Review of cosmogenic backgrounds and material activation

- Origin and quantification
- Studies on:
  - Surface activation
  - Underground activation
  - Cosmogenic backgrounds

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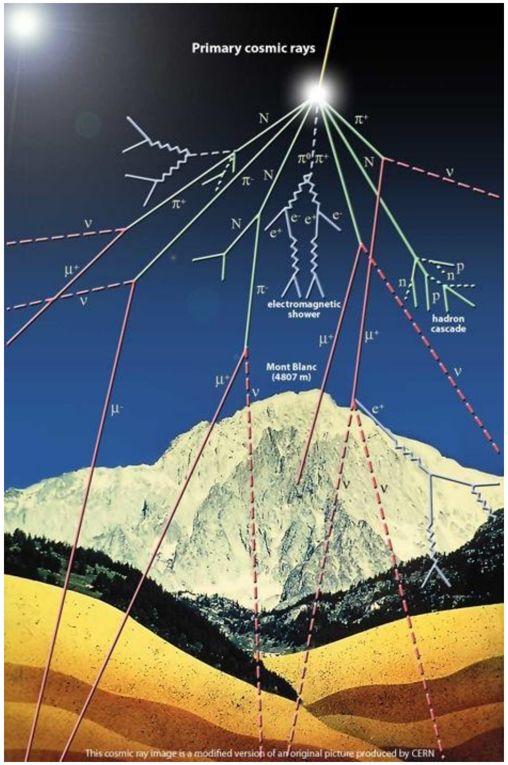
CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza
Facultad de Ciencias Universidad Zaragoza
ICTS Infraestructuras Científicas y Técnicas Singulares Laboratorio Subterráneo Canfranc

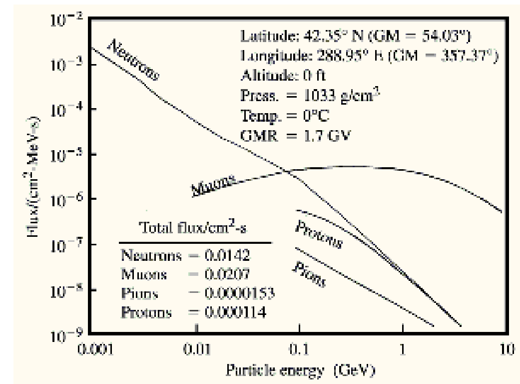
Cosmogenic backgrounds: origin



- **Primary cosmic rays:** ~90% p, 9% α, heavy nuclei totally attenuated in the upper atmosphere
- **Secondary cosmic rays** on the Earth surface $\pi^{\pm}$: p : $e^{\pm}$: n : $\mu^{\pm}$ observed with relative intensities 1 : 13 : 340 : 480 : 1420

Muon flux: ~10^2 m^{-2} s^{-1}
(mean energy ~4 GeV)

J.F. Ziegler, IBM J. R&D 42 (1998) 1



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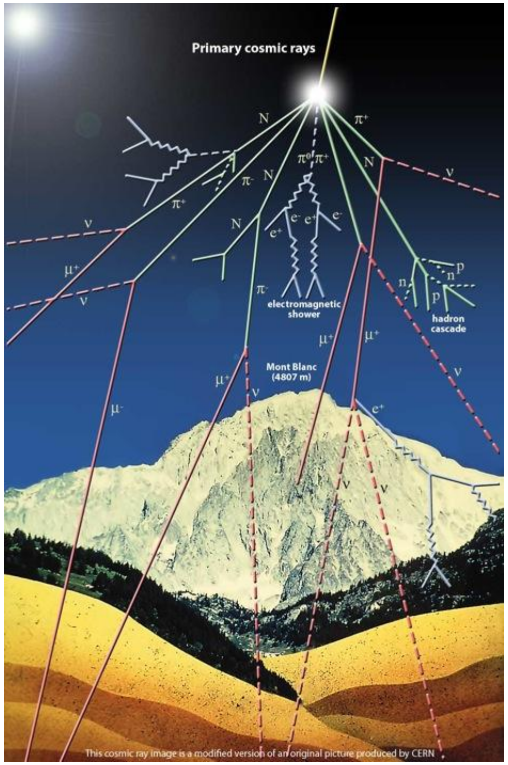

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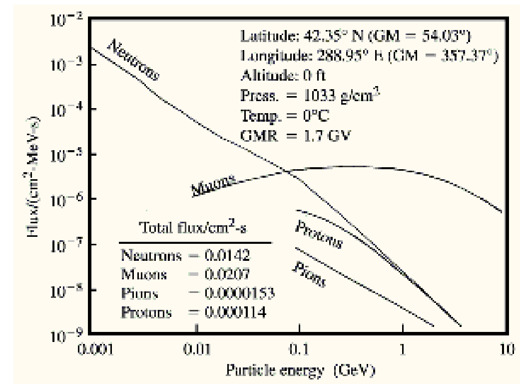
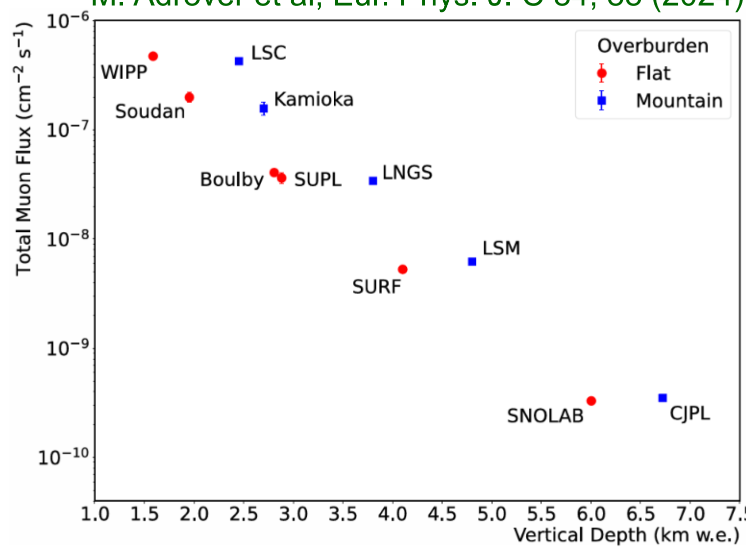


Only μ survive >15 m.w.e., flux reduced by orders of magnitude deeper

M. Adrover et al, Eur. Phys. J. C 84, 88 (2024)



Cosmogenic backgrounds: origin

Muonic background

- *Muon bremsstrahlung*, in high-Z shielding materials, contributes to low energy
- *Capture, spallation, photo-nuclear interactions* with nuclei or *inelastic scattering* can produce **neutrons** and **radioactivity** directly or indirectly

  $(\mu^- + p \rightarrow n + \nu_\mu)$.

  At any overburden, but with strongly depth-dependent rates!

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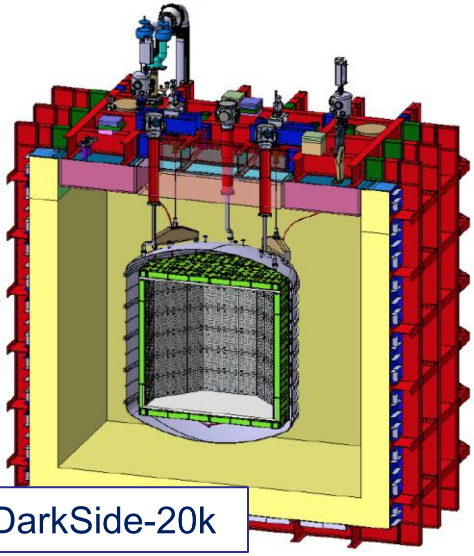
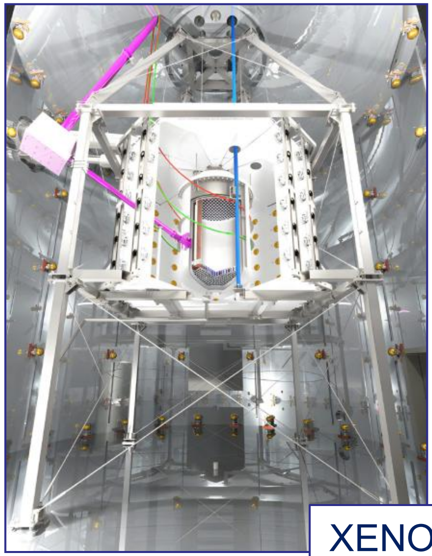
Muon vetos typically used at a cost of dead time but not for delayed backgrounds


ANAIS-112

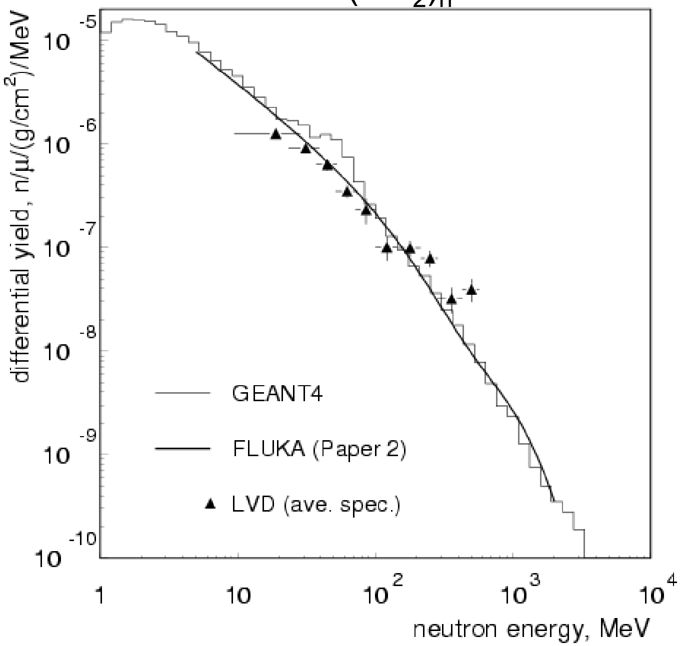

DarkSide-20k


XENONnT

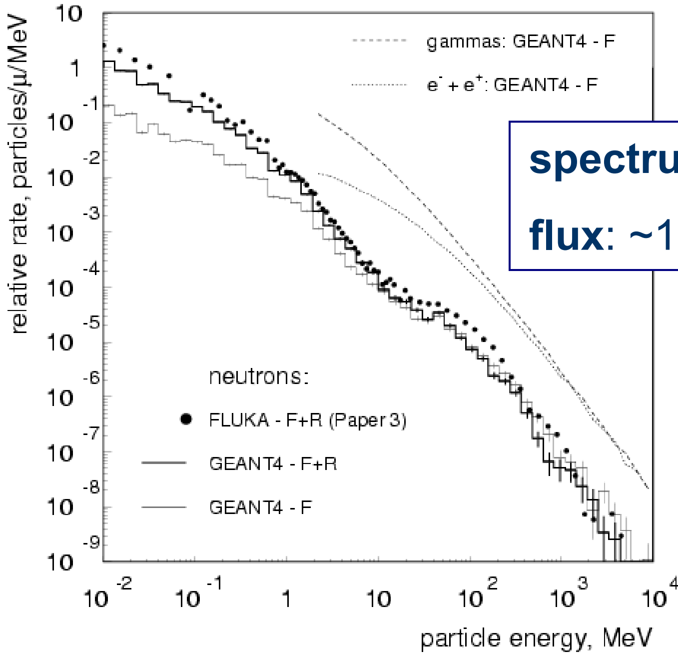
Cosmogenic backgrounds: origin

Cosmogenic neutrons induced by muons in rock and shieldings

in $(CH_2)_n$



at rock (NaCl) / cavern boundary



spectrum: up to GeV

flux: ~10^{-9} n/cm²/s (~3 km w.e.)

H. Araujo et al, NIMA 545 (2005) 398

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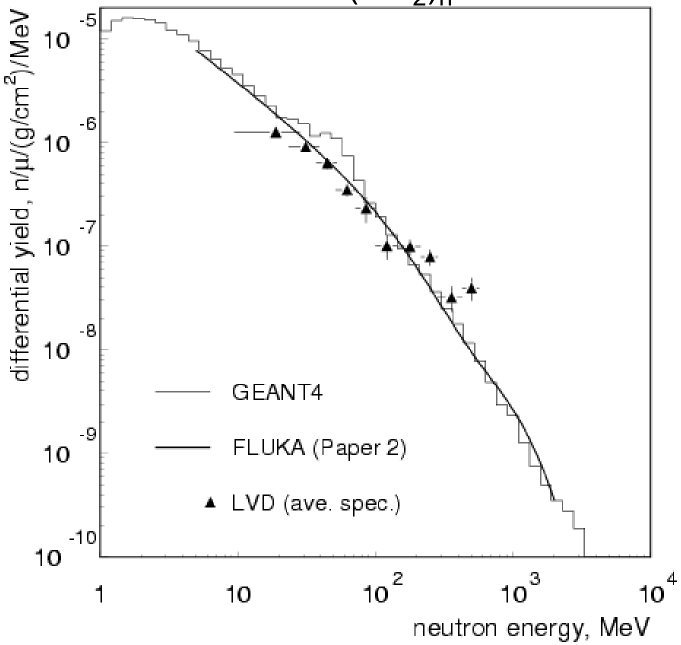

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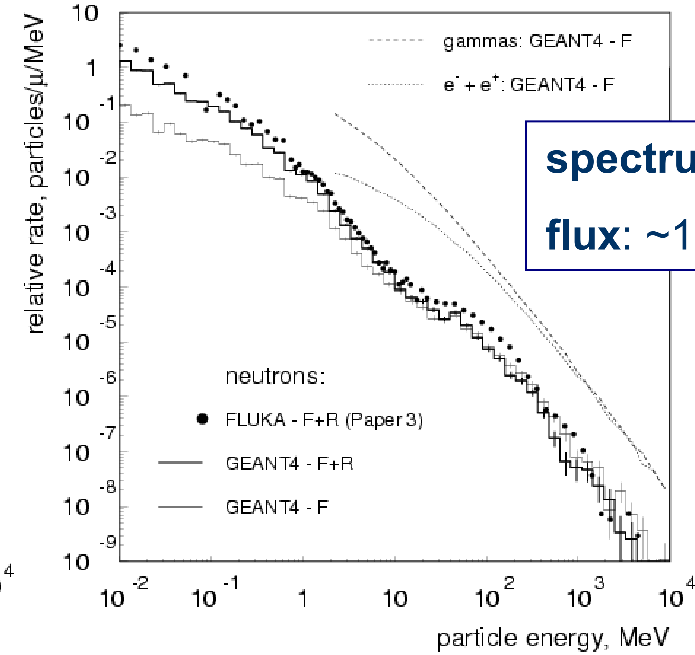

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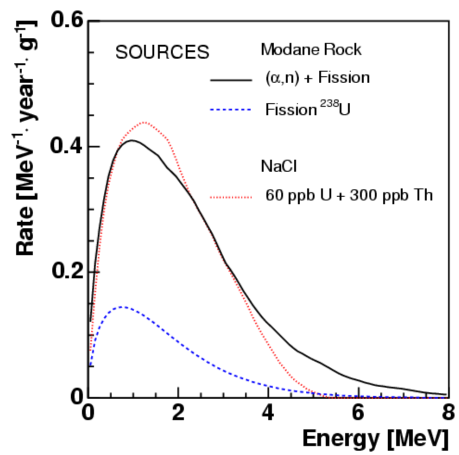
vs **radiogenic neutrons** by ^{238}U spontaneous fission and (α,n) reactions in rock and other light materials

spectrum: up to several MeV

flux: ~10^{-6} n/cm^2/s



Cosmogenic backgrounds: quantification

Calculations on **cosmogenic neutrons** allow to set requirements on muon flux and depth or veto capabilities

- Using just one code: to allow simultaneous detection of neutrons and other particles
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1. **Muon rate and distributions (E, θ):**
   measurements, analytical formulas and parametric fits, calculations from specific codes

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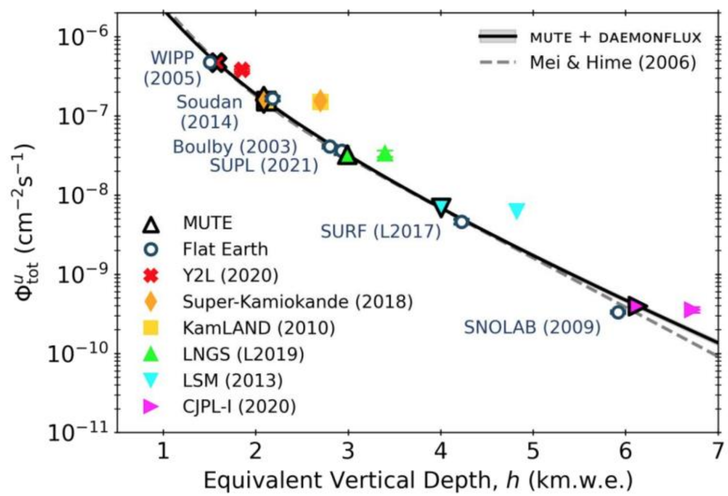
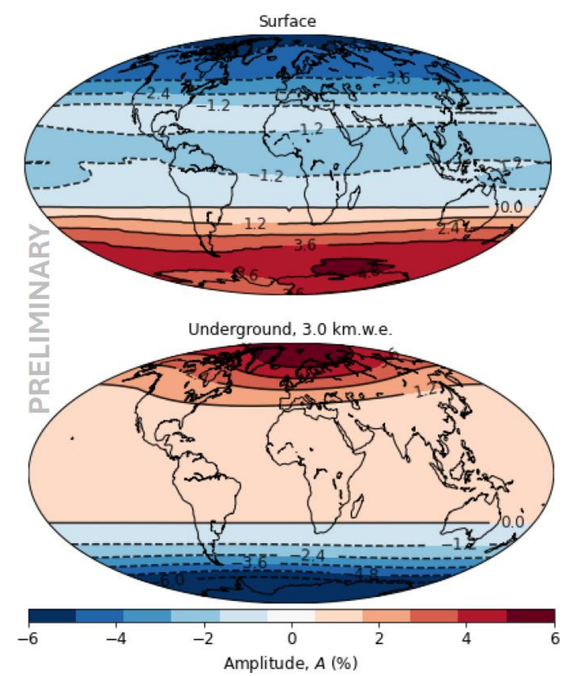
V. Kudryavstev, arXiv:0810.4635
W. Woodley et al, PoS (ICRC2023) 476
https://github.com/wjwoodley/mute





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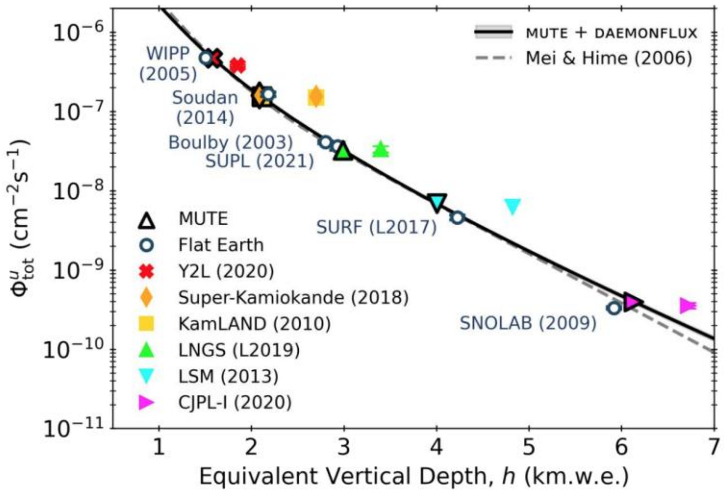
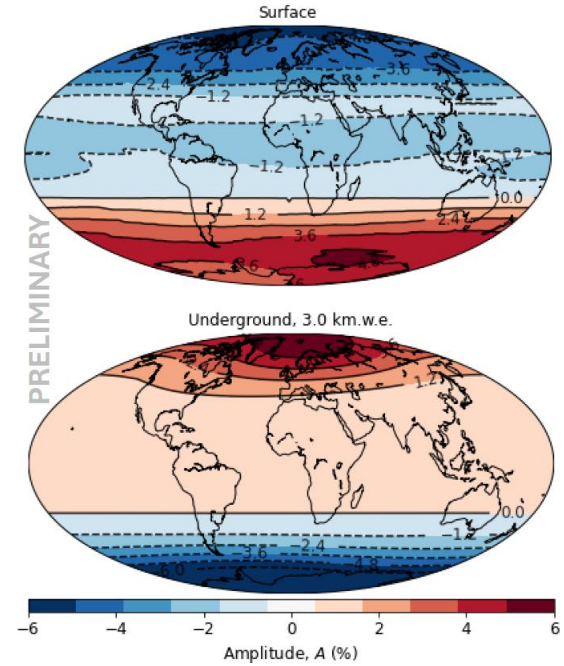
2. **Production, propagation and detection of neutrons**
   FLUKA, MCNPX, GEANT4





Cosmogenic activation: origin

Production of long-lived radioactive isotopes due to exposure to cosmic rays (**"cosmogenic activity"**) can be an hazard for ultra-low background experiments

- On the *Earth's surface*, dominated by **neutrons**; at *high altitude*, **proton** production also important
- **Muon** activation *deep underground* can also be relevant
    - Limited knowledge of cosmogenic activation considered one of the "*main uncertain nuclear physics aspects of relevance in the direct detection of dark matter*".

      P. Gondolo, Nucl. Data Sheets120 (2014) 175
    - Relevant also in different contexts: Astrophysics, Geophysics, or Archaeology

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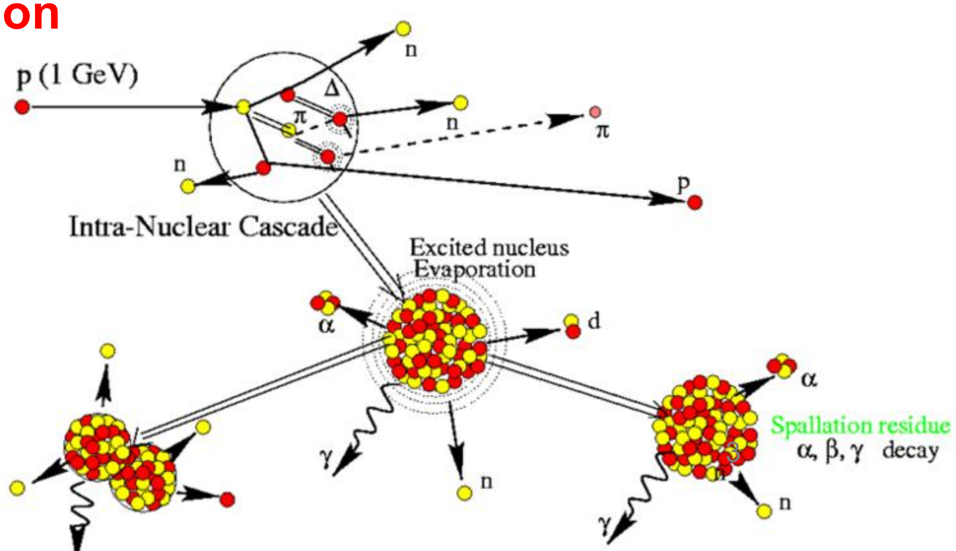
Processes of nucleon-nuclei interaction

- Low energies: formation and decay of a long-lived ***compound nucleus***
- GeV range: intranuclear cascade (**INC**) of nucleon-nucleon interactions followed by different deexcitation processes: ***spallation, fragmentation, break-up, fission***, …

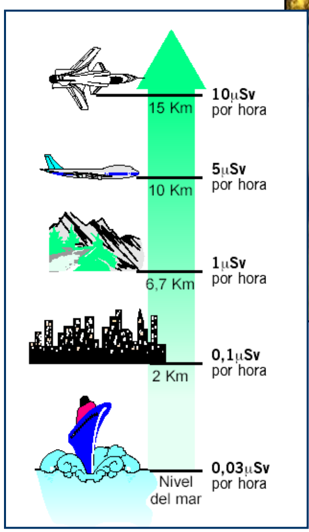


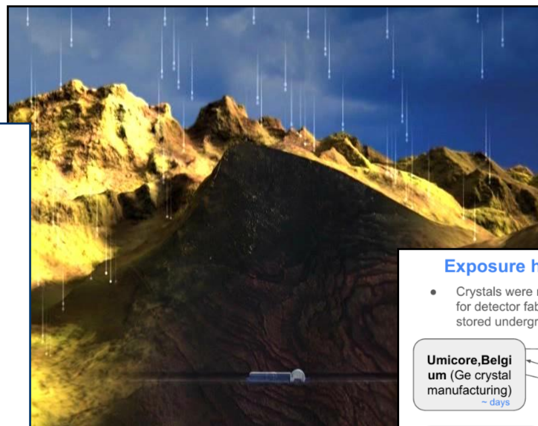
(from http://www-nds.iaea.org/spallations/)

Cosmogenic activation: mitigation

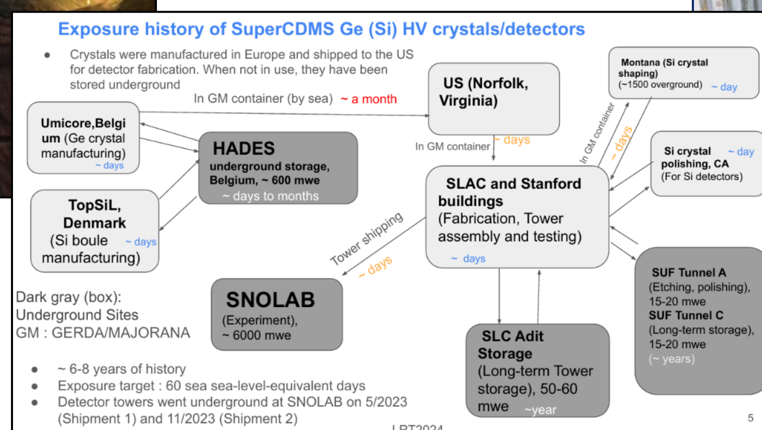
Avoid cosmic rays!

- Flights are forbidden
- Limit surface residency time during fabrication and transport of components
- Store, or even produce, materials underground D. Mei, arXiv:2409.03580
  Successful R&D for Ge crystal growth and detector fabrication
- Shielding against hadronic component of cosmic rays





S. Poudel, LRT2024



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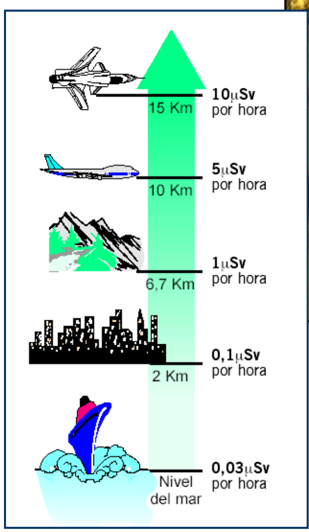

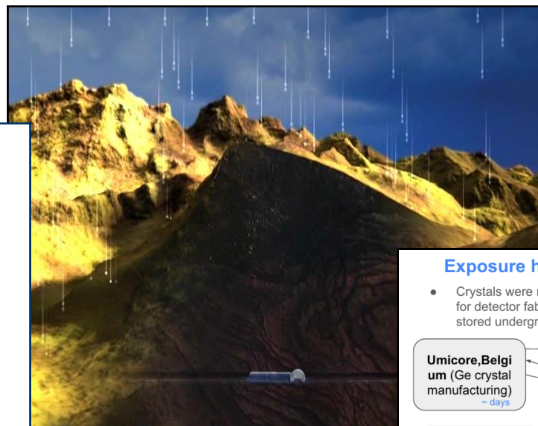

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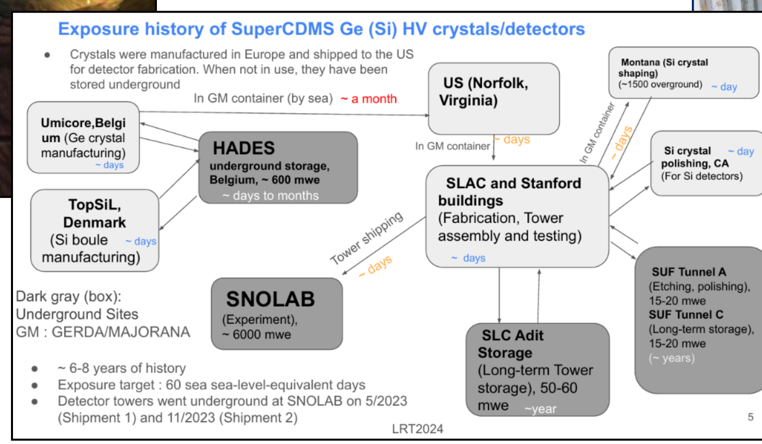

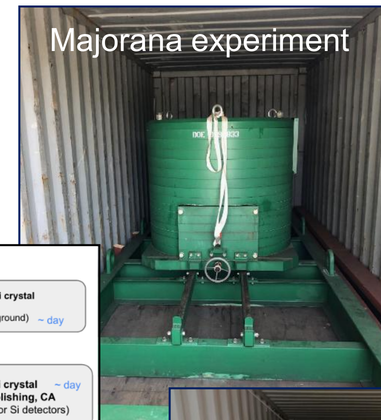

This complicates preparation of experiments → desirable to have reliable **estimates of activation yields** to assess real danger of cosmogenic activation

Cosmogenic activation: quantification

Recipe for estimates:

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

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

N_t = number of target nuclei

ϕ = flux of cosmic rays

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

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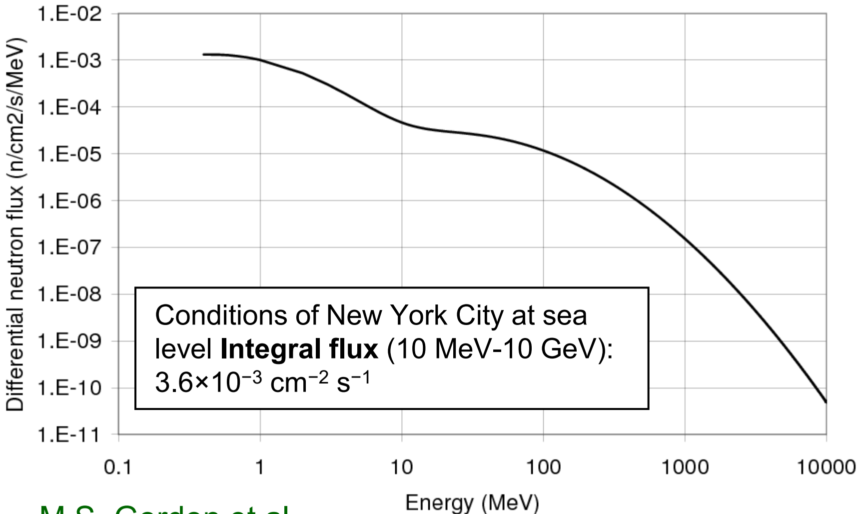
3. To compute the **background rate** generated by Monte Carlo simulation

Cosmogenic activation: flux of cosmic rays

At the Earth's surface nuclide production is dominated by **neutrons**

- Parametrization of **cosmic neutron spectrum** based on measurements on the ground across the US



M.S. Gordon et al,
IEEE Trans. Nucl. Sci. 51 (2004) 3427

Dependent on altitude and latitude
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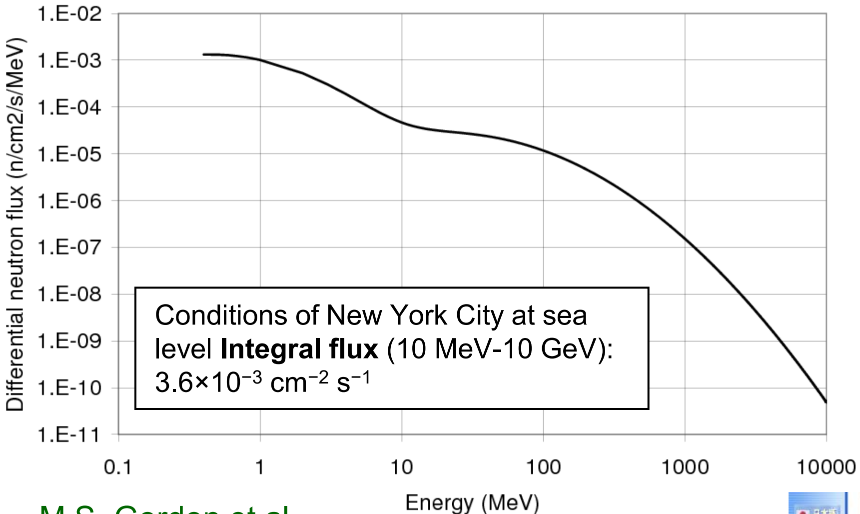

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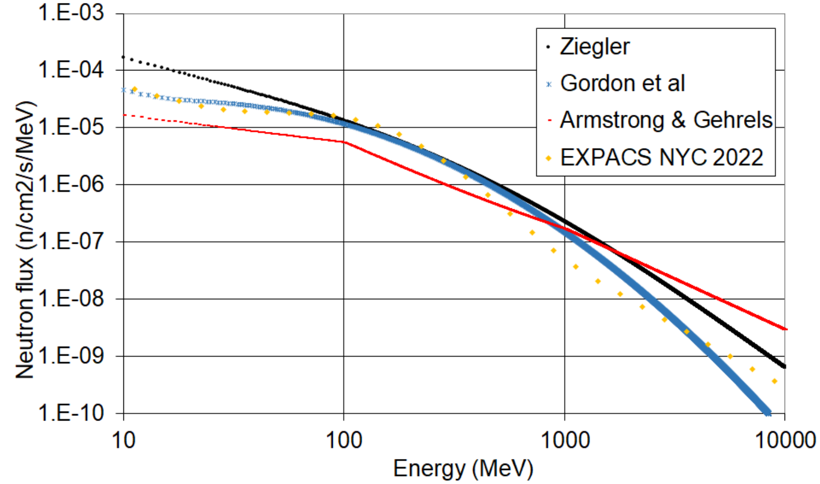
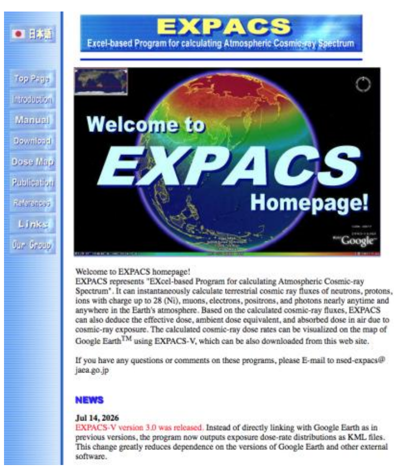
- Other descriptions available



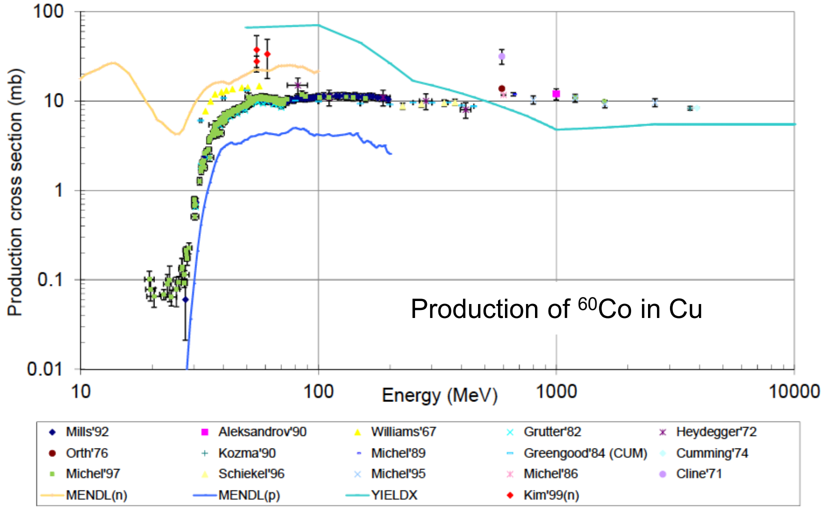


CRY (Cosmic-ray Shower Library) generator

EXPACS (EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum)
https://phits.jaea.go.jp/expacs/
to calculate terrestrial **fluxes** of **n, p**, light ions, **μ**, e+, e-, γ nearly ***anytime*** and ***anywhere*** in the Earth's atmosphere

Cosmogenic activation: cross sections

Select the best description of the **excitation function** $\sigma(E)$ by nucleons



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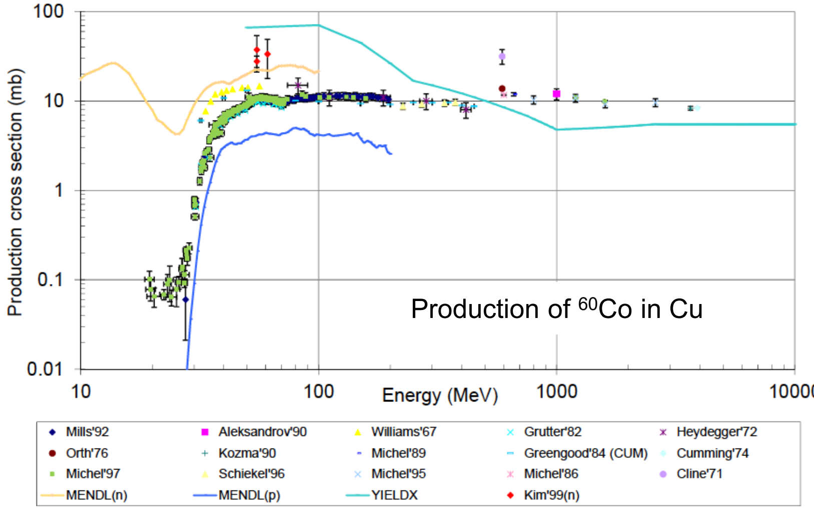
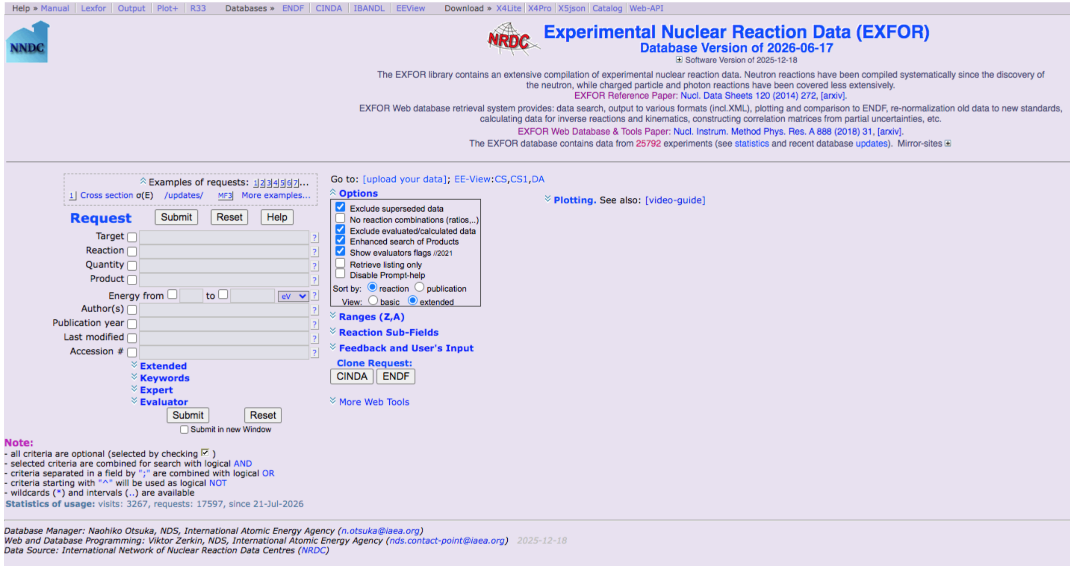


- **Experimental data**: from beam experiments, typically few data for neutrons

EXFOR (Experimental Nuclear Reaction Data) database
http://www-nds.iaea.org/exfor/exfor.htm



Cosmogenic activation: cross sections

- **Semiempirical formulae** (Silberberg&Tsao equations): targets A ≥3, products A ≥ 6 and E>100 MeV

COSMO written in FORTRAN with three modes of calculation

– **Excitation curve** of a specified nuclide for a specified target
– **Mass yield curve** for given target and energy
– **Activities** produced for a target exposed to cosmic rays

C. J. Martoff, P. D. Lewin, Computer Physics Comm. 72 (1992) 96

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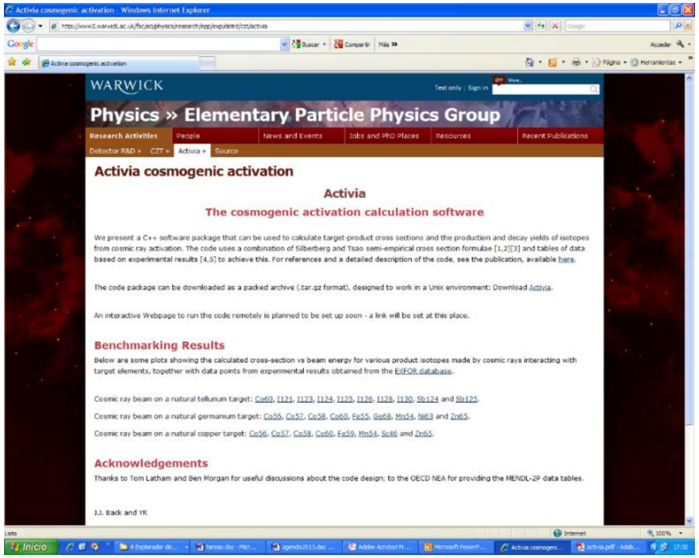
ACTIVIA C++ package to calculate

- **Target-product cross sections**
- **Production and decay yields** from cosmic ray activation

using semiempirical formulae but also experimental data tables if available

J. J. Back, Y. A. Ramachers, NIMA 586 (2008) 286



Cosmogenic activation: cross sections

- **Monte Carlo simulation:** standard packages (Geant4, FLUKA, …)

Specific codes for the interaction between nucleons and nuclei requiring the consideration of different reactions → libraries

GEM TALYS HMS-ALICE INUCL LAQGSM CEM ISABEL
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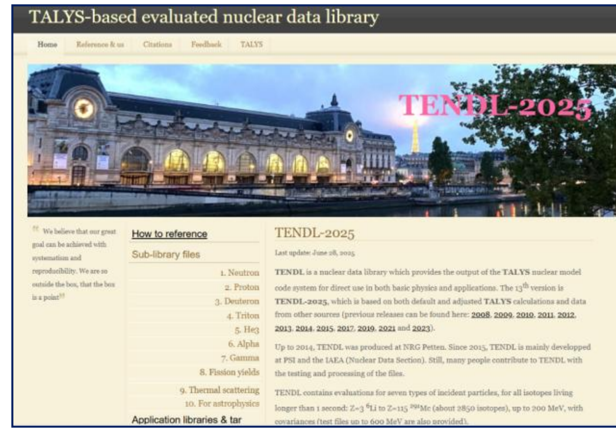

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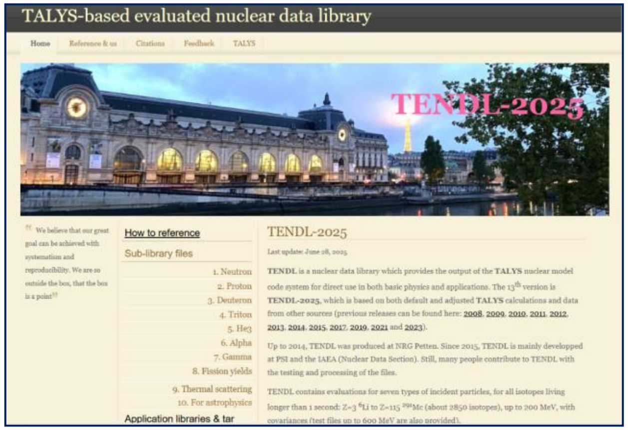

HEAD-2009 (High Energy Activation Data)
https://doi.org/10.1016/j.nima.2010.08.110

- Only for Z≥12
- Using a selection of models and codes dictated by an extensive comparison with EXFOR data
- For **protons from 150 MeV to 1 GeV**

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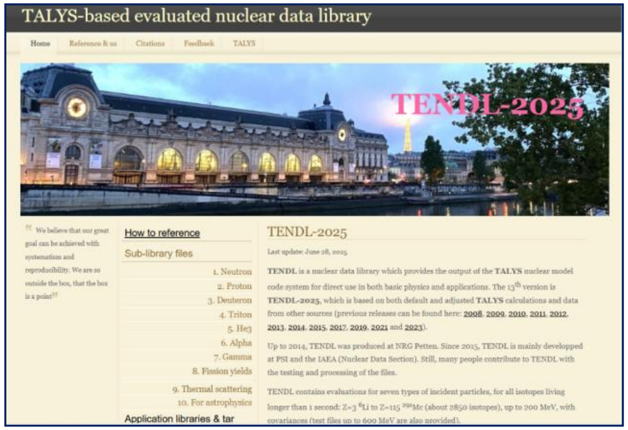

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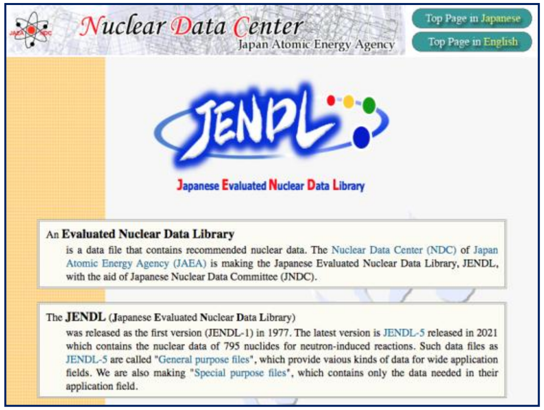
JENDL (Japanese Evaluated Nuclear Data Library)

https://wwwndc.jaea.go.jp/jendl/jendl.html

- Using GNASH code
- For **neutrons and protons up to 200 MeV,**

from **20 MeV to 3 GeV** in High Energy File



Review of cosmogenic backgrounds and material activation

- Origin and quantification
- Studies on:
  - Surface activation: Ar, NaI, Ge, Si, others
  - Underground activation
  - Cosmogenic backgrounds

CAPA Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

Facultad de Ciencias Universidad Zaragoza

ICTS Infraestructuras Científicas y Técnicas Singulares Laboratorio Subterráneo Canfranc

Surface activation: Ar

Relevant cosmogenic products

^{39}Ar: β^- emitter with Q=565 keV, **$T_{1/2}$=269 y** mainly produced by $^{40}\mathrm{Ar(n,2n)}^{39}\mathrm{Ar}$

Measured activity in

- **Atmospheric Ar:** ~1 Bq/kg (WARP, ArDM, DEAP)
- **Underground Ar:** (0.73±0.11) mBq/kg (DarkSide-50)

Surface activation: Ar

Relevant cosmogenic products

^{39}Ar: β^- emitter with Q=565 keV, **$T_{1/2}$=269 y** mainly produced by $^{40}\mathrm{Ar}(\mathrm{n,2n})^{39}\mathrm{Ar}$

Measured activity in

- **Atmospheric Ar:** ~1 Bq/kg (WARP, ArDM, DEAP)
- **Underground Ar:** (0.73±0.11) mBq/kg (DarkSide-50)

^{37}Ar: EC, $E_{e,K(L)\ shell}$=2.8 (0.27) keV, **$T_{1/2}$=35.02 d** mainly by $^{40}\mathrm{Ar}(\mathrm{n,4n})^{37}\mathrm{Ar}$

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^{42}Ar: β^- emitter, Q=599 keV, **$T_{1/2}$=32.9 y** producing **^{42}K** (β^- emitter, Q=3525 keV, $T_{1/2}$=12.4 h) → background for neutrinoless $\beta\beta$

In Atm Ar: DBA: 92^{+22}_{-46} μBq/kg
GERDA: 70-100 μBq/kg, 68^{+17}_{-32} μBq/kg
DEAP (40.4±0.5.9) μBq/kg

Produced by double n capture and $^{40}\mathrm{Ar}\ (\alpha,2\mathrm{p})\ ^{42}\mathrm{Ar}$

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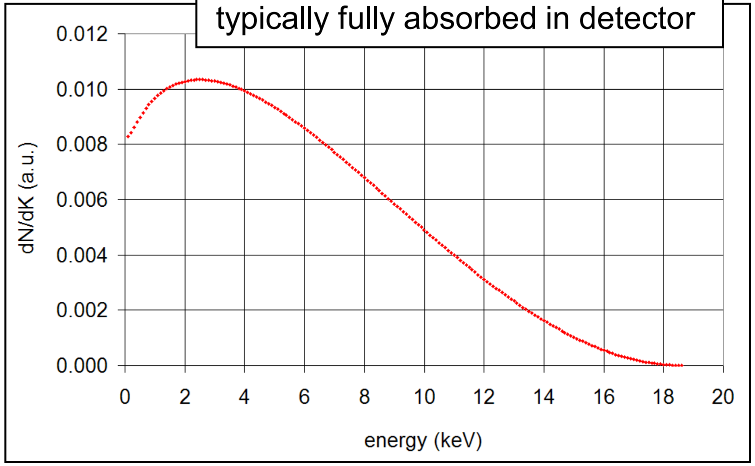
DEAP (40.4±0.5.9) μBq/kg

Produced by double n capture and $^{40}\mathrm{Ar}\ (\alpha,2p)\ ^{42}\mathrm{Ar}$

^{3}H: pure β^- emitter, with Q=18.6 keV, **$T_{1/2}$=12.3 y**
Purification should remove non-noble nuclides

Super-allowed beta spectrum:
57% electrons in 1-7 keV,
typically fully absorbed in detector



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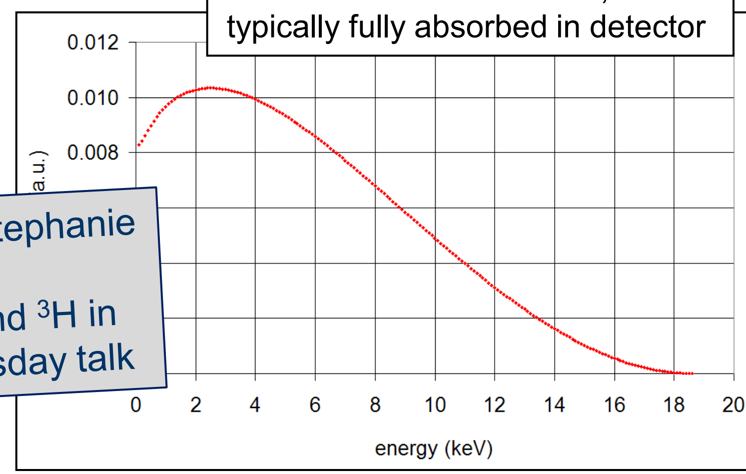
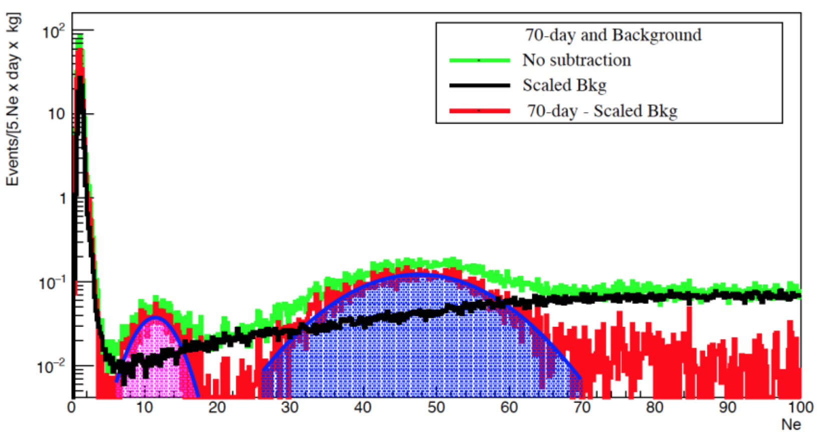


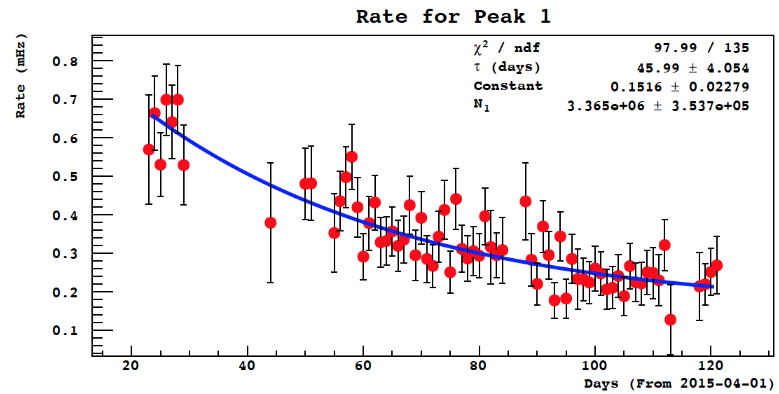
- "Towards Low-Level Tritium Background Quantification", Stephanie Lyons, Poster
- "Rapid low-background radioassay techniques for ^{210}Pb and ^{3}H in materials for rare-event searches", Marco Consonni, Thursday talk

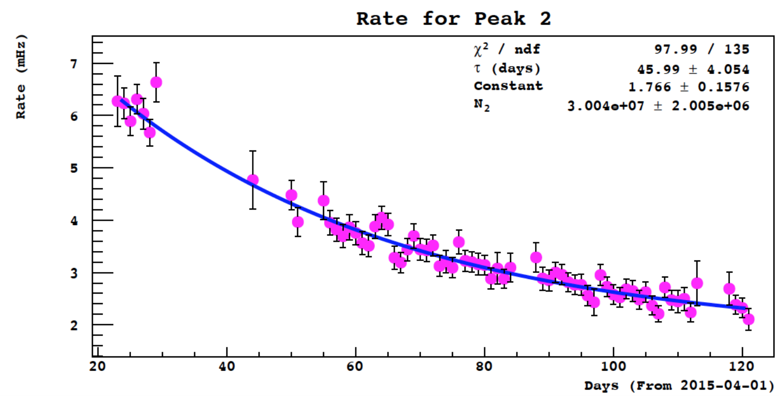
Surface activation: Ar

Activity of ^{37}**Ar** determined for **DarkSide-50** I. Ahmad, PhD thesis, AstroCENT, Warsaw, 2024

- UAr transported from Colorado to LNGS in two batches: 141.7 kg by ship, 16 kg by airplane.
- Time evolution of K- and L-shell peaks analyzed over 70+500 days, using 1-day bins







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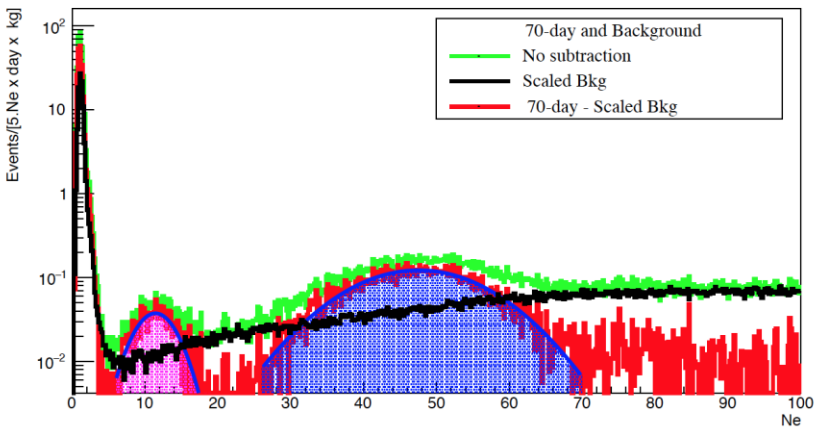

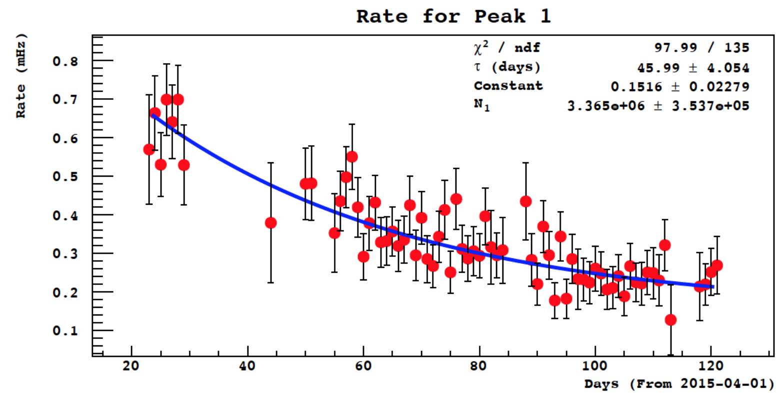

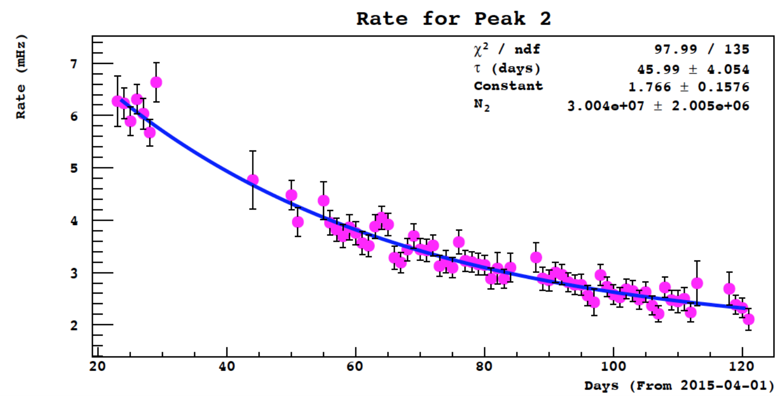

Branching Ratio L/K	0.09±0.03
Activity [L+K] (mBq/kg)	0.44±0.039
Activity [L+K+M] (mBq/kg)	0.45±0.039

- B.R.consistent with other measurements (0.1) and within 1σ with activity estimation

$$0.51^{+0.11}_{-0.07}\ \mathrm{mBq/kg\ for\ }^{37}\mathrm{Ar\ and\ } 0.21^{+0.07}_{-0.09}\ \mathrm{mBq/kg\ for\ }^{3}\mathrm{H}$$

T. Vallivilavyl, PhD thesis, GSSI, 2023

Surface activation: Ar

Production rates R of ^{39}Ar and ^{37}Ar

- First measurement in an **irradiation experiment** at Los Alamos (LANSCE) with a wide-band **neutron beam** that resembles the cosmic n flux, quantifying products with a proportional counter at PNNL
  + calculations at sea level from alternate mechanisms

R. Saldanha et al, Phys. Rev. C. 100 (2019) 024608

Reaction	Estimated ^{39}Ar production rate [atoms/(kg$_{Ar}$day)]	Fraction of total AAr (%)
^{40}Ar (n, 2n)^{39}Ar+ ^{40}Ar(n, d)^{39}Cl	759 ± 128	72.3
^{40}Ar (μ, n)^{39}Cl	172 ± 26	16.4
^{40}Ar (γ, n)^{39}Ar	89 ± 19	8.5
^{40}Ar (γ, p)^{39}Cl	23.8 ± 8.7	2.3
^{40}Ar (p, 2p)^{39}Cl	<0.1	<0.01
^{40}Ar (p, pn)^{39}Ar	3.6 ± 2.2	0.3
^{38}Ar(n, γ)^{39}Ar	≪ 0.1 (UAr)	–
	1.1 ± 0.3 (AAr)	0.1
Total	1048 ± 133	100

Reaction	Estimated ^{37}Ar production rate [atoms/(kg$_{Ar}$day)]
^{40}Ar (n, 4n)^{37}Ar	51.0 ± 7.4
^{40}Ar (γ, 3n)^{37}Ar	3.5 ± 0.7
^{40}Ar (p, p3n)^{37}Ar	1.3 ± 0.4
^{36}Ar(n, γ)^{37}Ar	0.9 ± 0.3 (UAr) 36 ± 11 (AAr)
^{38}Ar(n, 2n)^{37}Ar+ ^{38}Ar(γ, n)^{37}Ar+ ^{38}Ar(p, pn)^{37}Ar	<0.05 (UAr) 0.43 ± 0.05 (AAr)
Total	56.7 ± 7.5 (UAr) 92 ± 13 (AAr)

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- Rates for ^{37}**Ar,** ^{39}**Ar** and ^{42}**Ar** from n, p and μ estimated by **GEANT4** simulation

C. Zhang, D.M. Mei, Astropart. Phys. 142 (2022) 102733

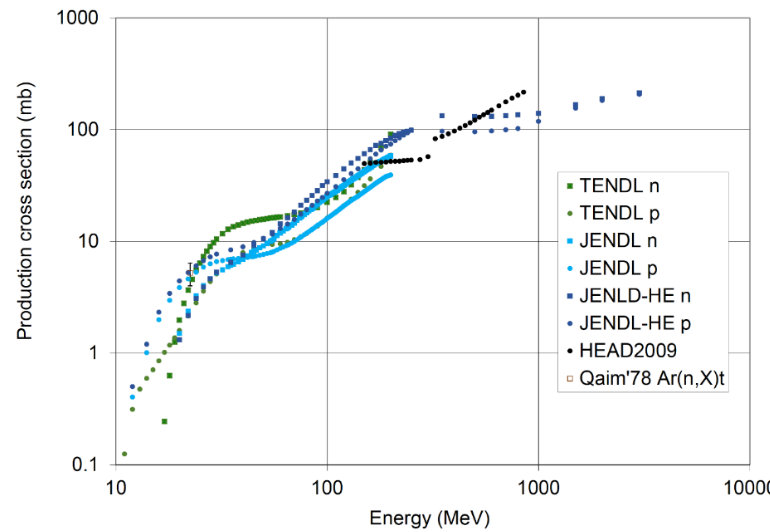
Surface activation: Ar

Production rates R of ^{39}**Ar** and ^{37}**Ar**

DarkSide-20k Col., Astropart. Phys. 152 (2023) 102878; 2024 JINST 19 C02011

- Calculations for **DarkSide-20k** also for ^{3}**H**

	R (atoms/kg/day)
TENDL	115.1
HEAD2009	177.2
JENDL-HE	221.6
Estimated rate in this work	168 ± 53
Not used for estimation:	
TALYS [16]	44.4
GEANT4 [33]	84.9
ACTIVIA [33]	82.9



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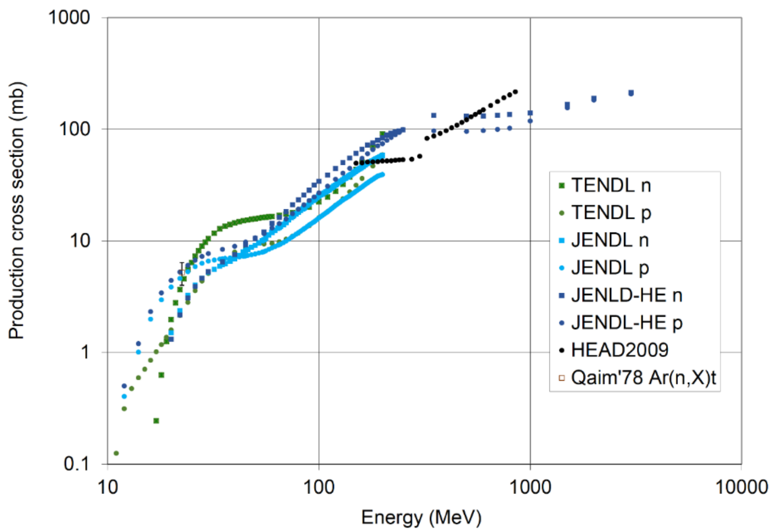

Activity A for **DarkSide-20k** from measured R for ^{37}Ar, ^{39}Ar and estimated R for ^{3}H assuming realistic exposure at URANIA → ARIA → LNGS

Isotope	Activity (μBq/kg)
^{39}Ar	20.7 ± 2.8
^{37}Ar	103 ± 14
^{3}H (1)	76 ± 24
^{3}H (2)	2.97 ± 0.94

(1) and (2): no / ideal purification

Tolerable residual level of 2.8% of quantified activity of ^{39}Ar in DarkSide-50

- "Production of Radiopure Argon for the DarkSide-20k Dark Matter Experiment: The Aria and Urania Projects", Celine Hidalgo, Monday talk
- "DArT-in-ArDM: A Dedicated Detector for 39Ar Characterization in Underground Argon", Sara Tullio, Tuesday talk

Surface activation: Ar

From GERDA and LEGEND data, drift of **^{42}K** to Ge detectors inmersed in LAr becomes a relevant background requiring mitigation techniques, as PSD and anticoincidence

→ Production of **high activity ^{42}Ar sources** injected to LAr needed to have enough statistics in background suppression studies for **LEGEND-1000**

M. Schwarz, NIMA 1087 (2026) 171434

"K-42 mitigation studies in Ar-42-spiked liquid argon for LEGEND", Christoph Vogl, Monday talk

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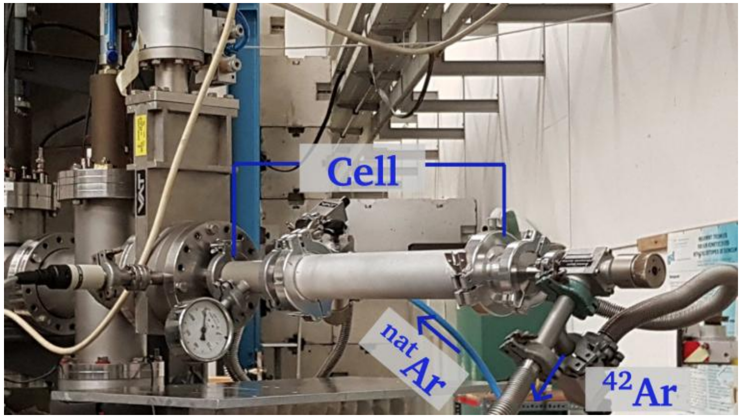
- **Production** of ^{42}**Ar** at a tandem accelerator at Garching irradiating gaseous ^{nat}Ar with ^{7}Li ions (34 MeV): (477±9) Bq, ~10^{6} atoms/s



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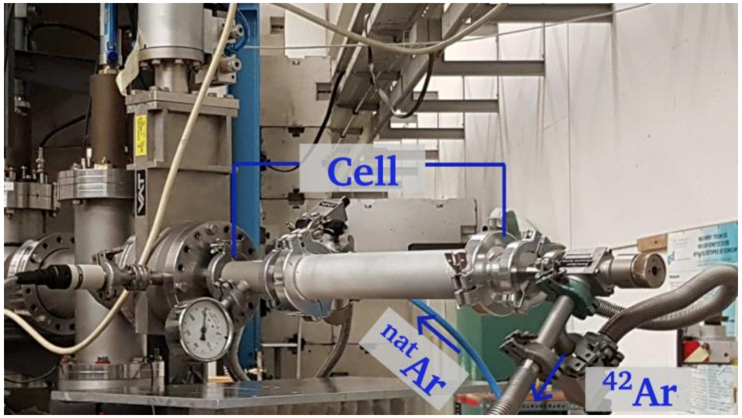
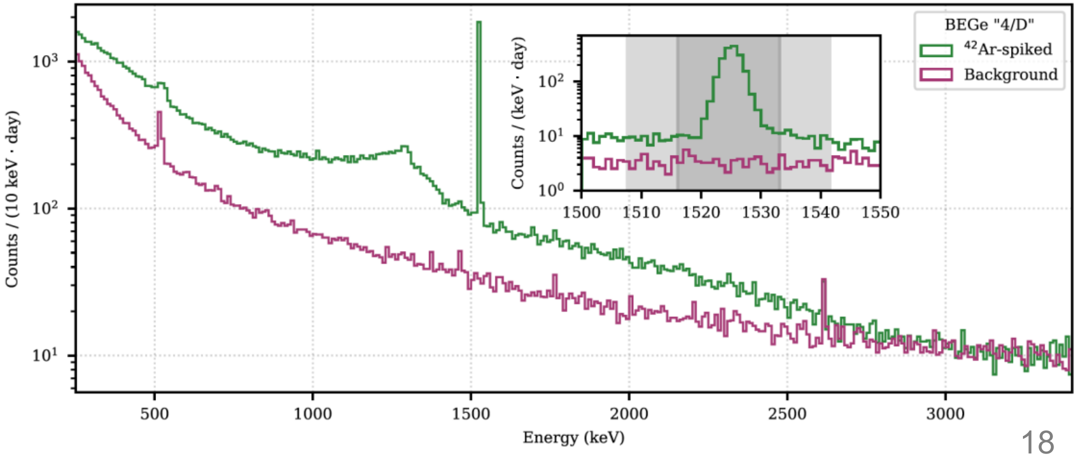


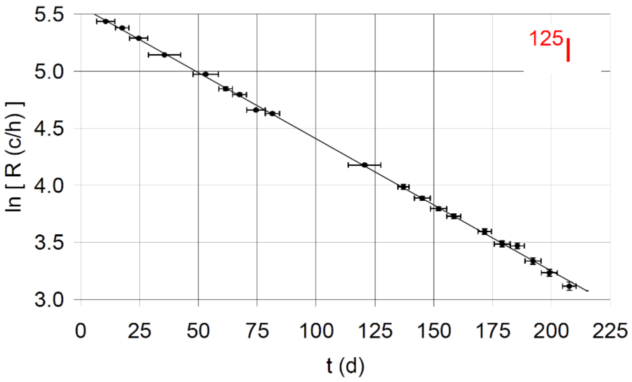
- **Injection** of ^{42}Ar into SCARF facility: 1 t LAr at TUM (15 m.w.e.) with two HPGe detectors for R&D: 0.43 Bq/kg, factor ~5000 higher than in Atm LAr



Surface activation: NaI

- From data of anual modulation DM experiments **ANAIS-112** and **COSINE-100, production rates** of **I**, **Te** isotopes, **^{22}Na, ^{109}Cd, ^{113}Sn** in NaI(Tl) crystals of known history derived from analysis of decaying signals

J. Amaré et al, JCAP 02 (2015) 046, P. Villar et al, IJMPA 33 (2018) 1843006; E. Barbosa et al, Astropart. Phys.115 (2020) 102390



Production rates in kg^{-1}d^{-1}

Isotope	Half-life[38,40]	Calculation[33]	ANAIS measurement[33]	ACTIVIA[34]	DM-Ice17 measurement[34]
^{126}I	12.93 d	297.0	283 ± 36	128	
^{125}I	59.407 d	242.3	220 ± 10	221	230
^{124}I	4.176 d	135.9			
^{127m}Te	106.1 d	7.1	10.2 ± 0.4	93	< 9
^{125m}Te	57.4 d	41.9	28.2 ± 1.3	74	27
^{123m}Te	119.3 d	33.2	31.6 ± 1.1	52	21
^{123}Te	$>10^{13}$ y	10.2			
^{121m}Te	164 d	23.8	23.5 ± 0.8	93	25
^{121}Te	19.16 d	8.4	9.9 ± 3.7	93	
^{113}Sn	115.09 d	9.9	6.8 ± 1.6	9.0	16
^{109}Cd	461.9 d	1.6	2.0 ± 0.6	4.8	
^{22}Na	2.6029 y	53.6	45.1 ± 1.9	66	

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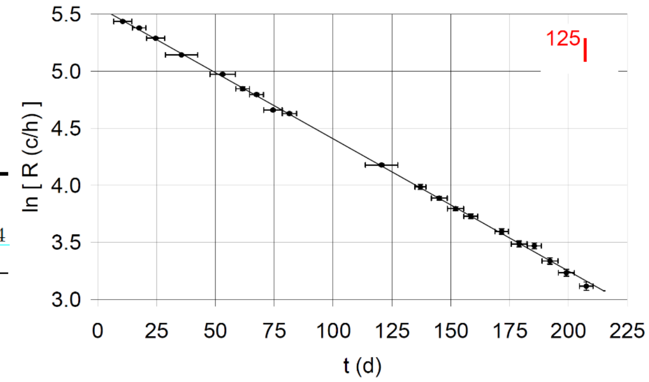
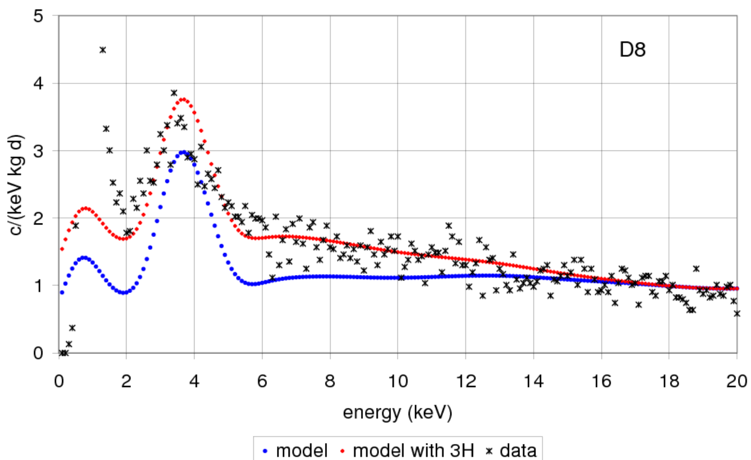


^{3}H: additional background source required in the very low energy region



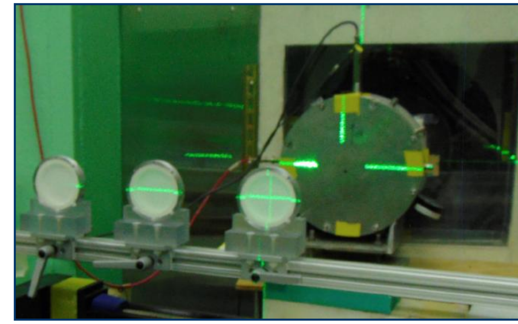
Surface activation: NaI

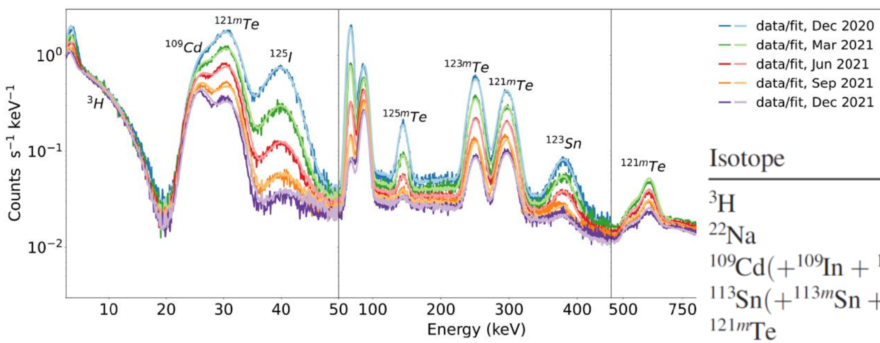
- Results from **neutron beam irradiation** at **Los Alamos** of NaI detectors to derive **production rates**, including **^{3}H** for the first time

Cosmogenic activation of Sodium Iodide

Pacific Northwest National Laboratory, Los Alamos National Laboratory, Australian National University, Yale, Illinois

Phys. Rev. D 107, 022006 (2023)
arXiv:2209.14898

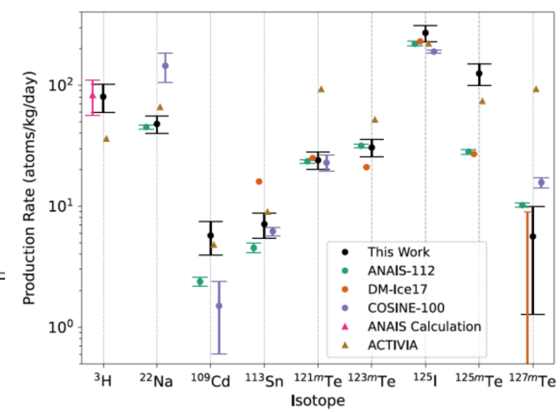




Previous calculation: 83 ± 27 kg^{-1}d^{-1}

J. Amare et al, Astropart. Phys. 97 (2018) 96

Isotope	(atoms/kg/day)
^{3}H	80 ± 21
^{22}Na	47.8 ± 7.8
^{109}Cd($+^{109}$In $+ ^{109}$Sn)	5.7 ± 1.8
^{113}Sn($+^{113m}$Sn $+ ^{113}$Sb $+ ^{113}$Te)	7.1 ± 1.7
^{121m}Te	24.0 ± 3.9
^{123m}Te	30.5 ± 5.0
^{125}I	271 ± 42
^{125}Sb($+^{125}$Sn)	2.53 ± 0.55
^{125m}Te	125 ± 25
^{127m}Te	5.6 ± 4.4



→ Reasonable agreement between different estimates

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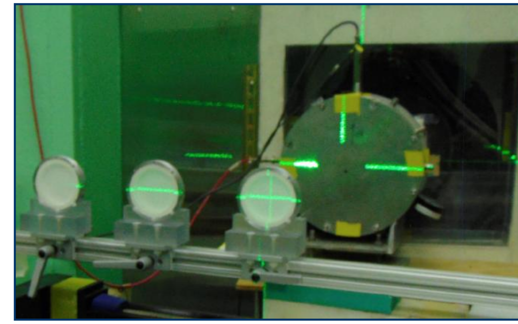

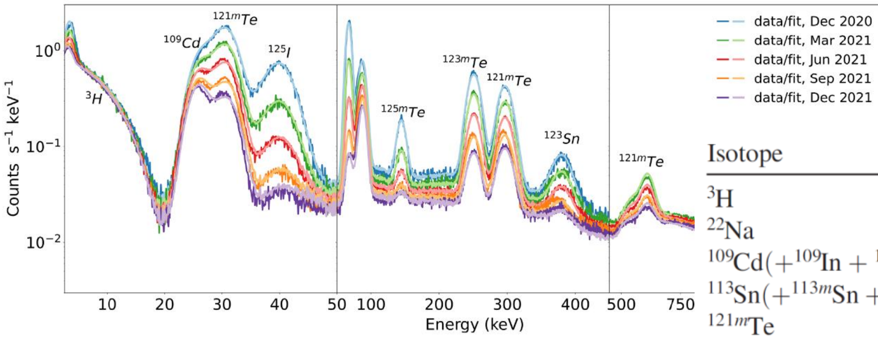

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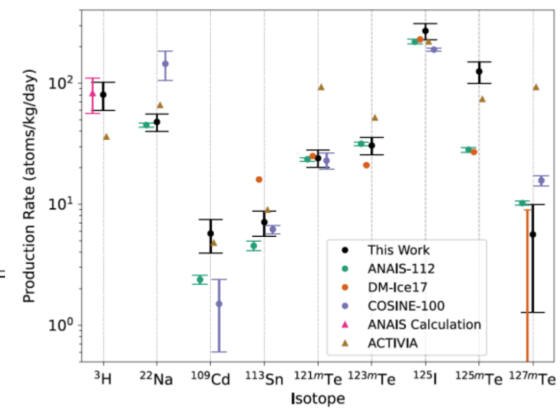


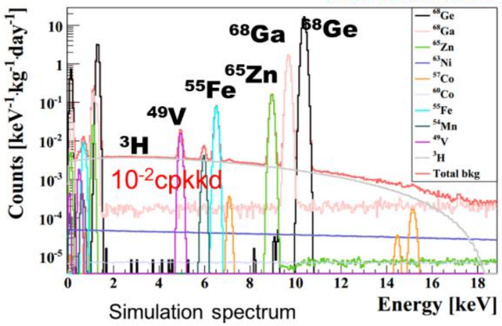
→ Reasonable agreement between different estimates

- Proposal from Australia for **muon beam irradiation** (3 GeV) at **CERN** of a NaI(Tl) detector followed by direct counting or Ge screening

Surface activation: Ge

- Widely used in detectors for DM, ββ, radioassay
- **Co isotopes** produced together with **^{65}Zn, ^{54}Mn** and Ge isotopes (e.g. **^{68}Ge**)

arXiv1802.09327



Simulation spectrum

Natural Ge

Production rates in kg^{-1}d^{-1}

	^{3}H	^{49}V	^{54}Mn	^{55}Fe	^{57}Co	^{58}Co	^{60}Co	^{65}Zn	^{68}Ge
Half-life [27,108] units	12.312(25) y	330 d d	312.19(3) y	2.747(8) d	271.81(4) d	70.85(3) y	5.2711(8) d	244.01(9) d	270.95(26)
Measurement [92]			3.3 ± 0.8		2.9 ± 0.4	3.5 ± 0.9		38 ± 6	30 ± 7
Meas. (EDELWEISS) [100]	82 ± 21	2.8 ± 0.6		4.6 ± 0.7				106 ± 13	>71
Meas. (CDMSlite) [101]	74 ± 9			1.5 ± 0.7				17 ± 5	30 ± 18
Monte Carlo [92]	210		2.7		4.4	5.3		34.4	29.6
Monte Carlo [93]					0.5	4.4	4.8	30.0	26.5
Sigma [95]			9.1	8.4	10.2	16.1	6.6	79.0	58.4
SHIELD [44]							2.9		81.6
TALYS [94]	27.7		2.7	8.6	13.5		2.0	37.1	41.3
TALYS+INCL++-ABLA [101]	95			5.6				51	49
MENDL+YIELDX [43]			5.2	6.0	7.6	10.9	3.9	63	60
TENDL+HEAD[28]	75±26								
ACTIVIA [36]			2.7	3.4	6.7	8.5	2.8	29.0	45.8
ACTIVIA [100]	46	1.9		3.5				38.7	23.1
ACTIVIA (MENDL-2P) [100]	43.5	1.9		4.0				65.8	45.0
ACTIVIA [45]	52.4		2.8	4.1	8.9	11.4	4.1	44.2	24.7
ACTIVIA [99]	30		3		6		3	20	10
GEANT4 [45]	47.4		2.0	7.9	7.4	5.7	2.9	75.9	182.8
GEANT4+CRY [91]	23.7	1.4	0.94	4.2	4.7		1.5	40.5	83.1
GEANT4+CRY [98]	21.6			2.9			0.9	27.7	63.6
CONUS [99]	50		5		7		4	60	66
CONUS experiment					9.0 ± 1.0			60 ± 10	200 ± 30

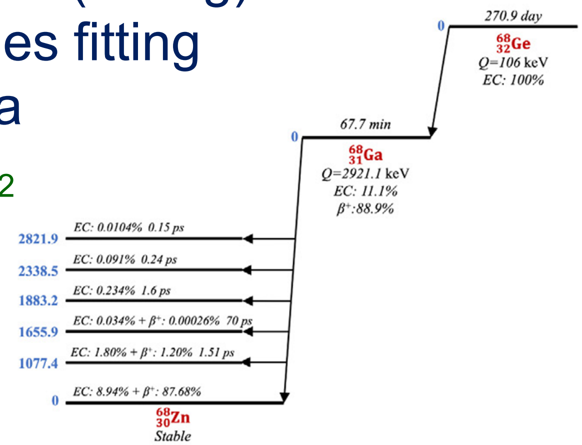
Evaluation of ^{68}**Ge** and daughter ^{68}**Ga** **activity** in a HPGe detector (2.5 kg) at Jinping lab via a time series fitting method from 90 days data

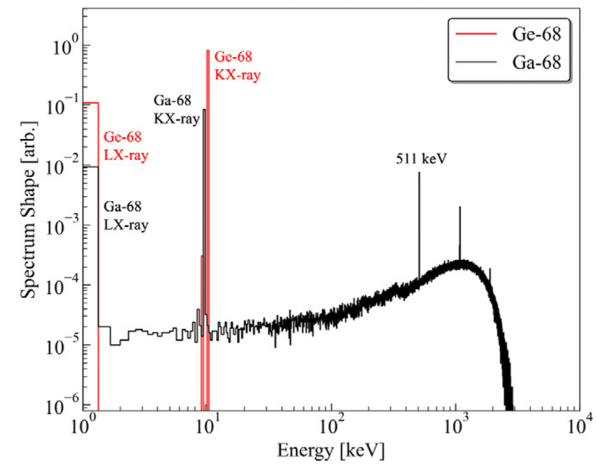
W. H. Dai et al, NIMA 1076 (2025) 170472

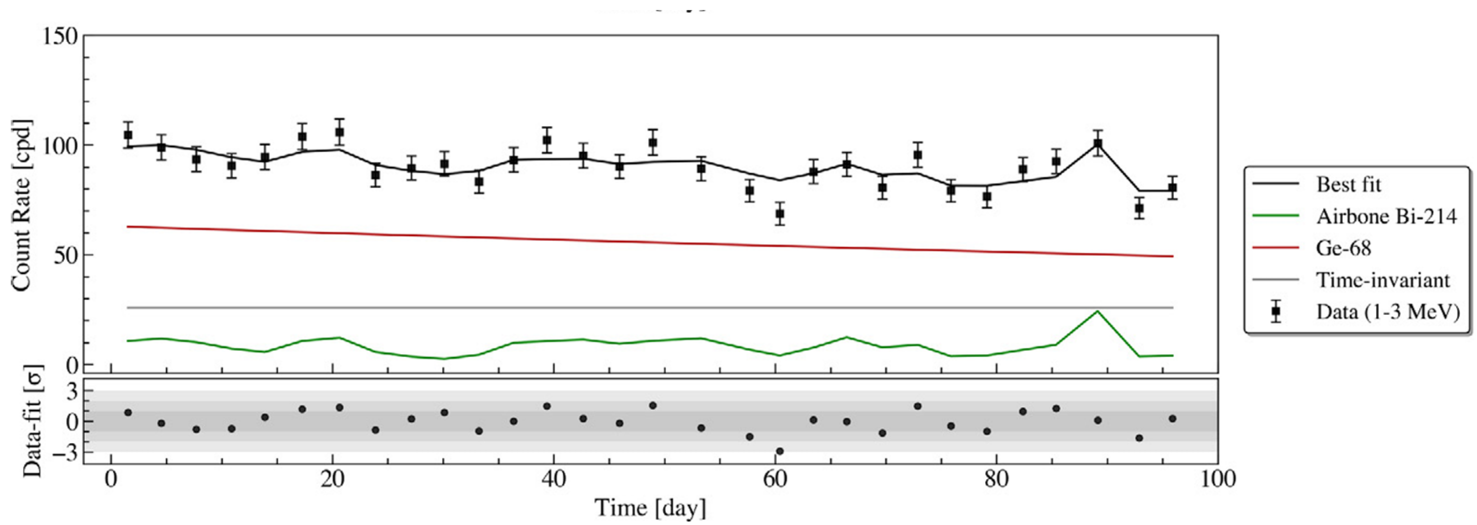
477.0±112.4μBq/kg

55.9 count/day

(62% at 1-3 MeV)



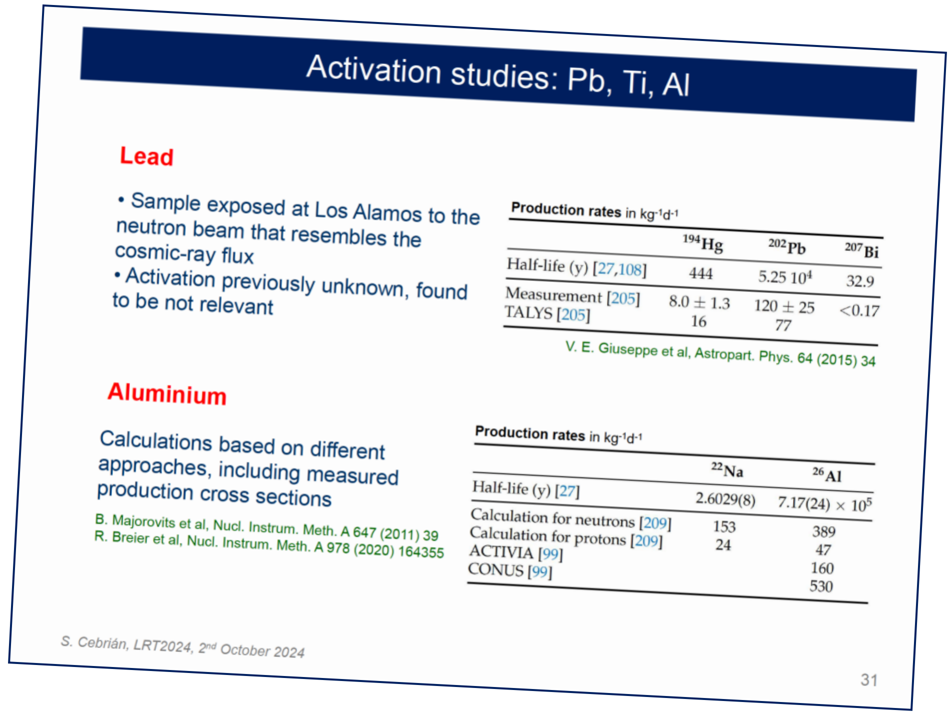




Surface activation: other targets

Production rates evaluated for many other targets from measurements and calculations
(see compilation from LRT2024 as extra slides)

- Detector targets:
  Xe, Si, Te, Mo, $CdWO_4$
- Other materials:
  Cu, Steel, Ti, Pb, Al



Activation studies: Pb, Ti, Al

Lead

- Sample exposed at Los Alamos to the neutron beam that resembles the cosmic-ray flux
- Activation previously unknown, found to be not relevant

Production rates in $kg^{-1}d^{-1}$

	^{194}Hg	^{202}Pb	^{207}Bi
Half-life (y) [27,108]	444	$5.25\ 10^4$	32.9
Measurement [205]	8.0 ± 1.3	120 ± 25	<0.17
TALYS [205]	16	77	

V. E. Giuseppe et al, Astropart. Phys. 64 (2015) 34

Aluminium

Calculations based on different approaches, including measured production cross sections

B. Majorovits et al, Nucl. Instrum. Meth. A 647 (2011) 39
R. Breier et al, Nucl. Instrum. Meth. A 978 (2020) 164355

Production rates in $kg^{-1}d^{-1}$

	^{22}Na	^{26}Al
Half-life (y) [27]	2.6029(8)	$7.17(24) \times 10^5$
Calculation for neutrons [209]	153	389
Calculation for protons [209]	24	47
ACTIVIA [99]		160
CONUS [99]		530

S. Cebrián, LRT2024, 2nd October 2024

31

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31

Irradiation of archeological Pb and $PbWO_4$ crystals with a neutron beam at UK followed by gamma spectroscopy measurements over a year to get residual **activity** within **RES-NOVA** project

"Cosmogenic activation of archeological Pb-based crystals at ChipIr neutron beamline for the RES-NOVA experiment", Simone Quitadamo, Poster

Review of cosmogenic backgrounds and material activation

- Origin and quantification
- Studies on:
  - Surface activation: Ar, NaI, Ge, Si, others
  - Underground activation
  - Cosmogenic backgrounds

CAPA Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza
Facultad de Ciencias
Universidad Zaragoza
ICTS Infraestructuras Científicas y Técnicas Singulares
Laboratorio Subterráneo Canfranc

Underground activation: shallow depth

First calculation of **production rates** of **^{3}H** in **Ge** and **Si** and **^{60}Co** in **Cu** at shallow depths within **SuperCDMS**

S. Poudel et al, arXiv:2605.16534

Multiple competing **physical processes** contributing to activation in materials at <100 m.w.e.

- Muon-induced **neutrons**
- Capture of stopping negative **muons**
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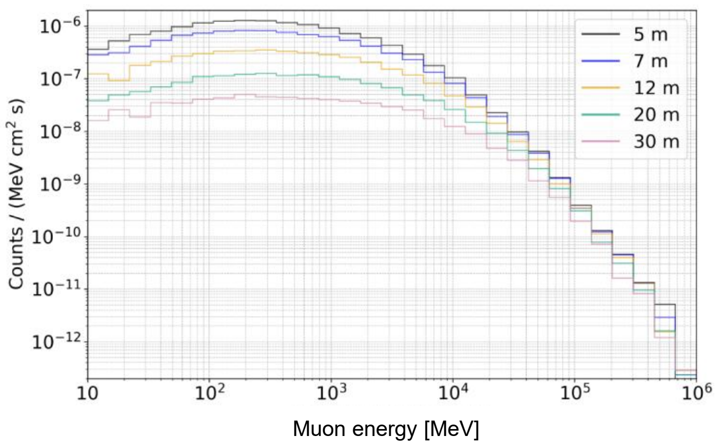
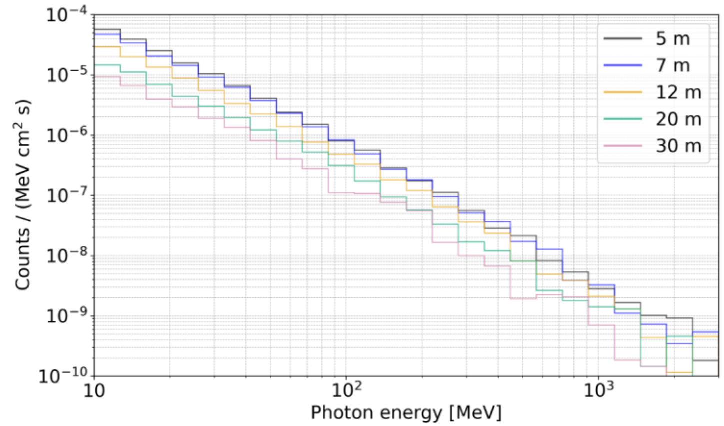
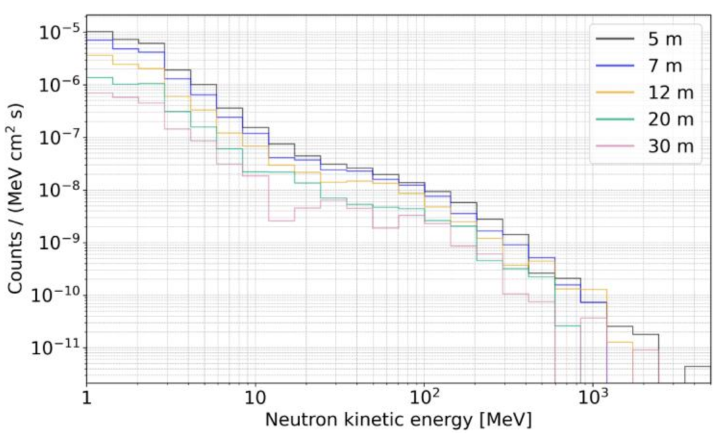
Fluxes from EXPACS, CRY and FLUKA

Cross sections from TALYS and INCL







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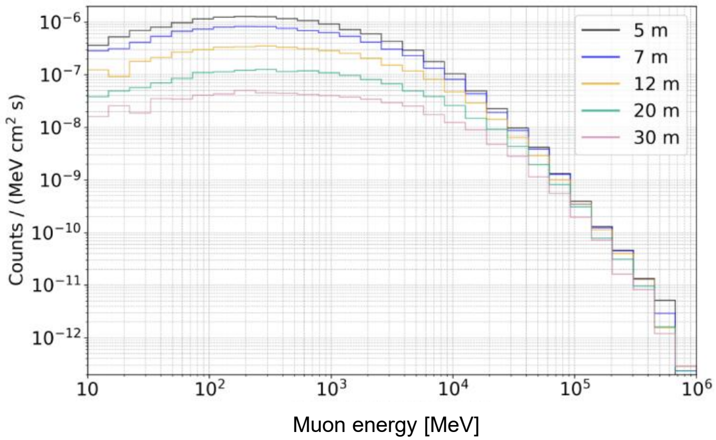

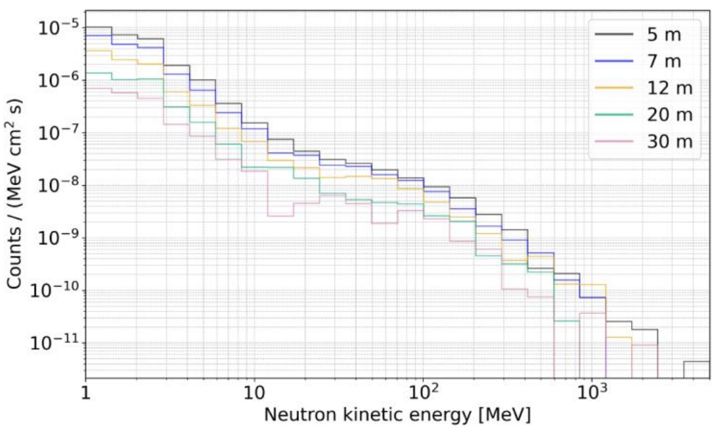

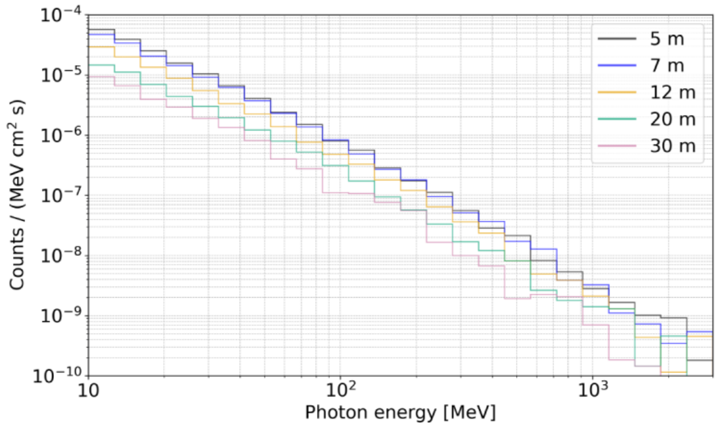

Location	Process	Tritium		^{60}Co
		Si	Ge	Cu
Sea-level	Neutrons Others	98% 2%	99% 1%	93% 1%
SUF Tunnels A/C 15-20 mwe	Stopping neg. muons Neutrons Gammas Others	50% 23% 9% 18%	38% 33% 1% 27%	57% 15% 16% 12%
PNNL SUL ∼ 30 mwe	Stopping neg. muons Neutrons Gammas Others	41% 28% 10% 21%	31% 39% 1% 29%	50% 19% 18% 14%
SLC Adit Storage 50-60 mwe	Stopping neg. muons Neutrons Gammas Others	37% 30% 13% 21%	25% 42% 2% 32%	41% 19% 22% 18%

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Production rates in $kg^{-1}d^{-1}$

Location	Tritium production in Si	Tritium production in Ge	^{60}Co production in Cu
Sea-level	125 (TALYS+INCL) 112±24 (R.Saldanha et.al 2020)	94 (TALYS+INCL) 74±9(CDMSLite 2019), 82±21 (EDELWEISS-III 2017)	46 (TALYS, S. Cebrian), 39.7 ± 5.7 (She et al. 2021), $29.4^{+7.1}_{-5.9}$ (Baudis et al. 2015), 86.2 ± 7.6 (Laubenstein et al. 2009).
SUF Tunnel A/C (15-20 mwe)	0.48	0.24	0.53
PNNL SUL (30 mwe)	0.27	0.14	0.28
SLC Adit Storage (50-60 mwe)	0.12	0.065	0.13

Significantly reduced production compared to sea level

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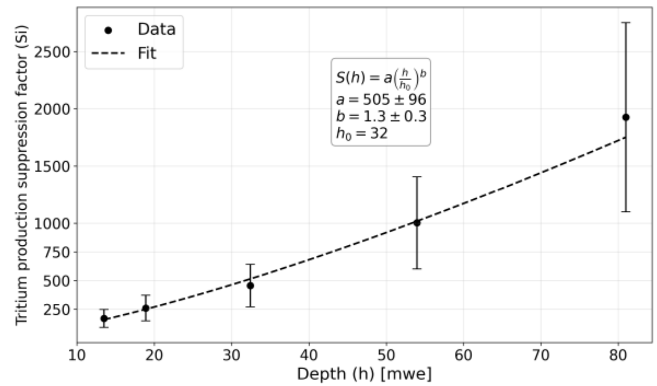
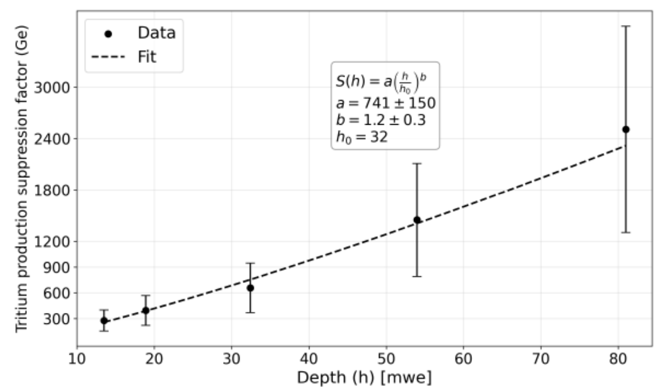
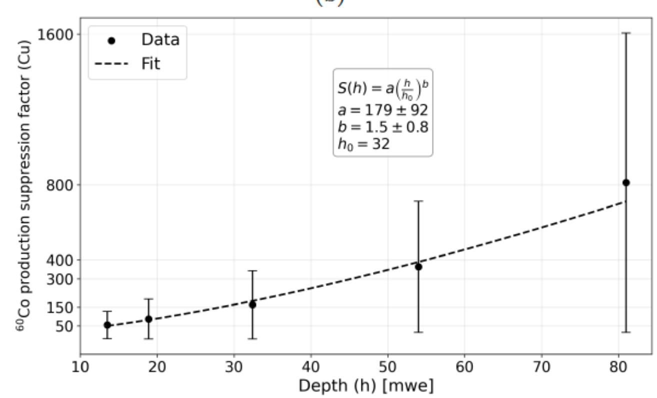


(a)



(b)



Suppression factors (relative to sea level) **vs depth**

Underground activation

Deep underground muons can produce by spallation radioisotopes inside detectors

Effect of short-lived isotopes mitigated by time correlation with μ, reducing life-time

^{11}C in **liquid scintillator:** three-fold coincidence between the crossing μ, the ejected n from ^{12}C, and the ^{11}C decay (EC, β+, $T_{1/2}$= 20.4 m)

Studies from irradiation experiments, data analysis of experiments like **KamLAND** and **Borexino**, and FLUKA simulations

T. Hagner et al, Astropart. Phys.14 (2000) 33
C. Galbiati et al, Phys. Rev. C 71 (2005) 055805
S. Abe et al, Phys. Rev. C 81 (2010) 025807
G. Bellini et al, J. Cosmol. Astropart. Phys. 08 (2013) 049
M. Agostini et al, Eur. Phys. J. C 81 (2021) 1075

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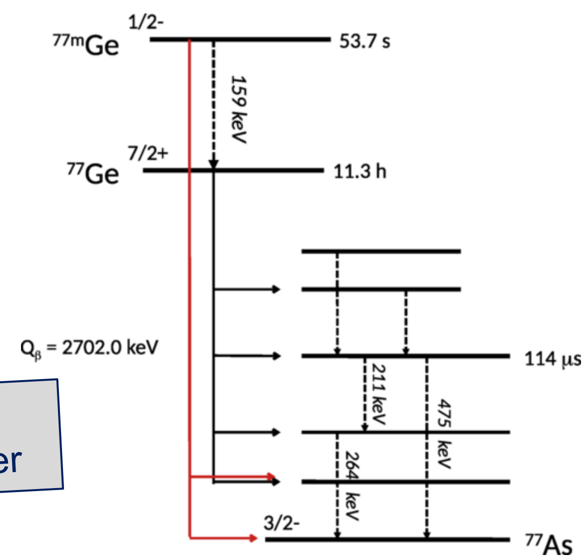
$^{77(m)}$Ge in **Germanium:** ^{77}Ge (β-, Q = 2.7 MeV) and metastable ^{77m}Ge affect ^{76}Ge $\beta\beta$ experiments

C. Wiesinger et al, Eur. Phys. J. C 78 (2018) 597
M Neuberger et al, J. Phys.: Conf. Ser. 2156 (2022) 012216



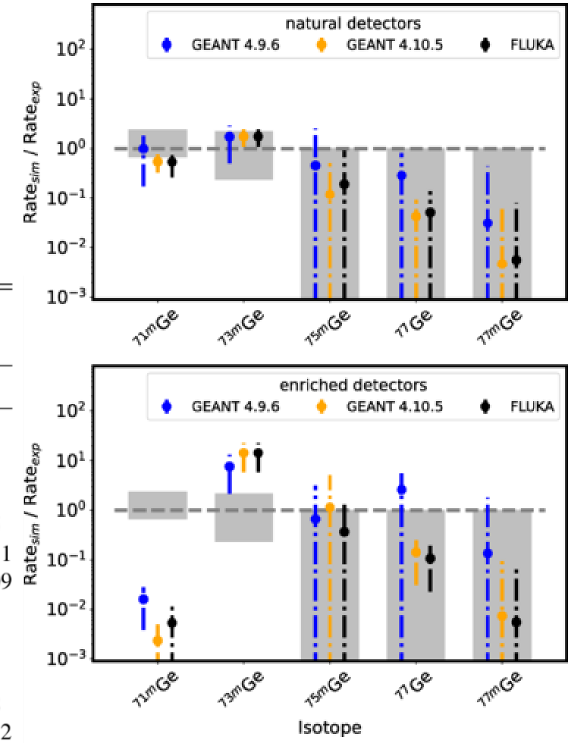
"Delayed Coincidence Based Active Suppression of In-Situ Muon-Induced Isotope Backgrounds in LEGEND", Moritz Neuberger, Poster

$^{77(m)}$Ge in Germanium

- Production of metastable Ge isotopes quantified from **Majorana Demonstrator** data and simulations, in good agreement

I. J. Arnquist et al, Phys. Rev. C 105 (2022) 014617

Isotope	Dominant production mechanism	Candidate	Experimental rate [cts/(kg yr)]	Simulated rate [cts/(kg yr)] GEANT 4.9.6	GEANT 4.10.5	FLUKA
			Natural detectors			
^{71m}Ge	^{70}Ge(n,γ)	$4^{+2.8}_{-1.7}$	$0.6^{+0.4}_{-0.2}$	0.59 ± 0.33	0.32 ± 0.10	0.32 ± 0.08
^{73m}Ge	^{73}Ge(n,n'), ^{74}Ge$(n,2n)$	$3^{+2.7}_{-1.5}$	$0.38^{+0.34}_{-0.19}$	0.65 ± 0.25	0.63 ± 0.16	0.66 ± 0.16
^{75m}Ge	^{74}Ge(n,γ)	0^{+16}_{-0}	$0^{+1.9}_{-0}$	0.43 ± 0.33	0.11 ± 0.03	0.18 ± 0.05
^{77}Ge	^{76}Ge(n,γ)	$0^{+1.3}_{-0.0}$	$0^{+0.7}_{-0.0}$	0.10 ± 0.04	0.015 ± 0.005	0.026 ± 0.011
^{77m}Ge	^{76}Ge(n,γ)	0^{+9}_{-0}	$0^{+6.4}_{-0.0}$	0.10 ± 0.04	0.015 ± 0.005	0.018 ± 0.009
			Enriched detectors			
^{71m}Ge	^{76}Ge$(n,6n)$	$6^{+3.3}_{-2.2}$	$0.3^{+0.2}_{-0.1}$	0.005 ± 0.003	$0^{+0.001}_{-0}$	$0^{+0.001}_{-0}$
^{73m}Ge	^{74}Ge$(n,2n)$, ^{76}Ge$(n,4n)$	$1^{+1.9}_{-0.5}$	$0.05^{+0.09}_{-0.020}$	0.38 ± 0.21	0.71 ± 0.17	0.70 ± 0.17
^{75m}Ge	^{76}Ge$(n,2n)$	0^{+38}_{-0}	$0^{+1.7}_{-0.0}$	0.56 ± 0.20	0.96 ± 0.2	0.31 ± 0.08
^{77}Ge	^{76}Ge(n,γ)	$0^{+1.3}_{-0.0}$	$0^{+0.3}_{-0.0}$	0.39 ± 0.21	0.021 ± 0.005	0.036 ± 0.012
^{77m}Ge	^{76}Ge(n,γ)	0^{+23}_{-0}	$0^{+5.8}_{-0.0}$	0.39 ± 0.21	0.021 ± 0.005	0.016 ± 0.007



Underground activation

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			Enriched detectors			
^{71m}Ge	^{76}Ge$(n,6n)$	$6^{+3.3}_{-2.2}$	$0.3^{+0.2}_{-0.1}$	0.005 ± 0.003	$0^{+0.001}_{-0}$	$0^{+0.001}_{-0}$
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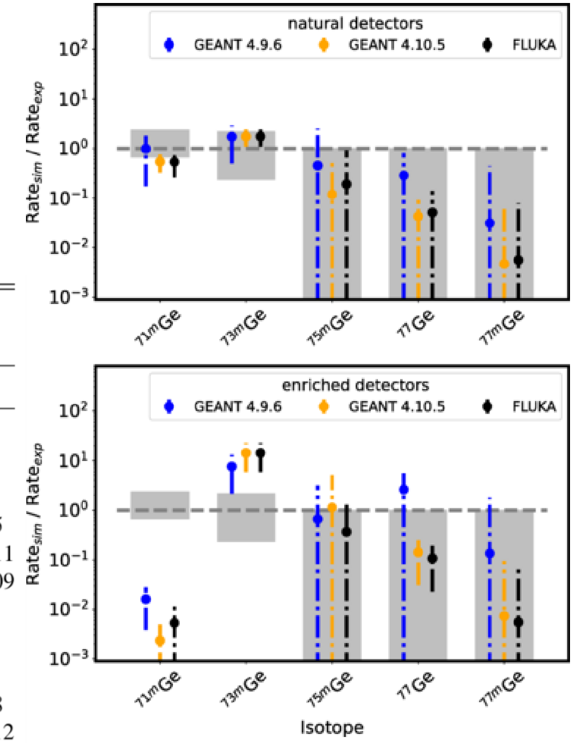
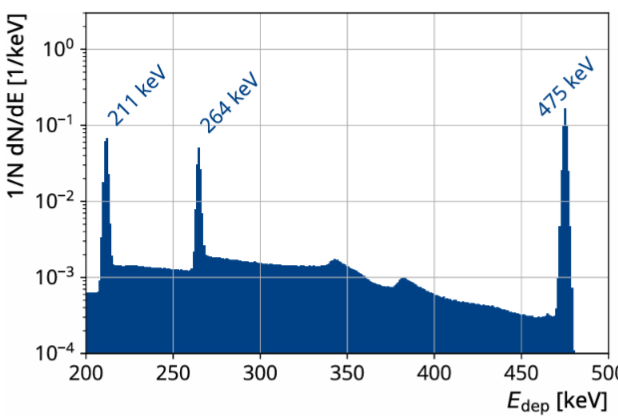


- **Production rate** of ^{77}Ge + ^{77m}Ge constrained from ^{77m}As decay from **GERDA data**
  <0.38 nuc/(kg·yr) (90% CL),
  in agreement with MC prediction: (0.21 ± 0.07) nuc/(kg.yr),
  M. Agostini et al, Eur. Phys. J. C 85, 809 (2025)



→ Sub-dominant contribution for **LEGEND-1000**

Underground activation

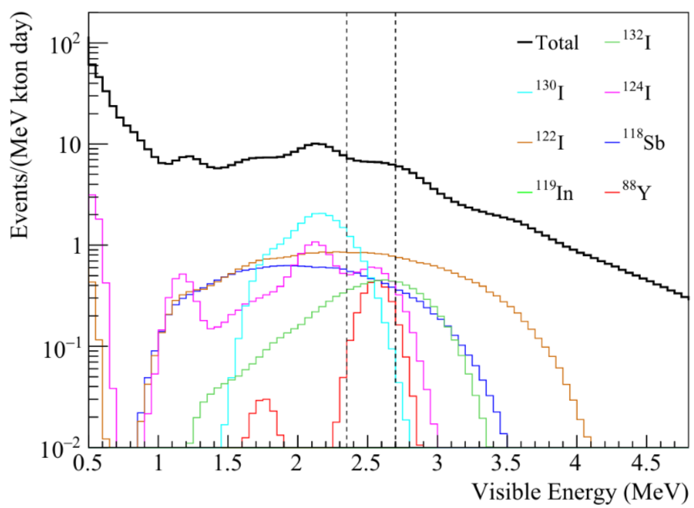
Xenon

Production rates of μ spallation products from **KamLAND-Zen** (Xe-loaded LS)

- Combination of delayed coincidence techniques and newly developed muon reconstruction
- Consistent results with **FLUKA** and **Geant4** simulation

S. Abe et al, PRC 107, 054612 (2023)

			Production rate (kton day)$^{-1}$				
	$\tau_{1/2}$	Q (MeV)	$\mathcal{R}_{n\text{-tag}}$	$\mathcal{R}_{\text{isolated}}$	$\mathcal{R}^{\text{Data}}_{\text{Total}}$	$\mathcal{R}^{\text{FLUKA}}_{\text{KamLAND-LS}}$	$\mathcal{R}^{\text{FLUKA}}_{\text{Xe-LS}}/\mathcal{R}^{\text{FLUKA}}_{\text{KamLAND-LS}}$
^{8}He	119.1 ms	10.7 (β^-)	$0.5^{+1.1}_{-0.5}$	$0.3^{+0.5}_{-0.3}$	$0.8^{+1.2}_{-0.5}$	0.55 ± 0.04	0.96 ± 0.03
^{9}Li	178.3 ms	13.6 (β^-)	$2.5^{+0.3}_{-0.3}$	$0.1^{+0.2}_{-0.1}$	$2.7^{+0.3}_{-0.4}$	4.9 ± 0.4	1.00 ± 0.01
^{12}B	20.2 ms	13.4 (β^-)	43^{+3}_{-2}	$14.4^{+0.6}_{-0.08}$	58^{+3}_{-2}	42 ± 3	1.013 ± 0.003
^{12}N	11.0 ms	17.3 (β^+)	$0.8^{+0.9}_{-0.7}$	$0.07^{+0.2}_{-0.06}$	$0.9^{+0.9}_{-0.7}$	0.74 ± 0.06	1.02 ± 0.03
^{8}Li	839.9 ms	16.0 (β^-)	21^{+4}_{-3}	$0.9^{+1.6}_{-0.9}$	22^{+4}_{-4}	47 ± 3	1.021 ± 0.004
^{8}B	770 ms	18.0 (β^+)	3^{+4}_{-3}	$0.8^{+1.0}_{-0.6}$	4^{+4}_{-3}	11.0 ± 0.8	1.024 ± 0.008
^{9}C	126.5 ms	16.5 (β^+)	1^{+2}_{-1}	$0.2^{+0.5}_{-0.2}$	2^{+2}_{-1}	1.5 ± 0.1	1.02 ± 0.02
^{11}Be	13.8 s	11.5 (β^-)	$1.2^{+0.3}_{-0.2}$	$0^{+0.06}_{-0}$	$1.2^{+0.3}_{-0.2}$	1.09 ± 0.08	1.02 ± 0.02
^{10}C	19.29 s	3.65 (β^+)	19^{+2}_{-2}	$0.5^{+0.6}_{-0.5}$	19^{+2}_{-2}	23 ± 2	1.029 ± 0.005
^{6}He	806.7 ms	3.51 (β^-)	10^{+1}_{-1}	1^{+1}_{-1}	11^{+2}_{-1}	28 ± 2	1.022 ± 0.005
^{11}C	1221.8 s	1.98 (β^+)	–	–	973 ± 10 [34]	679 ± 49	1.012 ± 0.001
n	207.5 μs	2.223(cap.γ)	–	–	3781 ± 296	4046 ± 292	1.1485 ± 0.0004



Underground activation

Xenon

Production rates of μ spallation products from **KamLAND-Zen** (Xe-loaded LS)

- Combination of delayed coincidence techniques and newly developed muon reconstruction
- Consistent results with **FLUKA** and **Geant4** simulation

S. Abe et al, PRC 107, 054612 (2023)

	$\tau_{1/2}$	Q (MeV)	Production rate (kton day)$^{-1}$				
			$\mathcal{R}_{n\text{-tag}}$	$\mathcal{R}_{\text{isolated}}$	$\mathcal{R}^{\text{Data}}_{\text{Total}}$	$\mathcal{R}^{\text{FLUKA}}_{\text{KamLAND-LS}}$	$\mathcal{R}^{\text{FLUKA}}_{\text{Xe-LS}}/\mathcal{R}^{\text{FLUKA}}_{\text{KamLAND-LS}}$
^{8}He	119.1 ms	10.7 (β^-)	$0.5^{+1.1}_{-0.5}$	$0.3^{+0.5}_{-0.3}$	$0.8^{+1.2}_{-0.5}$	0.55 ± 0.04	0.96 ± 0.03
^{9}Li	178.3 ms	13.6 (β^-)	$2.5^{+0.3}_{-0.3}$	$0.1^{+0.2}_{-0.1}$	$2.7^{+0.3}_{-0.4}$	4.9 ± 0.4	1.00 ± 0.01
^{12}B	20.2 ms	13.4 (β^-)	43^{+3}_{-2}	$14.4^{+0.6}_{-0.08}$	58^{+3}_{-2}	42 ± 3	1.013 ± 0.003
^{12}N	11.0 ms	17.3 (β^+)	$0.8^{+0.9}_{-0.7}$	$0.07^{+0.2}_{-0.06}$	$0.9^{+0.9}_{-0.7}$	0.74 ± 0.06	1.02 ± 0.03
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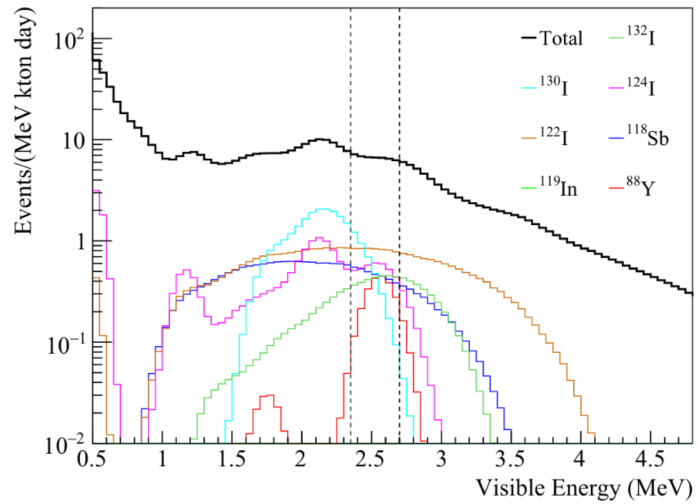

^{137}Xe (β^- emitter, Q=4173 keV, $T_{1/2}$=3.82 m) from n capture analyzed for ββ

- Yield at WIPP lab for **EXO-200** from measured μ flux and **Geant4** and **FLUKA** simulations
- From **KamLAND-Zen**: $\mathcal{R}_{^{137}\text{Xe}} = 4347 \times 0.00107$

J. Albert et al, JCAP 04 (2016) 029

$$= 4.6 \pm 0.5\ (\text{kton day})^{-1} = (16.8)\ 10^{-4}\ \text{kg}^{-1}\ \text{yr}^{-1}$$

FLUKA prediction is 5.5 ± 0.4 (kton day)$^{-1}$

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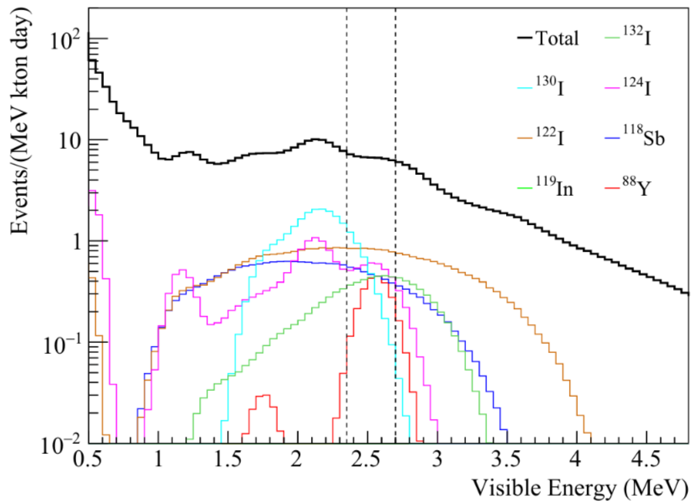

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FLUKA prediction is 5.5 ± 0.4 (kton day)$^{-1}$

- Mitigation proposed by adding to Xe a small quantity of ^{3}He to capture thermal n

L. Rogers et al, J. Phys. G 47 (2020) 075001

Underground activation

Xenon

Production rates of ^{3}H, ^{137}Xe and other unstable **Xe** isotopes evaluated from μ-induced n fluxes and spallation

- At four underground labs **LNGS, SURF, LSM** and **SNOLAB** for site selection of **DARWIN**
- Based on **MUSIC-MUSUN + Geant4** simulation
- Central values using *Shielding* phyiscs list and systematic uncertainty by using other physics lists

M. Adrover et al, Eur. Phys. J. C 84, 88 (2024)

^{3}H

Site	Rate (kg^{-1} $year^{-1}$)
LNGS	$(1.22 \pm 0.01 \pm 0.01_{sys}) \cdot 10^{-2}$
SURF	$(1.98 \pm 0.01 \pm 0.04_{sys}) \cdot 10^{-3}$
LSM	$(2.44 \pm 0.01 \pm 0.04_{sys}) \cdot 10^{-3}$
SNOLAB	$(1.40 \pm 0.05 \pm 0.50_{sys}) \cdot 10^{-4}$

^{137}Xe

Site	Rate (kg^{-1} $year^{-1}$)
LNGS	$(8.22 \pm 0.27 \pm 1.00_{sys}) \cdot 10^{-4}$
SURF	$(1.42 \pm 0.12 \pm 0.21_{sys}) \cdot 10^{-4}$
LSM	$(1.65 \pm 0.11 \pm 0.30_{sys}) \cdot 10^{-4}$
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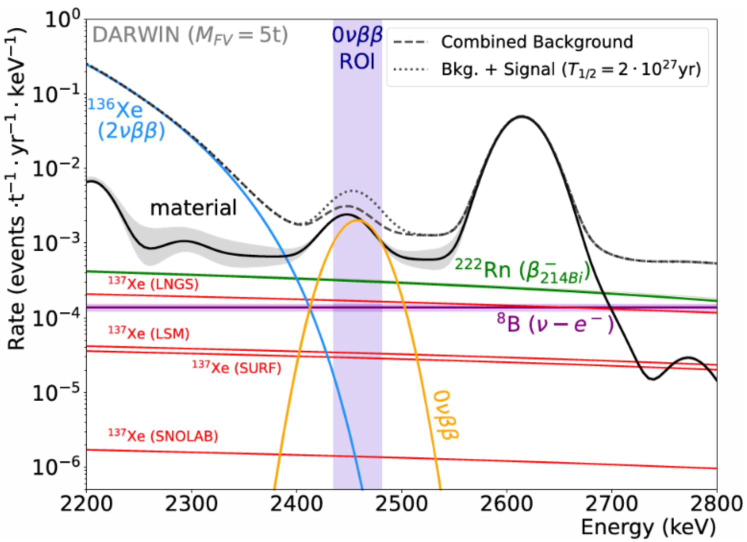

→ ^{137}Xe contribution at RoI for ββ comparable/below solar ^{8}B neutrinos signal at all locations

Underground activation

Argon

Production rates and **activity** of ^{39}Ar and ^{42}Ar at **LNGS** for **DarkSide-20k**

- Based on **FLUKA** simulations of μ for LNGS cavern considering DarkSide-20k geometry
- Compared with estimates from TALYS and INCL cross sections and Mei&Hime'2006 parametrization

Description	^{42}Ar production rate in Argon (per ton per year)	Time exposure	Specific Activity (mBq/kg)
At LNGS	6E-09	10 years	1E-11
In Argon (intrinsic)	-	-	< 6.3E-08 (Sagar et al, 2024)
During extraction, purification, and transport	5.81E-03 *1E03*365 = 2.12E03 (Zhang-Mei et al, 2022)	240 (effective sea-level equivalent days)	9.3E-07

Description	39Ar production rate in Argon (per ton per year)	Time exposure	Specific Activity
At LNGS	75 (FLUKA simulation)	10 years	6.04E-08 mBq/kg
In Argon (intrinsic)	-	-	0.73 mBq/kg (likely upper limit)
During extraction, purification and transport	1048 +/- 133 (sea level) (Richard saldhana et al, 2020) (per kg per day)	240 (effective sea-level equivalent days)	0.02 mBq/kg (Darkside collaboration, 2023)

S. Poudel et al, APS Global Physics Summit 2026
https://meetings-archive.aps.org/smt/2026/apr-s82/2

Underground activation

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→ Negligible compared to activity produced at sea level

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S. Poudel et al, APS Global Physics Summit 2026
https://meetings-archive.aps.org/smt/2026/apr-s82/2

Review of cosmogenic backgrounds and material activation

- Origin and quantification
- Studies on:
  - Surface activation: Ar, NaI, Ge, Si, others
  - Underground activation
  - Cosmogenic backgrounds

Centro de Astropartículas y Física de Altas Energías Universidad Zaragoza

Facultad de Ciencias Universidad Zaragoza

ICTS Infraestructuras Científicas y Técnicas Singulares

Laboratorio Subterráneo Canfranc

Cosmogenic background

Many specific studies on ***muons***, ***muon-induced neutrons*** and ***vetos***

Cosmogenic Backgrounds in **Borexino** at 3800 m water-equivalent depth
G. Bellini et al JCAP 08 (2013) 049

Muon-induced background in the **EDELWEISS** dark matter search
B. Schmidt et al Astropart. Phys. 44 (2013) 28

Radiogenic and Muon-Induced Backgrounds in the **LUX** Dark Matter Detector
D.S. Akerib et al Astropart. Phys. 62 (2015) 33

Cosmogenic Backgrounds to 0νββ in **EXO-200**
J. B. Albert et al JCAP 2016 (4) 029

The veto apparatus of **DarkSide-20k**: Dark Matter search in a background-free experiment
M. Rossi 2022 Nuovo Cimento C 45(1) 21

Water Cherenkov muon veto for the **COSINUS** experiment: design and simulation optimization
G. Angloher et al Eur. Phys. J. C 84, 551 (2024)

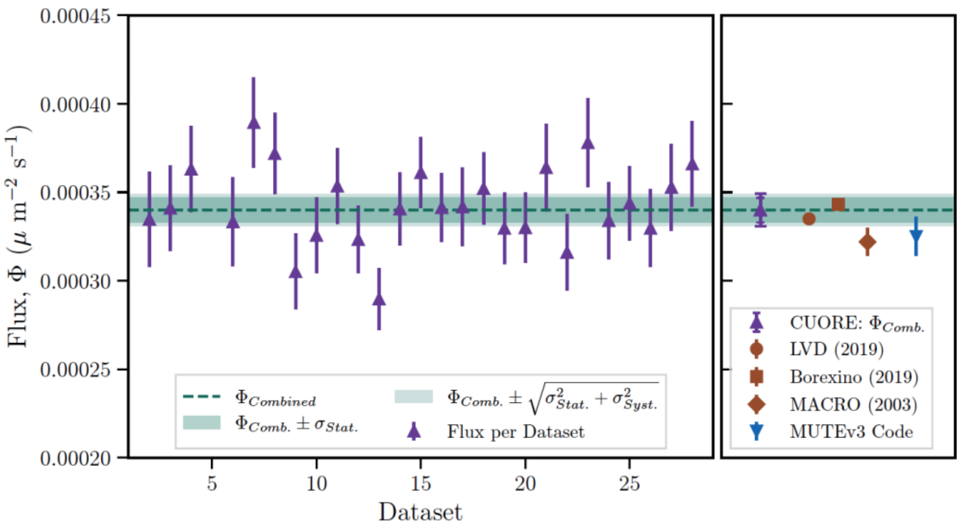
…

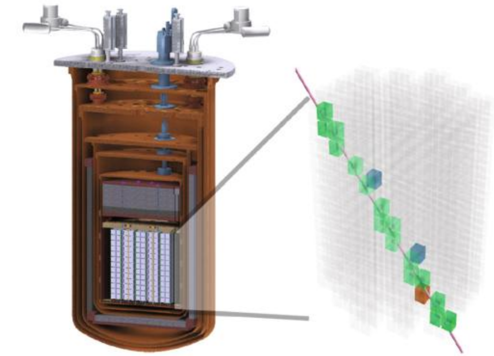
- "Neutron Backgrounds in the PICO 500 Detector", Rajan Anderson Dornan, Poster
- "A complete neutron-background model for the BUTTON-30 detector at Boulby mine", William Hopkins, Poster

Cosmogenic background

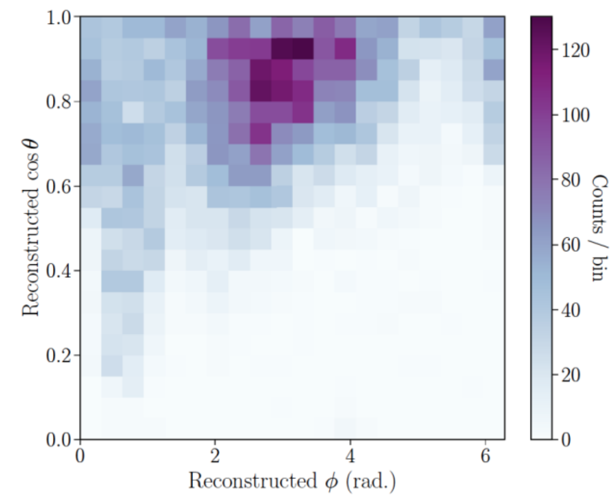
Reconstruction of cosmic-ray μ events from **CUORE**

- 3D particle tracking and reconstruction in 2.73 y
- Integral μ flux at **LNGS** and per-event angular determination





D. Q. Adams et al, EPJC (2026) 86:749



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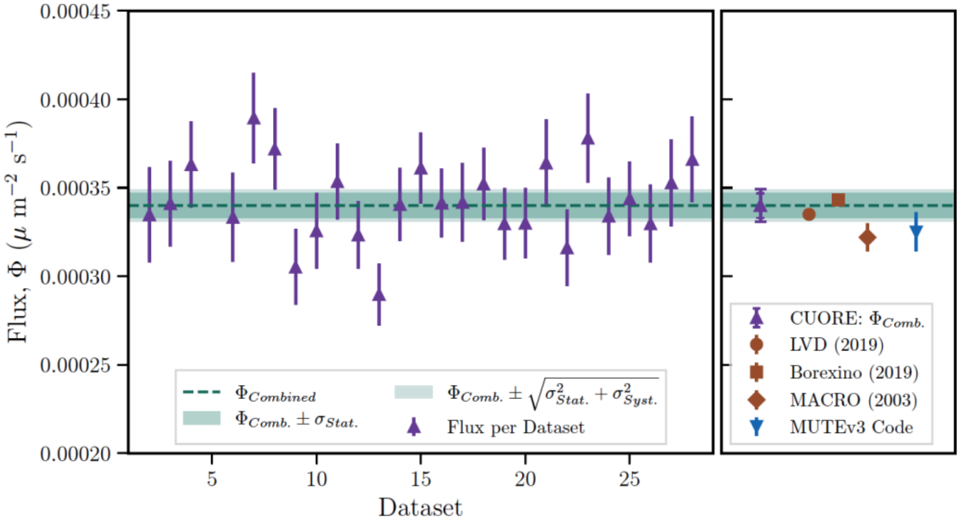

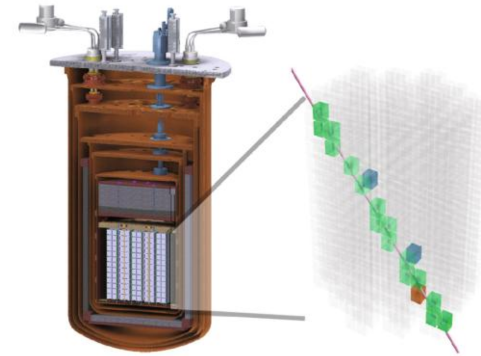

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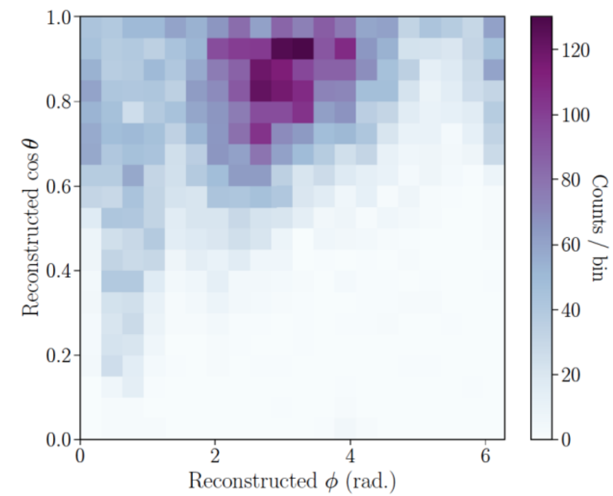
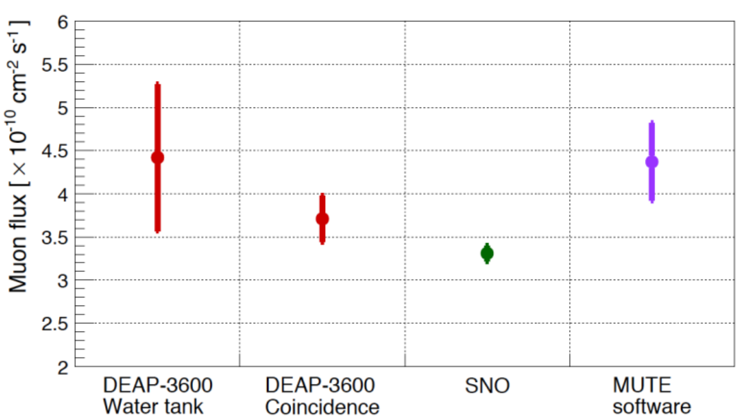


Measurement of μ flux at **SNOLAB** from **DEAP-3600**



- Data from 2016 to 2020
- Considering coincidences between μ veto (water tank) and LAr target to minimize systematics
- Simulations from MUTE software

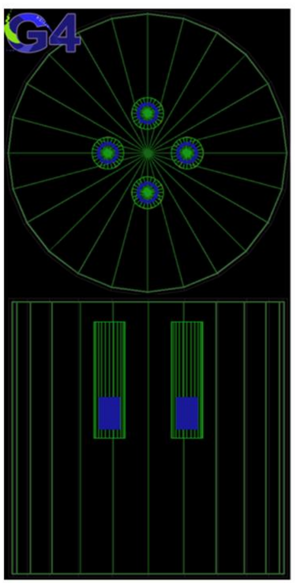
P. Adhikari et al arXiv:2608.20504

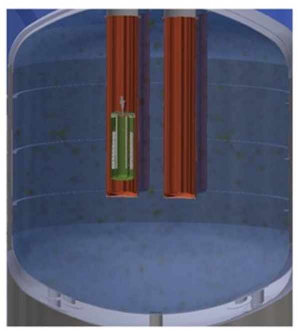
Cosmogenic background

Comparison of **simulated cosmogenic n** backgrounds for **LEGEND-1000** from **Geant4** and **MCNP**

C.J. Barton et al 2024 JINST 19 P05056

- MUSUN for μ at **LNGS**, LEGEND-1000 geometry, 10 y of μ-induced n simulated

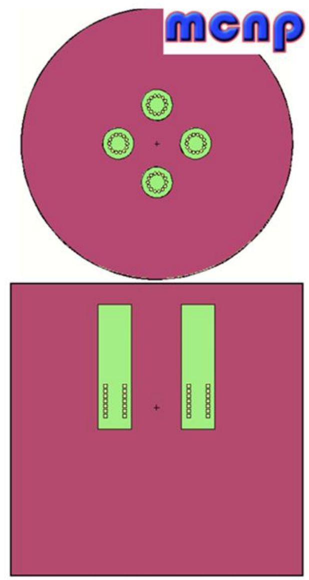




Left: representative LEGEND-1000 cryostat in Geant4

Middle: conceptual drawing of the Legend-1000 cryostat

Right: representative LEGEND-1000 cryostat in MCNP



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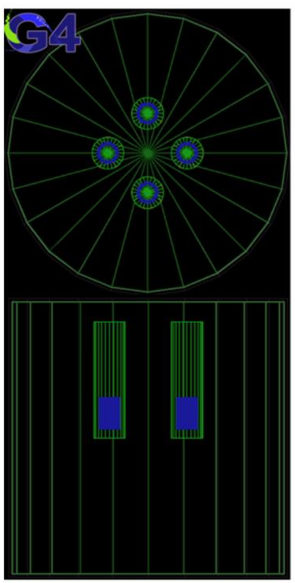

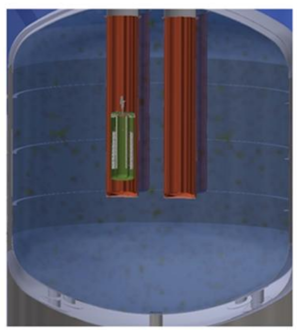

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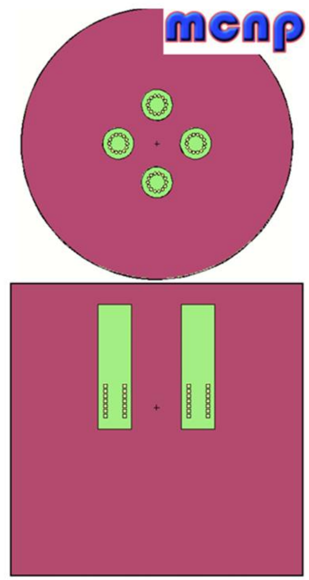

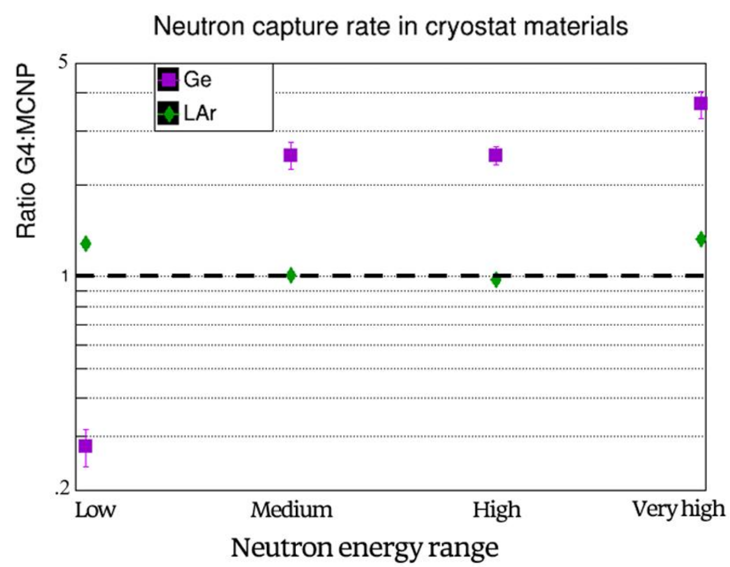

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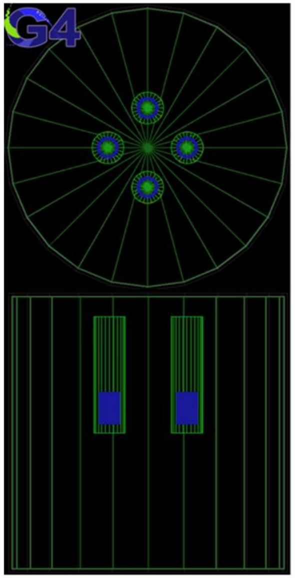

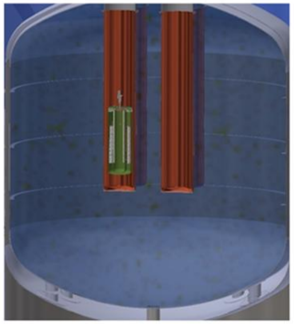

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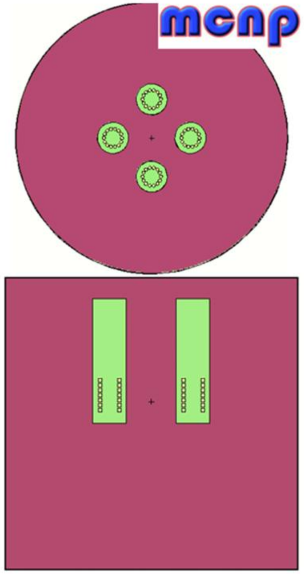

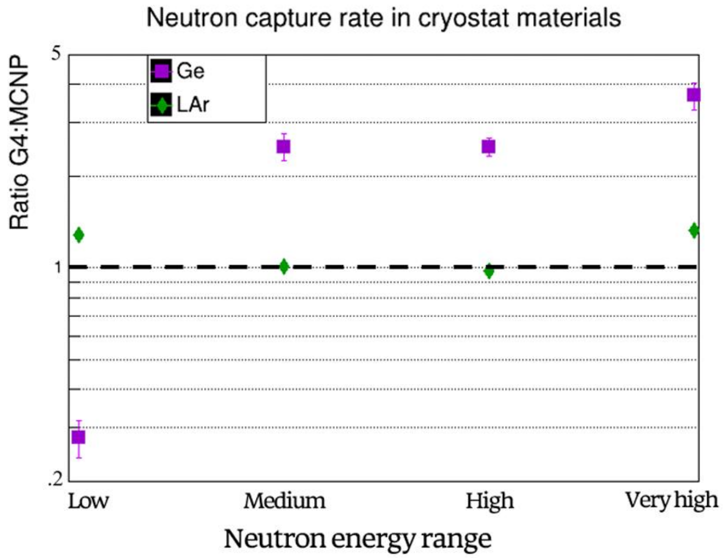

Summary

Cosmogenic background and **material activation** can jeopardize the sensitivity of ultra-low background experiments

- Continuous generation of **neutrons** and **short-lived nuclides** deep ***underground*** due to fast **muons**
- Production of **long-lived isotopes** at Earth's ***surface*** due to **nucleons**

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Production rates and **yields** evaluated in ββ, neutrino and DM experiments for many materials from direct **measurements** (with beams or from controlled, long exposures) and from **calculations** based on different approaches

- Precise evaluation of inclusive **production cross-sections**
  direct measurements needed to validate models
- Accurate description of **cosmic ray spectra**
  flux variation with depth, latitude, longitude, altitude, and even time
- Precise **exposure history**
  tracking materials from fabrication to deployment and operation

Summary

Cosmogenic background and **material activation** can jeopardize the sensitivity of ultra-low background experiments

- Continuous generation of **neutrons** and **short-lived nuclides** deep ***underground*** due to fast **muons**
- Production of **long-lived isotopes** at Earth's ***surface*** due to **nucleons**

Production rates and **yields** evaluated in ββ, neutrino and DM experiments for many materials from direct **measurements** (with beams or from controlled, long exposures) and from **calculations** based on different approaches

- Precise evaluation of inclusive **production cross-sections**
  direct measurements needed to validate models
- Accurate description of **cosmic ray spectra**
  flux variation with depth, latitude, longitude, altitude, and even time
- Precise **exposure history**
  tracking materials from fabrication to deployment and operation

Mitigation mainly based on **limiting exposure** to cosmic rays and **event tagging** but active suppression and removal techniques can be considered:

- *Underground crystal growth* and detector fabrication (Ge, NaI)
- *Removal via post-processing* (cryogenic distillation for ^{39}Ar in Ar)
- *Doping noble liquids* for neutron capture

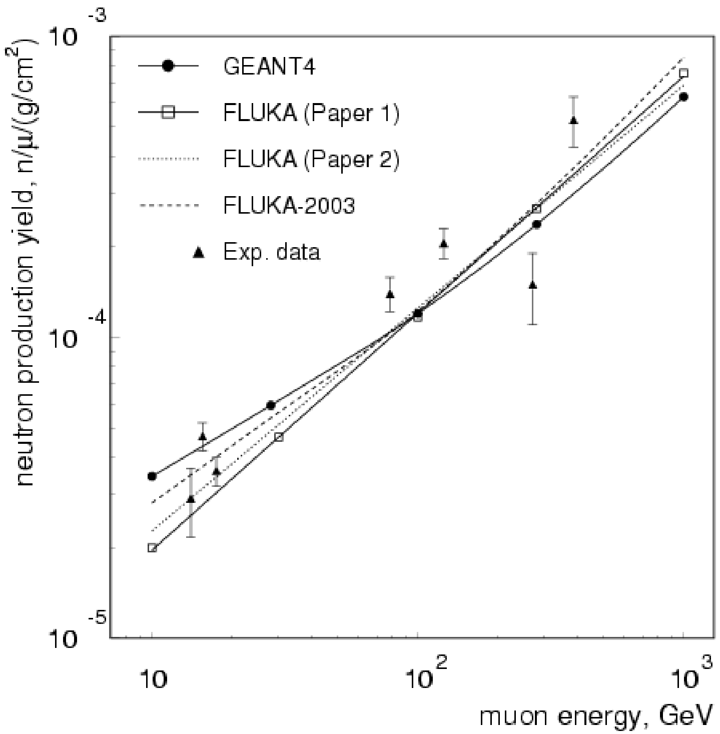
Extra slides

Cosmogenic backgrounds: origin

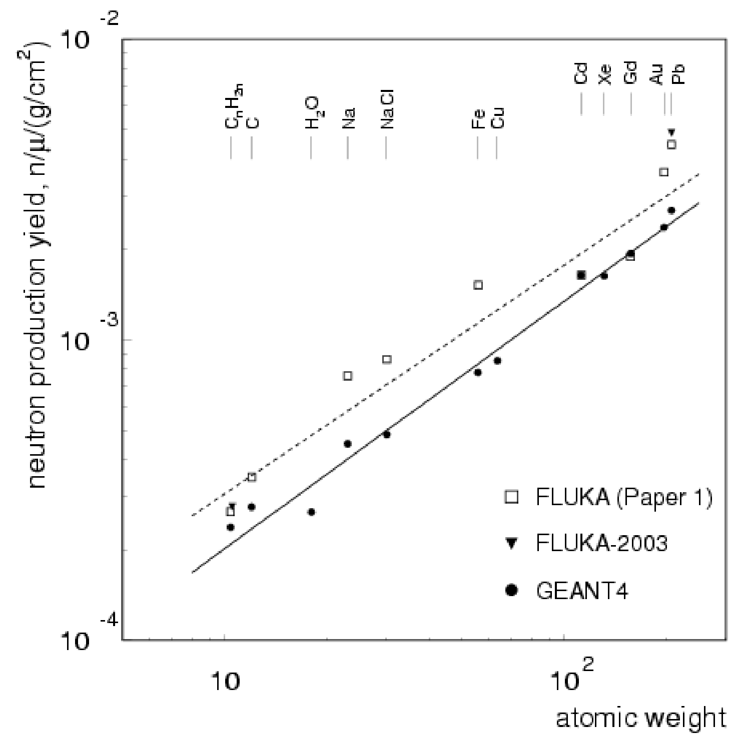
Cosmogenic neutrons induced by muons in rock and shieldings

Yiends dependent on muon energy and material

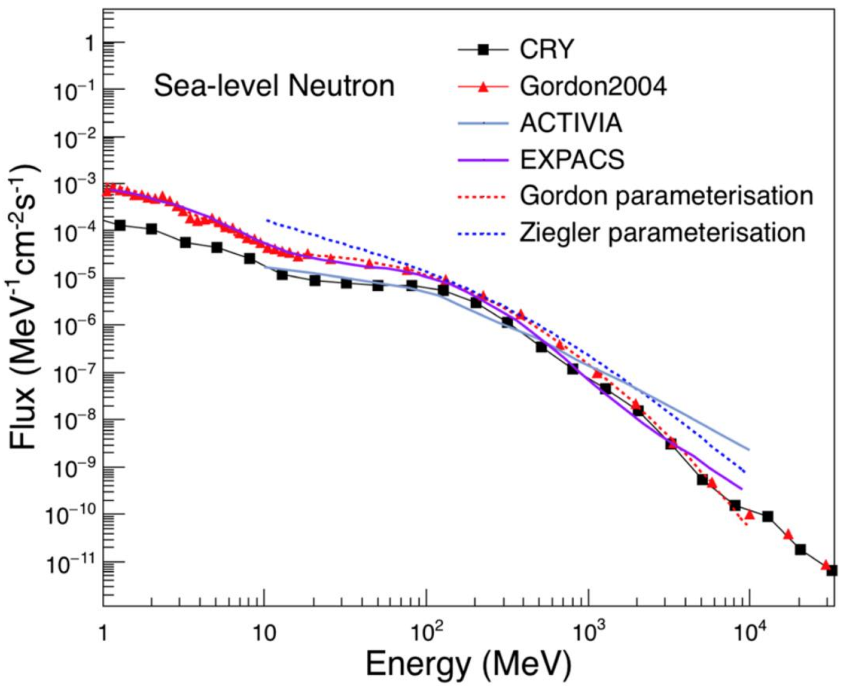
Neutron yield vs **muon energy** in $(CH_2)_n$



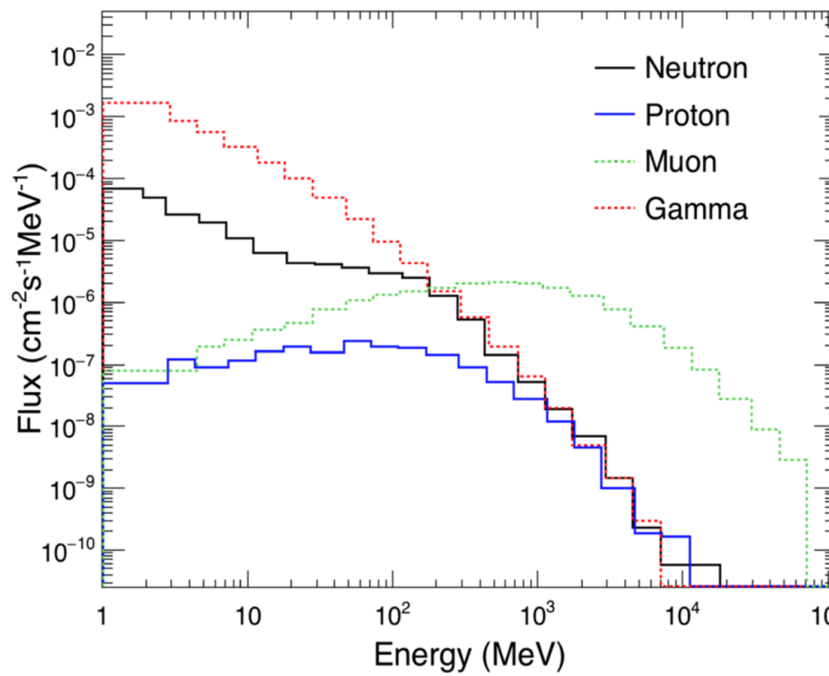
Neutron yield vs **A of target** for E_μ=270 GeV



H. Araujo et al, NIMA 545 (2005) 398



W. Chen et al, Eur. Phys. J. C 82 (2022) 549



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 (T $^{40}\mathrm{Ar}$ (α,2p) $^{42}\mathrm{Ar}$ ot possible for α from radioactivity

Isotope	Natural abundance (%)	Reaction	
43Ca	0.135	43Ca(n,2p)42Ar	Zero σ values <17 MeV (TALYS2017) $\rightarrow$ not possible for fission or (α,n) neutrons
44Ca	2.086	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 from other sources, Ca concentration in rock, emanation factor

Activity

- **Activity A** from measured production rates for ^{37}**Ar**, ^{39}**Ar** and estimated rate for ^{3}**H** for realistic exposure conditions

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

Fix tentative **exposure times** and **places (altitude)** for shipping:

URANIA → ARIA → LNGS

Planned to produce **120 t**, shipped in high pressure gas cylinder (2 t per skid)

1. **Extraction and storage of UAr at Urania:** 3 skids filled before transportation, exposures of 8, 16, 24 days
2. **Trip from Urania to a shipping port (Houston):** 7 days
3. **Trip overseas to Europe:** 60 days at sea + 7 days from Cagliari to Aria

Steps 1-3 repeated 20 times

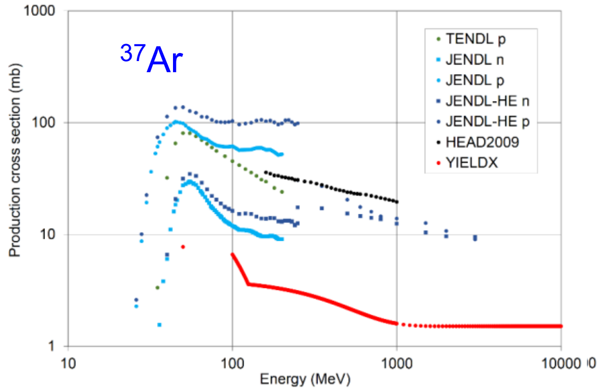
4. **Processing and storage of UAr at Aria:** 2 runs each taking 60 days, if stored underground
5. **Trip from Aria to LNGS:** 10 days, 10 trips with 12 t each

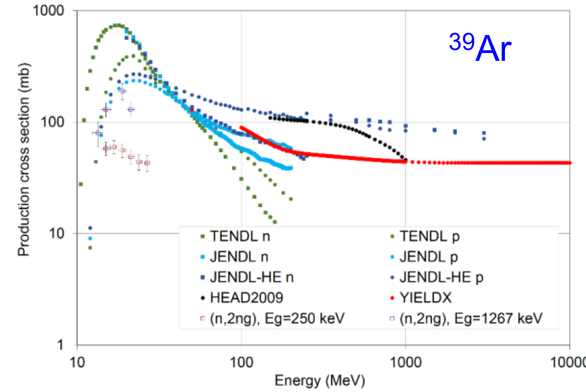
Total time: from Urania to Aria 614 days

Activation studies: Ar

Production rates R (sea level): new calculations for DarkSide-20k

DarkSide-20k Collaboration, Astropart. Phys. 152 (2023) 102878; 2024 JINST 19 C02011





		^{37}Ar			^{39}Ar
This work: LE+HE	Cut (MeV)	*R* (atoms/kg/day)	This work LE+HE	Cut (MeV)	*R* (atoms/kg/day)
TENDL(p)+HEAD2009	150	153.6	TENDL+HEAD2009	150	726.4
TENDL(p)+YIELDX	100	93.5	TENDL+YIELDX	100	697.1
TENDL(p)+YIELDX	200	122.7	TENDL+YIELDX	200	646.0
JENDL-HE(n)	30	63.9	TENDL+JENDL-HE(n)	20	804.3
Estimated rate in this work		109 ± 45	Estimated rate in this work		725 ± 79
Not used for estimation:					
Measurement [35]		51.0 ± 7.4			759 ± 128
ACTIVIA [35]		17.9 ± 2.2			200 ± 25
MENDL-2P [35]		155 ± 19			188 ± 24
TALYS [35]		76.8 ± 9.6			753 ± 94
INCL++ (ABLA07) [35]		79.3 ± 9.9			832 ± 104
			TENDL-2015 [35]		726 ± 91
GEANT4 [36]		176			858

^{39}Ar: fully compatible with measured value and several calculations

^{37}Ar: larger discrepancies

Activation studies: Xe

Large amounts of **Xe** being used in several huge DM and DBD experiments

Production rates in $kg^{-1}d^{-1}$

	^{3}H	^{7}Be	^{125}Sb	^{121m}Te	^{123m}Te	^{127}Xe
Half-life [27,108]	12.312(25) y	53.22(6) d	2.75855(25) y	154 d	119.3(1) d	36.358(31) d
Measurement [184]		32^{+21}_{-20}	51^{+22}_{-20}	<104	<53	162^{+25}_{-23}
Measurement [185]						132 ± 26
COSMO [184]		0.55	1.17	23.8	1.24	48.0
ACTIVIA [184]		0.55	0.017	25.8	1.27	35.9
ACTIVIA [46]	35.6		0.009	54.5	2.67	89.9
GEANT4 [46]	31.6		1.48	21.2	18.5	233.3
TALYS [94]	16.0		0.04	11.7	12.1	

Controlled, long exposure to cosmic rays at LNGS and results from **LUX**

L. Baudis et al, Eur. Phys. J. C 75 (2015) 485

^{37}**Ar** production by nuclear fragmentation of Xe quantified by **LUX-ZEPLIN**

- From **Silberberg&Tsao** cross sections + n, p spectra from **Gordon** and **CRY**
- Effect mitigated by Xe purification

$R = 0.024\ kg^{-1}\ d^{-1}$

J. Aalbers er al, Phys. Rev. D 105 (2022) 082004

Activation studies: other detector targets

Tellurium:

p/n irradiations of TeO_2 at Los Alamos and CERN and study for ^{nat}Te

Production rates in $kg^{-1}d^{-1}$

	^{60}Co	^{110m}Ag	^{124}Sb
Half-life [27]	5.2711(8) y	249.78(2) d	60.208(11) d
Measurement [136]	<0.0053	0.42	
ACTIVIA+TENDL [138]	0.070	0.206	15.7

A.F. Barghouty et al, Nucl. Instrum. Meth. B 295 (2013) 16
B. S. Wang et al, Phys. Rev. C 92 (2015) 024620
V. Lozza et al, Astropart. Phys. 61 (2015) 62

Molibdenum:

Production rates in LMO of **^{88}Y, ^{82}Rb** affecting double beta decay of ^{100}Mo
Simulation based on **Geant4** + **CRY** for n, p, μ and γ spectra

W. Chen, Eur. Phys. J. C 82 (2022) 549

$CaWO_4$:

Comparison of CRESST data and simulation based on **Geant4** + **ACTIVIA**

H Kluck et al, 2021 J. Phys.: Conf. Ser. 2156 012227

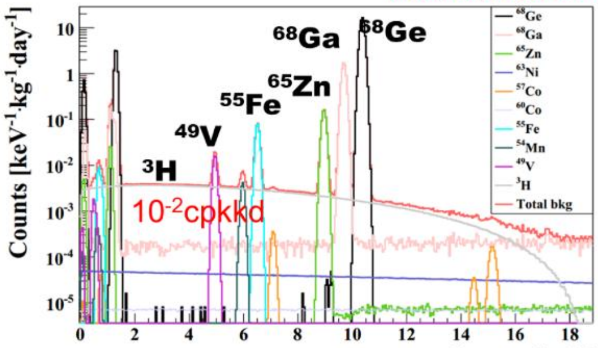
Nuclide i	^{14}C	^{3}H	^{178}W	^{179}Ta	^{175}Hf	^{181}W	^{37}Ar	^{173}Lu	^{172}Hf	^{171}Lu
R_i / kg^{-1} d^{-1}	84.06	34.82	25.91	24.59	16.67	13.74	12.17	11.25	11.12	9.18
TALYS		45.5								

D. M. Mei et al, Astropart. Phys. 31 (2009) 417

Activation studies: Ge

- Widely used in detectors for DM, DBD, radioassay
- Cobalt isotopes are produced together with ^{65}Zn, ^{54}Mn and germanium isotopes (e.g. ^{68}Ge)

arXiv1802.09327



Simulation spectrum

Enriched Ge

Production rates in $kg^{-1}d^{-1}$

	^{3}H	^{54}Mn	^{55}Fe	^{57}Co	^{58}Co	^{60}Co	^{65}Zn	^{68}Ge
Half-life [27] units	12.312(25) y	312.19(3) d	2.747(8) y	271.81(4) d	70.85(3) d	5.2711(8) y	244.01(9) d	270.95(26) d
Measurement [19]		2.3		1.6	1.2		11	
Measurement [103]		2.0 ± 1.0		0.7 ± 0.4		2.5 ± 1.2	8.9 ± 2.5	2.1 ± 0.4
Meas. (MAJORANA) [107]	140 ± 10	4.4 ± 4.1	2.1 ± 0.7				4.3 ± 3.6	3.3 ± 1.6
Monte Carlo [92]	140	1.4		1	1.8		6.4	0.94
Monte Carlo [93]				0.08	1.6	3.5	6.0	1.2
SHIELD [44]						3.3		5.8
TALYS [94]	24.0	0.87	3.4	6.7		1.6	20	7.2
MENDL+YIELDX [43]		3.7	1.6	1.7	4.6	5.1	20	12
TENDL+HEAD [28]	94 ± 34							
ACTIVIA [36]		2.2	1.6	2.9	5.5	2.4	10.4	7.6
ACTIVIA [45]	51.3	2.2	1.2	2.3	5.5	4.4	9.7	15.4
GEANT4 [45]	47.4	1.4	4.5	3.3	2.9	2.4	24.9	21.8
GEANT4+CRY [91]	22.8	0.96	2.9	2.8		1.9	18.0	20.0

Activation studies: Ge

- Study of cosmogenic activation in **^{76}Ge enriched Ge** detectors during fabrication and transportation above ground from CDEX experiment

Q. Nie et al., 2024 JINST 19 P03002

Based on CRY + Geant4 simulation

Table 2. Production rates of cosmogenic radionuclides in germanium at different fabrication sites.

Radionuclide	$T_{1/2}$	Production rate (kg^{-1} d^{-1})			
		Zelenogorsk	Kunming	Oak Ridge	Strasbourg
^{68}Ge	270.9 d	17.17	22.47	10.69	13.45
^{60}Co	5.3 yr	1.51	2.49	1.11	1.23
^{3}H	12.3 yr	39.16	70.74	29.25	31.89
^{65}Zn	243.9 d	15.17	21.97	10.08	12.33
^{55}Fe	2.7 yr	5.13	7.86	3.45	4.01
^{63}Ni	101.2 yr	2.52	4.65	1.95	2.19
^{57}Co	271.7 d	2.89	5.07	2.14	2.30
^{54}Mn	312.2 d	0.89	1.59	0.65	0.76
^{49}V	330.0 d	1.09	2.23	0.93	0.91

Table 3. Production rates of cosmogenic radionuclides in germanium generated by different components of cosmic rays with the transportation shield. The simulated results without the shield are listed in parentheses for comparison.

Radionuclide	Latitude	Production rate (kg^{-1} d^{-1})				
		Neutron	Proton	Muon	Gamma-ray	Total
^{68}Ge	24°N	0.51(5.62)	0.18(0.78)	0.12(0.04)	0(0.07)	0.81(6.51)
	56°N	0.99(11.98)	0.20(1.28)	0.15(0.05)	0(0.09)	1.34(13.40)
^{60}Co	24°N	0.02(0.48)	0.02(0.19)	0.02(0.01)	0(0.01)	0.06(0.69)
^{3}H	24°N	0.65(12.01)	0.56(5.31)	0.66(0.31)	0(0.09)	1.87(17.72)
^{65}Zn	24°N	0.35(4.95)	0.15(1.07)	0.17(0.07)	0(0.08)	0.67(6.17)
^{63}Ni	24°N	0.11(1.64)	0.06(0.46)	0.08(0.03)	0(0.03)	0.25(2.16)
^{57}Co	24°N	0.03(0.80)	0.03(0.42)	0.03(0.02)	0(0.01)	0.09(1.25)
^{55}Fe	24°N	0.04(0.89)	0.04(0.47)	0.02(0.01)	0(0.01)	0.01(1.38)
^{54}Mn	24°N	0.02(0.25)	0.01(0.12)	0.01(0.004)	0(0.002)	0.03(0.41)
^{49}V	24°N	0.01(0.35)	0.02(0.23)	0.01(0.004)	0(0.001)	0.04(0.59)

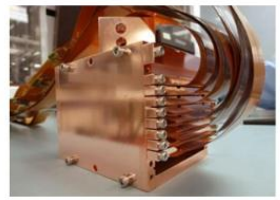
Surface activation: Si

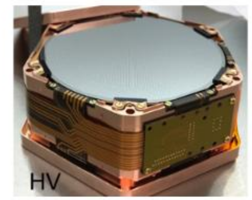
Controlled **neutron irradiation** of Si CCDs at **Los Alamos** to derive **production rates**

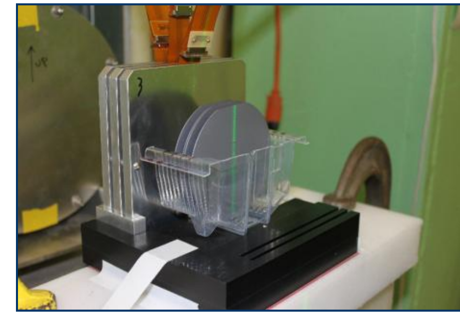
^{3}H (Tritium), ^{7}Be, ^{22}Na in Silicon

Pacific Northwest National Laboratory · Los Alamos National Laboratory · CENPA · KICP

Phys. Rev. D 102, 102006 (2020)
arXiv:2007.10584



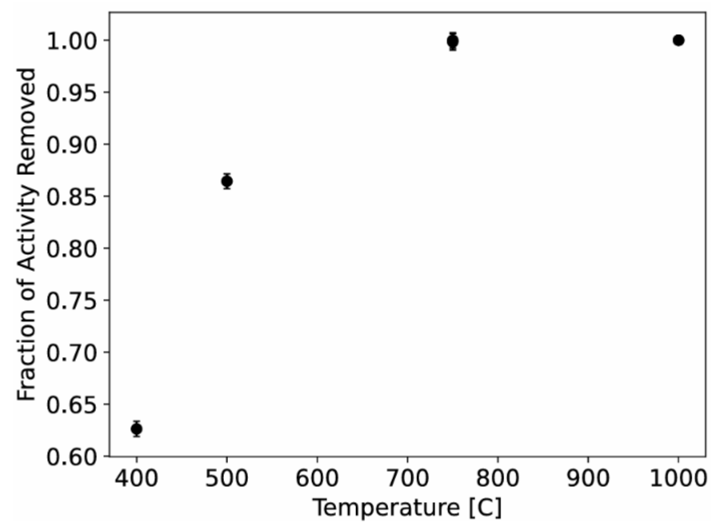




Production rates in kg^{-1}d^{-1}

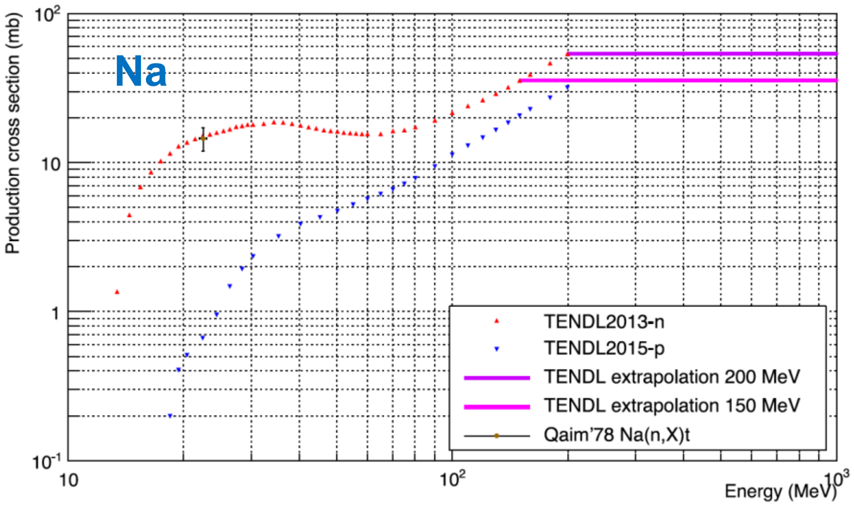
	^{3}H	^{7}Be	^{22}Na
Half-life [27]	12.312(25) y	53.22(6) d	2.6029(8) y
Measurement (neutrons) [232]	112 ± 24	8.1 ± 1.9	43.0±7.1
Measurement+Calculations (total) [232]	124 ± 24	9.4 ± 2.0	49.6 ± 7.3
TENDL+HEAD as [28]	120 ± 23		
TALYS+INCL++-ABLA [101]	124		
GEANT4 [46]	27.3		
ACTIVIA [46]	108.7		

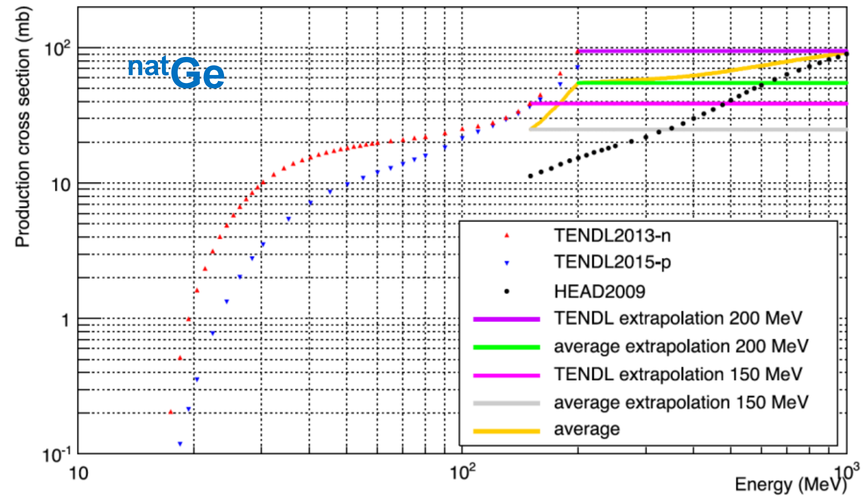
R. Saldanha, LRT2024



Demonstrated the ability to remove spallation-induced **^{3}H** from Si using elevated temperatures (>750 ºC) at PNNL

Activation studies: Tritium





J. Amare et al, Astropart. Phys. 97 (2018) 96

Production rates in kg^{-1}d^{-1}

Target	Ref. 55	TENDL+HEAD[71]	TALYS[59]	GEANT4[37]	GEANT4[36]	ACTIVIA[37]	ACTIVIA[36]	ACTIVIA	Others
^{nat}Ge	178/210	75 ± 26	27.7	48.3	47.4	52.4	52.4	46/43.5 (Ref. 65)	82 ± 21 (Ref. 65)
									76 ± 6 (Ref. 70)
^{enr}Ge	113/140	94 ± 34	24.0		47.4		51.3		140 ± 10 (Ref. 66)
Si		120 ± 23		27.3		108.7			125 (Ref. 52)
TeO_2			43.7						
NaI		83 ± 27	31.1	42.9		36.2			
CsI			19.7						
$CaWO_4$			45.5						
Ar		146 ± 31	44.4	84.9		82.9			
Ne		228 ± 16							
Xe			16.0	31.6		35.6			
Quartz									
C_2H_6				279.5					

New measurements with LANSCE beam:

Si: 112 ± 24

R. Saldanha et al, Phys. Rev. D 102 (2020) 102006

NaI: 80 ± 21

R. Saldanha et al, Phys Rev. D 107 (2023) 022006

Activation studies: Cu

Material largely used in experiments with many activation studies

Production rates in $kg^{-1}d^{-1}$

	^{46}Sc	^{48}V	^{54}Mn	^{56}Co	^{57}Co	^{58}Co	^{59}Fe	^{60}Co
Half-life[27,108]	83.787(16)	15.9735	312.19(3)	77.236	271.81(4)	70.85(3)	44.494	5.2711(8)
units	d	d	d	d	d	d	d	y
Measurement [202]	2.18 ± 0.74	4.5 ± 1.6	8.85 ± 0.86	9.5 ± 1.2	74 ± 17	67.9 ± 3.7	18.7 ± 4.9	86.4 ± 7.8
Measurement [184]	$2.33^{+0.95}_{-0.78}$	$3.4^{+1.6}_{-1.3}$	$13.3^{+3.0}_{-2.9}$	$9.3^{+1.2}_{-1.4}$	$44.8^{+8.6}_{-8.2}$	$68.9^{+5.4}_{-5.0}$	$4.1^{+1.4}_{-1.2}$	$29.4^{+7.1}_{-5.9}$
ACTIVIA (MENDL-2P) [36]	3.1		12.4	14.1	36.4	38.1	1.8	9.7
ACTIVIA [36,184]	3.1		14.3	8.7	32.5	56.6	4.2	26.3
COSMO [184]	1.5	3.1	13.5	7.0	30.2	54.6	4.3	25.7
ACTIVIA [46]	4.1		30.0	20.1	77.5	138.1	10.5	66.1
ACTIVIA [99]	3		16	9	34	60	2	29
GEANT4 [46]	1.2		12.3	10.3	67.2	57.3	8.8	64.6
TALYS [94]			16.2		56.2			46.4
MENDL+YIELDX [43]	2.7		27.7	20.0	74.1	123.0	4.9	55.4
CONUS [99]	3		14	10	50	76	5	92
Measurement (China)			18.6±2.0	9.9±1.3	48.3±5.5	51.8±2.5		39.7±5.7

Measured rates from sensitive screening with Ge detectors after exposing large samples for long time in controlled conditions at **LNGS / Jinping** labs

S. Cebrián, et al., Cosmogenic activation in germanium and copper for rare event searches, Astropart. Phys. 33 (2010) 316–329, http://dx.doi.org/10.1016/j.astropartphys.2010.03.002.

L. Baudis, et al., Cosmogenic activation of xenon and copper, Eur. Phys. J. C 75 (2015) 485, http://dx.doi.org/10.1140/epjc/s10052-015-3711-3.

C. Zhang, et al., Cosmogenic activation of materials used in rare event search experiments, Astropart. Phys. 84 (2016) 62–69, http://dx.doi.org/10.1016/j.astropartphys.2016.08.008.

M. Laubenstein, G. Heusser, Cosmogenic radionuclides in metals as indicator for sea level exposure history, App. Rad. Isot. 67 (2009) 750–754, http://dx.doi.org/10.1016/j.apradiso.2009.01.029.

Z. She, et al., Study on cosmogenic activation in copper for rare event search experiments, Eur. Phys. J. C 81 (2021) 1041, http://dx.doi.org/10.1140/epjc/s10052-021-09827-w.

Activation studies: Steel, Ti

Stainless steel

Sample exposed for a long time at **LNGS** outside laboratory

Production rates in $kg^{-1}d^{-1}$

Isotope	^{7}**Be**	^{46}**Sc**	^{48}**V**	^{54}**Mn**	^{56}**Co**	^{58}**Co**
Half-life (d) [27,108]	53.22(6)	83.787(16)	15.9735	312.19(3)	77.236	70.85(3)
Measurement [202]	389 ± 60	19.0 ± 3.5	34.6 ± 3.5	233 ± 26	20.7 ± 3.5	51.8 ± 7.8
GEANT4 [46]	0.05	8.8		230	16	90
ACTIVIA [46]	2.05	18		191	131	13

W. Maneschg et al. Nucl. Instrum. Meth. A 593 (2008) 448
M. Labustenstein, G. Heusser, ARI 67 (2009) 750

Titanium

^{46}Sc activity quantified by LUX

Production rates in $kg^{-1}d^{-1}$

	^{46}**Sc**	^{40}**K**
Half-life [27]	83.787(16) d	$1.2504(30) \times 10^{9}$ y
GEANT4 [46]	275.5	22.1
ACTIVIA [46]	270.1	61.0

C. Zhang et al, Astropart. Phys. 84 (2016) 62

Activation studies: Pb, Ti, Al

Lead

- Sample exposed at Los Alamos to the neutron beam that resembles the cosmic-ray flux
- Activation previously unknown, found to be not relevant

Production rates in $kg^{-1}d^{-1}$

	^{194}Hg	^{202}Pb	^{207}Bi
Half-life (y) [27,108]	444	$5.25\ 10^4$	32.9
Measurement [205]	8.0 ± 1.3	120 ± 25	<0.17
TALYS [205]	16	77	

V. E. Giuseppe et al, Astropart. Phys. 64 (2015) 34

Aluminium

Calculations based on different approaches, including measured production cross sections

B. Majorovits et al, Nucl. Instrum. Meth. A 647 (2011) 39
R. Breier et al, Nucl. Instrum. Meth. A 978 (2020) 164355

Production rates in $kg^{-1}d^{-1}$

	^{22}Na	^{26}Al
Half-life (y) [27]	2.6029(8)	$7.17(24) \times 10^5$
Calculation for neutrons [209]	153	389
Calculation for protons [209]	24	47
ACTIVIA [99]		160
CONUS [99]		530

Location	Si	Ge	Cu
	^{3}H	^{3}H	^{60}Co
Sea-level	125	94	46
SUF Tunnel A/C (15–20 mwe)	0.11	0.080	0.080
PNNL SUL (30 mwe)	0.075	0.055	0.052
SLC Adit Storage (50–60 mwe)	0.036	0.027	0.025

TABLE IV: Activation rate (atoms per kg per day) from neutrons at shallow-depth sites. Sea-level activation rates are also shown for comparison.

Location	Si	Ge	Cu
	Tritium	Tritium	^{60}Co
Sea-level	1.6	0.61	2.0
SUF Tunnel A/C (15–20 mwe)	0.24	0.092	0.30
PNNL SUL (30 mwe)	0.11	0.043	0.14
SLC Adit Storage (50–60 mwe)	0.044	0.016	0.053

TABLE VII: Activation rate (atoms per kg per day) from stopped negative muons at shallow-depth sites. Calculation at sea-level is also given for comparison.

Location	Si	Ge	Cu
	Tritium	Tritium	^{60}Co
Sea-level	0.73	0.044	1.5
SUF Tunnel A/C (15–20 mwe)	4.4×10^{-2}	2.7×10^{-3}	8.6×10^{-2}
PNNL (SUL 30 mwe)	2.8×10^{-2}	1.8×10^{-3}	5.0×10^{-2}
SLC Adit Storage (50–60 mwe)	1.5×10^{-2}	9.8×10^{-4}	2.8×10^{-2}

TABLE IX: Gamma-induced activation rates (atoms per kg per day.

S. Poudel et al, arXiv:2605.16534

Underground activation

Argon

Subsurface **cosmogenic** and **radiogenic** production of ^{42}Ar

Reactions	TALYS-based production rate from selected reactions [atoms/ton/y]	FLUKA residual-nuclei-recording-based) [atoms/ton/y]	Major ^{42}Ar yielding reactions
n,p,α,d,t-induced reactions	2.5×10^{-4}	4.2×10^{-4}	^{44}Ca(n,3He)^{42}Ar
Heavy-ion collisions	–	8.3×10^{-4}	^{56}Fe(H*,X)^{42}Ar ^{44}Ca(H*,X)^{42}Ar ^{48}Ca(H*,X)^{42}Ar
Photon-induced reactions	–	1.6×10^{-4}	^{44}Ca(γ,X)^{42}Ar
Pion-induced reactions	–	1.6×10^{-4}	^{56}Fe(Π^-,X)
Other cosmic-ray muon-induced reactions	–	2.0×10^{-4}	^{44}Ca(μ^-,2p)^{42}Ar ^{42}Cl β^- decay
Radiogenic reactions	4.8×10^{-18}	–	^{41}Ar(n,γ)^{42}Ar
All reactions (sum)	2.5×10^{-4}	1.8×10^{-3}	–

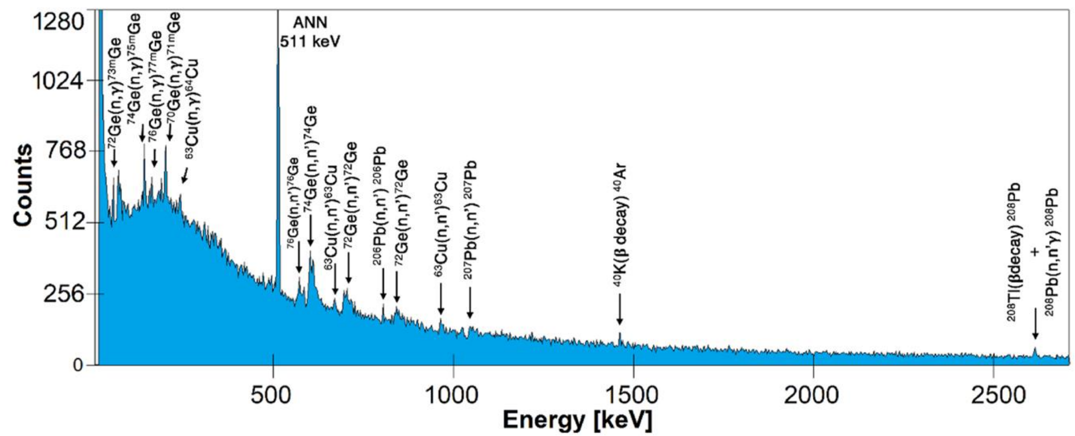
S. Poudel et al, PRD 110, 082010 (2024)

- Standard continental **crust**, 3000 mwe
- **Radiogenic** contribution, based on **TALYS** cross sections, totally negligible
- **Cosmogenic** production based on **FLUKA** simulation of μ's from **MUSIC**

Cosmogenic background

Exploration of **cosmic-ray induced nuclear processes** in a shielded Ge detector complemented by MC simulations

- Data with HPGe (2 kg) above ground (80 m) at Novi Sad University (China)
- CRY for n, μ + Geant4 simulation



D. Velimirovic et al, Radiation Physics and Chemistry 238 (2026) 113145

E [keV]	Nuclides and Reactions	Remarks	Intensity [c ks^{-1}]	
			Experiment	Simulation
5–2700	Continuum	–	$1.37\cdot10^3$	$1.31\cdot10^3$
5–500	Continuum	–	$0.76\cdot10^3$	$0.88\cdot10^3$
53.4	^{72}Ge (n, γ) ^{73}Ge	Thermal neutron capture	0.84 ± 0.13	–
66.7	^{72}Ge (n, γ) ^{73}Ge	Sum peak 13.3 + 53.4 keV Thermal neutron capture	1.08 ± 0.15	–
139.7	^{74}Ge (n, γ) ^{75}Ge	Thermal neutron capture	1.09 ± 0.14	0.94 ± 0.09
198.3	^{70}Ge (n, γ) ^{71}Ge	Sum peak 23.4 + 174.9 keV Thermal neutron capture	2.03 ± 0.21	–
511 (ANN)	–	Muon-induced pair production	30 ± 2	21 ± 2
569.7	^{207}Pb (n, n') ^{207}Pb	Inelastic scattering of neutrons	0.49 ± 0.11	0.40 ± 0.04
583.2	^{206}Pb (n, n') ^{206}Pb	Inelastic scattering of neutrons	0.29 ± 0.08	0.18 ± 0.02
595.9	^{74}Ge (n, n') ^{75}Ge	Inelastic scattering of neutrons	7.7 ± 0.6	7.1 ± 0.7
691.3	^{72}Ge (n, n') ^{72}Ge	Inelastic scattering of neutrons	4.0 ± 0.4	3.8 ± 0.4
803.3	^{206}Pb (n, n') ^{206}Pb	Inelastic scattering of neutrons	0.9 ± 0.2	0.76 ± 0.08
834.1	^{72}Ge (n, n') ^{72}Ge	Inelastic scattering of neutrons	4.6 ± 0.2	5.1 ± 0.5
962.1	^{63}Cu (n, n') ^{63}Cu	Inelastic scattering of neutrons	2.3 ± 0.5	2.1 ± 0.2
2614.5	^{208}Pb (n, n') ^{208}Pb	Inelastic scattering of neutrons	0.79 ± 0.11	0.33 ± 0.04

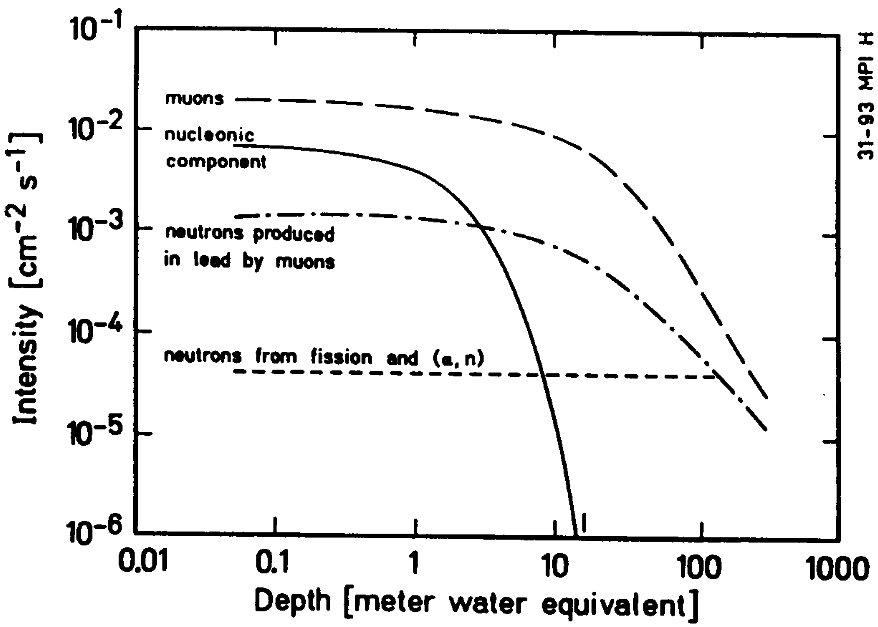
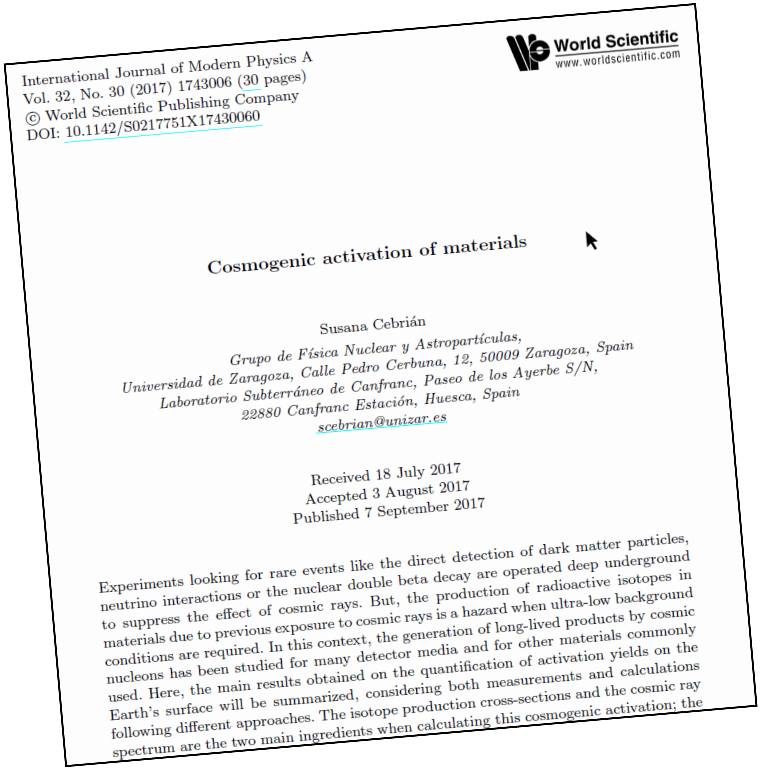


Figure 2 Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and (α, n) reactions is also shown. The nucleonic component is more than 97% neutrons.

G. Heusser, Ann. Rev. Part. Sci. 45 (1995) 543

Snowmass2021 Cosmic Frontier White Paper: Calibrations and backgrounds for dark matter direct detection, arXiv:2203.07623



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Cosmogenic activation of materials

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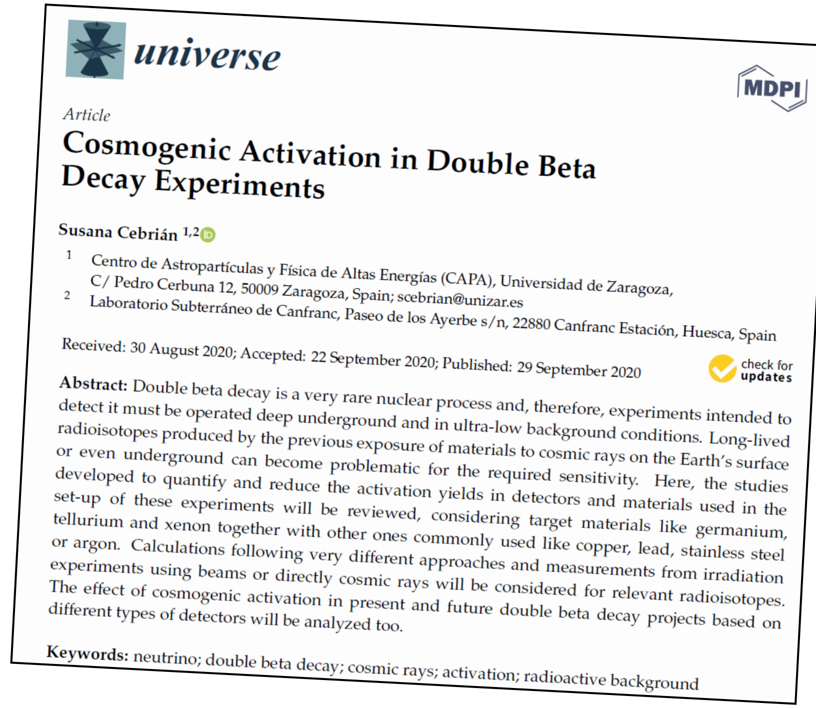
Experiments looking for rare events like the direct detection of dark matter particles, neutrino interactions or the nuclear double beta decay are operated deep underground to suppress the effect of cosmic rays. But, the production of radioactive isotopes in materials due to previous exposure to cosmic rays is a hazard when ultra-low background conditions are required. In this context, the generation of long-lived products by cosmic nucleons has been studied for many detector media and for other materials commonly used. Here, the main results obtained on the quantification of activation yields on the Earth's surface will be summarized, considering both measurements and calculations following different approaches. The isotope production cross-sections and the cosmic ray spectrum are the two main ingredients when calculating this cosmogenic activation; the



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Cosmogenic Activation in Double Beta Decay Experiments

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Abstract: Double beta decay is a very rare nuclear process and, therefore, experiments intended to detect it must be operated deep underground and in ultra-low background conditions. Long-lived radioisotopes produced by the previous exposure of materials to cosmic rays on the Earth's surface or even underground can become problematic for the required sensitivity. Here, the studies developed to quantify and reduce the activation yields in detectors and materials used in the set-up of these experiments will be reviewed, considering target materials like germanium, tellurium and xenon together with other ones commonly used like copper, lead, stainless steel or argon. Calculations following very different approaches and measurements from irradiation experiments using beams or directly cosmic rays will be considered for relevant radioisotopes. The effect of cosmogenic activation in present and future double beta decay projects based on different types of detectors will be analyzed too.

Keywords: neutrino; double beta decay; cosmic rays; activation; radioactive background

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