Neutron production in SURF rock

Vitaly A. Kudryavtsev
University of Sheffield, United Kingdom
for the DUNE Background Task Force

Remaining questions about backgrounds

- Open topics from 2019 review
  - 2. External neutron backgrounds were identified as a possible limiting factor for the SN burst trigger and solar neutrinos in the 2019 review. Essentially, neutrons from outside the active argon volume make their way into the fiducial volume where they capture and produce a 6 MeV gamma cascade that can resemble a SN neutrino event. At the time of the last review, there were uncertainties in the backgrounds from this source of an order of magnitude or more. This is a major factor in whether we need a neutron shield. Please update us with:
  - a) Progress on the calculation and measurements of external neutron rates expected from SF and (α, n) interactions in the rock and detector components. What is the current best estimate and what are the uncertainties?

Code

- W.B. Wilson, et al., SOURCES4A: a code for calculating (α,n), spontaneous fission, and delayed neutron sources and spectra, Technical Report LA-13639-MS, Los Alamos, 1999;
- Modifications and additions, explained in Tomasello et al. NIMA, 595 (2008) 431.
- Thick target neutron yield: the size of the material sample is much bigger than the range of alphas; edge effects are neglected.
- Uniform distribution of contaminants within the material.
- Code validated by comparison of cross-sections with experimental data.
- Uncertainty: up to 20-30% (differences between models and data sets) for most isotopes tested.
- Latest update at the (α, n) workshop at CIEMAT (Madrid, November 2019): https://agenda.ciemat.es/event/1127/contributions/2227/attachments/1691/2074/neutrons-alphan-nov2019.pdf
- Paper published: Kudryavtsev et al. *Nucl. Instrum. Meth. A* 972 (2020) 164095; e-Print: 2005.02499 [physics.ins-det].

Rock composition

mean DUNE rock

density [g/cm^3]	error	O [a%]	Fe [a%]	Mn [a%]	Ca [a%]	K [a%]	Si [a%]	Al [a%]	Mg [a%]	Na [a%]	N [a%]	C [a%]	H [a%]	total [a%]	norm Wt%toAt%
2.67	0.05	55.3	2.8	0.0	0.0	0.3	13.9	6.0	6.8	0.2	0.0	0.0	14.8	100.0	1.6284
2.65	0.10	62.4	0.6	0.1	0.0	2.0	26.2	3.1	1.1	0.5	0.0	0.0	4.0	100.0	1.5871
2.68	0.10	54.8	2.5	0.0	0.1	0.4	[illegible]	[illegible]	6.1	0.1	0.0	0.0	16.0	100.0	1.6411
2.60	0.09	62.8	0.0	0.0	0.4	3.7	26.8	2.0	0.0	2.0	0.0	0.0	0.5	100.0	1.5200
2.65	**0.04**	**58.742**	**1.501**	**0.030**	**0.112**	**1.554**	**19.854**	**4.940**	**3.580**	**0.692**	**0.000**	**0.000**	**8.996**	100.000	1.5941
		58.9	1.5	0.0	0.1	1.6	20.0	4.9	3.3	0.7	0.0	0.0	8.8	100.0	STDEV / sqrt(N)
Aran		59.0	2.3	0.0	0.1	1.4	18.3	7.6	2.2	0.6	0.0	0.0	8.5	100.0	STDEV sample
	<XRF>	56.4	4.1	0.05	6.63	3.04	21.32	4.95	2.29					98.78	
2.56	0.09	64.3	0.0	0.0	0.0	2.7	26.3	2.4	0.0	1.2	0.0	3.1	0.0	100.0	1.5989
2.66	0.10	64.6	0.0	0.0	0.0	2.4	28.3	2.2	0.0	1.1	0.0	1.4	0.0	100.0	1.5879
2.57	0.09	58.4	0.0	0.0	24.7	0.0	0.5	0.0	0.0	0.0	0.0	16.4	0.0	100.0	1.9925
2.49	0.09	63.1	0.0	0.0	0.0	5.1	27.4	3.6	0.0	0.8	0.0	0.0	0.0	100.0	1.5046
2.9 cement?															
1.34	0.14	54.1	0.2	0.0	29.9	0.0	6.5	0.1	2.3	0.0	0.6	3.4	3.0	100.0	1.8614
2.90	0.04	44.1	3.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0.0	0.0	0	96.4	XRF %
1.00	0.01	33.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.7	100.0	5.5510
2.332		**56.538**	**0.132**	**0.001**	**21.061**	**0.283**	**4.173**	**0.514**	**0.382**	**0.120**	**0.067**	**12.005**	**4.724**	100.000	[illegible].89629448
2.501		60.121	0.132	0.001	4.100	3.123	23.129	2.030	0.382	0.717	0.067	0.874	4.724	100.000	99.89629448
	<XRF>	53.787	2.737	0.055	28.798	0.550	7.033	1.291	0.359				4.724	99.335	
2.40	0.10	56.815	1.000	0.019	17.986	1.319	11.445	1.479	0.375	0.279	0.044	4.293	4.724	99.778	avg. shotcrete

mean shotcrete Pete Lien

- Given by the fraction of atoms.
- Neutron yield depends 'strongly' on the fraction of Al.
- Neutron transport depends on the amount of hydrogen.

Neutron production rate

Source	Rock measured	Initial LArSoft	Mei et al
U total	3.413×10^{-11}	2.885×10^{-11}	3.561×10^{-11}
U early	4.074×10^{-12}	3.171×10^{-12}	
U late	3.006×10^{-11}	2.271×10^{-11}	
Th	1.560×10^{-11}	1.299×10^{-11}	1.685×10^{-11}

Only (α,n) reactions are shown in the tables: production rate (top, in neutrons/g/s/ppb), mean energy (bottom, in MeV).

Spontaneous fission of U-238 (the only important): 1.353×10^{-11} n/g/s/ppb, 1.70 MeV.

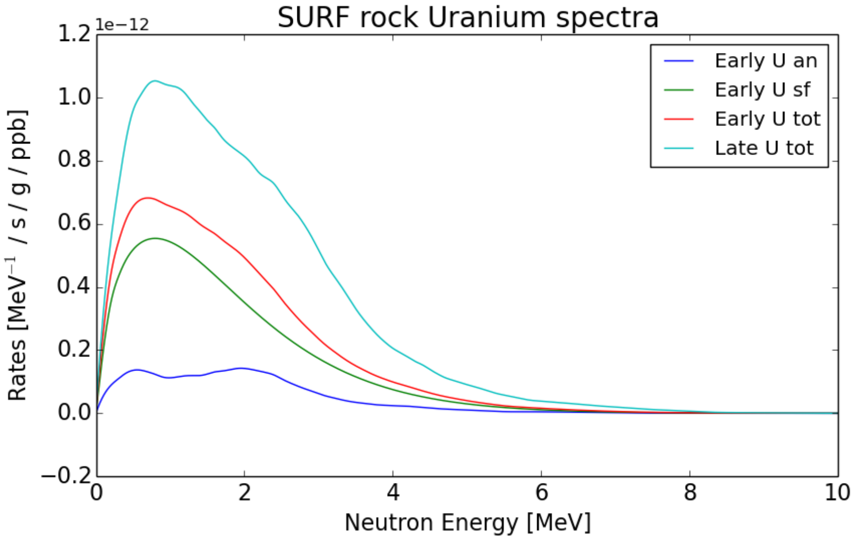
Mei et al. Astropart. Phys. 34, 33 (2010), arXiv:0912.0211; taken from Jordan, B. T., 2009, Geochemistry tectonic setting of the Yates unit of the Poorman Formation (DUSEL bedrock) and other northern Black Hills amphibolites: Geological Society of America Abstracts with Programs, v. 41, n. 7, p. 271.

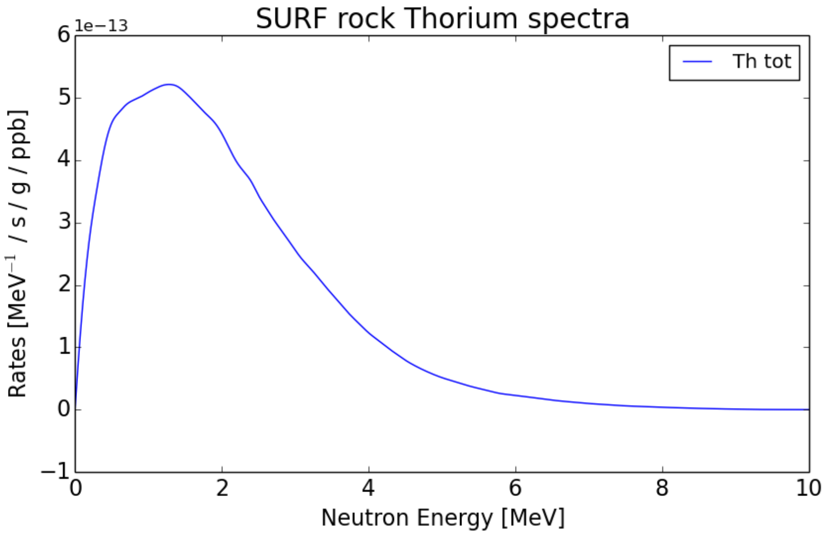
Source	Rock measured	Initial LArSoft	Mei et al
U total	1.93	1.97	1.84
U early	1.87	1.93	
U late	1.94	1.95	
Th	2.00	2.02	1.94

Neutrons from rock

- Different rock composition results in different neutron production rate.
  - In the case of SURF rock, the abundance of Al is important.
- The model used for cross-section can also affect the result.
  - Currently the cross-sections are taken from
    - Data if available and reliable (combined with a model),
    - EMPIRE3.2.3/2.19,
    - TALYS1.9.
  - Uncertainty is about 20% for rock.
- Measurements in Davis cavern: LZ Collaboration. Measurement of the Gamma Ray Background in the Davis Cavern at the Sanford Underground Research Facility, Astropart. Phys. 116 (2020) 102391; arXiv:1904.02112.
  - 29 ± 15 Bq/kg of ^{238}U, and 13 ± 3 Bq/kg of ^{232}Th, 220 ± 60 Bq/kg of ^{40}K.
  - Consistent with the measured contaminations of shotcrete.
  - It would be good to carry out a similar measurement in a future DUNE cavern.

Spectra of neutrons

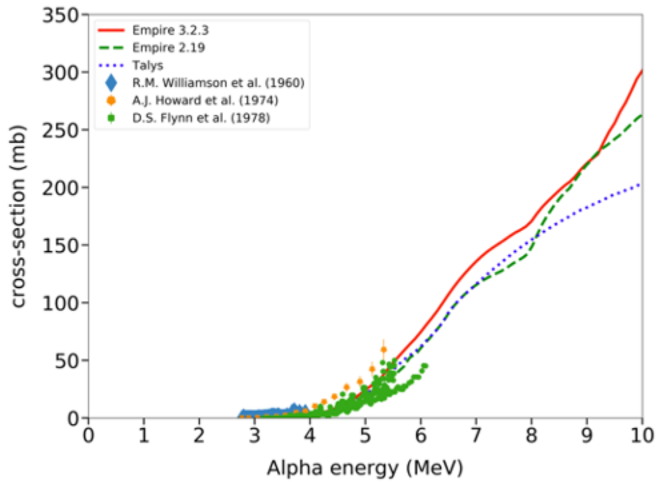


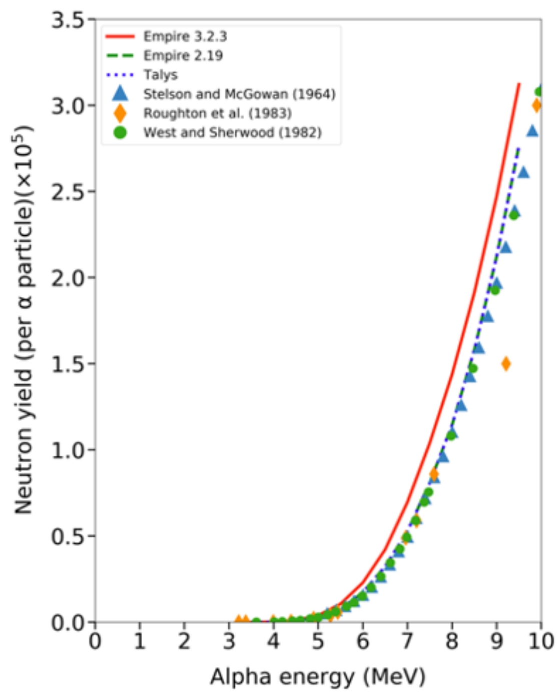


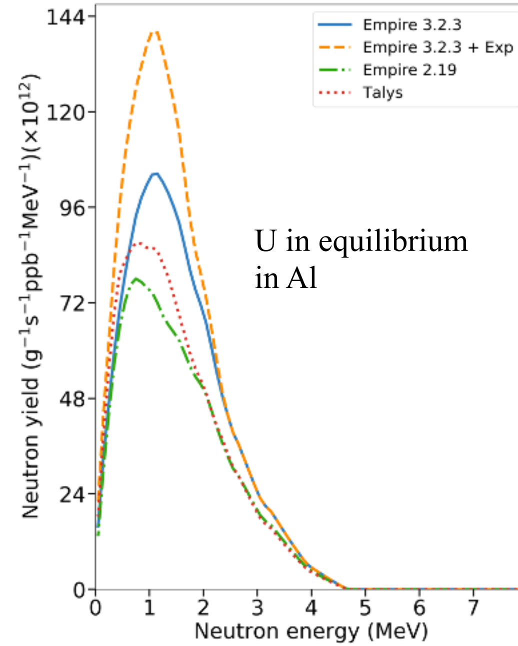
- Energy spectra of neutrons from uranium and thorium in rock.

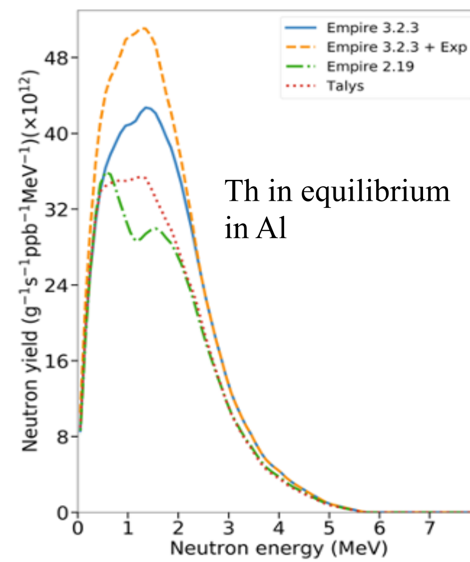
Cross-sections and spectra on Al

- Data sets on cross-section are not consistent and do not allow to choose the optimum model (top left).
- Data on neutron yield favour TALYS1.9 model for the cross-section.
- TALYS1.9 cross-section was used for Al.
- Neutrons spectra in Al from U in equilibrium (top right) and Th (bottom right). EMPIRE3.2.3 + Exp – shows the spectra calculated with the measured cross-section from Howard (1974) and EMPIRE3.2.3.









Neutrons from shotcrete

density [g/cm^3]	error	O [a%]	Fe [a%]	Mn [a%]	Ca [a%]	K [a%]	Si [a%]	Al [a%]	Mg [a%]	Na [a%]	N [a%]	C [a%]	H [a%]	total [a%]	norm Wt%toAt%
2.67	0.05	55.3	2.8	0.0	0.0	0.3	13.9	6.0	6.8	0.2	0.0	0.0	14.8	100.0	1.6284
2.65	0.10	62.4	0.6	0.1	0.0	2.0	26.2	3.1	1.1	0.5	0.0	0.0	4.0	100.0	1.5871
2.68	0.10	54.8	2.5	0.0	0.1	0.4	[illegible]	[illegible]	6.1	0.1	0.0	0.0	16.0	100.0	1.6411
2.60	0.09	62.8	0.0	0.0	0.4	3.7	26.8	3.0	0.0	3.0	0.0	0.0	0.5	100.0	1.5200
2.65	**0.04**	**58.742**	**1.501**	**0.030**	**0.112**	**1.554**	**19.854**	**4.940**	**3.580**	**0.692**	**0.000**	**0.000**	**8.996**	100.000	1.5941
		58.9	1.5	0.0	0.1	1.0	20.0	4.3	3.3	0.7	0.0	0.0	8.8	100.0	STDEV / sqrt(N)
Aran		59.0	2.3	0.0	0.1	1.4	18.3	7.6	2.2	0.6	0.0	0.0	8.5	100.0	STDEV sample
	<XRF>	56.4	4.1	0.05	6.63	3.04	21.32	4.95	2.29					98.78	
2.56	0.09	64.3	0.0	0.0	0.0	2.7	26.3	2.4	0.0	1.2	0.0	3.1	0.0	100.0	1.5989
2.66	0.10	64.6	0.0	0.0	0.0	2.4	28.3	2.2	0.0	1.1	0.0	1.4	0.0	100.0	1.5879
2.57	0.09	58.4	0.0	0.0	24.7	0.0	0.5	0.0	0.0	0.0	0.0	16.4	0.0	100.0	1.9925
2.49	0.09	63.1	0.0	0.0	0.0	5.1	27.4	3.6	0.0	0.8	0.0	0.0	0.0	100.0	1.5046
2.9 cement?															
1.34	0.14	54.1	0.2	0.0	29.9	0.0	6.5	0.1	2.3	0.0	0.6	3.4	3.0	100.0	1.8614
2.90	0.04	44.1	3.8	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.0	0	96.4	XRF %
1.00	0.01	33.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	66.7	100.0	5.5510
2.332		**56.538**	**0.132**	**0.001**	**21.061**	**0.283**	**4.173**	**0.514**	**0.382**	**0.120**	**0.067**	**12.005**	**4.724**	100.000	[illegible].89629448
2.501		60.121	0.132	0.001	4.100	3.123	23.129	2.630	0.382	0.717	0.067	0.874	4.724	100.000	99.89629448
	<XRF>	53.787	2.737	0.055	28.798	0.550	7.033	1.291	0.359				4.724	99.335	
2.40	0.10	56.815	1.000	0.019	17.986	1.319	11.445	1.479	0.375	0.279	0.044	4.293	4.724	99.778	avg. shotcrete

mean DUNE rock

mean shotcrete Pete Lien

Source	Rock	Shotcrete
U total	3.413×10^{-11}	9.465×10^{-12}
U early	4.074×10^{-12}	1.542×10^{-12}
U late	3.006×10^{-11}	7.922×10^{-12}
Th	1.560×10^{-11}	3.863×10^{-12}

- Neutron production rate in n/g/s/ppb.
- Production rate in shotcrete is 3-4 time smaller than in rock (for the same U/Th concentration)
  - Lower abundance of Al and Si.
- Background rates from rock and shotcrete may be comparable but depend on the thickness of shotcrete and contaminations of rock and concrete.

Foam

- Results for 'standard' foam: $C_{17}H_{16}N_2O_4$
- Spontaneous fission of ^{238}U: 1.353×10^{-11} n/g/s/ppb.
- Neutrons from (α, n), ^{238}U+ ^{235}U in equilibrium: 1.887×10^{-11} n/g/s/ppb.
- Neutrons from (α, n), ^{238}U+ ^{235}U early sub-chain: 0.273×10^{-11} n/g/s/ppb.
- Neutrons from (α, n), ^{238}U late sub-chain: 1.615×10^{-11} n/g/s/ppb.
- Neutrons from (α, n), ^{232}Th in equilibrium: 0.819×10^{-11} n/g/s/ppb.
- Should not be different by more than 20% from the measured foam.