The upgraded low-background germanium counting facility Gator for high-sensitivity γ-ray spectrometry

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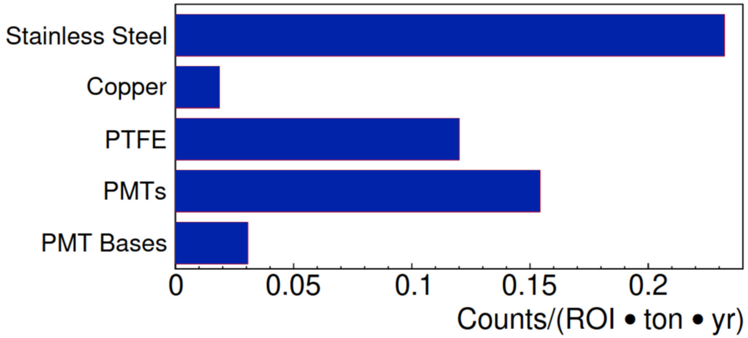
The Gator Facility

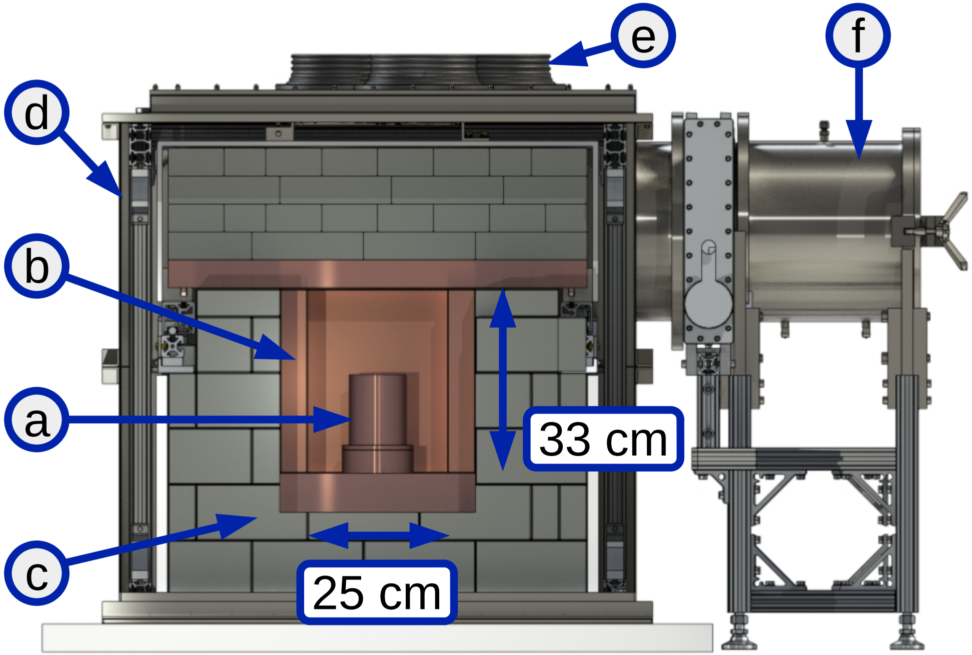
- Low-background germanium counting facility for high-sensitivity γ-ray spectrometry [2]
- Non-destructive and high-resolution material radioassay for rare-event search experiments
- Core: p-type coaxial high-purity germanium (HPGe) detector with 2.2 kg sensitive mass

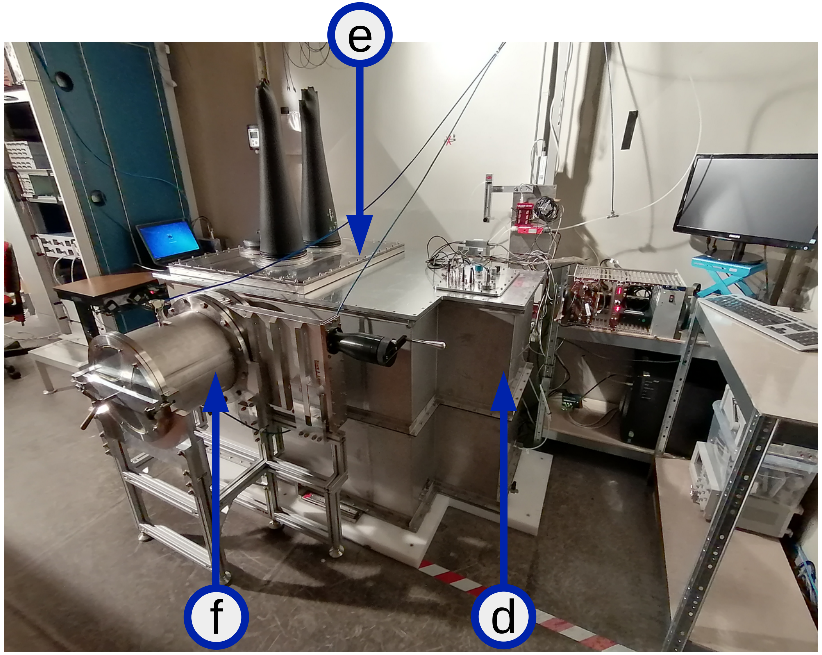
Predicted NR material backgrounds XENON1T [1]



[1] Eur. Phys. J. C77 (2017) 890; [2] JINST 6 (2011) P08010

The Upgraded Gator Detector

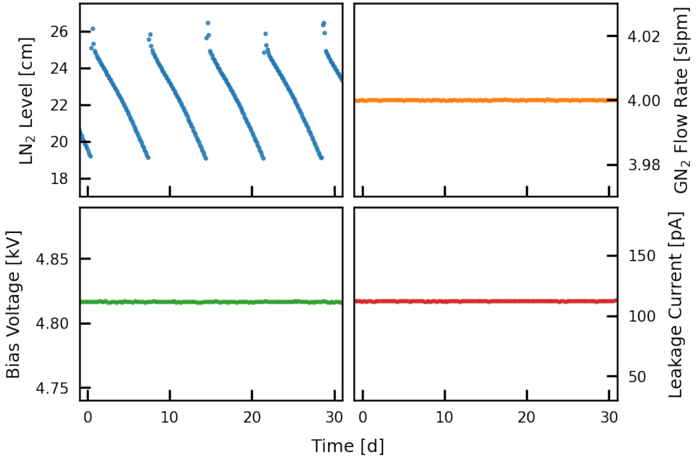


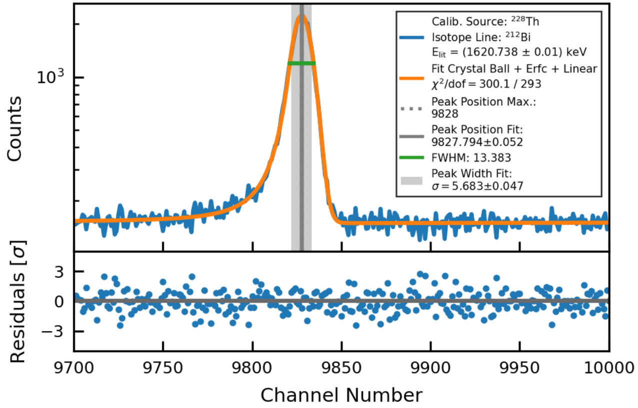


(a) HPGe detector inside Cu-OFE cryostat (cooled with LN_2 via copper coldfinger), **(b)** OFHC Cu cavity, **(c)** lead shield, polyethylene sheet, **(d)** airtight stainless steel enclosure (purged with GN_2), **(e)** glove ports, **(f)** sample load lock

Detector Operation and Performance

- Stable operation for over 10 years
- Remote monitoring (incl. alarms) of operations parameters to ensure detector stability and data quality
- Regular calibrations of the detector with radioactive sources (e.g. ^{228}Th, ^{137}Cs, or ^{60}Co) or high-activity samples
  - FWHM at 1332 keV: (1.98±0.07) keV (Maeve: 3.19 keV [3], GeOroel: 1.85 keV [4])
  - Verification of simulated efficiencies and consistent activities related lines



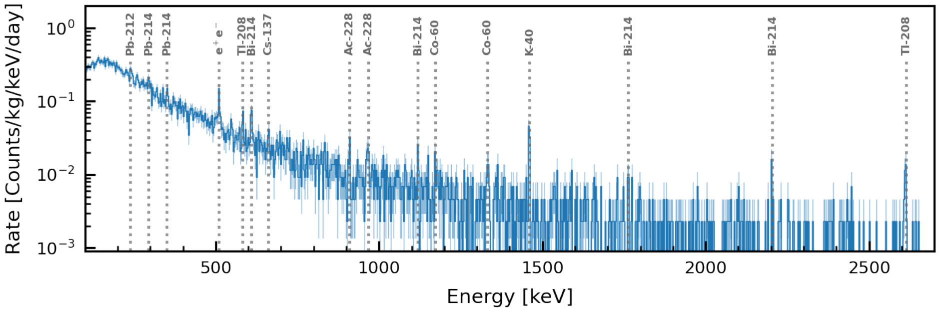


[3] Eur. Phys. J. C80 (2020) 1044
[4] Bandac, "Ultra-Low Background Services in the LSC", DS-Mat Meeting, GSSI, 2019

Background Contributions

- Integrated background rate in the energy region 100-2700 keV:
  $(82.0 \pm 0.7)\ d^{-1}kg^{-1}$;
  as compared to value from 2010 [2]:
  $(102.8 \pm 0.7)\ d^{-1}kg^{-1}$;
  stable within runs (χ^2/ndf ~ 1)
- Low energies (≲ 35 keV):
  - electronic noise
- Higher energies:
  - detector & shielding materials
  - environmental radon

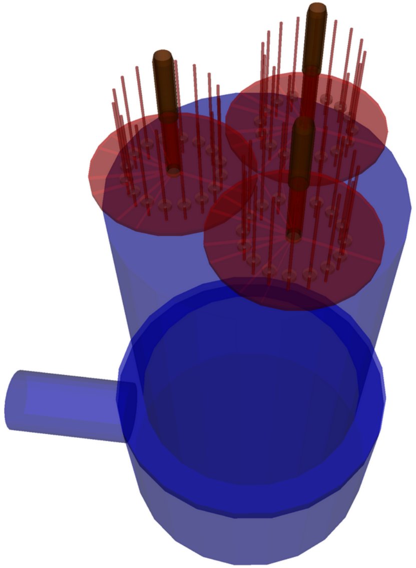
Energy [keV]	Isotope	Rate '21 [d^{-1}]	Rate '10 [d^{-1}]
351.932	Pb-214	< 0.7	0.7 ± 0.3
609.312	Bi-214	0.53 ± 0.11	0.6 ± 0.2
1120.29	Bi-214	0.15 ± 0.06	0.3 ± 0.1
1764.49	Bi-214	0.10 ± 0.03	0.08 ± 0.06
661.657	Cs-137	0.17 ± 0.08	0.3 ± 0.1
1173.24	Co-60	< 0.3	0.5 ± 0.1
1332.51	Co-60	0.11 ± 0.05	0.5 ± 0.1
1460.88	K-40	0.46 ± 0.08	0.5 ± 0.1
2614.51	Tl-208	0.14 ± 0.05	0.2 ± 0.1



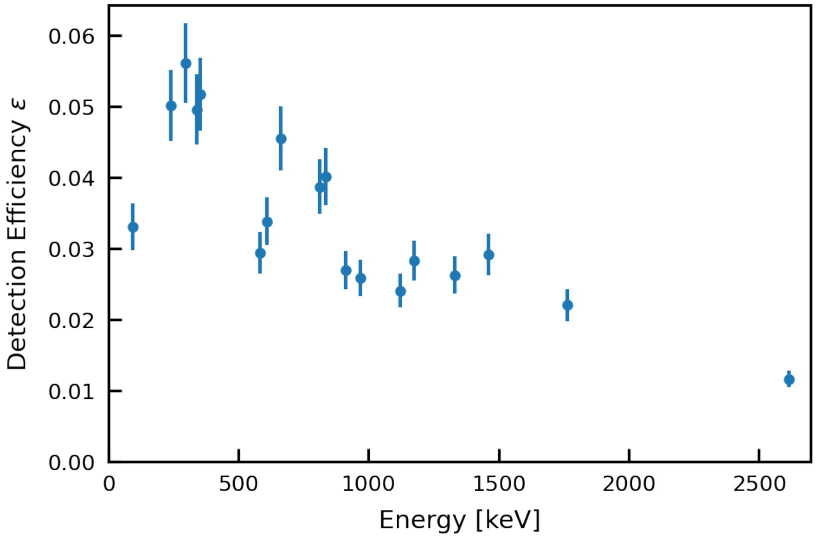
[2] JINST 6 (2011) P08010

Sample Simulation and Analysis

- Determination of the material-, geometry-, and energy-dependent detection efficiency ε of the respective γ-lines through GEANT4 Monte Carlo simulations for each sample



Simulated PMT stems on detector



Resulting detection efficiencies lines

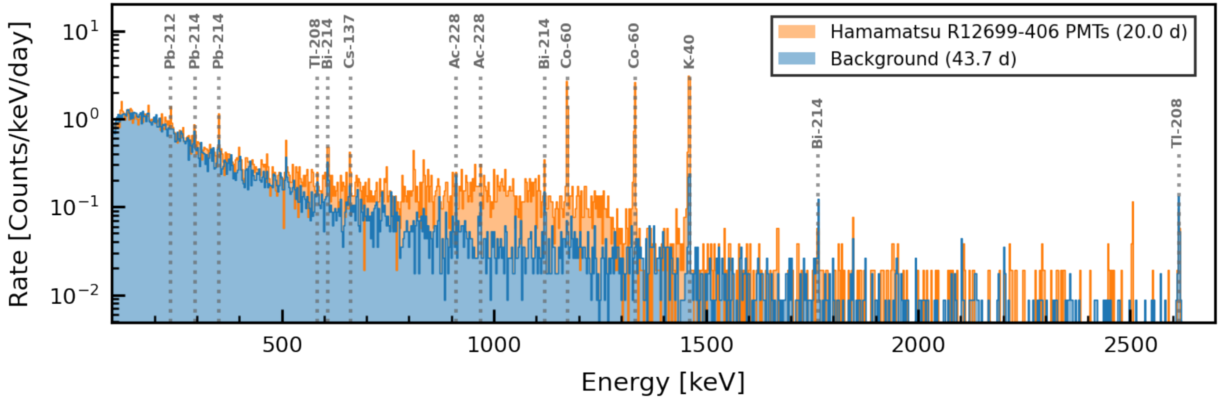
Sample Simulation and Analysis

- Calculation of the specific activities A from the background- and Compton-subtracted counts S_{net} at the location (±3σ) of the most prominent lines as

$$A = \frac{S_{net}}{r \cdot \varepsilon \cdot m \cdot t}$$

(branching ratio *r*, sample mass *m*, measuring time *t*)

- Combination to activities of isotopes / subchains (L_d @ ~95% C.L.)



$$S_{net} = S - B \cdot \frac{t_S}{t_B} - B_C$$

$$L_d = k^2 + 2 \cdot L_c$$
$$L_c = k \cdot \sigma_{net}$$

[6]

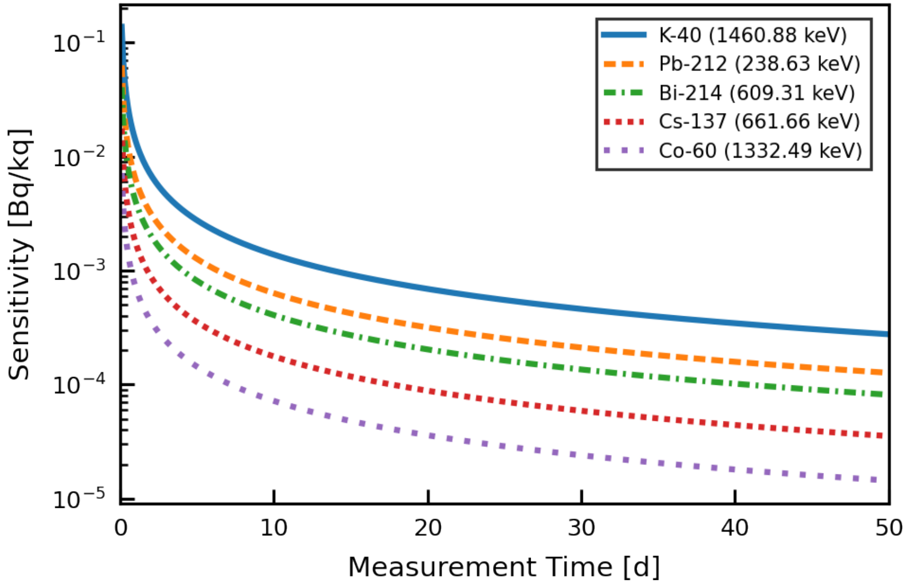
[6] Anal. Chem. 1968, 40, 3, 586–593

Sample Simulation and Analysis

- Isotopes / chains of interest:
  - primordial: ^{238}U, ^{232}Th, ^{40}K
  - cosmogenic: ^{54}Mn, ^{46}Sc, ^{60}Co,…
  - anthropogenic: ^{137}Cs, ^{110m}Ag,…

  ➔ decay products may mimic signals (e.g. NRs of neutrons from (α,n) reactions in XENON) or leak into the signal region

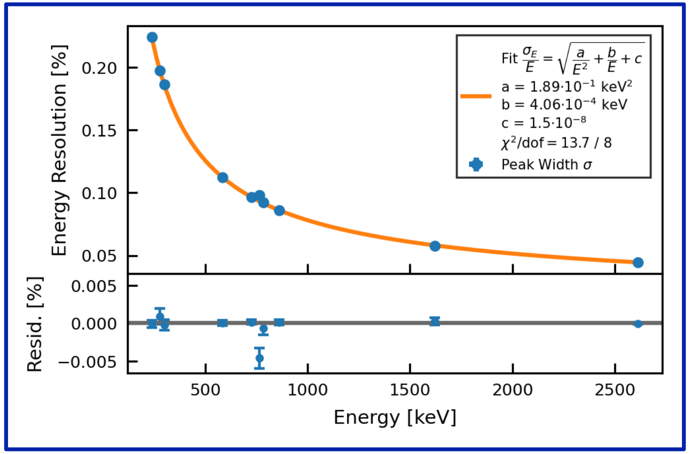
- Typical sensitivities: < a few mBq/kg for exposures of 1-3 weeks and several kg sample mass (a few μBq/kg for radio-pure samples, longer exposure & higher mass)

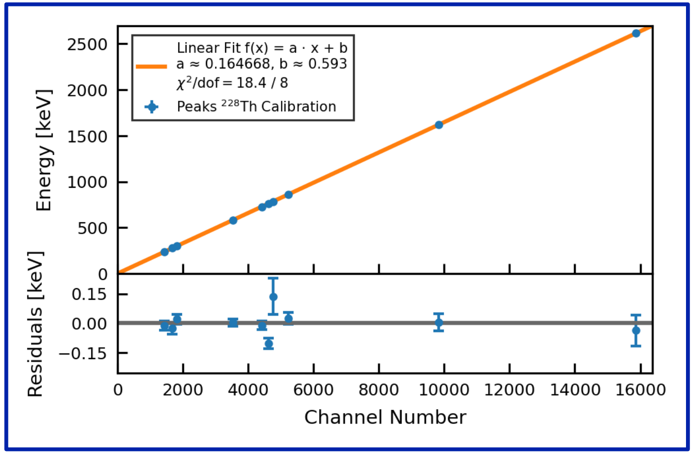


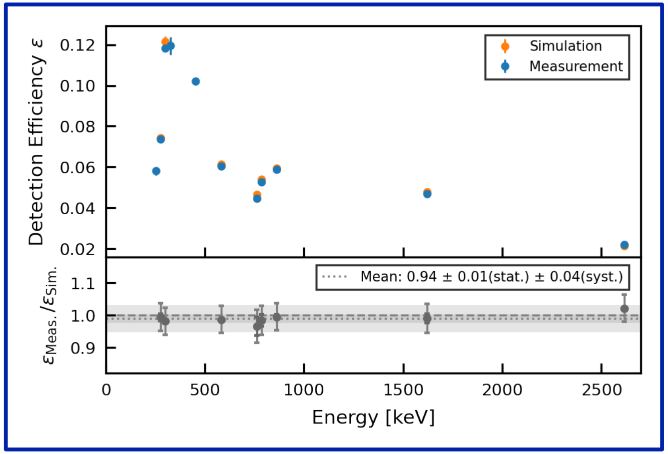
71.7 kg OFHC copper sample

Appendix

Th-228 Calibrations

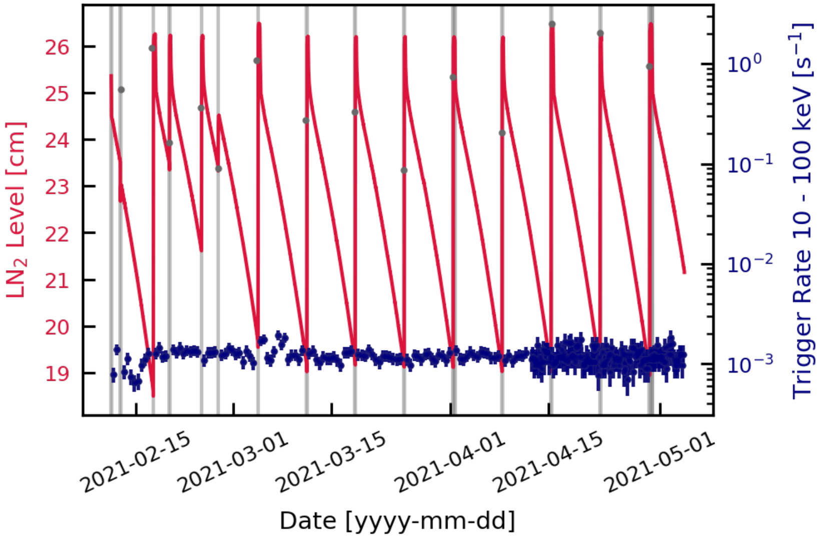


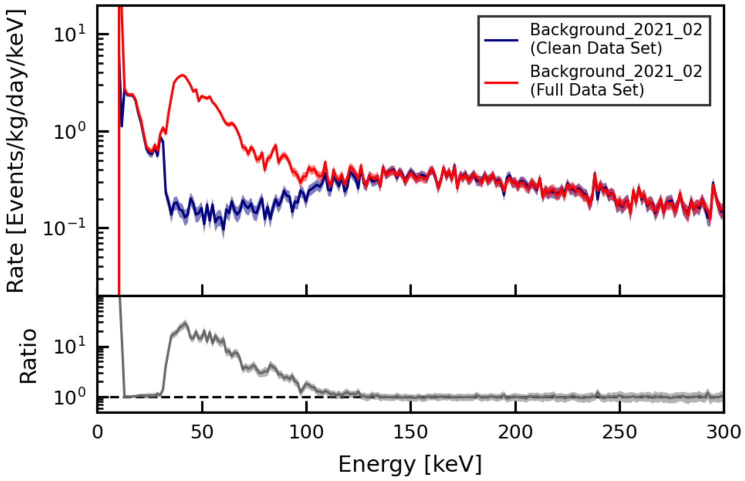




Reproducible Low-Energetic Noise

- Observed low-energetic electronic noise, temporally correlated with LN_2 dewar refills, that might leak into the ROI (going up to energies of up to ~ 150 keV)
- Unbiased removal of data based on derivative of LN_2 level reading





Example: Hamamatsu PMT R12699-406-M4

For isotopes where detection limit is exceeded, current (not yet optimized) prototype model has, per active photocathode area*,

- equal – threefold activities w.r.t. developed R11410 units [1]
- lower activity compared to the R8520 PMTs [5]

➔ Good potential for future improvements through material selection

* R12699 ~ 23.5 cm^2 , R11410 ~ 32.2 cm^2 , R8520 ~ 4.2 cm^2

Isotope	Hamamatsu R12699-406-M4	Hamamatsu R11410-21	Ratio R12699/ R11410	Hamamatsu R8520-06	Ratio R12699/ R8520-06
Activity [mBq/PMT]					
^{238}U	< 8.02	(8 ± 2)	–	< 15	–
^{226}Ra	(0.75 ± 0.19)	(0.6 ± 0.1)	(1.3 ± 0.4)	< 0.28	–
^{228}Ra	< 1.23	(0.7 ± 0.2)	–	< 0.59	–
^{228}Th	(0.54 ± 0.17)	(0.6 ± 0.1)	(0.9 ± 0.3)	(0.3 ± 0.1)	(1.8 ± 0.7)
^{235}U	< 0.37	(0.37 ± 0.09)	–	< 0.67	–
^{60}Co	(2.03 ± 0.19)	(0.84 ± 0.09)	(2.4 ± 0.3)	(0.60 ± 0.04)	(3.4 ± 0.4)
^{40}K	(26.2 ± 3.2)	(12 ± 2)	(2.2 ± 0.5)	(12.0 ± 0.8)	(2.2 ± 0.3)
^{137}Cs	(0.16 ± 0.05)	–	–	< 0.1	–
^{54}Mn	< 0.229	–	–	–	–
Activity [mBq/cm^2]					
^{238}U	< 0.341	(0.25 ± 0.06)	–	< 3.569	–
^{226}Ra	(0.032 ± 0.008)	(0.019 ± 0.003)	(1.7 ± 0.5)	< 0.067	–
^{228}Ra	< 0.052	(0.022 ± 0.006)	–	< 0.140	–
^{228}Th	(0.023 ± 0.007)	(0.019 ± 0.003)	(1.2 ± 0.4)	(0.071 ± 0.017)	(0.32 ± 0.13)
^{235}U	< 0.016	(0.012 ± 0.003)	–	< 0.159	–
^{60}Co	(0.086 ± 0.008)	(0.026 ± 0.003)	(3.3 ± 0.5)	(0.144 ± 0.010)	(0.60 ± 0.07)
^{40}K	(1.11 ± 0.14)	(0.37 ± 0.06)	(3.0 ± 0.6)	(2.86 ± 0.18)	(0.39 ± 0.05)
^{137}Cs	(0.007 ± 0.002)	–	–	< 0.024	–
^{54}Mn	< 0.010	–	–	–	–

[1] arXiv:1705.01828; [5] arXiv:1103.5831

References

[1] XENON collaboration, E. Aprile et al.,Material radioassay and selection for the XENON1T dark matter experiment, Eur. Phys. J. C77 (2017) 890

[2] L. Baudis et al.,Gator: a low-background counting facility at the Gran Sasso Underground Laboratory, JINST 6 (2011) P08010

[3] LZ collaboration, D. S. Akerib et al., The LUX-ZEPLIN (LZ) radioactivity and cleanliness control programs, Eur. Phys. J. C80 (2020) 1044

[4] Bandac, "Ultra-Low Background Services in the LSC." Talk a the DS-Mat Parallel meeting at GSSI, 2019

[5] E. Aprile et al., Material screening and selection for XENON100, Astropart. Phys.35 (2011) 43–49

[6] L. Currie, Limits of qualitative detection and quantitative determination, Analytical Chemistry, 1968, 40 (3), 586-593