Muon-induced background in a next-generation dark matter experiment based on liquid xenon

Viktor Pěč¹, Vitaly Kudryavtsev² and Boulby Feasibility Study Working Group

¹ FZU – Institute of Physics of the Czech Academy of Sciences (previously at University of Sheffield), viktor.pec@fzu.cz
²University of Sheffield

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Motivation

Search for dark matter

- Many operational experiments search for WIMP-like DM
- No signs yet \rightarrow **new generation** of experiments with increased sensitivity
- Multiple technologies exist (liquid noble gase TPC, cryogenic bolometers,...)
- This work aimed at dual phase xenon TPC
- Focus on cosmogenic background
- Key question: Is depth of about 3 km w.e. sufficient for the next generation (G3) dark matter experiment?



Boulby mine model case

- Work part of feasibility study for next generation DM experiment at Boulby mine Funded by UKRI-STFC
- Two locations considered at currently used level and at deeper level (different rock)
- Results relevant to sites of similar depth

Simulation of cosmic muons

Geometry based on LZ design

- LZ scaled up to 71 tonne active LXe
- Water shield, liquid scintillator, two-phase Xe TPC with LXe skin



Cavern



Detector



TPC



Depth/overburden



 Red line calculated for flat overburden and standard rock (Z = 11, A = 22)



Muons

As generated



- MUSUN/MUSIC [*]
- Flat overburden
- Uniform rock composition
- Calculated flux: 2850 m w.e., NaCl: $3.75 \times 10^{-8} \text{ cm}^{-2} \text{s}^{-1}$ 3575 m w.e., polyhalite: $1.13 \times 10^{-8} \text{ cm}^{-2} \text{s}^{-1}$
- Approximation same distributions for both depths
- Mean energy: 261 GeV
- Mean zenith: 30.6°

* Comput.Phys.Commun. 180 (2009), pp. 339

Simulated sample

- Simulated 800M muons for each site
- Equivalent to 29 years (NaCl) and 97 years (polyhalite)
- GEANT4 v10.5, Shielding physics list



Muon start positions

Analysis

Event selection I

- Based on true energy depositions no signal propagation and processing was simulated
- Veto:
 - skin (100 keV)
 - LS (200 keV)
 - WS (200 MeV)
 - 0.5 ms before and after TPC signal



Event selection II

- Single Xe recoil above 1 keV within 1 ms
- >5 cm away from border of active volume
- No other recoil above 0.5 keV considered resolvable from ionisation charge; sign of multiple neutron scatters
- No other depositions above 10 keV (non-NR)



Option without liquid scintillator

- Is LS needed to help rejecting muon-induced background?
- No new simulations, simply reanalysed
- LS treated as part of water shield
- Veto: LXe skin and combined LS+WS



Energy depositions in TPC

Veto includes LS



* only events with NR activity shown

Energy depositions in TPC (NaCl)

Option without LS



More activity/lower veto efficiency

* only events with NR activity shown

Results

Few background events

No events passed full selection in NaCl – with or without LS

Background events observed in polyhalite: One event passed selection in option with LS Two events passed selection in option without LS

With scintillator

Depth/Rock material	Observed events	Rate [/10 yrs/71 t]	90% CL			
2850 m w.e./NaCl (29 yr)	0		< 0.84			
3575 m w.e./polyhalite (97 yr)	1	0.10	0.01-0.45			
Without scintillator						
2850 m w.e./NaCl	0		< 0.84			
3575 m w.e./polyhalite	2	0.21	0.05-0.61			

2850 m w.e./NaCl	0		< 0.84
3575 m w.e./polyhalite	2	0.21	0.05-0.61

Note on uncertainties

- Only statistical errors considered
- Additional factor 2 uncertainty comes from neutron production in GEANT4
- Muon flux can be determined to within 10%
- Difference in spectra for 2 sites not taken into account
 - \blacksquare mean energy 261 GeV \rightarrow 282 GeV
 - neutron production increase by 7%



Example event — passing I



- Single detectable recoil
- Within fiducial volume
- Small depositions in veto systems
- Delayed neutron emission from PTFE

Example event — passing II



Example event — NOT passing I



Example event — NOT passing II



Conclusion

- Only few background events observed
- LS does not play major role in rejecting cosmogenic background
- Events from delayed neutrons from cosmogenic ¹⁷N in PTFE
 - $\blacksquare\,$ used 3 cm thick \rightarrow 2.8 t
 - can be reduced if needed
- Rate lower than expected other backgrounds
- **3 km w.e. deep enough** for cosmogenic background

BACKUP

Cosmogenic ¹⁷N in PTFE



- Significant contribution from neutrons from PTFE
- Many signal candidates passing selection except for multi-scatter requirement
- ¹⁷N from π , n, γ and μ interactions with ¹⁹F
- ¹⁷N half-life 4.2 s
- 3 cm thick PTFE in our simulation \rightarrow 2.8 t

Cavern size and material comparison

Cavern size doesn't make difference



Does cavern size and layout make difference?

neutrons produced preferentially in muon direction

- Simulations repeated for cavern of smaller size (by 40%)
- No difference observed in spectra of depositions in TPC

Rock material doesn't make difference



Energy depositions in veto systems



Shown depositions coincident with NR-only events in TPC

GEANT4 neutron production

Simulated mono-energetic muons in simplified geometry. Recorded neutrons produced within tested material.



Neutrons in various materials for 280 MeV muons

GEANT4 v10.5, Shielding physics list

Material	Neutron yield $[\times 10^{-3} \text{ n/}\mu/(\text{g/cm}^2)]$	Material	Neutron yield $[\times 10^{-3} \text{ n/}\mu/(\text{g/cm}^2)]$
C _n H _{2n} H ₂ O polyhalite PTFE NaCl	$\begin{array}{c} 0.31{\pm}0.01\\ 0.37{\pm}0.01\\ 0.46{\pm}0.02\\ 0.65{\pm}0.03\\ 0.81{\pm}0.03\end{array}$	Mg Ti Mn Fe Cu Pb	0.49 ± 0.02 1.39 ± 0.06 1.46 ± 0.04 1.31 ± 0.05 1.30 ± 0.05 3.27 ± 0.13

Neutron yield in polyethylene v muon energy



Neutron yield v material – $E_{\mu} = 280 \text{ GeV}$



Neutron production spectrum in lead – GEANT4 v9.5 v v10.5



Neutron production spectrum in various materials - GEANT4 v10.5



* Astropart.Phys. 31 (2009), 366

Neutron production processes

GEANT4 v10.5 v v9.5, lead

GEANT4 v10.5, $E_{\mu} = 280 \text{ GeV}$ multiple materials



Neutron production spectrum by process

Geant4 v10.5, $E_{\mu} = 280 \text{ GeV}$

Geant4 v9.5, $E_{\mu} = 260 \text{ GeV}$



10

^{-10⁻³/_ν [*n*/Me//*μ*/(d/cm³)}

10-7 10^{-8}

10⁻⁹

10-1