DarkSide Materials Weekly Meeting: Cosmogenic activation

- Copper
- Steel
- Other materials
- Argon

Susana Cebrián scebrian@unizar.es
5th March 2019

Universidad Zaragoza
1542

LSC
Laboratorio Subterráneo de Canfranc

Cosmogenic activation

To estimate the effect of possible cosmogenic activation of materials:

1. To know the **production rates** ***R*** of relevant isotopes in the targets
   - Scarce experimental data from irradiation/exposition experiments
   - Calculations from production cross sections and cosmic nucleon spectrum:

$$R = N \int \sigma(E)\phi(E)dE$$

N = number of target nuclei
ϕ = flux of cosmic rays
σ = production cross section
E = particle energy

   Dispersion for different calculations of productions rates is usually important (even at 50%)

2. To estimate the **induced activity** ***A*** knowing the exposure history to cosmic rays

$$A = R[1 - \exp(-\lambda t_{\mathrm{exp}})] \exp(-\lambda t_{\mathrm{cool}})$$

t_{exp} = exposure time
t_{cool} = cooling time underground

3. To compute the **background rate** generated from Monte Carlo simulation

Interaction with MC group: which isotopes have already been considered for estimating the gamma background?

Copper: 1. Production rates

Cu is a material widely used in experiments and many activation studies are available

Table 7. Production rates (in kg^{-1} d^{-1}) at sea level for isotopes induced in natural copper following measurements in Refs. 113 and 103 and different calculations (see text).

	^{46}Sc	^{48}V	^{54}Mn	^{59}Fe	^{56}Co	^{57}Co	^{58}Co	^{60}Co
Half-life[67,68]	83.787 d	15.9735 d	312.19 d	44.494 d	77.236 d	271.82 d	70.85 d	5.2711 y
Measurement[113]	2.18 ± 0.74	4.5 ± 1.6	8.85 ± 0.86	18.7 ± 4.9	9.5 ± 1.2	74 ± 17	67.9 ± 3.7	86.4 ± 7.8
Measurement[103]	$2.33^{+0.95}_{-0.78}$	$3.4^{+1.6}_{-1.3}$	$13.3^{+3.0}_{-2.9}$	$4.1^{+1.4}_{-1.2}$	$9.3^{+1.2}_{-1.4}$	$44.8^{+8.6}_{-8.2}$	$68.9^{+5.4}_{-5.0}$	$29.4^{+7.1}_{-5.9}$
ACTIVIA[17,103]	3.1		14.3	4.2	8.7	32.5	56.6	26.3
ACTIVIA (MENDL-2P)[17]	3.1		12.4	1.8	14.1	36.4	38.1	9.7
TALYS[59]			16.2			56.2		46.4
MENDL+YIELDX[61]	2.7		27.7	4.9	20.0	74.1	123.0	55.4
COSMO[103]	1.5	3.1	13.5	4.3	7.0	30.2	54.6	25.7
GEANT4[37]	1.2		12.3	8.8	10.3	67.2	57.3	64.6
ACTIVIA[37]	4.1		30.0	10.5	20.1	77.5	138.1	66.1

S. Cebrián, Cosmogenic activation of materials, Int. J. Mod. Phys. A 32 (2017) 1743006

113. M. Labustenstein and G. Heusser, *App. Radiat. Isot.* **67**, 750 (2009).

Dedicated measurement: 125 kg, 275 d of exposure at Gran Sasso, gamma screening using GeMPI detector

^{60}Co: longest half-life, beta/gamma emitter, important dispersion

Copper: 2. Induced activity

- Particular exposure history of each component should be know as precisely as possible
- **Example estimates of A** for extreme cases: t_{exp}=1 month, t_{exp}=1 year (t_{cool}=0, sea level)

Isotope	T1/2 (d)	R (*)		A for 1 m		A for 1 y		A for 1 y/A for 1 m
	(d)	(kg-1 d-1)		(mBq/kg)		(mBq/kg)		
46Sc	83.79	2.18	0.74	0.006	0.002	0.024	0.008	4.33
48V	15.97	4.5	1.6	0.038	0.013	0.052	0.019	1.37
54Mn	312.19	8.85	0.86	0.007	0.001	0.057	0.006	8.62
59Fe	44.49	18.7	4.9	0.081	0.021	0.216	0.057	2.67
56Co	77.24	9.5	1.2	0.026	0.003	0.106	0.013	4.08
57Co	271.82	74	17	0.063	0.014	0.519	0.119	8.22
58Co	70.85	67.9	3.7	0.200	0.011	0.764	0.042	3.82
60Co	1923.95	86.4	7.8	0.011	0.001	0.123	0.011	11.46

(*) Rates from Gran Sasso measurement

Control of exposure time can be relevant if some of these isotopes give a significant contribution to background

Copper: 2. Induced activity

- **Copper components and masses**

(from neutron budget sheet http://darkmatter.ciemat.es/links/neutron-background)

CABLES+FIBERS bottom to top	position		material	mass [kg]
Cathode HV	TPC side		Cu	1.767145868
LV, HV, control cable	TPC side		SAMI cable Cu	11.5
ELECTRONICS NEW	**#/PDM**		**material**	**[mg/PDM]**
SiPM tiles				
Cu Luvata	1		Cu Luvata	1600
Front end board				
Cu Luvata	1		Cu Luvata	1700
mushrooms	2		Cu	7000
Mother board	**(1/25 PDM)**			
Cu plate	0.04		Cu	8.10E+04
Finger board	**(2/25 PDM)**			
Cu Luvata	1		Cu Luvata	384
Steering module	**(1/25 PDM)**			
Cu Luvata	1		Cu Luvata	790
LV, HV, control cable	0.04		SAMI cable Cu	2640
Optical Module	**(1/25 PDM)**			
Cu Luvata	1		Cu Luvata	380
Total Cu in Electronics				95494

Copper Faraday cage at Veto should be added?

Steel: 1. Production rates

Some activation studies are available for **steel**

Table 9. Production rates (in $kg^{-1}d^{-1}$) at sea level for isotopes induced in stainless steel, from the measurement following an exposure to cosmic rays in Gran Sasso and from calculations using GEANT4 and ACTIVIA packages.

Isotope	Half-life (d)[67,68]	Measurement[113]	GEANT4[37]	ACTIVIA[37]
^{7}Be	53.22	389 ± 60	0.05	2.05
^{54}Mn	312.19	233 ± 26	230	191
^{58}Co	70.85	51.8 ± 7.8	90	13
^{56}Co	77.236	20.7 ± 3.5	16	131
^{46}Sc	83.787	19.0 ± 3.5	8.8	18
^{48}V	15.9735	34.6 ± 3.5		

S. Cebrián, Cosmogenic activation of materials, Int. J. Mod. Phys. A 32 (2017) 1743006

113. M. Labustenstein and G. Heusser, *App. Radiat. Isot.* **67**, 750 (2009).

Dedicated measurement: Nironit stainless steel, 314 d of exposure at Gran Sasso, gamma screening using GeMPI detector

^{60}Co: obscured by previous contamination (typical in steel)

Steel: 2. Induced activity

- **Example estimates of A** for extreme cases: t_{exp}=1 month, t_{exp}=1 year (t_{cool}=0)

Isotope	T1/2 (d)	R (*)		A for 1 m		A for 1 y		A for 1 y/A for 1 m
	(d)	(kg-1 d-1)		(mBq/kg)		(mBq/kg)		
7Be	53.22	389	60	1.456	0.225	4.464	0.688	3.07
46Sc	83.79	19.0	3.5	0.048	0.009	0.209	0.039	4.33
48V	15.97	34.6	3.5	0.292	0.029	0.400	0.041	1.37
54Mn	312.19	233	26	0.174	0.019	1.498	0.167	8.62
56Co	77.24	20.7	3.5	0.057	0.010	0.231	0.039	4.08
58Co	70.85	51.8	7.8	0.152	0.023	0.583	0.088	3.82
(*) Rates from Gran Sasso measurement								

- **Steel components and masses**

(from neutron budget sheet http://darkmatter.ciemat.es/links/neutron-background)

Component	**position**		**material**	**mass [kg]**
CRYOSTAT				
Stainless steel	cryostat		Stainless steel MSS0364 DUNE	27104
TPC				
TPC support structure	Steel structure		SS DS50	1071

Other materials

Silicon: cosmogenic isotopes identified by other experiments should not be a problem for SiPMs

ELECTRONICS NEW	#/PDM		material	[mg/PDM]
SiPM tiles				
SiPMs	24		Si SiPM	2000

^{32}**Si** quantified by DAMIC (β^- emitter, Q= 224.5 keV, half-life 150 y)
^{3}**H** considered by CDMS (β^- emitter, Q= 18.6 keV, half-life 12.3 y)

Argon: previous works

Estimates of **activity induced** for a certain exposure using COSMO code: **^{3}H, ^{22}Na, ^{37}Ar, ^{39}Ar, …**

DS-20K Activation
C. J. Martoff, H. Back
Nov. 19, 2015

The estimated schedule of exposure to cosmic rays for ds20k argon is as follows:

period	days	alt (m)	end day
production	25	2134	-111
truck to seaport	10	2134	-101
sea transp	40	0	-61
Sardinia	30	(UG)	-31
truck to LNGS	1	762	-30
UG LNGS	30	(UG)	0

To estimate the resulting activation I summed COSMO runs for each of the indicated periods with decay times to day 0 (end of 30 days underground storage at LNGS). Altitude effect are estimated using the star-density (cosmic ray activation rate) vs. atmospheric pressure from Lal & Peters, Handbuch der Physik, Band 46/2, pp 555 ff (1967), and a table of pressure vs. altitude for the "standard atmosphere". For example, the standard atmosphere pressure at the Colorado collection site, elevation 2134 m is 79.8 kPa and the corresponding cosmic ray activation rate is 6.9 times the sea-level value. I modified COSMO to add an option to activate at an accelerated rate so that the decay corrections it does will come out correctly for exposure at elevated altitude.

For the above exposure schedule, the resulting COSMO total decay rates from cosmogenic nuclides on day 0 are:

ip	Z	A	$t_{1/2}$ (da)	dn/dt (/kg da)
1	1	3	4503	3.45
2	4	7	53.3	2.85
3	4	10	584000000	0
4	5	11	11000000000	0
5	6	14	2090000	0
6	10	20	11000000000	0
7	11	22	950.4	3.23
8	13	26	266000000	0
9	14	32	237000	0.01
10	15	31	11000000000	0
11	15	32	14.28	42.36
12	15	33	25.3	54.05
13	16	35	87.4	108.54
14	17	36	110000000	0
15	18	37	35	19.09
16	18	39	98200	0.67

Argon: previous works

Different cosmogenics studies mainly for **^{37}Ar, ^{39}Ar** from different contexts (like Geophysics, Hydrology) presented at **The Low-Radioactivity Underground Argon Workshop**
(March 2018, PNNL, Richland, WA) arXiv:1901.10108 [physics.ins-det]

R. Saldanha et al, Cosmogenic isotope production in argon, http://doi.org/10.5281/zenodo.1239049

- Estimates of **production rates** and **induced activity** of **^{39}Ar** for long exposures at Colorado + sea level using COSMO and ACTIVIA (including modifications):

  A=1-17 10^{-5} Bq/kg (2-23% of DS-50 measurement)

- Irradiation experiment at Los Alamos Neutron Science Center (LANSCE) (3 days, December 2017) with a neutron beam having an energy spectrum similar to cosmic neutrons to quantify **^{39}Ar** and other products using a proportional counter at PNNL

Argon: previous works

Different cosmogenics studies mainly for **^{37}Ar, ^{39}Ar** from different contexts (like Geophysics, Hidrology,) presented at **The Low-Radioactivity Underground Argon Workshop**
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C. Johnson, Background sources of ^{37}Ar,http://doi.org/10.5281/zenodo.1239130

Estimates of activity of **^{37}Ar** in air for:

- Atmospheric production: spallation on ^{40}Ar by cosmic neutrons
- Shallow subsurface and deep underground production: $^{40}Ca(n,\alpha)^{37}Ar$

O. Šramek and W. F. McDonough, Subterranean production of ^{39}Ar and implications for Doe Canyon well gas, http://doi.org/10.5281/zenodo.1239072

Estimates of production rates of **^{39}Ar** for subterranean nucleogenic production in rock at upper, medium, lower crust, mantle $^{39}K(n,p)^{39}Ar$

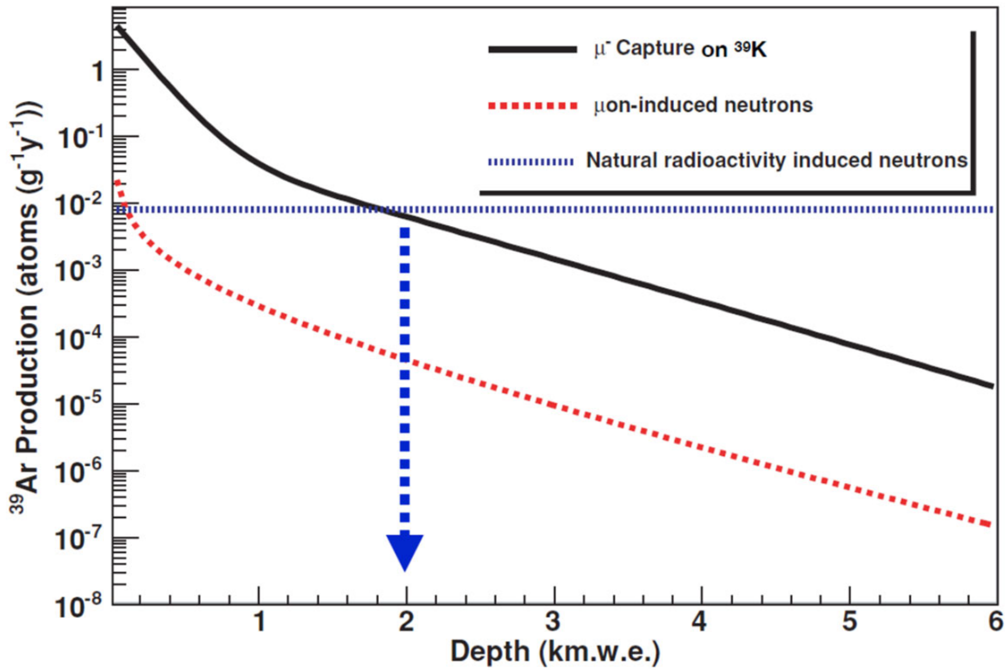
Low ^{39}Ar level in Doe Canyon gas is puzzling – isotopic composition suggests both atmospheric and crustal contribution to the magmatic origin gas, low ^{39}Ar requires »3000 year isolation.

Argon: previous works

Prediction of underground argon content for dark matter experiments
D.-M. Mei, Z.-B. Yin, J. Spaans, M. Koppang, A. Hime, C. Keller, and V. M. Gehman
Phys. Rev. C **81** (2010) 055802
https://journals.aps.org/prc/abstract/10.1103/PhysRevC.81.055802

•Use of physical models to evaluate the production of ^{39}**Ar** underground considering both cosmogenic and nucleogenic mechanisms
•Production as a function of depth:

At depths >2000 m.w.e. nucleogenic ^{39}Ar production dominates

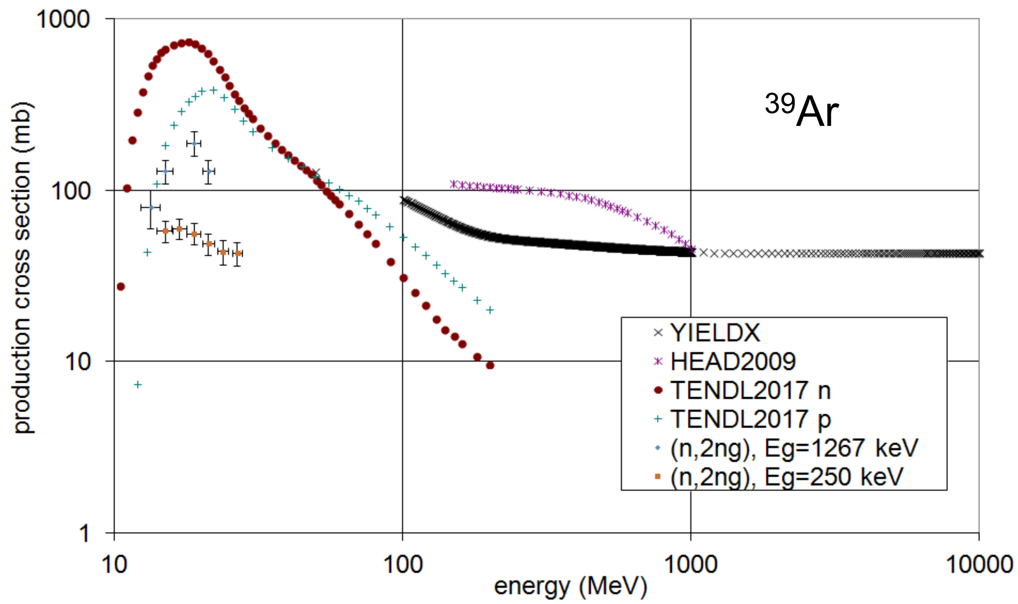


Argon

Production at surface of ^{39}Ar and ^{3}H

DarkSide Document https://darkside-docdb.fnal.gov/cgi-bin/private/ShowDocument?docid=3124

1. **Production rate:** estimated from cross sections from different libraries + Gordon et al cosmic neutron spectrum



2. **Induced activity:** for t_{exp}=35 days at an altitude of 2134 m (using a correction factor estimated for Colorado) followed by t_{exp}=41 days at sea level

Argon

Isotope	Lambda (d-1)	Ref.	R (kg-1 d-1)	err	A (kg-1 d-1)	err	Martoff & Back
39Ar	7.06E-06	Tol	686	40	**1.266**	**0.074**	0.67
3H	1.54E-04	DDEP	146	31	**5.8**	**1.2**	3.45

Comparison with previous results:

- Production rate of ^{39}**Ar** in the range of the estimates at R. Saldanha, Cosmogenic isotope production in argon, http://doi.org/10.5281/zenodo.1239049 62 to 898 kg^{-1} d^{-1}
- These new activity results are a factor 1.9 and 1.7, respectively, higher than the decay rates obtained previously by Martoff & Back (for same exposure).

The ^{39}Ar activity for the assumed exposure is 1.5 10^{-5} Bq/kg much lower (2%) than the residual level quantified for underground argon
(0.73 mBq/kg = 63 kg^{-1} d^{-1}).

Argon

Production at surface of ^{37}Ar

- Not very relevant as half-life is 35 days, but to cross-check calculations
- Same methodology than for ^{39}Ar

1. **Production rate:** R=(124 ± 30) kg^{-1} d^{-1}
2. **Induced activity:** for t_{exp}=100 days at sea level A=106.9 kg^{-1} d^{-1}

Comparison with previous results:

- Very good agreement with Martoff & Back calculation by COSMO: A=115 kg^{-1} d^{-1}
- The corresponding saturation activity in air (0.93% Ar, density 1.2 kg/m^3 at 20º) is 1.5 mBq/m^3, within the range estimated as average tropospheric concentration at C. Johnson, Background sources of ^{37}Ar, http://doi.org/10.5281/zenodo.1239130

Argon

Production of ^{42}Ar in underground argon

Motivation:

- Potential background for neutrinoless double beta decay searches doping LAr with ^{136}Xe
  ^{42}Ar (β^-, Q=599 keV, 32.9 y half-life) gives **^{42}K** (β^- emitter, Q=3525.4 keV, 12.36 h half-life)
- ^{42}Ar specific activity in **atmospheric argon** studied by ICARUS, measured by DBA, GERDA, DEAP
  - DBA: 92^{+22}_{-46} microBq/kg
  - GERDA: similar values 50-100 microBq/kg

On concentration of ^{42}Ar in liquid argon, A S Barabash et al (DBA) 2016, J. Phys.: Conf. Ser. 718 062004
On atmospheric ^{39}Ar and ^{42}Ar abundance, P. Cennini et al (ICARUS), NIMA 356 (1995) 526
Expected atmospheric concentration of ^{42}Ar, A.J. Peurrung et al, NIMA 396 (1997) 524

Production mechanisms: two-step neutron capture and $^{40}\mathrm{Ar}\ (\alpha,2\mathrm{p})\ ^{42}\mathrm{Ar}$

- ^{42}Ar content in **underground argon** shoud be estimated

Argon

Production of ^{42}Ar in underground argon

Production mechanisms:

- Two-step neutron capture: high neutron flux required due to short half-life of ^{41}Ar (1.8 h) $\rightarrow$ not possible underground
- (α,2p) reaction: zero σ values <15 MeV (TALYS2017) $\rightarrow$ not possible for α from radioactivity

$$^{40}\mathrm{Ar}\ (\alpha,2\mathrm{p})\ ^{42}\mathrm{Ar}$$

- Neutron reactions on Ca:

Isotope	Natural abundance (%)	Reaction	
43Ca	2.086	43Ca(n,2p)42Ar	Zero σ values <17 MeV (TALYS2017) $\rightarrow$ not possible for fission or (α,n) neutrons
44Ca	0.135	44Ca(n,n2p)42Ar	Zero σ values <23 MeV (TALYS2017) $\rightarrow$ not possible for fission or (α,n) neutrons

Precise estimate requires: neutron spectrum underground, Ca concentration in rock, emanation factor

Summary

- It must be determined if activation could be an issue for **gamma background** to help to identify limits on the surface residency time and assess the real necessity of taking some steps:
  - Storing materials underground
  - Avoiding flights
  - Using shields against the hadronic component of cosmic rays during surface detector building or operation.
- A rough estimate of activation yields in massive components like those made of **copper or steel** can be made quite easily from available production rates, its effect has to be evaluated by MC.
- New estimates of **^{39}Ar** production in **argon** are in reasonable agreement with previous estimates, confirming that the ^{39}Ar activation should be lower than the residual level quantified for UAr.
- An estimate of **^{42}Ar** underground production seems complicated as no relevant production channels have been identified.