Radiopurity and Screening for XLZD

Initial look at requirements & key challenges, informed by UK project work

XLZD Collaboration Meeting

LNGS 02/07/25

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Scaling-up challenges

- Longer run time → ~ factor 3
- Critical materials scale with length$^{2\text{-}4}$ → factor 4-8
- Some external backgrounds helped by improved self-shielding → low-energy gammas largely mitigated by this

Challenge is for background sources that are poorly fiducialised:

- Rn-emanation ← important for low-energy signals (DM, solar-ν)
- High-energy gammas ^{214}Bi and ^{208}Tl from U/Th decay chains ← important for 0νββ
- To some extent neutrons with longer scattering length

Logic for an initial estimate of radiopurity requirements

- Take high-level requirements from task force and use these to set top-level events/tonne/year (for a given energy range) for
  - **WIMP NR: 5-60 keVnr** ← 10% of Atm. CEvNS
  - **WIMP ER: 1.5-13.5 keVee** ← 40% of irreducible SolarPP + ^{136}Xe + ^{124}Xe
  - **High-energy: 0νββ [Q+/-1%: 2441.8–2473.8 keV]** ← 25% of LZ gamma flux
- Divide up into a budget for each sub-system
  - Division based on a “fair” share given contributions to LZ/XENONnT and known improvements for material/component radiopurity
  - Includes a 30% contingency factor given early stage of design
- Convert from events/tonne/year/ROI → material radiopurity requirements
  - For now, using simple scaling laws to project from LZ to XLZD background model
  - Then will switch to dedicated XLZD G4 simulations soon

Neutron backgrounds

- Atm. neutrinos 0.046 cts/tonne.year (*LNGS flux as most conservative case)*

2.5 cts/year (for 60t det. with 53.7t FV)

- Consider the TF background requirement of 10% of this:

Require total NRs material background < 0.25 NRs/year
(0.0046 cts/tonne.year)

- Coming from: material and dust alpha-n, TPC wall backgrounds

- ROI: 5-60 keVnr
  - Also: single scatter neutrons, same FV to-wall dist*ances as LZ (4 cm radial, 2 cm from cathode, 13.5 cm from gate: for 53.7 tonne FV), pass veto (assumes 95% veto efficiency)*

Alpha-n yields typical materials

Material	alpha-n yield U+Th [n/s/g/ppb]	1/ratio to PTFE
Titanium	4.7E-11	26.0
PTFE	1.2E-09	1.0
Aluminium	2.5E-10	4.8
PEEK	2.3E-11	53.3
QUARTZ, SiO2	2.3E-11	53.3
STAINLESS STEEL	1.1E-11	114.3
KOVAR	6.4E-12	189.8
CERAMIC	1.2E-10	9.8
COPPER	1.3E-12	954.1
CIRLEX (Kapton)	2.8E-11	44.0
ACRYLIC	1.8E-11	67.7
Borosilicate glass	2.1E-10	5.8

Neutron backgrounds – alpha-n fixed contamination

Alpha-n from bulk U/Th in detector materials:

Component	Scale factor LZ to XLZD	cts/year with LZ radiopurity	Example neutron flux reduction	XLZD [cts/year]	Relative contribution [%]
Top TPC Array	7.4	0.09	25%	0.021	27%
Bottom TPC Array	7.77	0.09	25%	0.022	29%
Cryostats (ICV)	6.53	0.01	25%	0.003	3%
Cryostats (OCV)	5.47	0.01	25%	0.004	4%
Field cage	6.82	0.08	25%	0.021	27%
Skin	3.5	0.03	25%	0.007	10%
OD (Scintillator)	11.68	0.00	100%	0.00	0%
OD (PMTs + Other)	2.83	0.00	100%	0.00	0%
All Components		0.31		0.08	

Even with factor 4 reduction in neutron flux (radiopurity/material choice) use 30% of total budget.

Neutron backgrounds – now include plate-out and dust

Plate-out of Rn222 daughters:

- Consider different plate-out requirements for detector regions/materials
  - High target: 10 mBq/m (all else)
  - Middle target: 2 mBq/m (other such as Ti vessel)
  - Low target: 0.25 mBq/m2 (PTFE fieldcage)
  - *c.f. LZ target of 0.5 mBq/m2 for PTFE fieldcage (10 mBq all else)*

- Scale LZ model to XLZD based on surface area scaling:
  0.015 NR cts/year

Dust: alpha-n from intrinsic contamination

- Also include alpha-n from dust itself (assumes* 200 ng/cm2): 0.22 NR cts/year

- *Depends on many assumptions – may need stricter requirement 100 ng /cm2 c.f. LZ achieved 214 ng/cm2*

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  - *c.f. LZ target of 0.5 mBq/m2 for PT*
- Scale LZ model to XLZD based on surf
  0.015 NR cts/year

Plate-out requirements	Ambient radon level in lab	Exposure time to requirement*
10 mBq/m2	0.3 mBq/m3	~1.5 years
2 mBq/m2	0.3 mBq/m3	~4 months
0.25 mBq/m2	0.05 mBq/m3	~3 months

* worst case static "dead air" model

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Neutron backgrounds – now include plate-out and dust

Plate-out of Rn222 daught

- Consider different plate ... terials
  - High target: 10 m
  - Middle target: 2 m
  - Low target: 0.25 n
  - *c.f. LZ target of 0.5*

- Scale LZ model to XLZD
  0.015 NR cts/year

Dust: alpha-n from intrins

- Also include alpha-n fro ... 22 NR cts/year

- *Depends on many assumptions – may need stricter requirement 100 ng /cm2 c.f. LZ achieved 214 ng/cm2*

Summary of all NR sources

Source	NR counts/Year
(alpha,n)	0.08
Plate-out	0.015
Pb206 wall BG	0.1
Dust	0.11
Total	**0.3**
Fraction of 10% Atm. [LNGS flux]	121%
Fraction of 10% Atm. [Boulby/SURF flux]	92%

Gammas from material background

- In WIMP low-energy ROI:
  - 1.5-13.5 keVee
  - Even with no improvements to radiopurity the projected ER counts from gammas < 10% of SolarPP + 136Xe
  - Does not drive requirements
- As we saw in Alex Lindote's talk, gamma flux requirement driven by 0vBB
  - Baseline requires the gamma flux to be reduced to 25% of current. This is the main challenge
  - See table from 0vBB sensitivity paper showing required reduction
- This is baseline -> we plan to do better
  - Any reduction directly impacts 0vBB sensitivity/discovery potential
  - Material search: screening requirements (< 10 uBq/kg)
  - Impacts on design choices

XLZD 0νββ sensitivity paper: A. Lindote

	^{214}Bi events		
	LZ (967 kg × 1000 d)		XLZD (8.2 t × 10 yr)
Component	Nominal	Reduced	Projected
TPC PMTs	2.95	0.98	0.61
PMT structures	2.75	0.54	0.33
Field-cage resistors	2.46	0	0
Internal sensors	1.81	0.22	0.14
PMT bases	1.52	0.39	0.24
Cryostat	1.26	0.82	0.51
PMT cables	1.01	0.16	0.10
Field-cage rings	0.97	0.40	0.25
OD tank supports	0.73	0	0
OD foam	0.71	0	0
Skin PMTs	0.69	0.06	0.04
Other skin parts	0.68	0.05	0.03
Other components	3.56	1.42	0.88
Total	21.10	5.05	3.15

Overall reduction of gamma flux to 25% of the LZ model

Radon emanation

- 0.1 uBq/kg translates to 7.8 mBq* total in the Xe payload (78 tonnes from design book)
  - Gives 6 cts/t.y c.f. which is < 20% of solar PP (32.3 cts/t.y)
- Partition this based on LZ "best estimate" of emitters (1.8 uBq/kg, 17.6 mBq)
- Work out reductions for each sub-system required to get to 7.8 mBq
- Translate to required material emanation rates/unit area
- Do not taken credit for radon analysis veto **NOR** online distillation/purification ← would loosen emanation requirements by ~2-4
- This assumes a more aggressive Kr85 requirement (<50 ppq)

* *emanation/unit area helped by factor ~2 reduction from volume/surface as $2^3/2^2$*

Radon emanation

Subsystem	LZ "best estimate"	Example XLZD rate [mBq]
Cryostat	2.6 mBq (15%)	2.7 mBq (35%)
PMT systems*	3.7 mBq (21%)	3.5 mBq (45%)
Xenon circulation systems	9.9 mBq (56%)	0.4 mBq (5%)
Dust**	1.6 mBq (6%)	1.2 mBq (15%)
Total	17.6 mBq	7.8 mBq

** 3" PMTs (1.8 mBq) + bases (1.1 mBq) + other PMT/supports/cables (0.72 mBq)*

*** assumes 15% warm to cold suppression*

Except for circulation, total mBq per sub-system ~constant
→ minimum factor 4 scale-up in area → require at least ~4 reduction in material emanation per unit area

Radon emanation from dust

Radon emanation also drives the requirement on amount of dust on detector components.

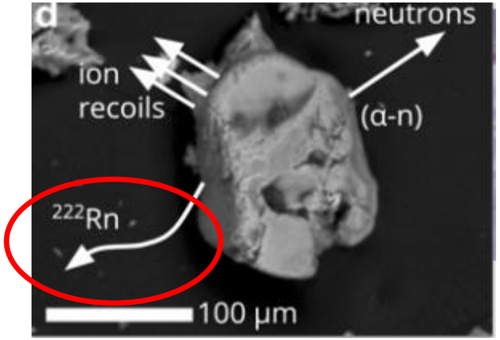
For radon emanation from dust to make up half of the total radon budget then dust on internal detector components, needs to be kept below 200 ng/cm² (LZ achieved 214 ng/cm²). This corresponds to ~0.9 g of dust over 450 m² of surface area.

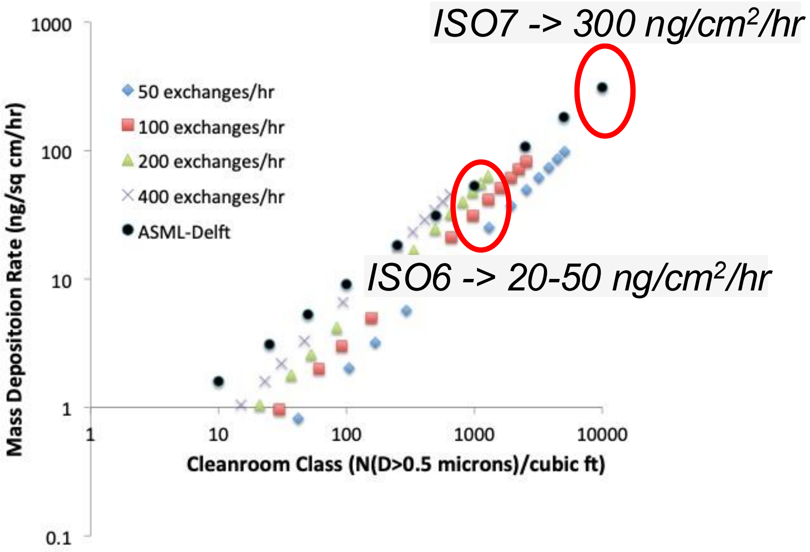
*This **applies to all components inside the ICV <u>including the inner surface of the ICV + xenon handling</u>**.*

This depends on emanation rate from dust, total surface area assumed.

Determines exposure times for parts: days in ISO6, < 1 hr in ISO7

Caveats: very different deposition rates for triboelectric materials (PTFE!), dust carry in rate a key variable, emenation from dust (LZ saw only 14% warm, 4% cold --> loosens above requirements)





Dust deposition rates from LZ technical note "Dust Deposition and Radon Plate-out Calculators" J. Busenitz, J. Dobson

Summary of key radiopurity/cleanliness challenges

- $0\nu\beta\beta$ drives bulk gamma (late chain U/Th) drive bulk radiopurity requirements
  - Getting to 25% of current LZ gamma flux is challenging but there is a path
  - Directly impacts discovery potential -> motivates an ambitious goal (10%?)
  - **High-level requirement on a par with WIMP-search -> has to feed into every aspect of design and material selection**

- Neutrons for low-energy WIMPs still challenging – requires~ factor 4 reduction in material neutron emission to get to 10% of Atm. CEvNs. N.B. here we assumed a 95% veto efficiency.

- Surface contamination
  - Radon plate-out key for PTFE internals (0.25 mBq/m2 factor 2 below LZ)
  - Dust at less than at ~0.5 g but with larger surface area (200 -> 100 nBq/cm2 factor 2 below LZ)

A cross calibration screening campaign (A. Stevens' Uni Freiburg)

- Much screening coming up. Understanding sensitivity and any systematics between sites is critical
- Effort to cross-calibrate SURF, Alabama, LNGS, Gator, GeMSE, Heidelberg and Boulby screening assets --> please contact Andrew if you are missing!
- Range of samples being circulated to screening site
  - Testing large signal, low-signal and complex geometry
- Radon samples 226Ra implanted into steel plate as Rn-source (H. Simgen, MPIK)

Aluminum blocks

TML rock sample

PMT stems

A cross calibration screening campaign (A. Stevens' Uni Freiburg)

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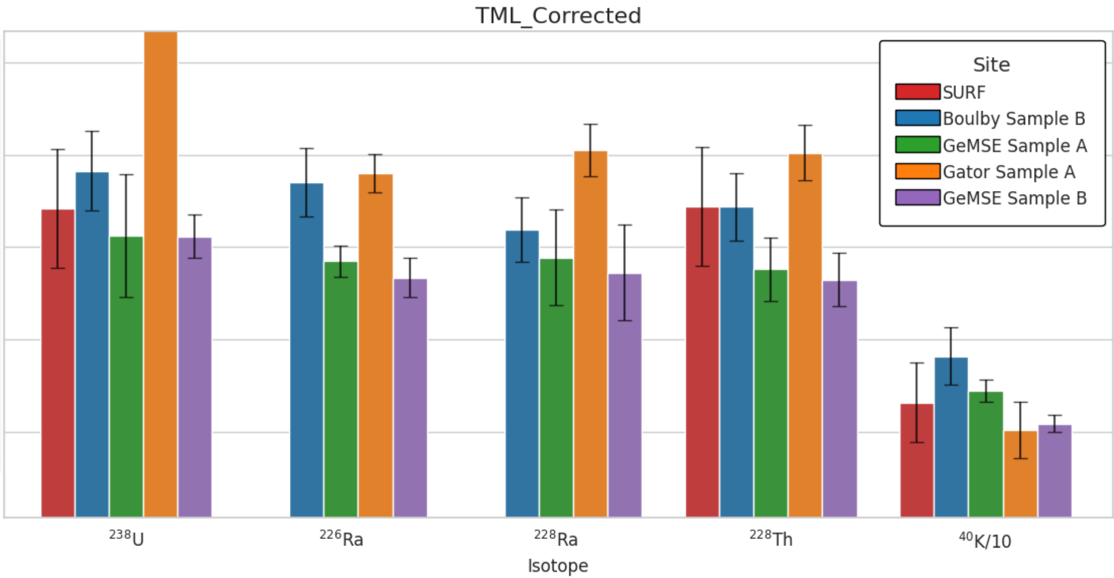

MT stems