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R&D Towards Next Generation Dark Matter Experiment at Boulby

Abstract

Rare event experiments, such as those targeting dark matter interactions and neutrinoless double beta (0νββ) decay, should be shielded from ɣ-rays originating in rock. This poster presents the simulation of gamma-ray transport through water shielding and assessment of the water thickness needed to suppress the background from rock down to a negligible level. The simulation studies the effectiveness of water shielding around a detector, focusing on the Weakly Interacting Massive Particle (WIMP) energy range (0 – 20 keV) and the region of interest (ROI) around the 0νββ decay Q-value (2.458 MeV). This poster also presents the measurements of radioactivity of rock in the Boulby mine that is a potential site for a future dark matter experiment. The measurements are used to normalise simulation results in assessing the required shielding at Boulby.

Simulation geometry

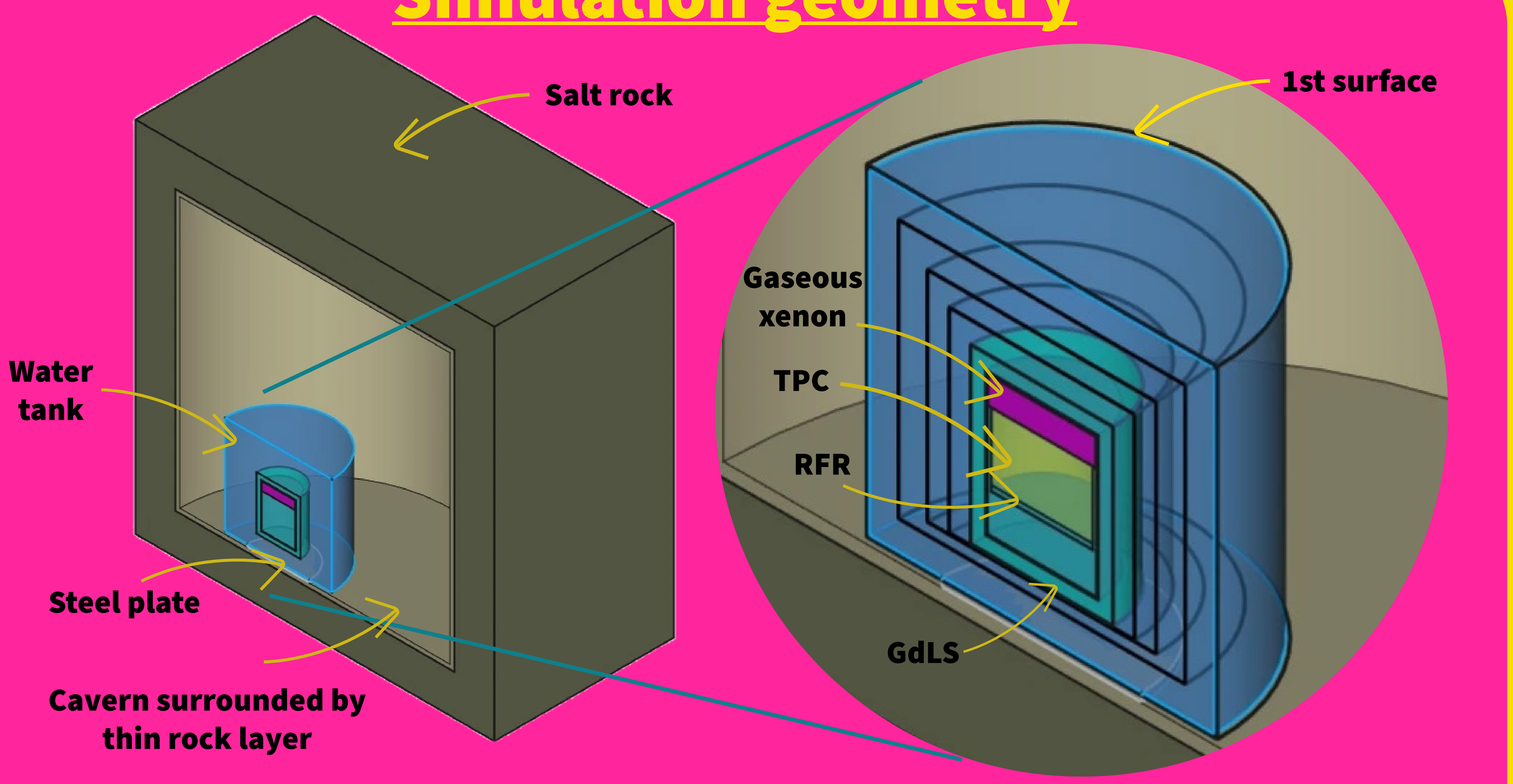


Figure 1: The GEANT4 [1] simulation generates ɣ-rays in a 0.5 m thick layer of rock surrounding a large, cylindrical cavern and transports them towards the TPC. They are stopped at each of the concentric surfaces before being propagated again towards the next surface in increased numbers.

Key:

- TPC = time projection chamber
- RFR = reverse field region
- GdLS = Gd liquid scintillator

Geometry features:

- Dual-phase TPC with 71 tonne LXe target.
- 3.5 m water shielding on top and sides.
- 1.5 m water shielding plus 30 cm thick steel plate below the detector.
- Water tank and detector sits in a 30 x 30 m cylindrical cavern.

Flux attenuation

This biasing method allows us to boost statistics by enlarging the total number of ɣ-rays generated from ^{208}Tl, ^{232}Th, ^{235}U and ^{40}K. The energy, position and momentum direction are recorded at each surface.

The decay rate of each parent radionuclide and the flux at each surface was normalised to 1 Bq/kg.

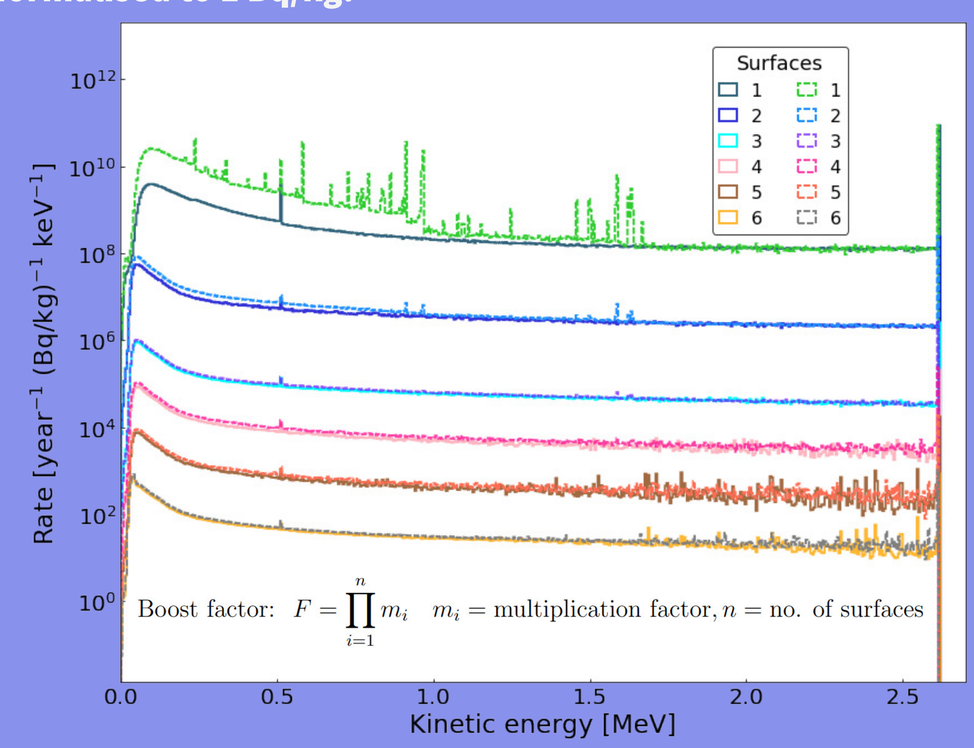


Figure 2: Gamma-ray energy spectra from ^{208}Tl (solid line) and ^{232}Th dashed line) at each surface from the outside of the water tank and in stages throughout until reaching the outside of the TPC. By the time the ɣ-rays reach the TPC, only those originating from the ^{208}Tl decay survive.

The final stage of the simulation propagates the ɣ-rays from the final (6th) surface. We collect data from every particle that deposits more than 0.1 keV of energy in the skin, TPC, and GdLS. These particles primarily include electrons and ɣ-rays, with the occasional positron.

Analysis and results

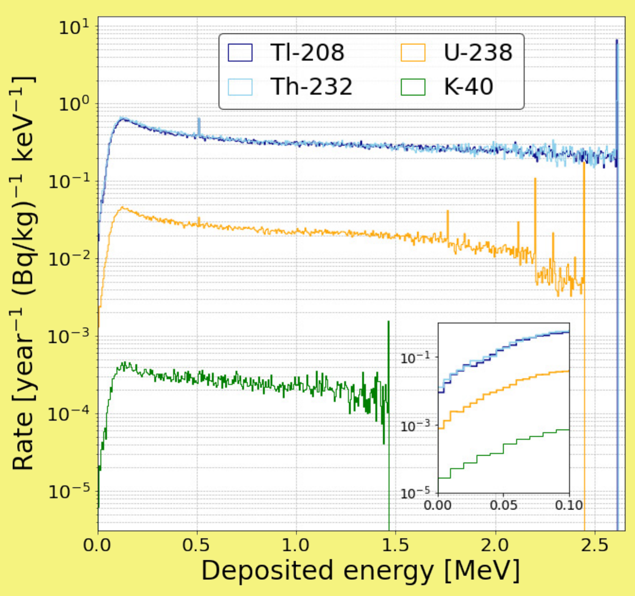
Analysis cuts to suppress background events:

- 200 keV threshold in the GdLS & 100 keV threshold in the skin to avoid false vetoes from other decays.
- Multiple scatter cuts $\sigma_R < 5$ cm and $\sigma_z < 0.5$ cm
- Fiducial volume cut -123 < Z < 113 cm, radius < 170 cm

$$\sigma_r = \sqrt{\frac{\sum_{i=1}^{N} w_i((x_i-\bar{x})^2+(y_i-\bar{y})^2)}{\sum_{i=1}^{N} w_i}}$$

$$\sigma_z = \sqrt{\frac{\sum_{i=1}^{N} w_i(z_i-\bar{z})^2}{\sum_{i=1}^{N} w_i}}$$

N = no. of entries in x_i
w_i = array of weights
x_i = array of data
$\bar{x}$ = weighted mean of array



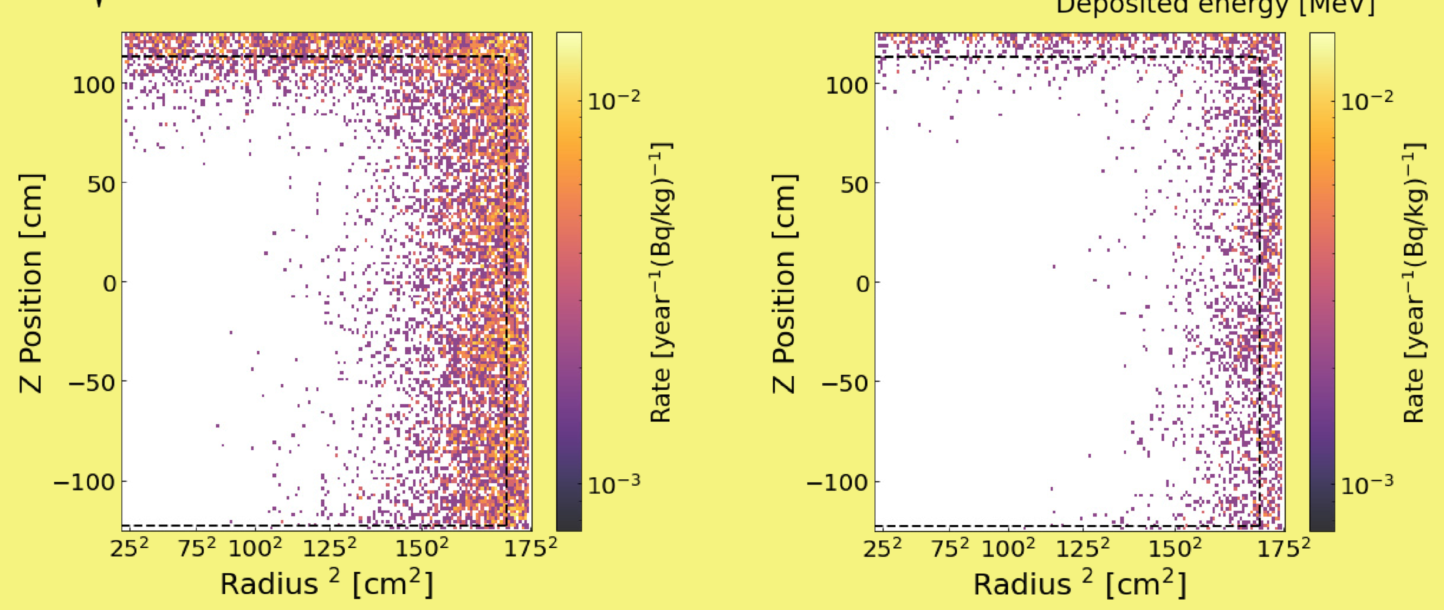


Figure 3. Top: Deposited energy of all events in the TPC. Bottom: Radial plots of the mean position of events from ^{232}Th decay in the TPC within the energy range 2.408 - 2.508 MeV (± 2 σ around the 0νββ decay Q-value) [left] before and [right] after multiple-scatter cuts have been applied. The dotted black line outlines the fiducial volume boundaries.

	0 - 20 keV		0 - 100 keV		2408 - 2508 keV	
Isotope	Events	Rate [year^{-1} (Bq/kg)$^{-1}$]	Events	Rate [year^{-1} (Bq/kg)$^{-1}$]	Events	Rate [year^{-1} (Bq/kg)$^{-1}$]
^{208}Tl	$1^{+1.75}_{-0.63}$	$(1.9^{+3.3}_{-1.2}) \times 10^{-3}$	$9^{+3.79}_{-2.67}$	$(1.7^{+0.7}_{-0.5}) \times 10^{-2}$	1593 ± 40	3.01 ± 0.08
^{232}Th	$2^{+2.25}_{-1.26}$	$(3.8^{+4.3}_{-2.4}) \times 10^{-3}$	$8^{+3.32}_{-2.7}$	$(1.5^{+0.6}_{-0.5}) \times 10^{-2}$	1579 ± 40	3.02 ± 0.08
^{238}U	$0^{+2.44}_{-0}$	$0^{+0.0007}_{-0}$	$2^{+2.25}_{-1.26}$	$(6.0^{+7.0}_{-4.0}) \times 10^{-4}$	633 ± 25	0.186 ± 0.074
^{40}K	$0^{+2.44}_{-0}$	$0^{+0.00004}_{-0}$	$0^{+2.44}_{-0}$	$0^{+0.00004}_{-0}$	n/a	n/a

Table 1. These results represent rates of events in the TPC for 1 Bq/kg each of ^{238}U, ^{232}Th and ^{40}K, with all analysis cuts applied. For WIMP search we need < 1 event per year and for 0νββ decay we need < 0.1 events per year.

Boulby Mine gamma-ray background

- Boulby (fig.4) is the deepest mine in England at a depth of 1.1 km and houses many experiments spanning multiple scientific disciplines.
- Potential location for the next-generation dark matter detector to be built in the layer of polyhalite (1300 m below sea level).
- Polyhalite is high in ^{40}K, but low in ^{238}U and ^{232}Th.
- Rock samples have been screened for radioactivity in the Boulby UnderGround Screening (BUGS) facility (fig.5), a class 1000 cleanroom which houses multiple high-purity Ge (HPGe) detectors.
- The radioactivity from these calculations has been used to normalise the main simulation to give an accurate assessment of the background levels in the new laboratory.

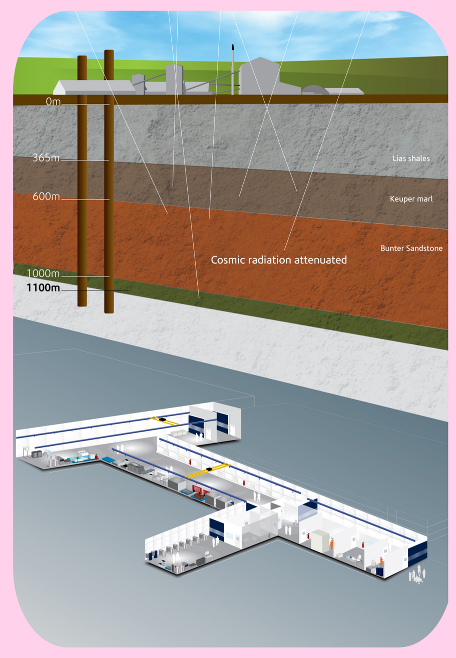


Figure 4. CAD image of Boulby Underground Laboratory, credit: BUL.

Isotope	0 - 20 keV Rate [year^{-1}]	0 - 100 keV Rate [year^{-1}]	2408 - 2508 keV Rate [year^{-1}]
^{232}Th	$(5.7^{+6.4}_{-3.6}) \times 10^{-5}$	$(2.3^{+1.0}_{-0.8}) \times 10^{-4}$	0.045 ± 0.011
^{238}U	$0^{+0.0003}_{-0}$	$(2.5^{+2.8}_{-1.6}) \times 10^{-4}$	0.078 ± 0.003
^{40}K	$0^{+0.1}_{-0}$	$0^{+0.1}_{-0}$	n/a

Table 2. Rates of events in the TPC with analysis cuts applied, normalised to measurements of polyhalite from Boulby mine.

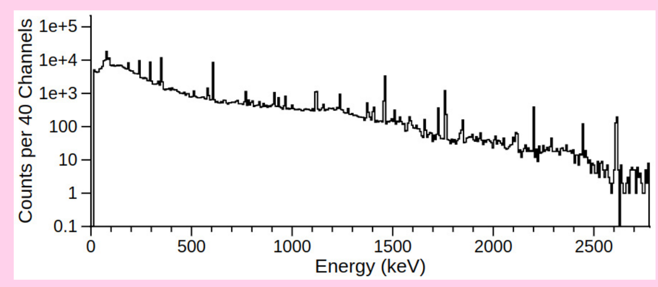


Figure 6. Left: A sample on Chaloner, a HPGe detector. Right: Example energy spectrum of a rock sample as measured by Chaloner.

Figure 5. HPGe detectors in BUGS. Credit: T. Palin.

Conclusions

- The simulation demonstrates that for 1 Bq/kg, the shielding is sufficient for WIMP search, but a smaller fiducial volume (FV) is needed for 0νββ decay.
- Reducing the shielding by 1 m will increase the rate by a factor of 80.9 and 111.9 for Th and U respectively, which, at 1 Bq/kg, are still within sensitivity limits for WIMP search. However, for low enough rates in the 0νββ decay ROI, the FV would need to be reduced from ~ 63 t to ~ 12 t.
- If a future detector were to come to Boulby, the shielding is sufficient for WIMP search and 0νββ decay, but this takes only ɣ-rays from the cavern into account (and neutrons from the rock as they are more easily attenuated), not ɣ-rays from detector materials.

Acknowledgements

We would like to thank STFC for financial support and the ICL Mining Company for access to Boulby mine, their rock samples and two of their very knowledgeable geologists, P. Edey and D. Webb, who provided me with materials to understand the geology of Boulby. We would also like to thank V. Pec for original GEANT4 source code and the whole team from the Boulby Underground Laboratory.

References

[1] S. Agostinelli et al, Nucl.Instrum.Meth., 2003, 506, pp250-303, 10.1016/S0168-9002(03)01368-8