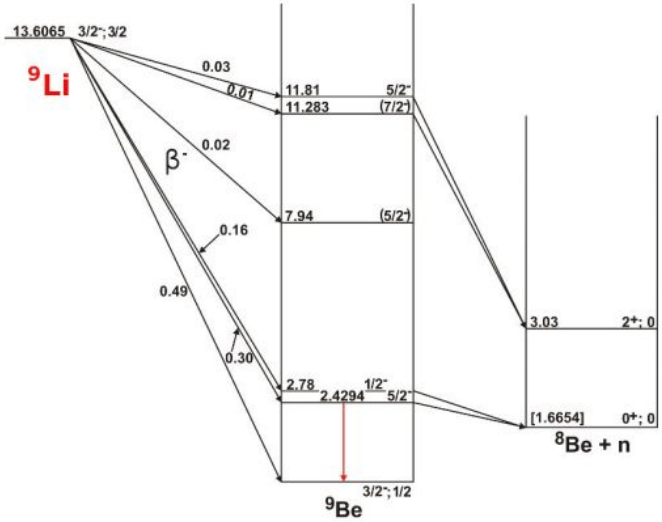
Delayed neutrons from material activation underground

- **Problem:** Passing muons can produce isotopes that β-decay with half lives on the O(ms) to O(s) scale that decay to highly excited daughter nuclei that can emit a neutron with energy O(MeV)
  - These events are not remoted by prompt veto cuts
  - Lifetimes that are long compared to the time between muons may be impossible to correlate
- **People:**
  - Igor, Susana, Sagar, Teena, Shawn
- **Procedure:**
  - FLUKA simulation of muons to determine activation rate of muons
  - G4DS simulation to determine background rates from relevant isotopes
- **Mitigation strategy:**
  - Neutron veto cuts and delayed muon tags
  - Need full MC model to finalize exactly what these cuts will be

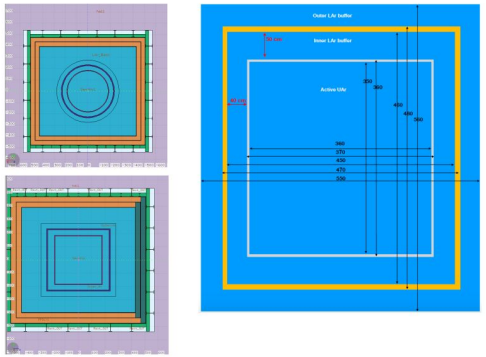


Current status and results

- These will naturally come out of the FLUKA simulations that Sagar is running, with a dedicated analysis of the output
  - Teena is picking this work up from Sagar, to continue the next steps
- Igor is running muon simulations in Geant4, to compare with Sagar's and Teena's FLUKA simulations

Isotope	Yield (per μ)
^{8}He ($t_{1/2}$ = 119 ms)	1.59E-5
^{9}Li ($t_{1/2}$ = 178 ms)	1.2E-4
^{11}Li ($t_{1/2}$ = 8.75 ms)	3.44E-5
^{11}Be ($t_{1/2}$ = 13.76 s)	7.99E-5
^{13}B ($t_{1/2}$ = 17.3 ms)	1.0E-4
^{17}N ($t_{1/2}$ = 4.17 s)	7.60E-5
^{22}F ($t_{1/2}$ = 4.23 s)	2.2E-6
^{24}F ($t_{1/2}$ = 382 ms)	1.2E-6
^{27}Na ($t_{1/2}$ = 301 ms)	2.6E-8
^{31}Al ($t_{1/2}$ = 644 ms)	1.28E-6
^{32}Al ($t_{1/2}$ = 31.9 ms)	1.4E-7

FLUKA simulations of muons on ^{40}Ar, by Andrew Erlandson for DEAP

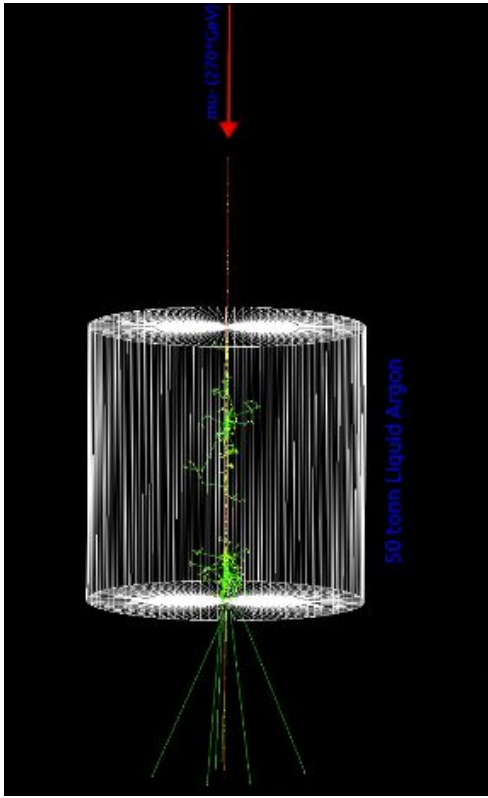


DS-20k geometry in FLUKA by Sagar

Comparison of GEANT4 and FLUKA muon activation in LAr for beta-n isotopes.

Vertical muon E=270 GeV in the center of 50 tonn LAr cylinder.

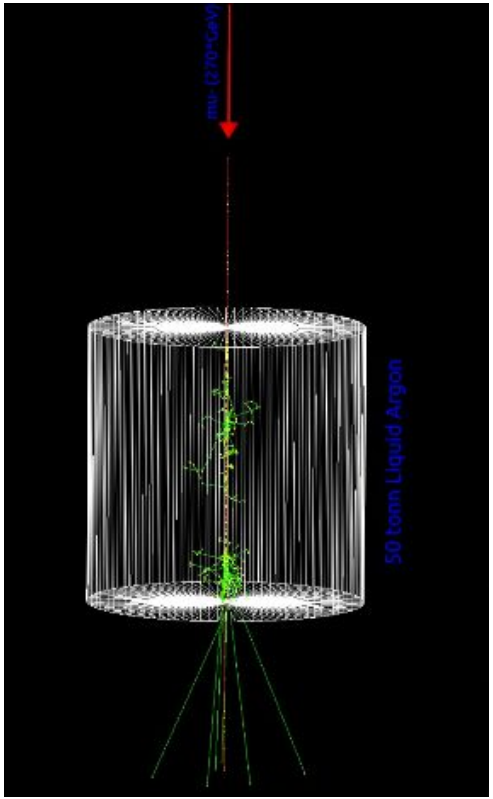
Isotopes	Suzanna (estimation from DEAP simulation)	Geant4 (Igor) QGSP_BERT_HP	Geant4 (Igor) QGSP_BIC_HP	Fluka (Alexandre Bakalyarov)
		Yield (per muon)		
8He	1.59E-5	$<1\cdot10^{-6}$	$2\cdot10^{-6}$	$1.30\cdot10^{-5}$
9Li	1.2E-4	$< 1\cdot10^{-6}$	$7\cdot10^{-6}$	$3.80\cdot10^{-5}$
11Li	3.44E-5	$< 1\cdot10^{-6}$	$<1\cdot10^{-6}$	$5.00\cdot10^{-6}$
11Be	7.99E-5	$< 1\cdot10^{-6}$	$3\cdot10^{-6}$	$1.10\cdot10^{-5}$
13B	1.0E-4	$< 1\cdot10^{-6}$	$1\cdot10^{-6}$	$3.00\cdot10^{-5}$
17N	7.60E-5	$3\cdot10^{-6}$	$6\cdot10^{-6}$	$2.10\cdot10^{-5}$
22F	2.2E-6	$8\cdot10^{-6}$	$7\cdot10^{-6}$	$5.00\cdot10^{-6}$
24F	1.2E-6	$< 1\cdot10^{-6}$	$<1\cdot10^{-6}$	$<1.00\cdot10^{-6}$
27Na	2.6E-8	$1.5\cdot10^{-5}$	$4\cdot10^{-6}$	$2.00\cdot10^{-6}$
31Al	1.28E-6	$1.7\cdot10^{-6}$	$1.9\cdot10^{-5}$	$2.20\cdot10^{-5}$
32Al	1.4E-7	$3\cdot10^{-6}$	$8\cdot10^{-6}$	$1.00\cdot10^{-6}$



Comparison of GEANT4 and FLUKA muon activation in LAr for beta isotopes.

Vertical muon E=270 GeV in the center of 50 tonn LAr cylinder.

Isotopes	Suzana	Geant4 (Igor) QGSP_BERT_HP	Geant4 (Igor) QGSP_BIC_HP Yield (per muon)	Fluka (Alexandre Bakalyarov)
41Ar	0.2113	0.00323	$2.545 \cdot 10^{-3}$	$3.274 \cdot 10^{-3}$
40Cl	0.0023	0.0014	$14.14 \cdot 10^{-4}$	$8.570 \cdot 10^{-4}$
39Cl	0.0159	0.00714	$9.817 \cdot 10^{-3}$	$6.960 \cdot 10^{-3}$
39Ar	0.1626	0.07675	$7.8193 \cdot 10^{-2}$	$7.290 \cdot 10^{-2}$
38Cl	0.0123	0.00524	$10.102 \cdot 10^{-3}$	$5.350 \cdot 10^{-3}$
37S	0.0016	0.00185	$1.975 \cdot 10^{-3}$	$8.720 \cdot 10^{-3}$
37Cl	0.0134	0.01054	$1.5858 \cdot 10^{-2}$	$6.860 \cdot 10^{-4}$
35S	0.0108	0.00498	$6.599 \cdot 10^{-3}$	$4.830 \cdot 10^{-3}$
34P	0.0014	0.00063	$1.264 \cdot 10^{-3}$	$6.270 \cdot 10^{-4}$
33P	0.0043	0.00174	$2.339 \cdot 10^{-3}$	$1.890 \cdot 10^{-3}$
32P	0.0050	0.00138	$2.982 \cdot 10^{-3}$	$2.060 \cdot 10^{-3}$
31Si	0.0018	0.00076	$9.5 \cdot 10^{-4}$	$7.070 \cdot 10^{-4}$
28Al	0.0019	0.00036	$5.54 \cdot 10^{-4}$	$6.600 \cdot 10^{-4}$
10Be	0.0010	<0.00001	$3.7 \cdot 10^{-5}$	$2.150 \cdot 10^{-4}$
3H	0.0161	0.00418	$5.216 \cdot 10^{-3}$	$3.274 \cdot 10^{-3}$



Prospects and plans

- Problems:
  - No significant roadblocks are foreseen
  - The biggest challenge may be if we cannot practically achieve sufficiently muon veto windows and the neutron veto cuts alone aren't enough, but this seems unlikely to be a major problem
- Uncertainties:
  - There are very significant uncertainties on the muon activation physics
- Plans:
  - Now that Sagar has working FLUKA simulations and has simulated muons in the detector, the path forward is fairly straightforward
  - Mostly, this will be a matter of time, as Sagar passes the baton to Teena
    - A lot of this work comes naturally from the work already being done for the prompt cosmogenic neutrons
  - Sagar is preparing an internal note for his work, which will cover most of what is needed
  - Once we have results from the delayed neutron analysis from this work, a note will be written summarizing that
  - **We need to have the data files for muon flux in Gran-Sasso Hall C - at CNAF computer**