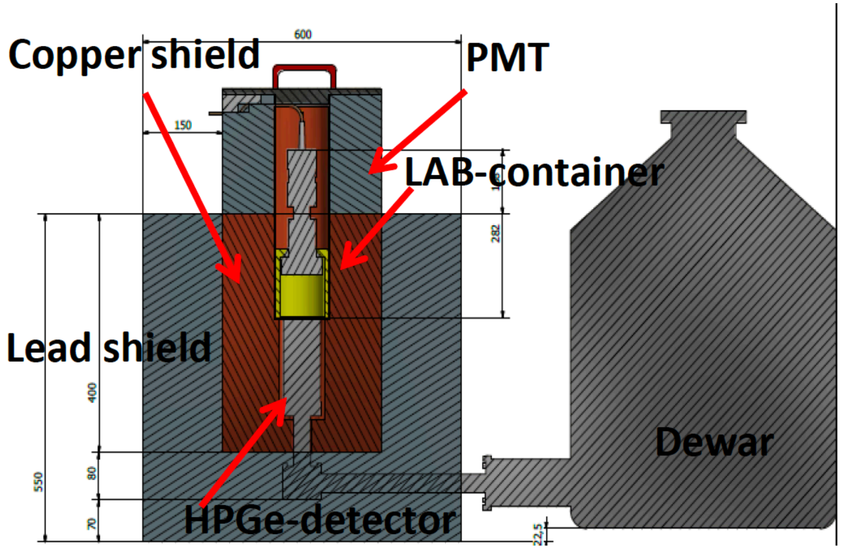
Neutron activation analysis

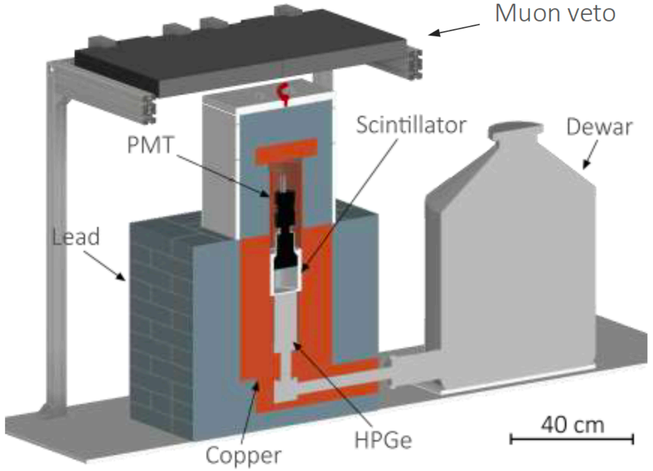
How to increase the sensitivities?

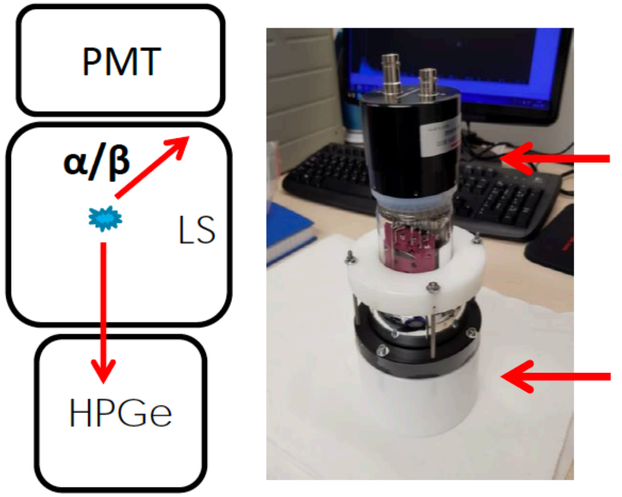
β-γ coincidence measurements:

$$^{A}X + n \longrightarrow {}^{A+1}X \xrightarrow{\beta^-} {}^{A+1}_{Z+1}Y + \gamma_{cascade}$$

⇒ strong background reduction







PMT

Liquid Scintillator Container

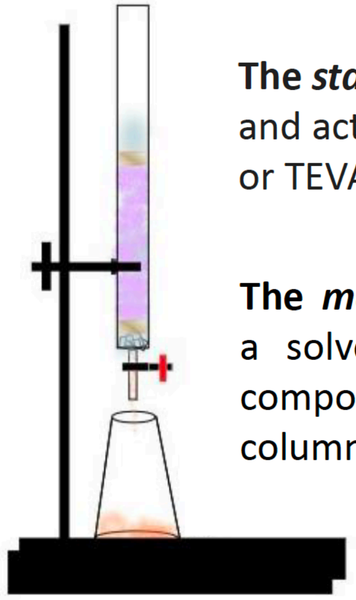
[Milano-Bicocca Radioactivity Lab]

Neutron activation analysis

How to increase the sensitivities?

Extraction Chromatography

Column Chromatography



The *stationary phase*: column and actinide absorb resin (TRU or TEVA)

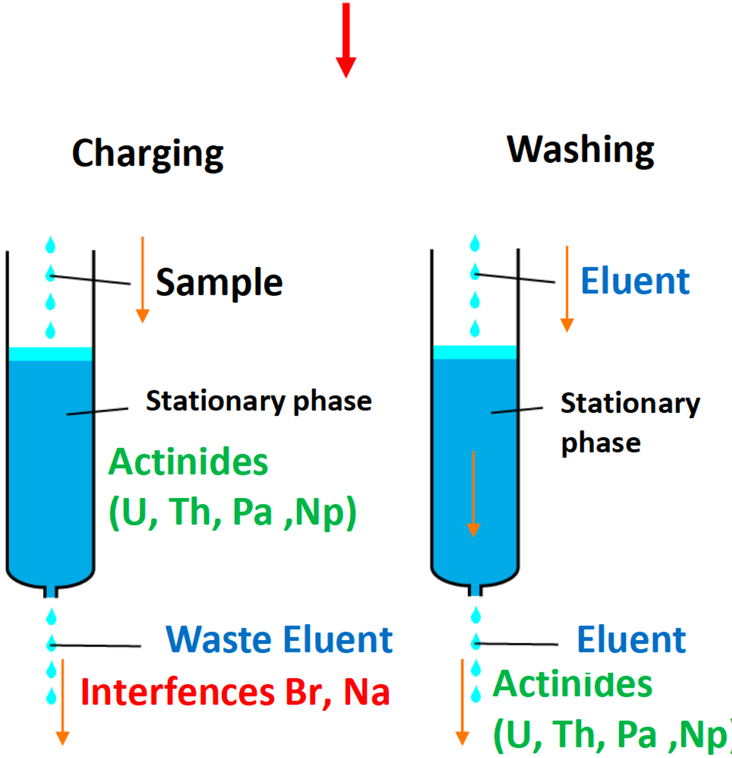
The *mobile phase* or *eluent* is a solvent used to move the compounds through the column.

Ideally the column chromatography **selectively absorbs actinide activities** (U, Th, Pa ,Np) while allowing interferences (Br, Na) pass through

$$^{238}_{92}U + n \xrightarrow{\beta^-} {}^{239}_{93}Np + \gamma$$

$$^{232}_{90}Th + n \xrightarrow{\beta^-} {}^{233}_{91}Pa + \gamma$$

After irradiation



Neutron activation analysis

Procedure developed at Milano-Bicocca for the JUNO liquid scintillator

Cleaning protocol (Pre-Irradiation) → Any sample manipulation before neutron irradiation could introduce contaminations (radiopurity of containers is also crucial)

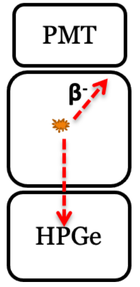
Chemical/Radiochemical Treatments (Pre and Post Irradiation) → Allow to **remove interferences** and **concentrate** the sample

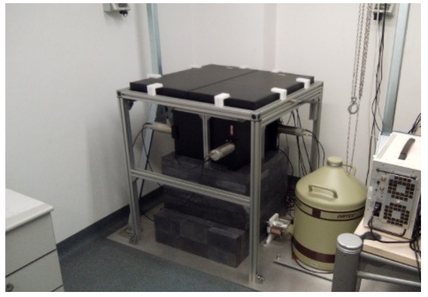
Sample irradiation → Allows to transform long life nuclides ^{238}U/^{232}Th into the radioactive short life ^{239}Np/^{233}Pa nuclides. Sensitivity < 1ppt

$$^{232}_{90}Th + \mathrm{n} \longrightarrow {}^{233}_{91}Pa$$

$$^{238}_{92}U + \mathrm{n} \longrightarrow {}^{239}_{93}Np$$

γ measurements → We developed a new detector suitable for **β – γ coincidence** measurements of irradiated liquid samples





Neutron activation analysis

Procedure developed at Milano-Bicocca for the JUNO liquid scintillator

Our to-date best achievements for natural contaminants in JUNO LS

Nuclide	Sensitivity @ 95 %	Limitating factor
^{238}U	< 0,7 ppq @ 500 mL < 0,4 ppq @ 1 L	Resin background
^{232}Th	< 1,6 ppq @ 1 L	Activation rate and resin background
^{40}K	< 0,7 ppq @ 126 g	Sample mass, interfering element (Na) and high contamination probability

Neutron activation analysis

How to increase the sensitivities?

$$^{A}_{Z}X + n \rightarrow {}^{A+1}_{Z}X \xrightarrow{\beta^-} {}^{A+1}_{Z+1}Y + \gamma$$

Neutron activation + HPGe γ measurement

10^{-12}g/g

β–γ coincidence detector: GeSparK

- Beta-gamma coincidence
- ^{239}Np delayed coincidence
- Cosmic muon veto

10^{-13}g/g - 10^{-14}g/g

Radiochemical treatments

- Concentration of the nuclides of interest (higher equivalent sample mass)
- Removal of interfering nuclides

$<10^{-15}$g/g

Neutron activation analysis

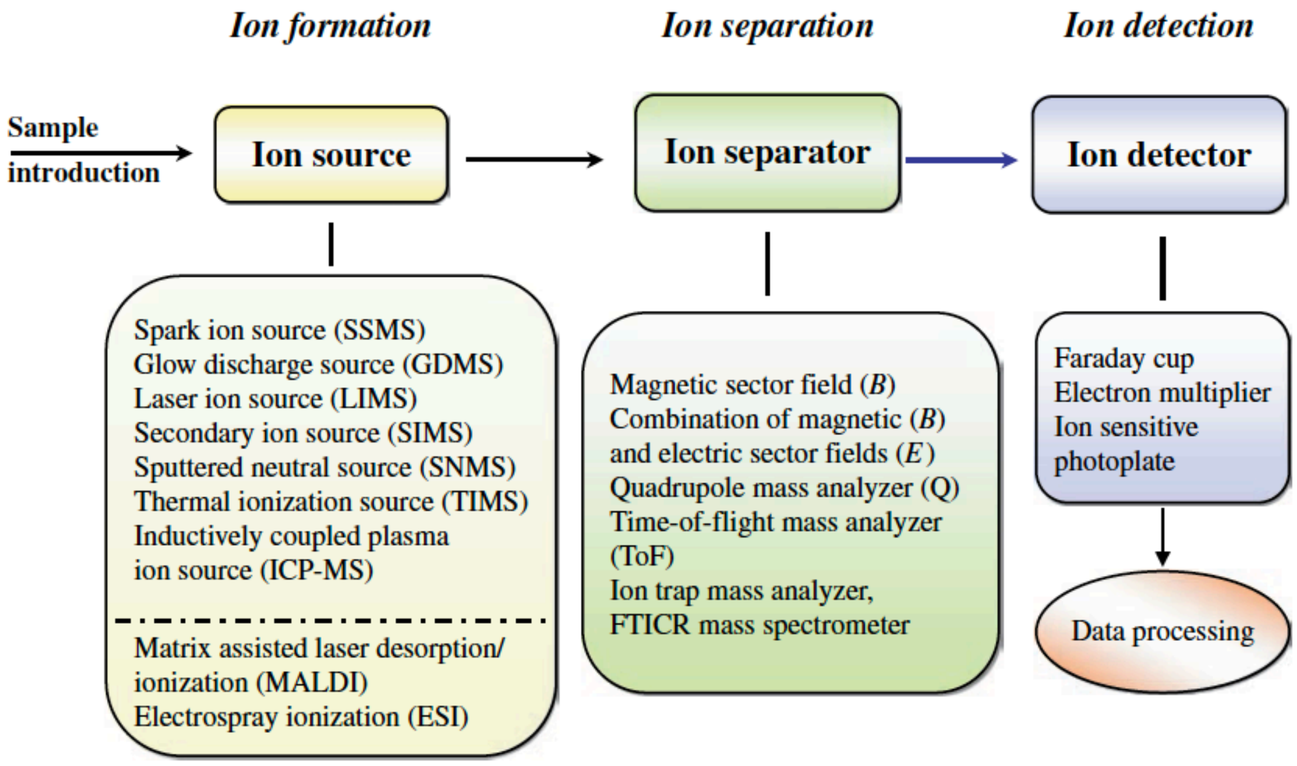
Pros and Cons for ultra-low background material screening

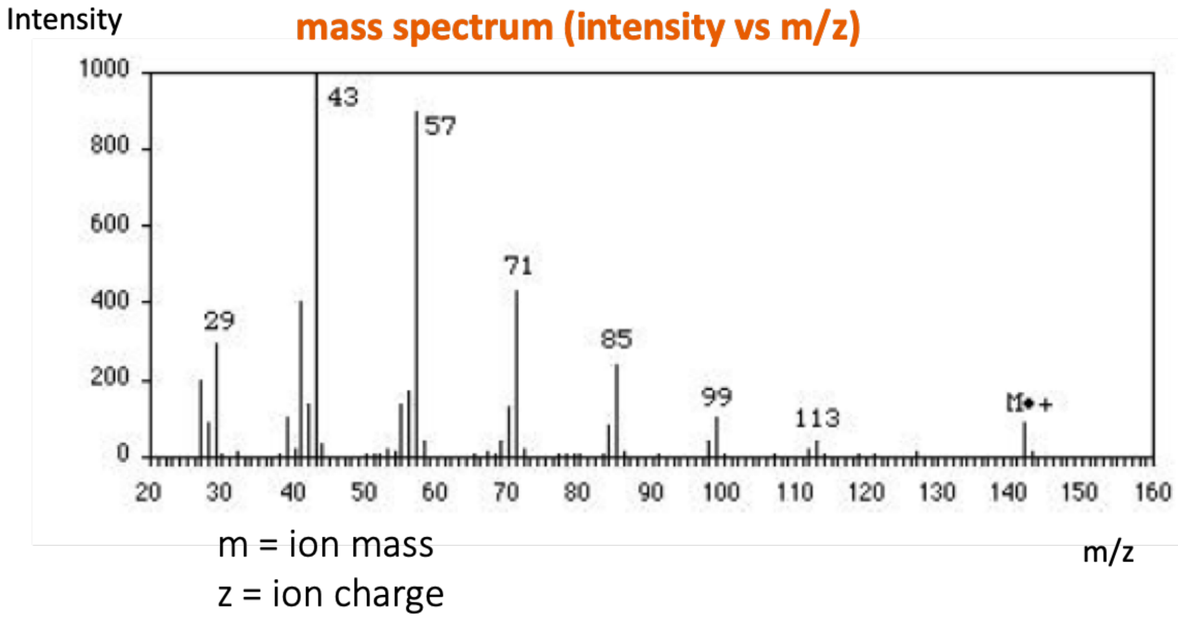
- High Sensitivity: NAA can detect trace amounts of natural contaminants with sub-ppt sensitivities.
- Non-Destructive: the sample remains mostly intact after analysis.
- After the neutron irradiation, samples can be further treated (e.g. radiochemistry) without the risk of contamination.
- Small samples are required.

- Only sensitive to decay chain precursors
- Not effective for all elements
- Measuring times are long for U/Th (up to 4 weeks for Th)

Inductively coupled plasma mass spectroscopy

ICP-MS, Inorganic mass spectrometry

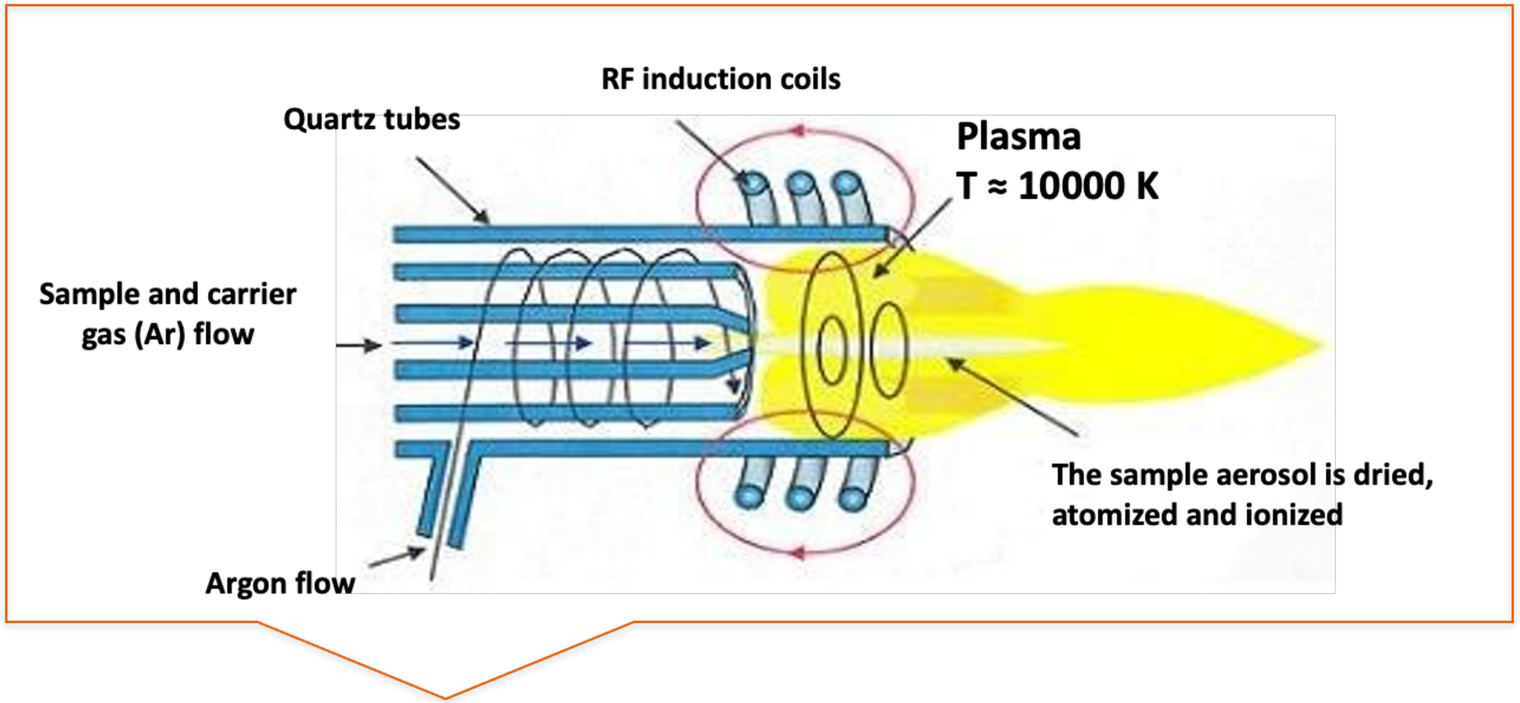




m = ion mass
z = ion charge

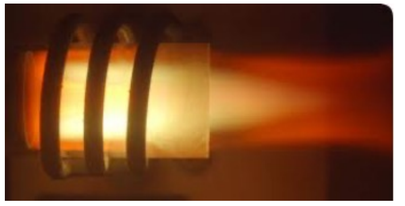
Inductively coupled plasma mass spectroscopy

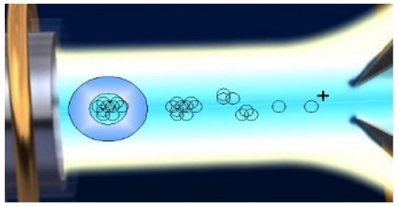
The ion source

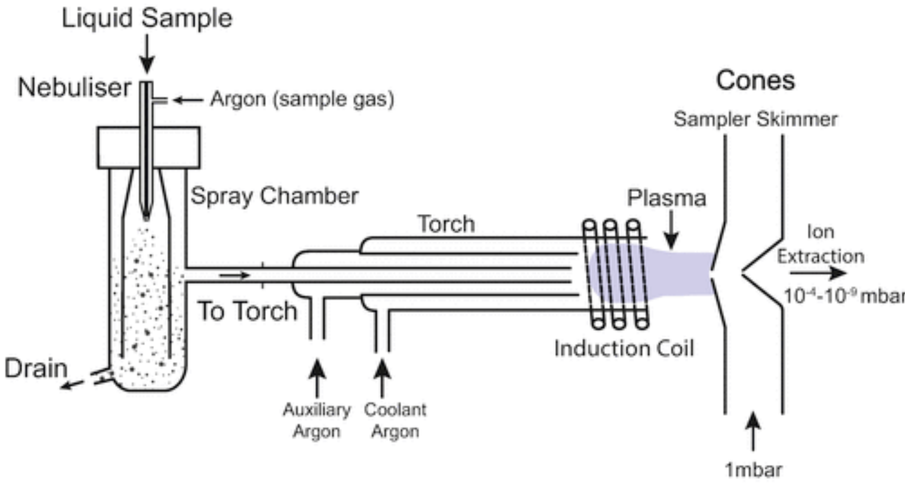


Plasma torch ion source

Plasma is capable to ionize almost all chemical elements

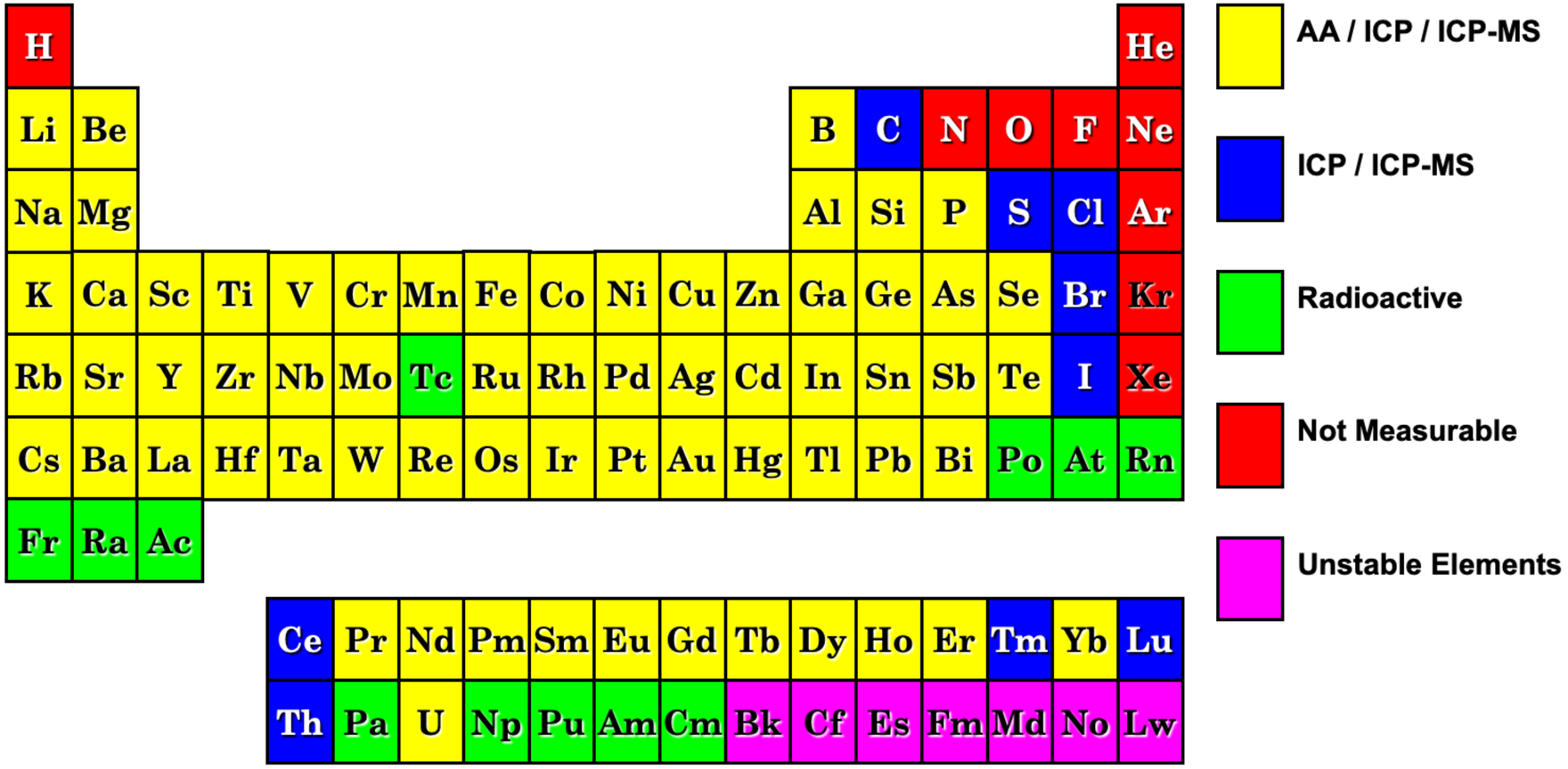






ICP-MS

Measurable elements



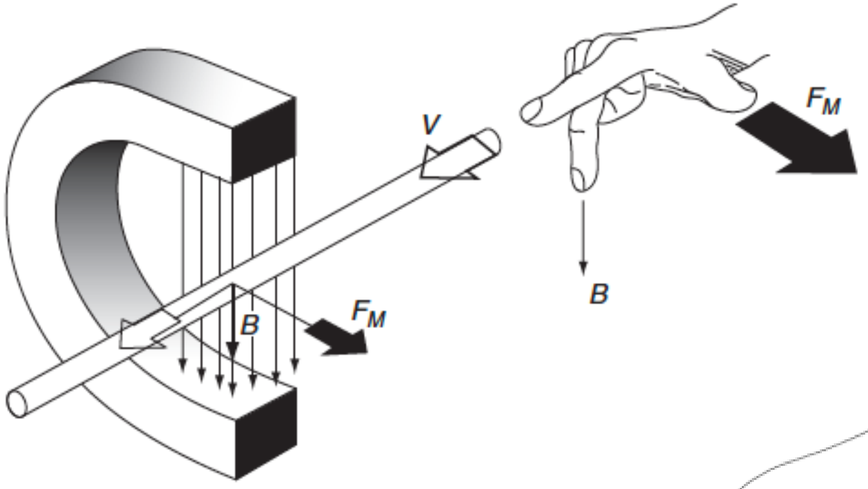
Ultra - trace → Trace

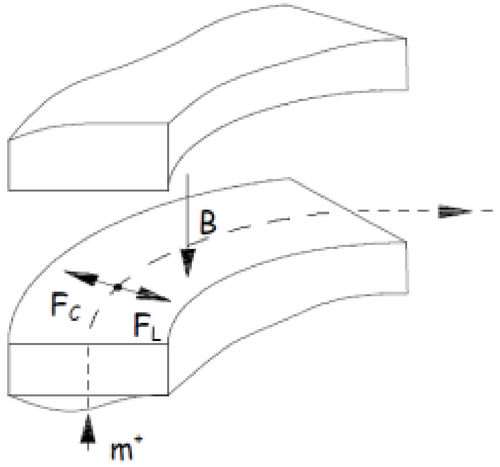
[credits: S. Nisi]

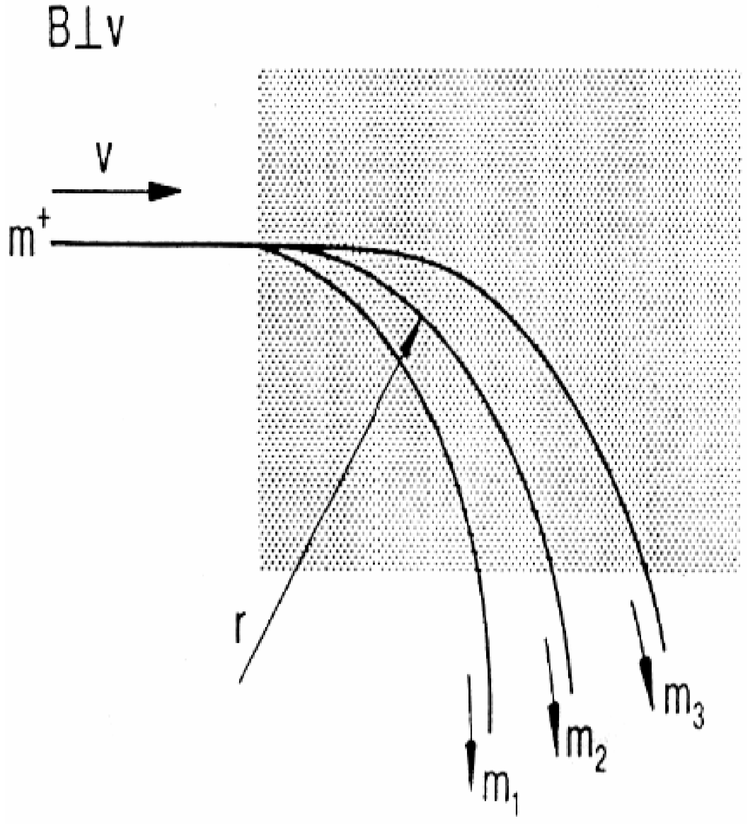
1ppq (10^{-15} g/g) 1ppt (10^{-12} g/g) 1ppb (10^{-9} g/g) 1ppm (10^{-6} g/g)

ICP-MS

The magnetic sector







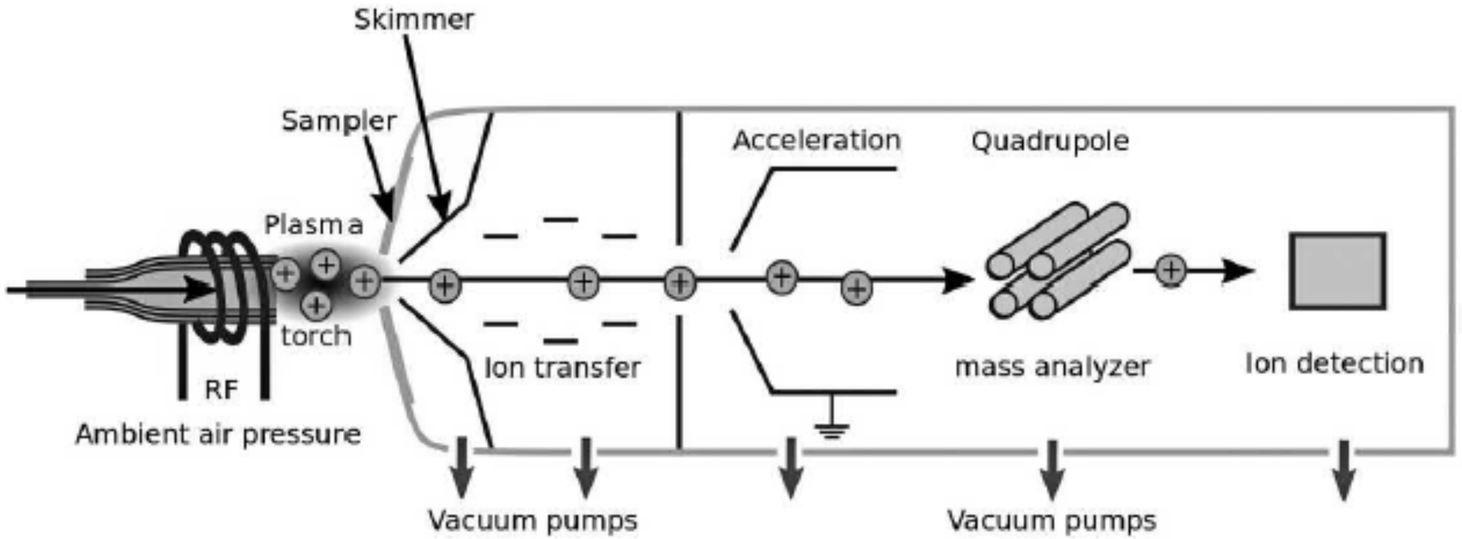
Lorentz force: $F_L = q(E + v \times B)$

Centrifugal force: $Fc = \frac{m \cdot v^2}{r}$

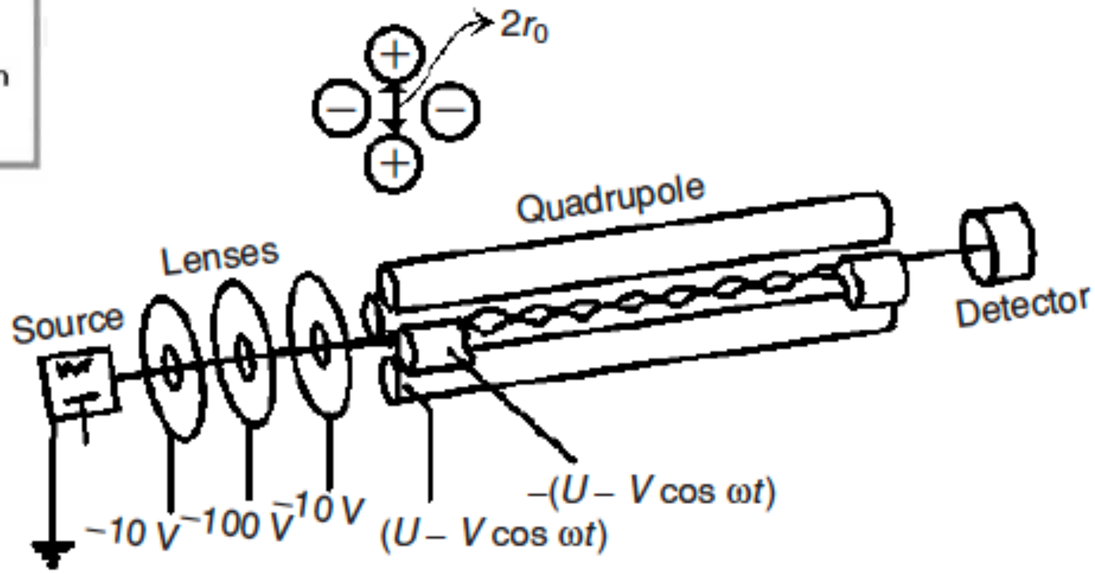
$r = (m*v)/(e*B)$

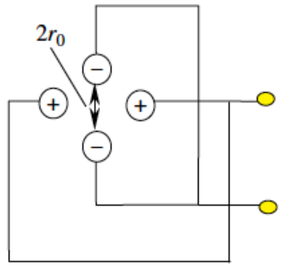
ICP-MS

Quadrupole mass analyser



Four hyperbolic rods supplied with DC current and radio frequency

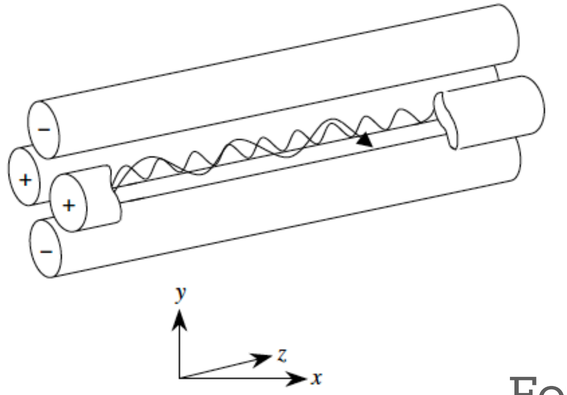




$U + V\cos\omega t$

U – dc voltage

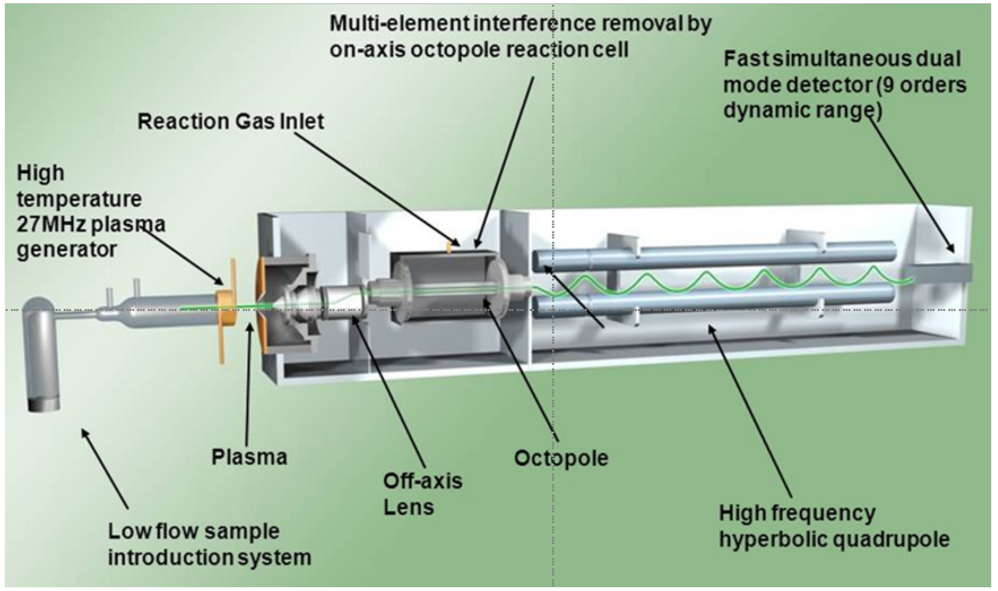
$V\cos\omega t$ – rf voltage



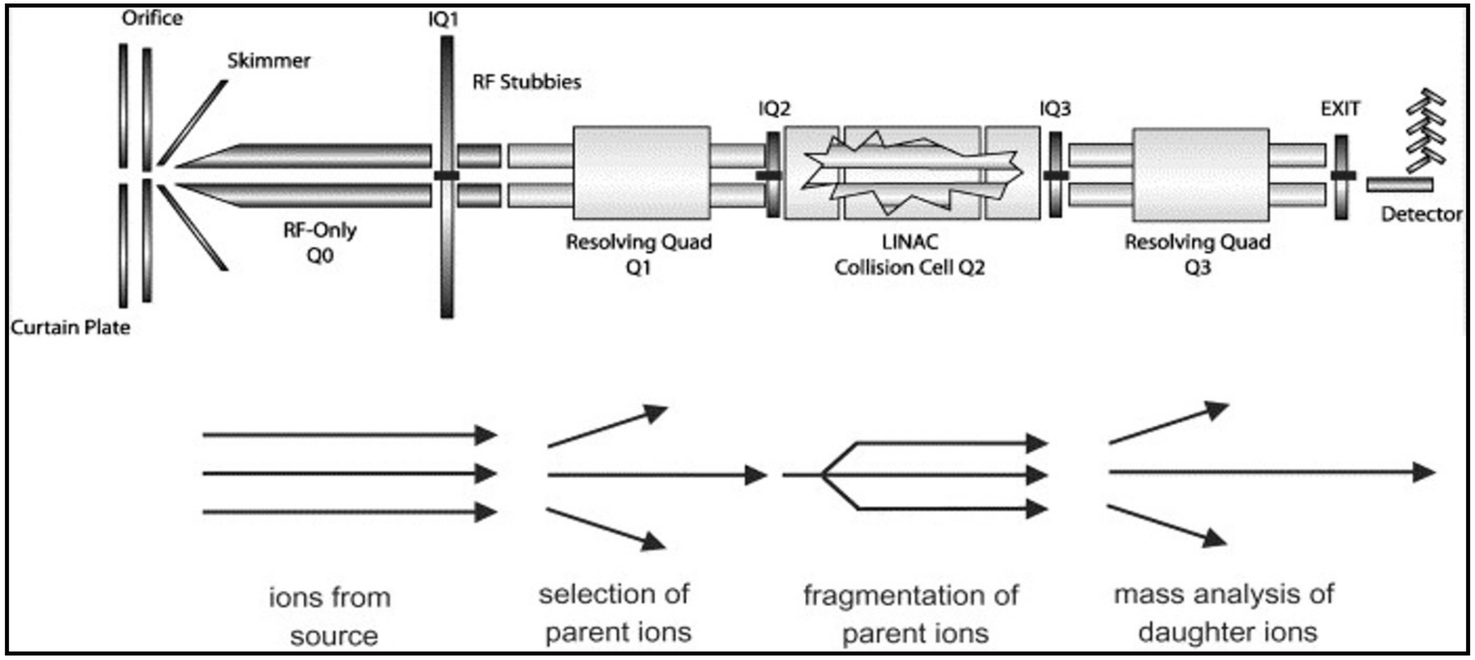
For a given combination of RF and DC voltages, only ions with a specific mass-to-charge ratio can reach the detector.

ICP-MS

Recent advances in quadrupole mass analyser



He gas collision cell



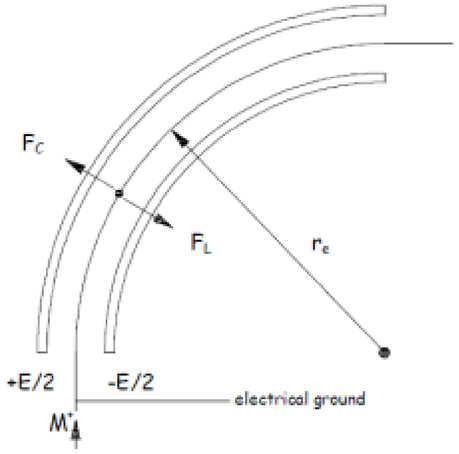
Triple quadrupole

[credits: S. Nisi]

ICP-MS

The electrostatic sector

- Circular trajectory: centripetal force equals the electrostatic force



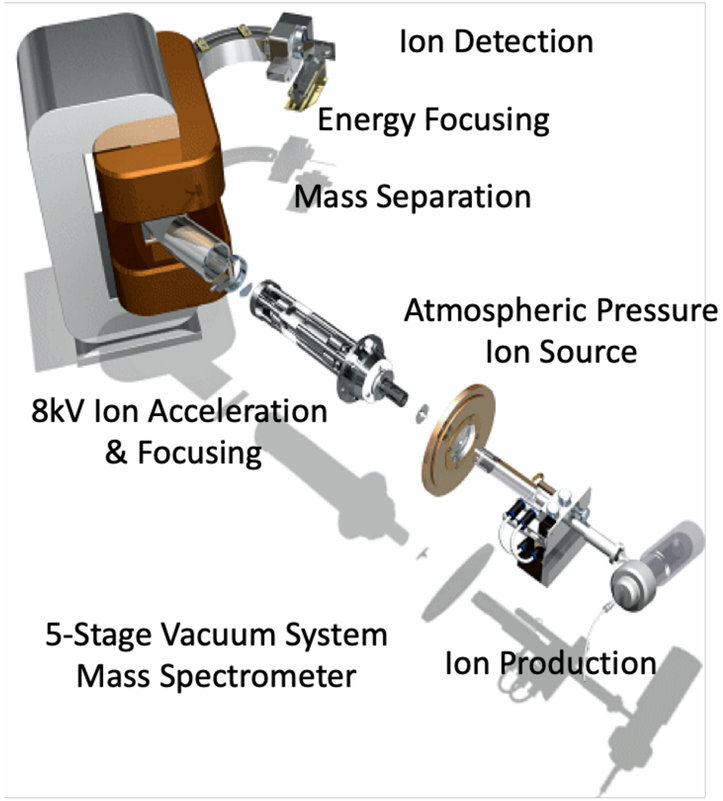
$$E_{kin} = q \cdot U_0$$

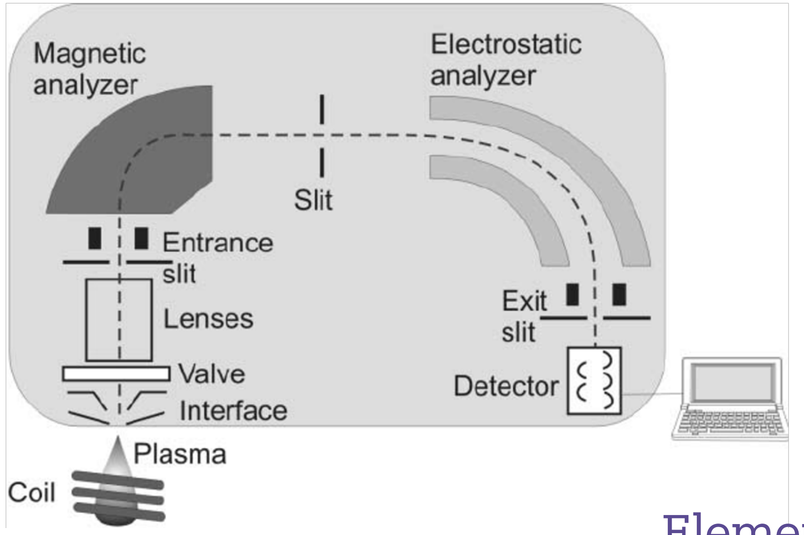
$$r_e = \frac{2 \cdot E_{kin}}{q \cdot E}$$

- No mass dispersion
- With the slit at a particular radius, the systems acts as an energy filter

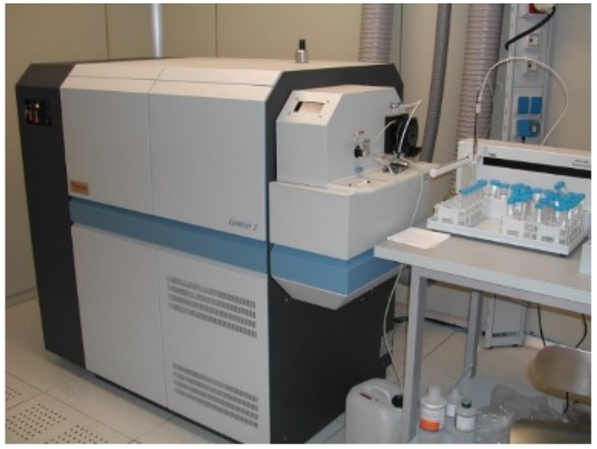
ICP-MS

Double focusing mass spectrometer





Element 2 @ LNGS

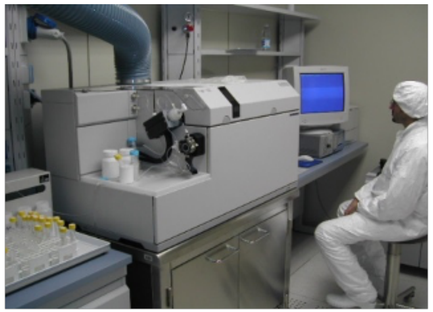


Double focusing ICP-MS have high sensitivity and high mass resolution

[credits: S. Nisi]

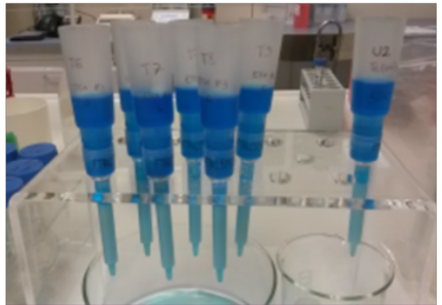
ICP-MS

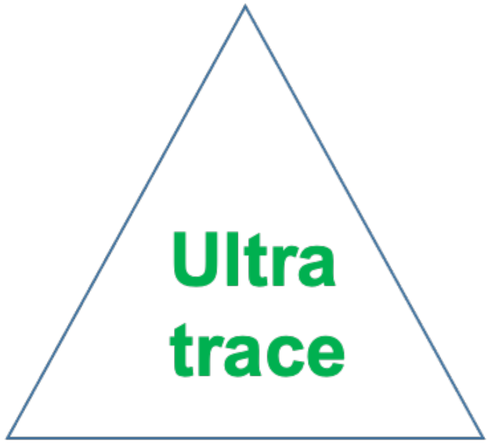
What is needed for high sensitivity measurements



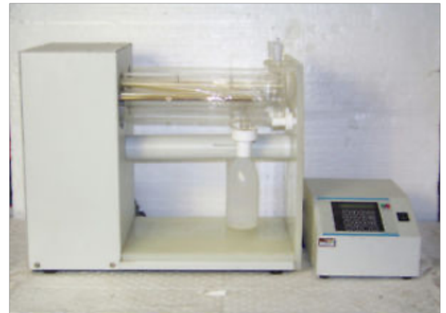
Instrumentation

Sample preparation





"Clean chemistry"



[credits: S. Nisi]

ICP-MS

Example of measurement results: copper sample

	Measured in Cu sample
Th	4.6 ± 1.3 ppt
U	1.0 ± 0.3 ppt

	DL* (in solid Cu)	Recovery %
Th	2.6 ppt	90.0 ± 0.6
U	0.8 ppt	97.9 ± 6.1

Cu separation efficiency: >99%

	DL	Recovery %
Th	very good	excellent
U	excellent	excellent

*DL = 3 × BLKStdDev

[Measured by S. Nisi]

ICP-MS

Example of measurement results: Roman lead sample

	Conc [10^{-12} g/g]	[µBq/Kg]
Th232	1,2 ± 0,6	4,9 ± 2,5
U238	1,2 ± 0,5	15 ± 7

Roman Pb contaminations

	Method Detection Limit* [10^{-12} g/g]
Th232	0,5
U238	0,3

*DL = 3 × BLKStdDev

[Measured by S. Nisi]

ICP-MS

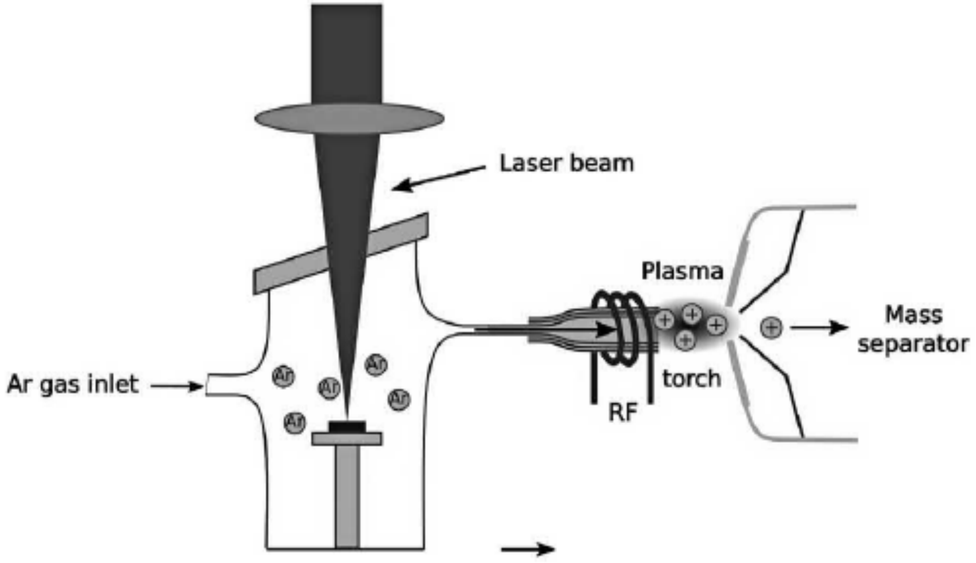
Example of measurement results: Teflon (PTFE) sample

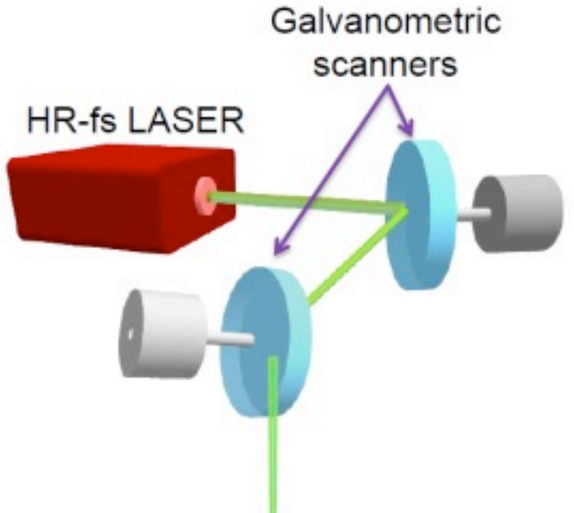
Contaminations in PTFE samples						
Element	Unit	Sample 1	Sample 2	Sample 3	Sample 4	Sample 5
Th	[pg*g^{-1}]	9.9 ± 3.0	7.4 ± 2.2	< 10	3.4 ± 1.0	2.0 ± 0.6
U	[pg*g^{-1}]	14.8 ± 4.4	13.3 ± 4.0	< 10	8.2 ± 2.5	0.8 ± 0.2
K	[ng*g^{-1}]	32.3 ± 9.7	34.3 ± 10.3	< 20	< 10	< 20

[Measured by S. Nisi]

Laser ablation ICP-MS

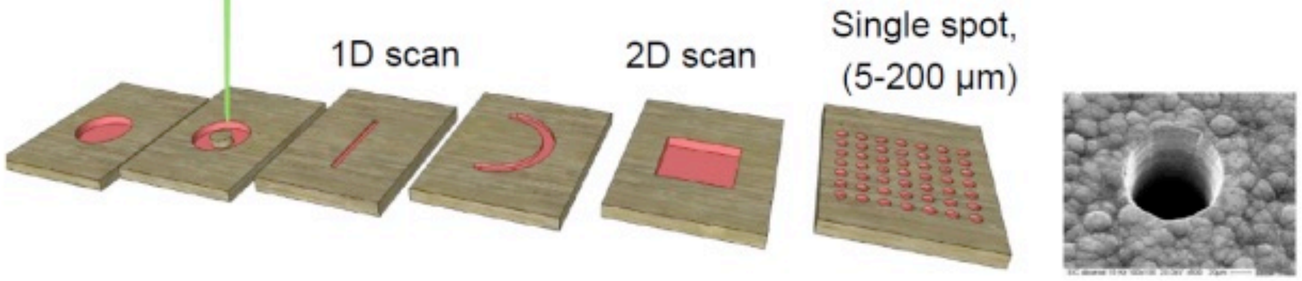
An interesting recent development to screen solid samples





Possibility to move in 2D the sample and/or the laser beam in order to fit with the morphology of the sample

- Size of the beam ~10 µm
- High repetition rate ~100 kHz
- Translation speed < 2m/s

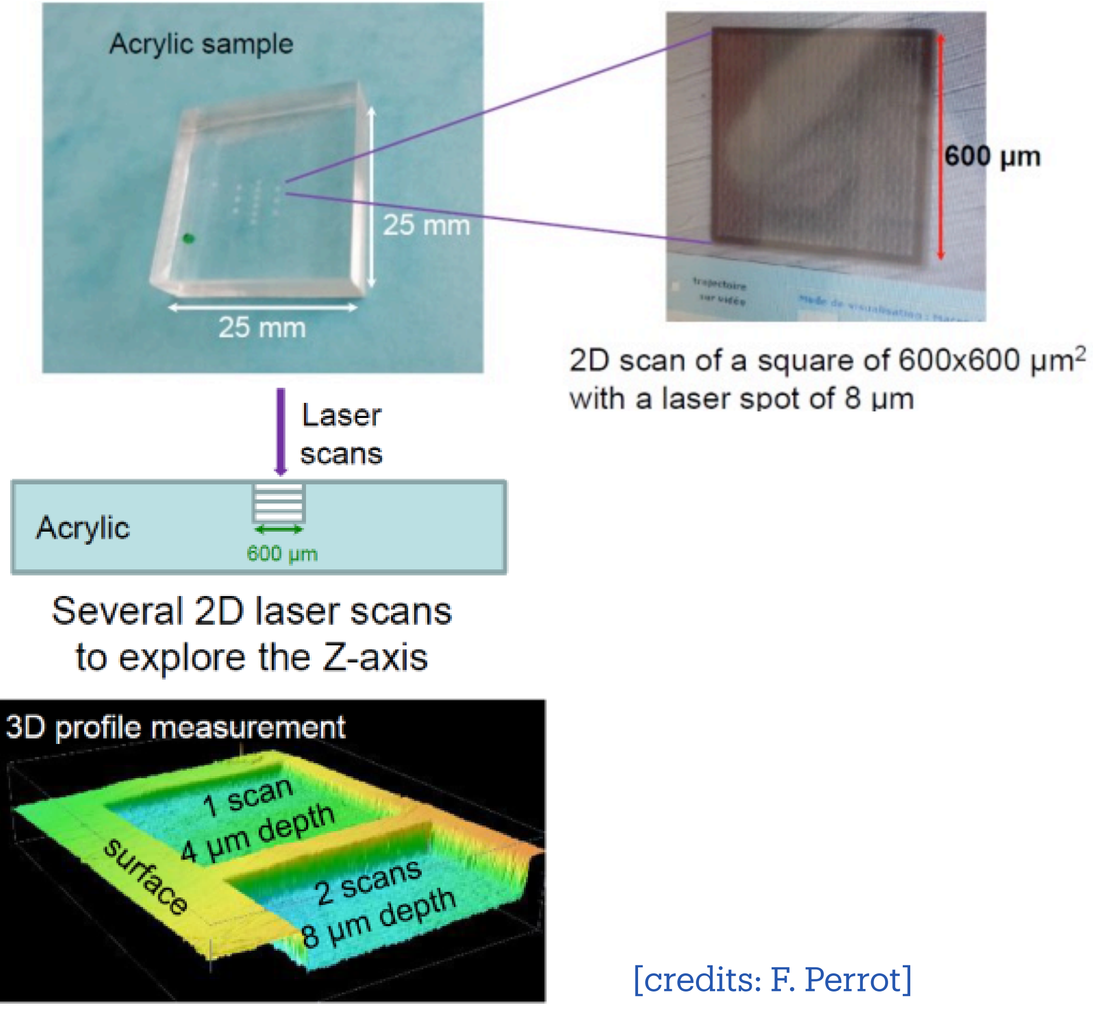


[credits: F. Perrot]

Laser ablation ICP-MS

Applied to JUNO acrylic samples

- A very interesting method to assess the surface radiopurity of a solid material
- Caveat: surface impurities may not be uniformly distributed on the sample
- The bottleneck with this method is the quantification of U/Th contamination level



[credits: F. Perrot]

ICP-MS

Pros and Cons for ultra-low background material screening

- Sensitivity: Can detect elements at extremely low concentrations (ppt or even lower).
- Very fast analysis: high sensitivity measurement can be performed in a few hours.
- Small sample masses are needed: best technique to check different material batches.
- Wide dynamic range: Can measure concentrations over several orders of magnitude.
- Multi-element detection: Simultaneously detects multiple elements in a single run.

- Destructive analysis and high risk of contamination during sample preparation and measurement.
- Interference: ICP-MS can suffer from spectral interferences. This can be mitigated by using techniques like collision/reaction cells.
- Matrix effects: The presence of high concentrations of other substances in the sample can affect the ionization efficiency or cause signal suppression.
- Low sensitivity for ^{40}K.

What we have seen until now

A short summary

- Material screening for ultra-low background experiments is **highly challenging** and often requires dedicated R&D to achieve the necessary sensitivities.
- **Gamma spectroscopy** with HPGe detectors is the most effective method for providing comprehensive information on both natural contaminants (including entire decay chains) and anthropogenic radionuclides in a single measurement. In the best detector configurations, sensitivities can reach the low tens of ppt, though extended measurement times are often required.
- **NAA and ICP-MS** offer even higher sensitivities, reaching sub-ppt levels, but are limited to detecting natural decay chain progenitors.
- These techniques are **complementary**: gamma spectroscopy provides broad coverage, while NAA and ICP-MS deliver deeper sensitivity for specific elements.

Is material screening all we need?

This is not the end of the story

Once a material that meets our requirements has been identified, several factors still require careful consideration:

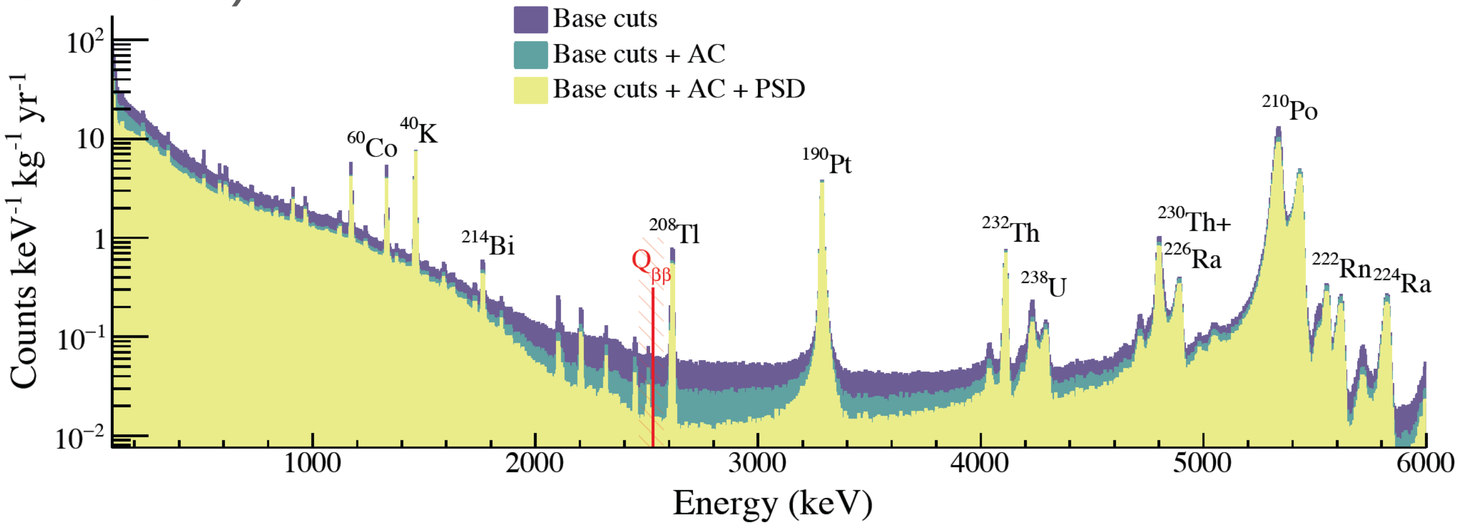
- **Material consistency**: different batches may vary in quality. It is crucial to coordinate with the vendor to ensure that the entire quantity comes from the same production batch that was screened.
- **Machining contamination**: the machining process can introduce unwanted contaminants, both natural and artificial. We must oversee the entire production chain and consider additional screenings for all materials that come into contact with our sample.
- **Storage conditions**: proper storage is essential to prevent surface recontamination, such as radon plate-out.
- **Surface cleanliness**: the surface of the material may not be as clean as the bulk, requiring extra precautions.

Alpha spectroscopy

The method to screen surfaces

- Surface contaminations are a great concern for $0\nu\beta\beta$ and dark matter searches
- In same cases those contaminations can become the ultimate limitation to sensitivity (e.g. CUORE experiment)

CUORE: 2039 kg×y of TeO_2 exposure [arXiv 2404.04453]

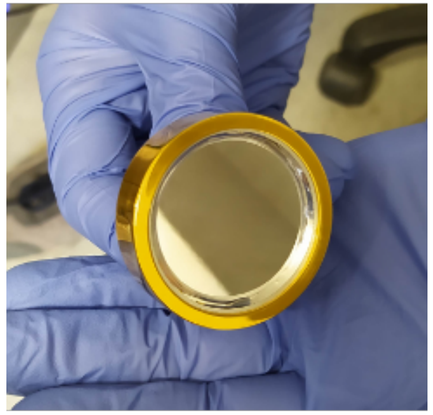


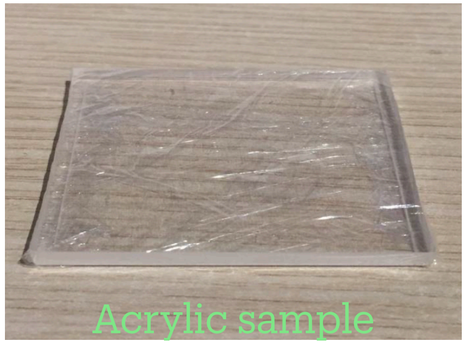
- Unfortunately, at present, only few technologies are able to measure low levels contaminations on surfaces

Alpha spectroscopy

with commercial detectors for small samples

- Si barrier detectors with 900 mm^2 active area
- Sample size: 5×5 cm^2
- Typical sensitivity for U/Th chains: ~ μBq/cm^2
- Typical measuring time: ~ 30 days





[Milano-Bicocca Radioactivity Lab]

Alpha spectroscopy

with commercial detectors for large samples

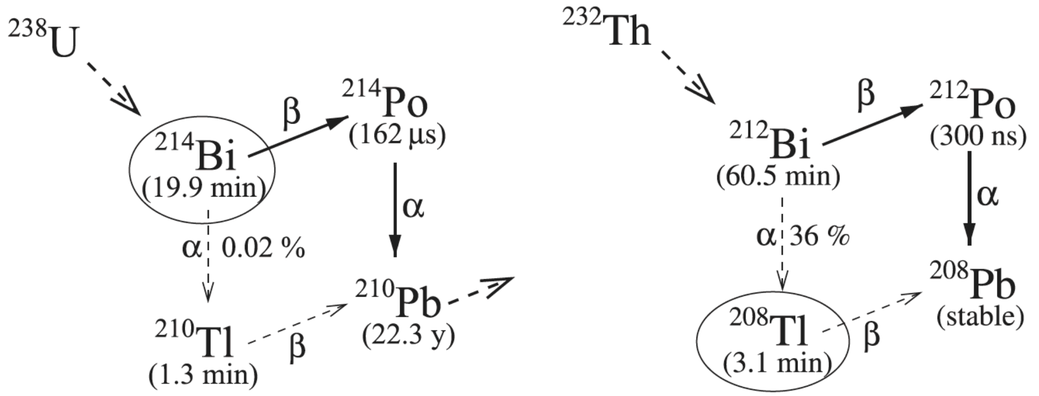
- XIA Ultralo 1800 Alpha counter (https://xia.com)
- Sample size: 43×43 cm^2
- Sensitivity for ^{210}Po: ~ 10 nBq/cm^2
- Measuring time: ~76 days

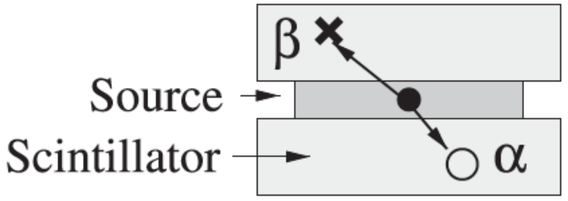
[Credits: G. Zuzel, LRT 2022]

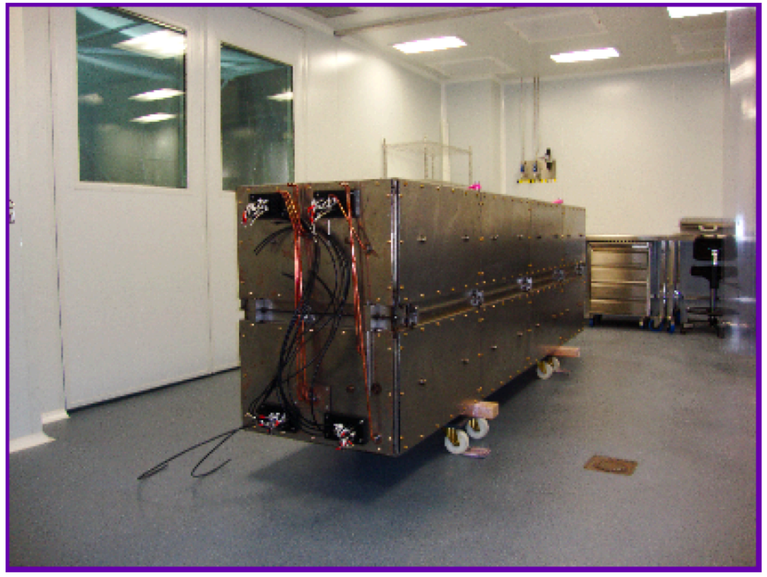
Alpha spectroscopy

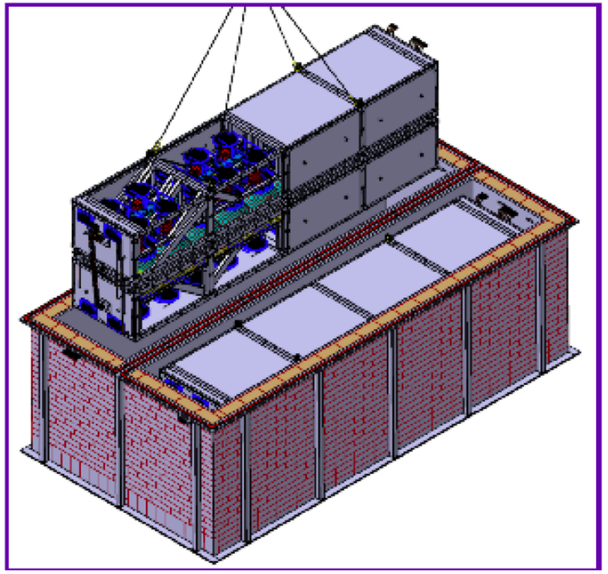
with an ad-hoc detector: the Bi-Po3 detector at LSC

- Sample size: 3.6 m^2
- Sensitivity for $^{208}Tl/^{214}Bi$: ~ 0.1 nBq/cm^2
- Measuring time: ~76 days









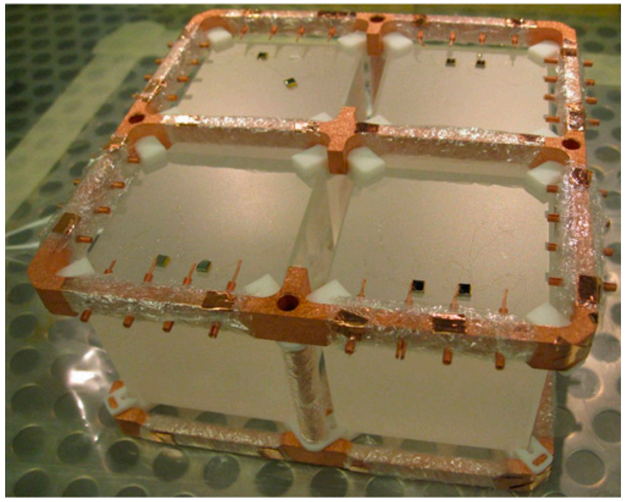
[Credits: P. Loaiza]

What if you need more?

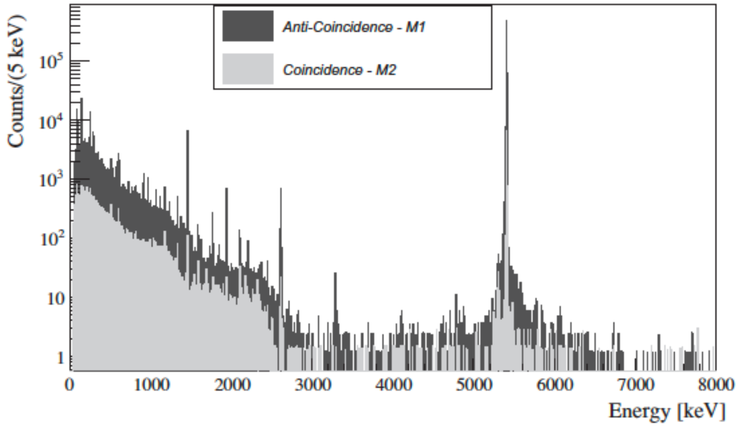
Building your own "custom" detector

Example: CUORE Crystal Validation Runs (CCVR)

- In some cases, "standard" techniques do not reach the required sensitivity.
- You may need to develop an ad-hoc experimental setup, e.g. for the periodic control of the mass production of the detector material



1 CUORE detector module



Upper limits at 90% C.L. on the activity and on the bulk contamination of uranium and thorium decay chains in the hypothesis of secular equilibrium.

Chain	Nuclide	Upper limit [Bq/kg]	Upper limit [g/g]
^{238}U	^{238}U	2.5E−07	2.0E−14
	^{234}U	4.7E−07	3.6E−14
	^{230}Th	5.7E−07	4.4E−14
	^{226}Ra	6.7E−07	5.3E−14
	^{218}Po	1.6E−07	1.3E−14
^{232}Th	^{232}Th	1.3E−07	3.1E−14
	^{212}Bi	8.4E−07	2.1E−13

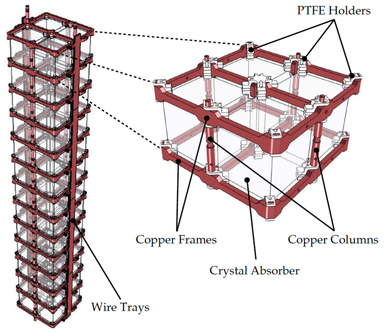
Upper limits at 90% C.L. for surface contamination, for different penetration length values. See text for details on the calculation of confidence intervals.

Depth	Nuclide	Upper limit 90% C.L. [Bq/cm^2]
0.01 μm	^{238}U	3.1E−09
	^{226}Ra	6.3E−09
	^{232}Th	1.6E−09
0.1 μm	^{238}U	3.2E−09
	^{226}Ra	6.6E−09
	^{232}Th	1.6E−09
0.2 μm	^{238}U	3.8E−09
	^{226}Ra	7.6E−09
	^{232}Th	2.0E−09
1 μm	^{238}U	3.7E−09
	^{226}Ra	8.9E−09
	^{232}Th	1.9E−09
5 μm	^{238}U	2.0E−09
	^{226}Ra	5.4E−09
	^{232}Th	1.0E−09
10 μm	^{238}U	1.7E−09
	^{226}Ra	4.4E−09
	^{232}Th	8.3E−10

[Astroparticle Physics 35 (2012) 839–849]

Building a prototype

Example: CUORE-0, the first CUORE tower



[2016 *JINST* 11 P07009]

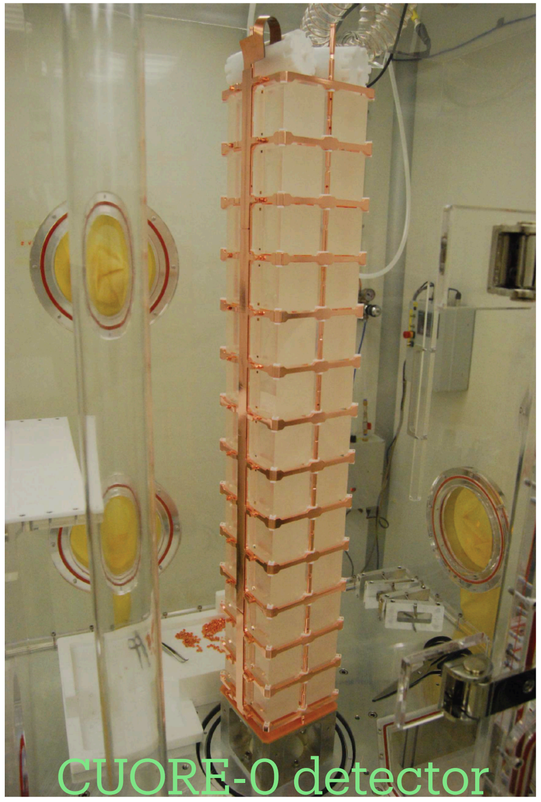
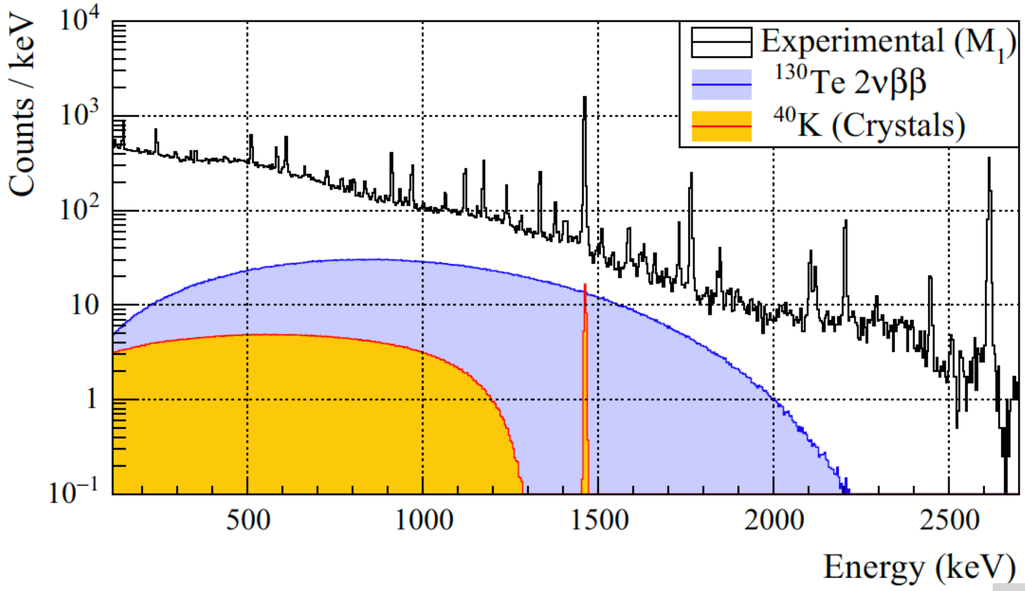


Table 8 List of the sources used to fit the CUORE-0 background data. The columns show (1) the name of the contaminated element, (2) the source index (j in Eq. 1), and (3) the contaminant. If not otherwise specified, ^{232}Th, ^{238}U, and ^{210}Pb refer to the whole decay chains in secular equilibrium, while the label "only" indicates that only the decay of the specified isotope is generated. For surface contaminants, the simulated depth is indicated in μm. Column (4) reports the prior used in the fit, when not specified a non-informative prior is used (see text for details). Column (5) reports the posterior with the statistical error (limits are 90% C.L.). Column (6) reports the range of systematic uncertainties (limits are 90% C.L.). In the case of crystal sources, systematic uncertainties can arise from non-uniform contaminants in the different crystals

Component	Index	Bulk sources	Prior [Bq/kg]	Posterior [Bq/kg]	Systematics [Bq/kg]
Crystals	1	^{130}Te – $2\nu\beta\beta$		$3.43(9)\times10^{-5}$	3.1×10^{-5}–3.7×10^{-5}
	2	^{210}Po	$2.36(11)\times10^{-6}$	$2.39(11)\times10^{-6}$	
	3	^{210}Pb		$1.37(19)\times10^{-6}$	5.4×10^{-7}–2.2×10^{-6}
	4	^{232}Th (only)		$7(3)\times10^{-8}$	$<1.2\times10^{-7}$
	5	^{228}Ra–^{208}Pb		$<3.5\times10^{-8}$	$<7.5\times10^{-8}$
	6	^{238}U –^{230}Th		$<7.5\times10^{-9}$	$<3.6\times10^{-8}$
	7	^{230}Th (only)		$2.8(3)\times10^{-7}$	
	8	^{226}Ra–^{210}Pb		$<7.0\times10^{-9}$	$<2.2\times10^{-8}$
	9	^{40}K		$5.1(14)\times10^{-6}$	$<8.2\times10^{-6}$
	10	^{60}Co	$<3.0\times10^{-7}$	$<5.1\times10^{-7}$	
	11	^{125}Sb		$9.6(4)\times10^{-6}$	7.5×10^{-6}–1.2×10^{-5}
	12	^{190}Pt		$2.00(5)\times10^{-6}$	1.6×10^{-6}–2.3×10^{-6}
Holder	13	^{232}Th	$<2.0\times10^{-6}$	$<2.1\times10^{-6}$	
	14	^{238}U	$<6.5\times10^{-5}$	$<1.2\times10^{-5}$	$<2.2\times10^{-5}$
	15	^{40}K	$7(2)\times10^{-4}$	$8(2)\times10^{-4}$	
	16	^{60}Co	$5(1)\times10^{-5}$	$3.5(8)\times10^{-5}$	
	17	^{54}Mn		$1.0(2)\times10^{-5}$	$<1.7\times10^{-5}$
	18	^{57}Co		$2.9(3)\times10^{-5}$	2.3×10^{-5}–3.7×10^{-5}
CryoInt	19	^{232}Th		$<1.5\times10^{-5}$	$<3.5\times10^{-5}$
	20	^{238}U		$<1.5\times10^{-5}$	$<3.9\times10^{-5}$
	21	^{40}K		$1.1(3)\times10^{-3}$	
	22	^{60}Co	$<1.8\times10^{-4}$	$2.4(10)\times10^{-5}$	
	23	^{137}Cs		$9.9(15)\times10^{-6}$	
IntPb	24	^{232}Th	$<4.5\times10^{-5}$	$5.3(7)\times10^{-5}$	1.7×10^{-5}–6.6×10^{-5}
	25	^{238}U	$<4.6\times10^{-5}$	$2.7(10)\times10^{-5}$	
	26	^{40}K	$<2.3\times10^{-5}$	$<2.4\times10^{-5}$	$<4.6\times10^{-4}$
	27	^{108m}Ag		$6.1(12)\times10^{-6}$	
	28	^{202}Pb		$6(3)\times10^{-6}$	
CryoExt	29	^{232}Th		$<1.2\times10^{-4}$	$<1.8\times10^{-4}$
	30	^{238}U		$2.4(6)\times10^{-4}$	$<5.9\times10^{-4}$
	31	^{40}K		$<1.6\times10^{-3}$	$<2.6\times10^{-3}$
	32	^{60}Co	$<4.2\times10^{-5}$	$2.5(9)\times10^{-5}$	
ExtPb	33	^{232}Th	$<2.6\times10^{-4}$	$3.1(3)\times10^{-4}$	2.1×10^{-4}–3.5×10^{-4}
	34	^{238}U	$<7.0\times10^{-4}$	$5.0(6)\times10^{-4}$	3.5×10^{-4}–6.2×10^{-4}
	35	^{40}K	$<5.4\times10^{-3}$	$3.1(5)\times10^{-3}$	
	36	^{207}Bi		$5.9(5)\times10^{-5}$	4.7×10^{-5}–7.2×10^{-5}
	37	^{210}Pb		5.96(11)	5.4–6.3

Table 8 continued

Component		Surface sources	Prior [Bq/cm^2]	Posterior [Bq/cm^2]	Systematics [Bq/cm^2]
Crystals	38	^{232}Th (only) – 0.01 μm		$3.0(10)\times10^{-10}$	
	39	^{228}Ra–^{208}Pb – 0.01 μm		$2.32(12)\times10^{-9}$	2.1×10^{-9}–2.7×10^{-9}
	40	^{238}U –^{230}Th – 0.01 μm		$2.07(11)\times10^{-9}$	1.8×10^{-9}–2.2×10^{-9}
	41	^{230}Th (only)–0.01 μm		$1.15(14)\times10^{-9}$	
	42	^{226}Ra – ^{210}Pb – 0.01 μm		$3.14(10)\times10^{-9}$	2.9×10^{-9}–3.5×10^{-9}
	43	^{210}Pb – 0.001 μm		$6.02(8)\times10^{-8}$	4.8×10^{-8}–7.2×10^{-8}
	44	^{210}Pb – 1 μm		$8.6(8)\times10^{-9}$	7.2×10^{-9}–1.1×10^{-8}
	45	^{210}Pb – 10 μm		$<2.7\times10^{-9}$	$<4.9\times10^{-9}$
	46	^{232}Th – 10 μm		$7.8(14)\times10^{-10}$	
	47	^{238}U – 10 μm		$<3.3\times10^{-11}$	$<1.2\times10^{-10}$
Holder	48	^{210}Pb – 0.01 μm		$2.9(4)\times10^{-8}$	2.1×10^{-8}–4.3×10^{-8}
	49	^{210}Pb – 0.1 μm		$4.3(5)\times10^{-8}$	3.1×10^{-8}–5.1×10^{-8}
	50	^{210}Pb – 10 μm		$<1.9\times10^{-8}$	$<3.9\times10^{-8}$
	51	^{232}Th – 10 μm		$5.0(17)\times10^{-9}$	$<1.0\times10^{-8}$
	52	^{238}U – 10 μm		$1.39(16)\times10^{-8}$	8.4×10^{-9}–1.6×10^{-8}
CryoInt	53	^{210}Pb – 0.01 μm		$1.4(7)\times10^{-5}$	$<2.7\times10^{-5}$
IntPb	54	^{210}Pb – 0.01 μm		$5.1(18)\times10^{-5}$	$<8.2\times10^{-5}$
Component		Other sources	Prior [Bq]	Posterior [Bq]	
50mK Spot	55	^{232}Th	$2.4(2)\times10^{-4}$	$2.41(18)\times10^{-4}$	
Bottom plate ExtPb	56	^{40}K	16.8(2)	18(2)	



[Eur. Phys. J. C (2017) 77:13]

Bibliography

1. G. Heusser, “Low-radioactivity background techniques,” Ann. Rev. Nucl. Part. Sci. 45 (1995) 543
2. J.A. Formaggio, C.J. Martoff, “Backgrounds to sensitive experiments underground”, Ann. Rev. Nucl. Part. Sci. 54 (2004) 361
3. G.F Knoll, “Radiation detection and measurement”, Wiley-Blackwell (2010)
4. P. Theodorsson, “Measurement of weak radioactivity”, World Scientific (1996)
5. M.F. L’Annunziata (edited by), “Handbook of radioactivity analysis”, Elsevier (2020)
6. M. Wojcik, G. Zuzel, and H. Simgen, “Review of high-sensitivity Radon studies”, Int.J. Mod. Phys. A 32 (2017) 30 1743004
7. Low Radioactivity Techniques workshop series: LRT 2024 (and links to previous editions)
8. https://www.radiopurity.org/ a useful collection of many material screening measurements