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UKRI Science and Technology Facilities Council

Boulby Underground Laboratory

R&D Towards Next Generation Dark Matter Experiment at Boulby

Simulation Geometry

Rare event experiments, such as those targeting dark matter interactions and neutrinoless double beta (0νββ) decay, should be shielded from gamma 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 (2458 ± 50 keV). 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 to assess the required shielding at Boulby.

Simulation Geometry

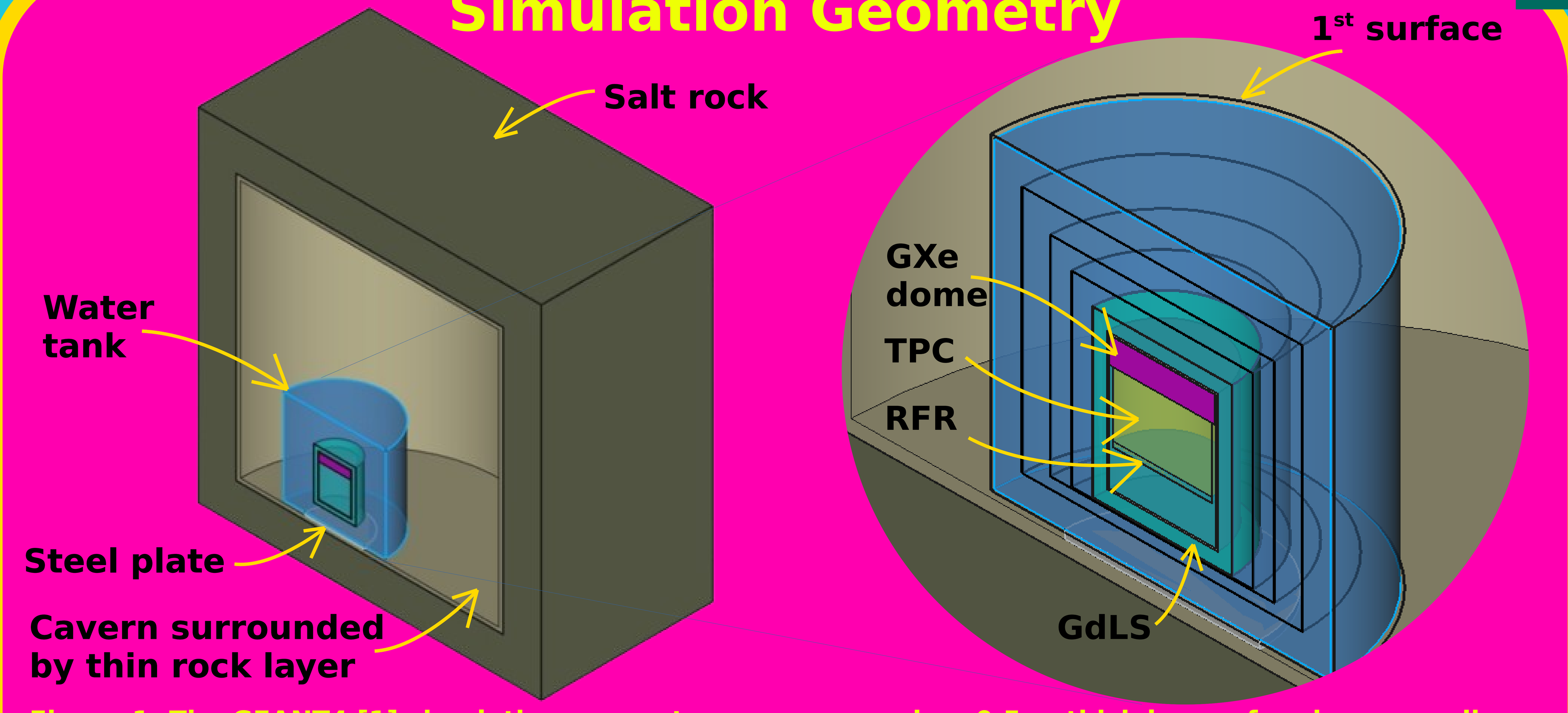

Figure 1: The GEANT4 [1] simulation generates gamma rays in a 0.5 m thick layer of rock surrounding a large, cylindrical cavern and transports them towards the TPC. They are stopped at each of the surfaces before being re-propagated towards the next surface in increased numbers. The simulation's geometry is similar to that described in Ref. [2].

Key:
- TPC = time projection chamber
- RFR = reverse field region
- GdLS = Gd liquid scintillator
- 1st surface = first of multiple surfaces layered concentrically throughout the shielding

Geometry features:
- Water tank and detector sits in a 30 x 30 m cylindrical cavern.
- Dual-phase TPC with 71 tonne LXe target.
- 3.5 m water shielding on top and sides of the detector.
- 1.5 m water shielding + 30 cm thick steel plate below the detector.
- 0.5 m of Gd-loaded liquid scintillator surrounding the TPC on all sides.

Flux through the shielding

- This biasing method allows us to boost statistics by enlarging the total number of gamma rays generated from ^{208}Tl, ^{232}Th, ^{238}U and ^{40}K.
- Energy, position and momentum direction are recorded at each surface.
- Decay rate of each parent radionuclide was set as 1 Bq/kg.

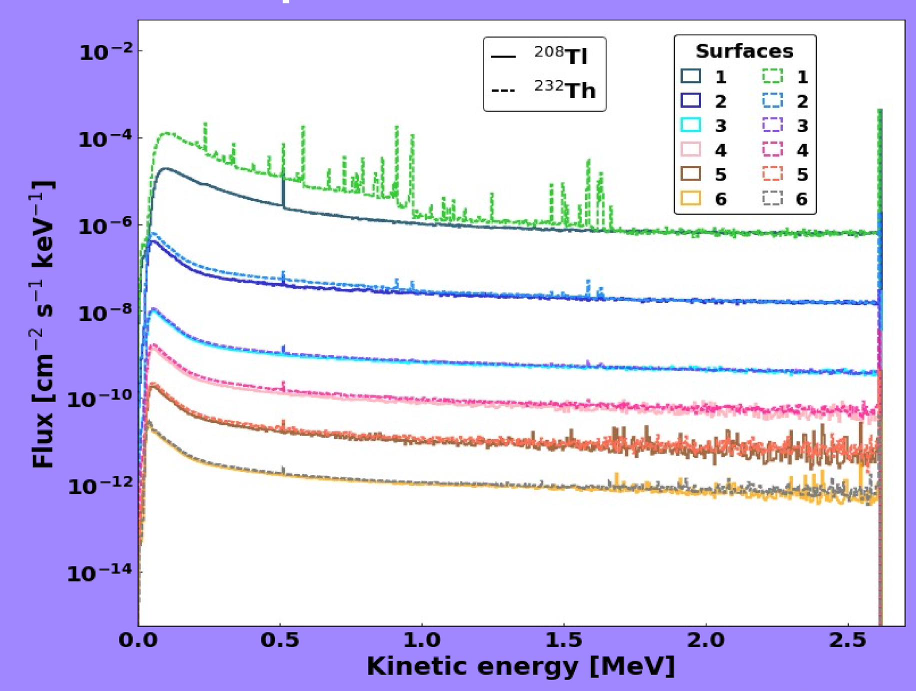

Figure 2: Gamma-ray energy spectra from ^{208}Tl and ^{232}Th at each surface from the outside of the water tank and in stages throughout until reaching the outside of the TPC. By the time the gamma rays reach the TPC, only those originating from the 208 Tl decay survive.

The final stage of the simulation propagates the gamma rays from the final surface. Data is stored from every particle (mostly electrons, with the odd positron) that deposits > 0.1 keV of energy in the skin, TPC, and GdLS.

Analysis and results

Analysis cuts to suppress background events:

- Coincident gammas depositing energy in above a 200 keV threshold in the GdLS and a 100 keV threshold in the skin are rejected (thresholds are set to avoid false vetoes from other decays).
- Multiple scatter cuts: energy-weighted standard deviation: σ_r < 5 cm and σ_z < 0.5 cm
- Fiducial volumes (FVs) of LXe:
  - WIMP ROI: -123 cm < z < 113 cm, r < 170 cm
  - ^{232}Th 0νββ: -115 cm < z < 101 cm, r < 141 cm
  - ^{238}U 0νββ: -122 cm < z < 110 cm, r < 165.5 cm

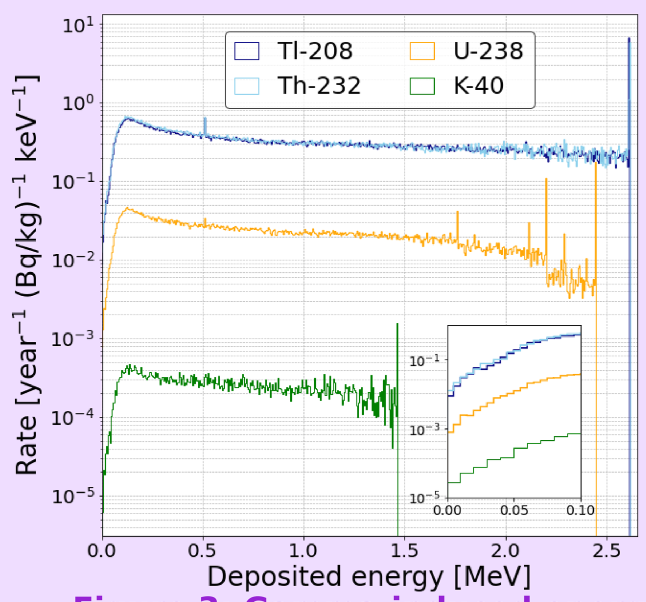

Figure 3: Gamma-induced energy deposits in the TPC before cuts.

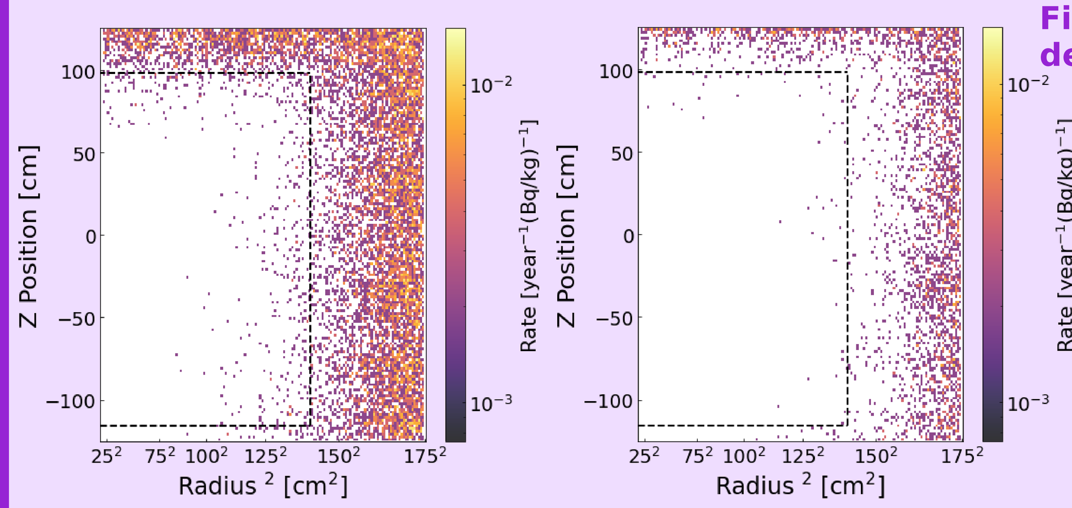

Figure 4: Radial plots of the mean position of events from the ^{232}Th decay chain in the TPC in the 0νββ ROI.

The plots in Fig. 4 are made before (left) and (after) multiple-scatter cuts have been applied. The dotted black line outlines the FV that will need to be in place for 0νββ decay background sensitivity.

This analysis has been done for each of ^{208}Tl, ^{232}Th, ^{238}U and ^{40}K with in the WIMP and 0νββ ROIs.

	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	$1^{+1.75}_{-0.63}$	$(1.9^{+3.3}_{-1.2})\times10^{-3}$	$9^{+3.79}_{-2.67}$	$(1.7^{+0.72}_{-0.51})\times10^{-2}$	56 ± 7.5	0.106 ± 0.014
^{232}Th	$2^{+2.25}_{-1.26}$	$(3.8^{+4.3}_{-2.4})\times10^{-3}$	$8^{+3.32}_{-2.70}$	$(1.53^{+0.64}_{-0.52})\times10^{-2}$	52 ± 7.2	0.100 ± 0.014
^{238}U	$0^{+2.44}_{-0}$	$(0^{+2.9}_{-0})\times10^{-4}$	$7^{+3.30}_{-2.75}$	$(8.3^{+3.8}_{-3.2})\times10^{-4}$	793 ± 28	$(9.35 \pm 0.33)\times10^{-2}$
^{40}K	$0^{+2.44}_{-0}$	$(0^{+3.8}_{-0})\times10^{-5}$	$0^{+2.44}_{-0}$	$(0^{+3.8}_{-0})\times10^{-5}$	n/a	n/a

Table 1: Background events in the TPC with the analysis cuts applied. The 0 – 100 keV covers an extended range of energies of interest for WIMP-nucleon effective field theory couplings [3].

Boulby Mine gamma-ray background

- Boulby Mine 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 a layer of polyhalite, 1300 m below sea level.
- 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 results been used to normalise the GEANT4 simulation to give an accurate assessment of the background levels in the new laboratory.

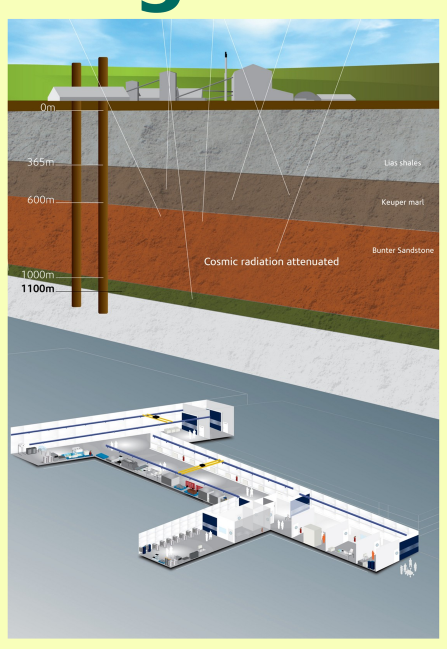

Figure 4. CAD image of Boulby Underground Laboratory, credit: BUL

	0 – 20 keV	0 – 100 keV	2408 – 2508 keV
Isotope	Rate [year^{-1}]	Rate [year^{-1}]	Rate [year^{-1}]
^{232}Th	$(4.3^{+4.9}_{-2.7})\times10^{-5}$	$(1.74^{+0.73}_{-0.59})\times10^{-4}$	$(1.14 \pm 0.37)\times10^{-3}$
^{238}U	$(0^{+1.0}_{-0})\times10^{-4}$	$(3.0^{+1.4}_{-1.1})\times10^{-4}$	$(1.14 \pm 0.37)\times10^{-3}$
^{40}K	$(0^{+9.5}_{-0})\times10^{-2}$	$(0^{+9.5}_{-0})\times10^{-2}$	n/a

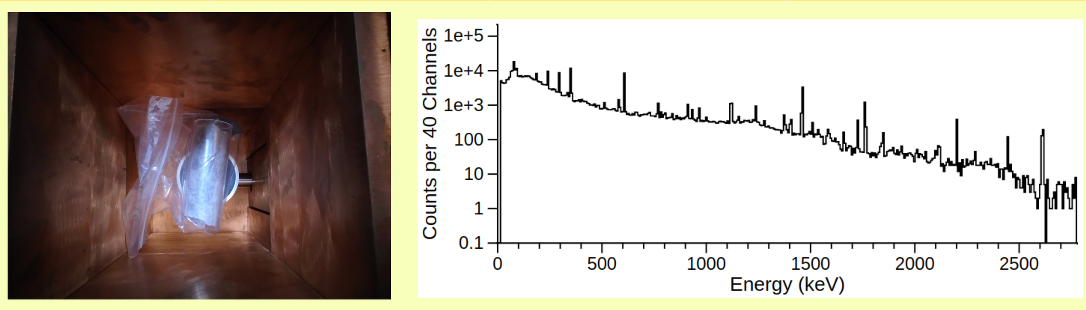

Figure 6. Left: A sample on Chaloner, a HPGe detector. Right: Energy spectrum as measured by Chaloner

Figure 5. Photo of HPGe detectors in BUGS, credit: T. Palin

Conclusions

- To shield the next-generation dark matter detector from the surrounding rock's gamma-ray and neutron background, 4 m of water and GdLS shielding on the top and sides, and 2 m on the bottom with a steel plate base, has been shown to be sufficient for WIMP search and 0νββ decay detection, based on a full GEANT4 Monte Carlo simulation.
- In the WIMP search ROI, 0 - 20 keV, ^{40}K, ^{238}U and ^{232}Th each contribute << 1 event per year to the background, assuming their activity of 1 Bq kg-1. Similarly, there was < 1 event per 10 years in the 0νββ ROI, 2408 – 2508 keV, from ^{238}U and ^{232}Th.
- We estimate that a reduction in water shielding of 1 m from all sides would be feasible as the simulated results in the WIMP ROI are sufficiently low. However, the FV for 0νββ decay will need to be reduced further to accommodate this.
- The polyhalite in Boulby, although high in ^{40}K, is low in both ^{238}U and ^{232}Th which makes the location a suitable site for a high-sensitivity dark matter experiment.

Acknowledgements

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References

[1] S. Agostinelli et al., Geant4 - a simulation toolkit, Nucl. Instr. Meth. A 506 (3) (2003) 250–303. doi:10.1016/S0168-9002(03)01368-8.

[2] V. Pěč, V. A. Kudryavtsev, H. M. Araújo and T. J. Sumner, Muon-induced background in a next-generation dark matter experiment based on liquid xenon, Eur. Phys. J. C 125 (2024). doi:10.1140/epjc/s10052-024-12768-9

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