Cosmogenic activation in materials used in low background experiments

- Cosmogenic activation: origin and quantification
- Examples of activation studies:
    - Detector targets: Ar, Xe, NaI, Ge, others
    - Other materials: Cu, Pb, others
    - Underground activation

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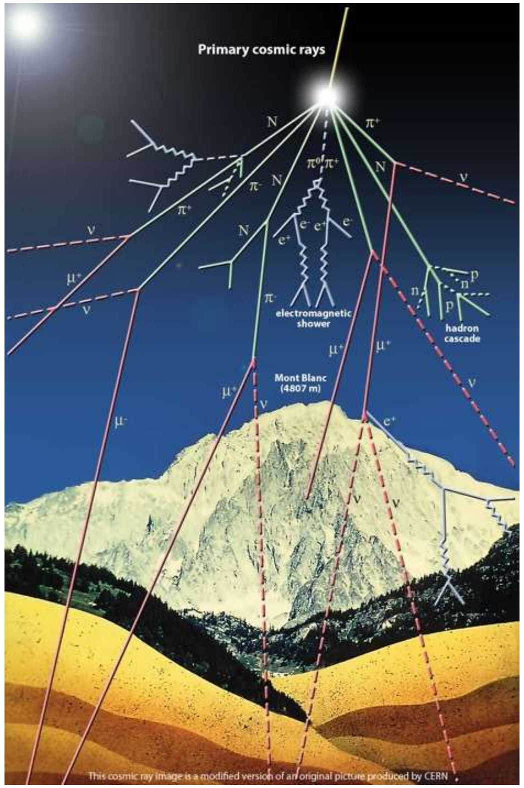
Universidad Zaragoza 1542

Cosmogenic activation: origin

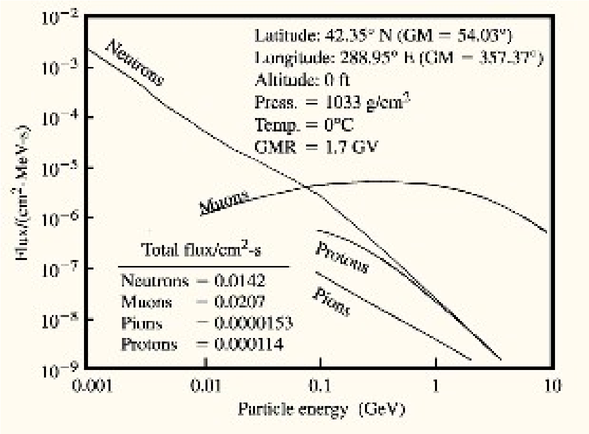


This cosmic ray image is a modified version of an original picture produced by CERN

- **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



J.F. Ziegler, IBM J. Res. & Develop. 42 (1998) 1

Only μ survive >10 m.w.e: flux reduced by several orders of magnitude

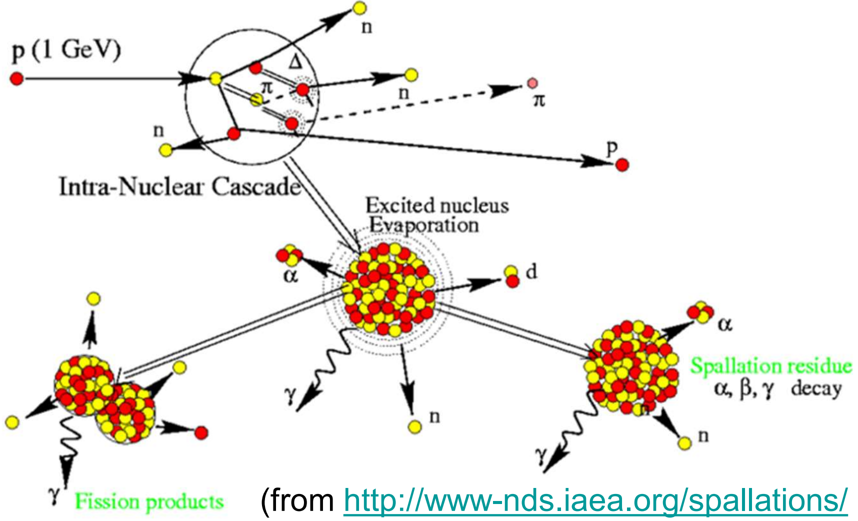
Cosmogenic activation: origin

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

- On the *Earth's surface*, is dominated by **neutrons**; at *high altitude*, **proton** production is 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

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**, …

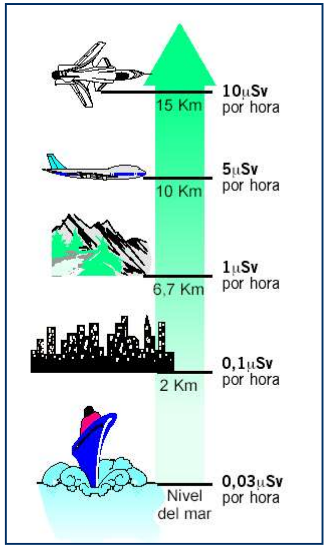


(from http://www-nds.iaea.org/spallations/)

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
  - Successful R&D for Ge crystal growth and detector fabrication D. Mei, arXiv:2409.03580
- Shielding against hadronic component of cosmic rays



Majorana experiment

CDEX experiment

This complicates the preparation of experiments → it is desirable to have reliable **estimates of activation yields** to assess the 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

σ = production cross section

E = particle energy

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

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

t_{exp} = exposure time

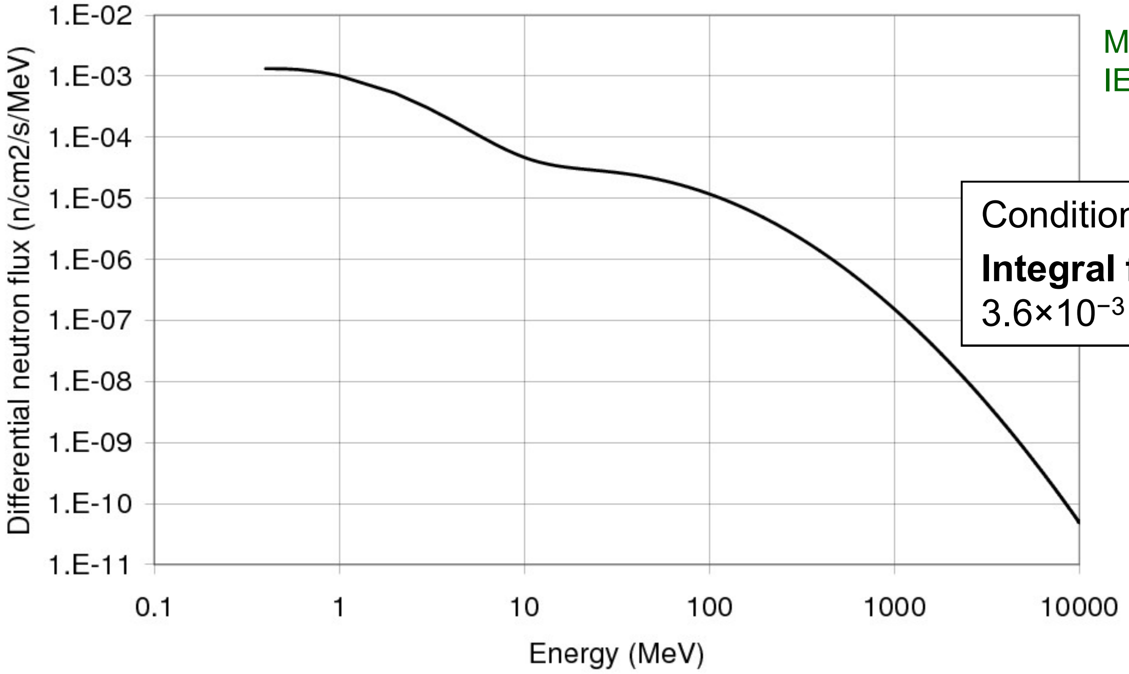
t_{cool} = cooling time underground

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**

→ A parametrization based on a set of measurements of cosmic neutrons on the ground across the US considered



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

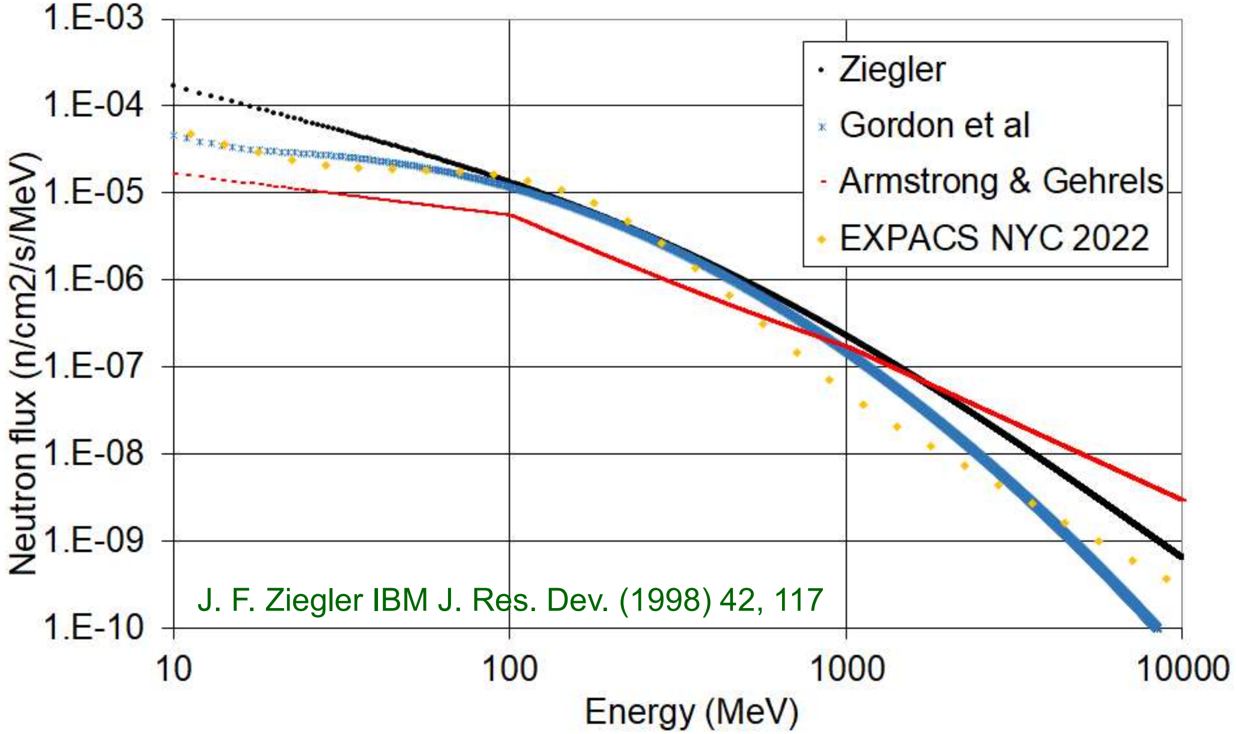
Conditions of New York City at sea level

Integral flux (10 MeV-10 GeV): 3.6×10^{-3} cm^{-2} s^{-1}

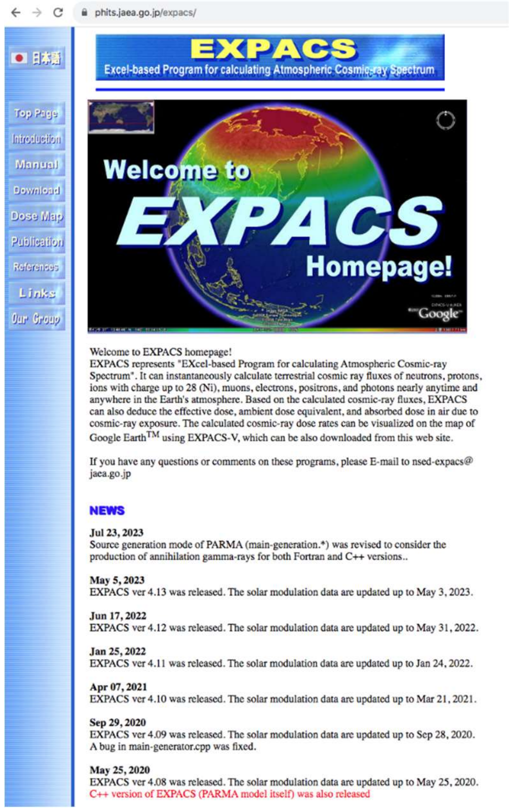
Dependent on altitude (height of the atmosphere) and geomagnetic rigidity
→ **correction factors** must be applied at different altitudes / latitudes

Cosmogenic activation: flux of cosmic rays

Other descriptions of the **cosmic neutron spectrum** are available



J. F. Ziegler IBM J. Res. Dev. (1998) 42, 117



Welcome to EXPACS homepage!
EXPACS represents "EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum". It can instantaneously calculate terrestrial cosmic ray fluxes of neutrons, protons, ions with charge up to 28 (Ni), muons, electrons, positrons, and photons nearly anytime and anywhere in the Earth's atmosphere. Based on the calculated cosmic-ray fluxes, EXPACS can also deduce the effective dose, ambient dose equivalent, and absorbed dose in air due to cosmic-ray exposure. The calculated cosmic-ray dose rates can be visualized on the map of Google Earth^{TM} using EXPACS-V, which can be also downloaded from this web site.

If you have any questions or comments on these programs, please E-mail to nsed-expacs@jaea.go.jp

NEWS

Jul 23, 2023
Source generation mode of PARMA (main-generation.*) was revised to consider the production of annihilation gamma-rays for both Fortran and C++ versions..

May 5, 2023
EXPACS ver 4.13 was released. The solar modulation data are updated up to May 3, 2023.

Jun 17, 2022
EXPACS ver 4.12 was released. The solar modulation data are updated up to May 31, 2022.

Jan 25, 2022
EXPACS ver 4.11 was released. The solar modulation data are updated up to Jan 24, 2022.

Apr 07, 2021
EXPACS ver 4.10 was released. The solar modulation data are updated up to Mar 21, 2021.

Sep 29, 2020
EXPACS ver 4.09 was released. The solar modulation data are updated up to Sep 28, 2020.
A bug in main-generator.cpp was fixed.

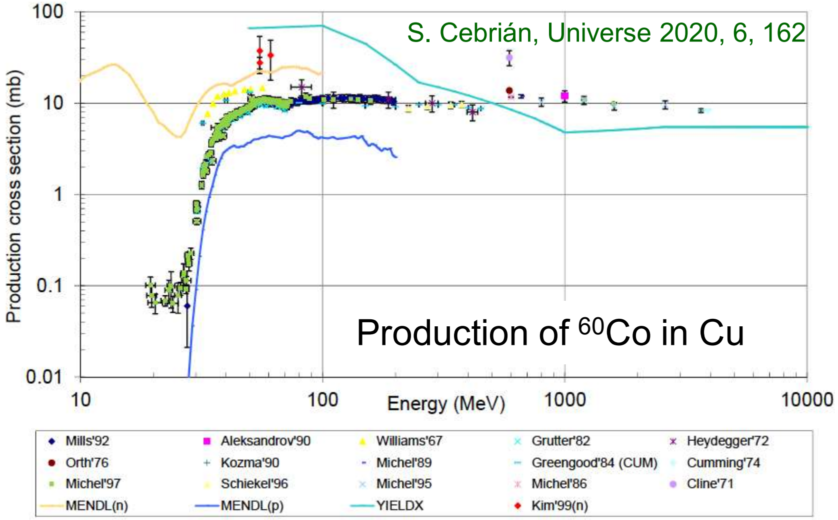
May 25, 2020
EXPACS ver 4.08 was released. The solar modulation data are updated up to May 25, 2020.
C++ version of EXPACS (PARMA model itself) was also released

EXPACS (EXcel-based Program for calculating Atmospheric Cosmic-ray Spectrum):
https://phits.jaea.go.jp/expacs/
to calculate terrestrial **cosmic ray fluxes** of **neutrons, protons**, light ions, **muons,** electrons, positrons, and photons nearly ***anytime*** and ***anywhere*** in the Earth's atmosphere.

CRY (Cosmic-ray Shower Library) generator

Cosmogenic activation: production cross sections

Select the best description of the excitation function **σ*(E)*** by nucleons

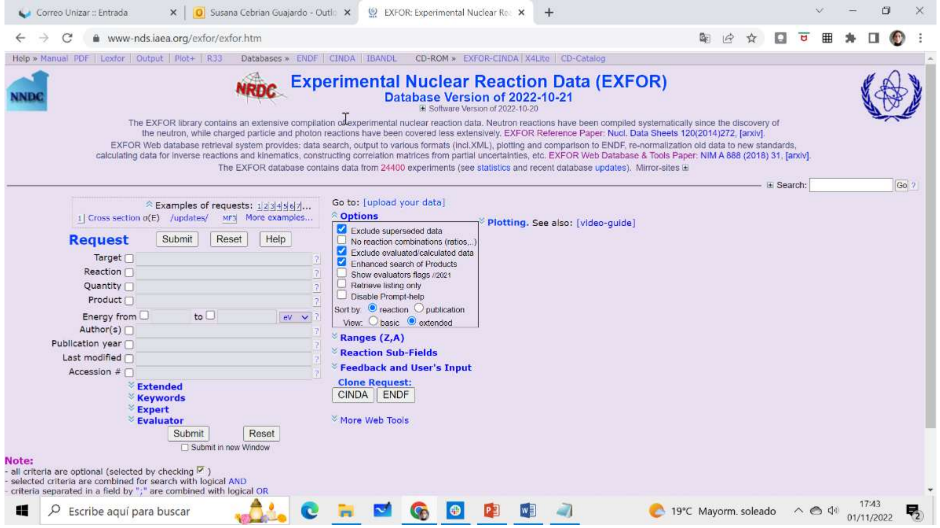

S. Cebrián, Universe 2020, 6, 162

Production of ^{60}Co in Cu

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

  EXFOR (Experimental Nuclear Reaction Data) database

  http://www-nds.iaea.org/exfor/exfor.htm



Experimental Nuclear Reaction Data (EXFOR)
Database Version of 2022-10-21
Software Version of 2022-10-20

The EXFOR library contains an extensive compilation of experimental nuclear reaction data. Neutron reactions have been compiled systematically since the discovery of the neutron, while charged particle and photon reactions have been covered less extensively. EXFOR Reference Paper: Nucl. Data Sheets 120(2014)272, [arxiv].

EXFOR Web database retrieval system provides: data search, output to various formats (incl.XML), plotting and comparison to ENDF, re-normalization old data to new standards, calculating data for inverse reactions and kinematics, constructing correlation matrices from partial uncertainties, etc. EXFOR Web Database & Tools Paper: NIM A 888 (2018) 31, [arxiv].

The EXFOR database contains data from 24400 experiments (see statistics and recent database updates). Mirror-sites

Search: Go ?

Examples of requests: 1 2 3 4 5 6 7...
1 Cross section σ(E) /updates/ MF3 More examples...

Request Submit Reset Help

Target ☐
Reaction ☐
Quantity ☐
Product ☐
Energy from ☐ to ☐ eV
Author(s) ☐
Publication year ☐
Last modified ☐
Accession # ☐

Extended
Keywords
Expert
Evaluator

Submit Reset
☐ Submit in new Window

Go to: [upload your data]

Options
☑ Exclude superseded data
☐ No reaction combinations (ratios,..)
☑ Exclude evaluated/calculated data
☑ Enhanced search of Products
☐ Show evaluators flags //2021
☐ Retrieve listing only
☐ Disable Prompt-help
Sort by: ● reaction ○ publication
View: ○ basic ● extended

Ranges (Z,A)
Reaction Sub-Fields
Feedback and User's Input
Clone Request: CINDA ENDF
More Web Tools

Plotting. See also: [video-guide]

Note:
- all criteria are optional (selected by checking ☑)
- selected criteria are combined for search with logical AND
- criteria separated in a field by ";" are combined with logical OR

Cosmogenic activation: production 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

YIELDX FORTRAN routine to calculate the **production cross-section** of a nuclide in a particular target at a certain energy

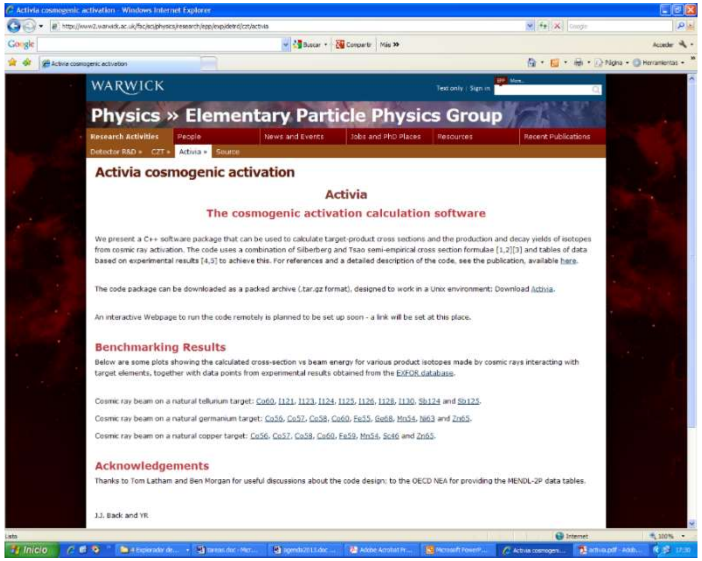
- Including the latest updates of the Silberberg & Tsao equations (1998)

ACTIVIA C++ computer 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, Nucl. Instrum. Meth. A 586 (2008) 286



Activia cosmogenic activation

Activia

The cosmogenic activation calculation software

We present a C++ software package that can be used to calculate target-product cross sections and the production and decay yields of isotopes from cosmic ray activation. The code uses a combination of Silberberg and Tsao semi-empirical cross section formulae [1,2][3] and tables of data based on experimental results [4,5] to achieve this. For references and a detailed description of the code, see the publication, available here.

The code package can be downloaded as a packed archive (.tar.gz format), designed to work in a Unix environment: Download Activia.

An interactive Webpage to run the code remotely is planned to be set up soon - a link will be set at this place.

Benchmarking Results

Below are some plots showing the calculated cross-section vs beam energy for various product isotopes made by cosmic rays interacting with target elements, together with data points from experimental results obtained from the EXFOR database.

Cosmic ray beam on a natural tellurium target: Co60, I121, I123, I124, I125, I126, I128, I130, Sb124 and Sb125.

Cosmic ray beam on a natural germanium target: Co56, Co57, Co58, Co60, Fe55, Ge68, Mn54, Ni63 and Zn65.

Cosmic ray beam on a natural copper target: Co56, Co57, Co58, Co60, Fe59, Mn54, Sc46 and Zn65.

Acknowledgements

Thanks to Tom Latham and Ben Morgan for useful discussions about the code design; to the OECD NEA for providing the MENDL-2P data tables.

J.J. Back and YR

Cosmogenic activation: production 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 LAHET
INCL+ABLA CASCADE MARS SHIELD BERTINI …

TENDL (TALYS-based Evaluated Nuclear Data Library)
https://tendl.web.psi.ch/tendl_2023/tendl2023.html

- Using the TALYS code
- For **neutrons and protons up to 200 MeV**

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**

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


TALYS-based evaluated nuclear data library

TENDL-2021

How to reference

Sub-library files

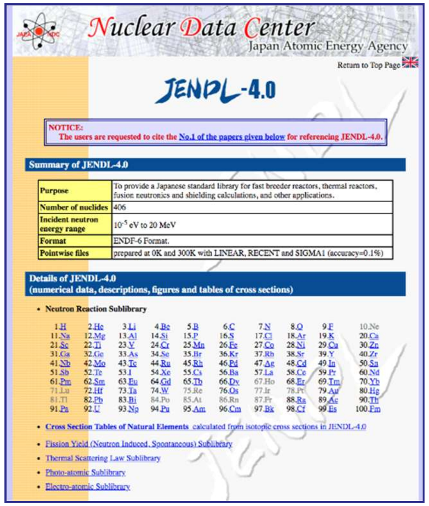
1. Neutron
2. Proton
3. Deuteron (updated)
4. Triton
5. He3
6. Alpha
7. Gamma
8. Fission yields
9. Thermal scattering
10. For astrophysics

Application libraries & tar files (ENDF, GND, ACE, PENDF...)

V&V

Total Monte Carlo files

TENDL-2021: (release date: December 30, 2021)


Nuclear Data Center
Japan Atomic Energy Agency

Return to Top Page

JENDL-4.0

NOTICE:
The users are requested to cite the No.1 of the papers given below for referencing JENDL-4.0.

Summary of JENDL-4.0

Purpose	To provide a Japanese standard library for fast breeder reactors, thermal reactors, fusion neutronics and shielding calculations, and other applications.
Number of nuclides	406
Incident neutron energy range	10^{-5} eV to 20 MeV
Format	ENDF-6 Format.
Pointwise files	prepared at 0K and 300K with LINEAR, RECENT and SIGMA1 (accuracy=0.1%)

Details of JENDL-4.0
(numerical data, descriptions, figures and tables of cross sections)

- **Neutron Reaction Sublibrary**

1.H 2.He 3.Li 4.Be 5.B 6.C 7.N 8.O 9.F 10.Ne
11.Na 12.Mg 13.Al 14.Si 15.P 16.S 17.Cl 18.Ar 19.K 20.Ca
21.Sc 22.Ti 23.V 24.Cr 25.Mn 26.Fe 27.Co 28.Ni 29.Cu 30.Zn
31.Ga 32.Ge 33.As 34.Se 35.Br 36.Kr 37.Rb 38.Sr 39.Y 40.Zr
41.Nb 42.Mo 43.Tc 44.Ru 45.Rh 46.Pd 47.Ag 48.Cd 49.In 50.Sn
51.Sb 52.Te 53.I 54.Xe 55.Cs 56.Ba 57.La 58.Ce 59.Pr 60.Nd
61.Pm 62.Sm 63.Eu 64.Gd 65.Tb 66.Dy 67.Ho 68.Er 69.Tm 70.Yb
71.Lu 72.Hf 73.Ta 74.W 75.Re 76.Os 77.Ir 78.Pt 79.Au 80.Hg
81.Tl 82.Pb 83.Bi 84.Po 85.At 86.Rn 87.Fr 88.Ra 89.Ac 90.Th
91.Pa 92.U 93.Np 94.Pu 95.Am 96.Cm 97.Bk 98.Cf 99.Es 100.Fm

- **Cross Section Tables of Natural Elements** calculated from isotopic cross sections in JENDL-4.0
- Fission Yield (Neutron Induced, Spontaneous) Sublibrary
- Thermal Scattering Law Sublibrary
- Photo-atomic Sublibrary
- Electro-atomic Sublibrary

Cosmogenic activation: quantification

The main **sources of uncertainty** in the evaluations come from difficulties on

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

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

Cosmogenic activation in materials used in low background experiments

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- **Examples of activation studies:**
  - Detector targets: Ar, Xe, NaI, Ge, others; ^{3}H
  - Other materials: Cu, Pb, others
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Activation studies: 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)

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

Observed in early data of DarkSide-50

^{42}Ar: β$^-$ emitter, Q=599 keV, **$T_{1/2}$=32.9 y** producing **^{42}K** (β$^-$ emitter, Q=3525 keV, $T_{1/2}$=12.36 h) → potential background for neutrinoless double beta decay

In Atm Ar: DBA: 92^{+22}_{-46} μBq/kg, GERDA: 50-100 μBq/kg, DEAP (40.4±0.5.9) μBq/kg
Production mechanisms: two-step neutron capture and $^{40}\mathrm{Ar}\ (\alpha,2\mathrm{p})\ ^{42}\mathrm{Ar}$

Talks by Mario Schwarz and Niko Lay

^{3}H: β$^-$ emitter with Q=18.6 keV, **$T_{1/2}$=12.3 y**

- Purification systems for LAr should remove all non-noble radionuclides, as also assumed in **LXe**, but tritium proposed as a possible explanation for the XENON1T excess

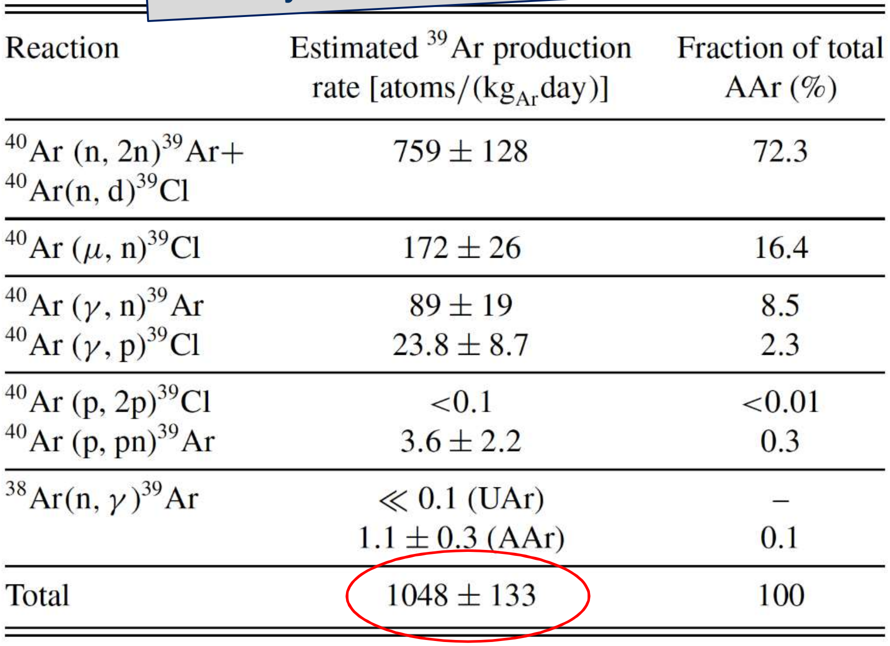
Activation studies: Ar

Production rates R (sea level)

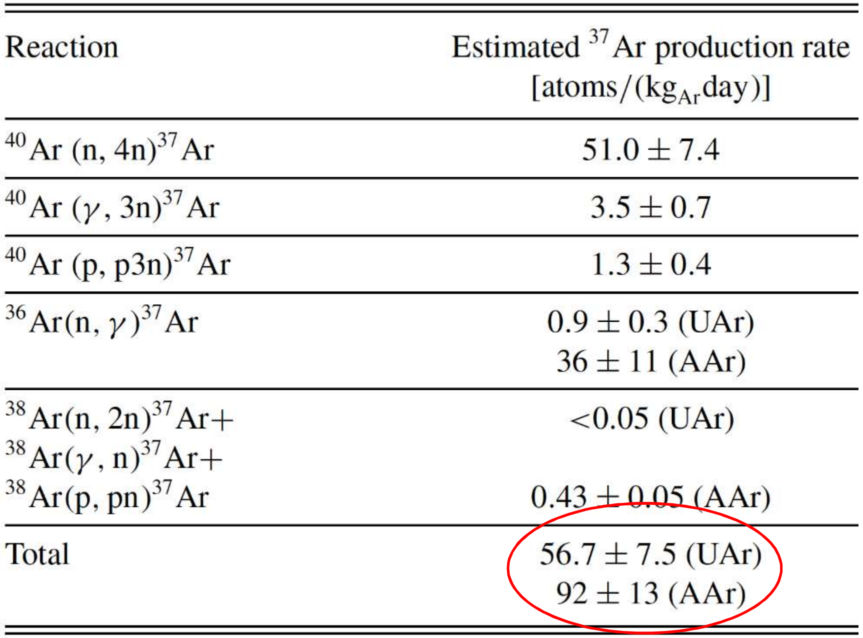
- First measurement for ^{39}**Ar** and ^{37}**Ar** in an **irradiation experiment** at Los Alamos (LANSCE) with a wide-band **neutron beam** that resembles the cosmic-ray neutron flux, quantifying products with a proportional counter at PNNL
  + calculations at sea level from alternate mechanisms

Talk by Richard Saldanha

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



Reaction	Estimated ^{39}Ar production rate [atoms/(kg$_{\mathrm{Ar}}$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 ^{40}Ar (γ, p)^{39}Cl	89 ± 19 23.8 ± 8.7	8.5 2.3
^{40}Ar (p, 2p)^{39}Cl ^{40}Ar (p, pn)^{39}Ar	<0.1 3.6 ± 2.2	<0.01 0.3
^{38}Ar(n, γ)^{39}Ar	$\ll 0.1$ (UAr) 1.1 ± 0.3 (AAr)	– 0.1
Total	1048 ± 133	100



Reaction	Estimated ^{37}Ar production rate [atoms/(kg$_{\mathrm{Ar}}$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)

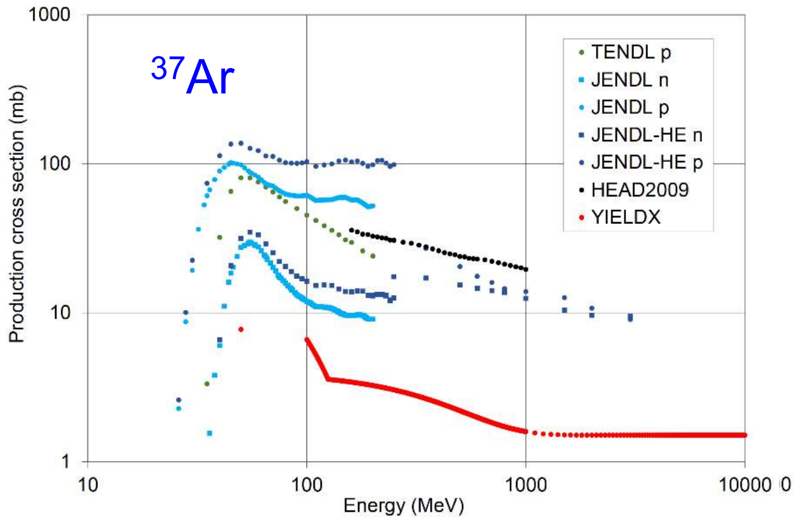
- Rates for ^{37}**Ar,** ^{39}**Ar** and ^{42}**Ar** from n, p and μ estimated by **GEANT4** simulation

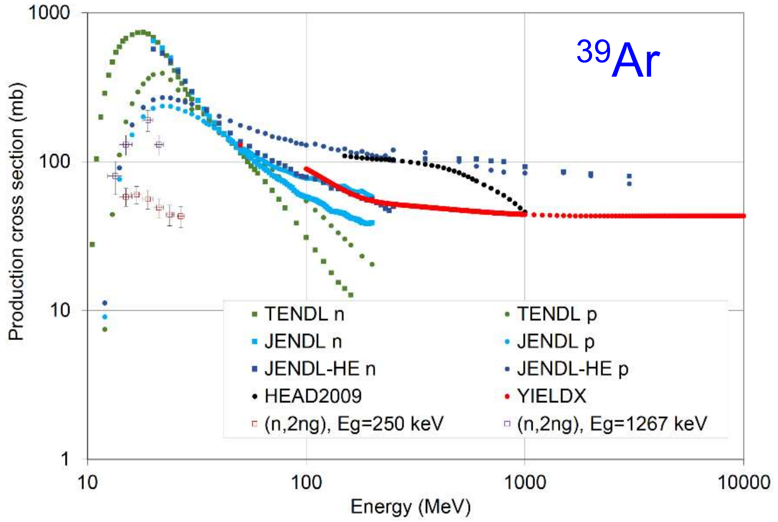
C. Zhang, D.M. Mei, Astropart. Phys. 142 (2022) 102733

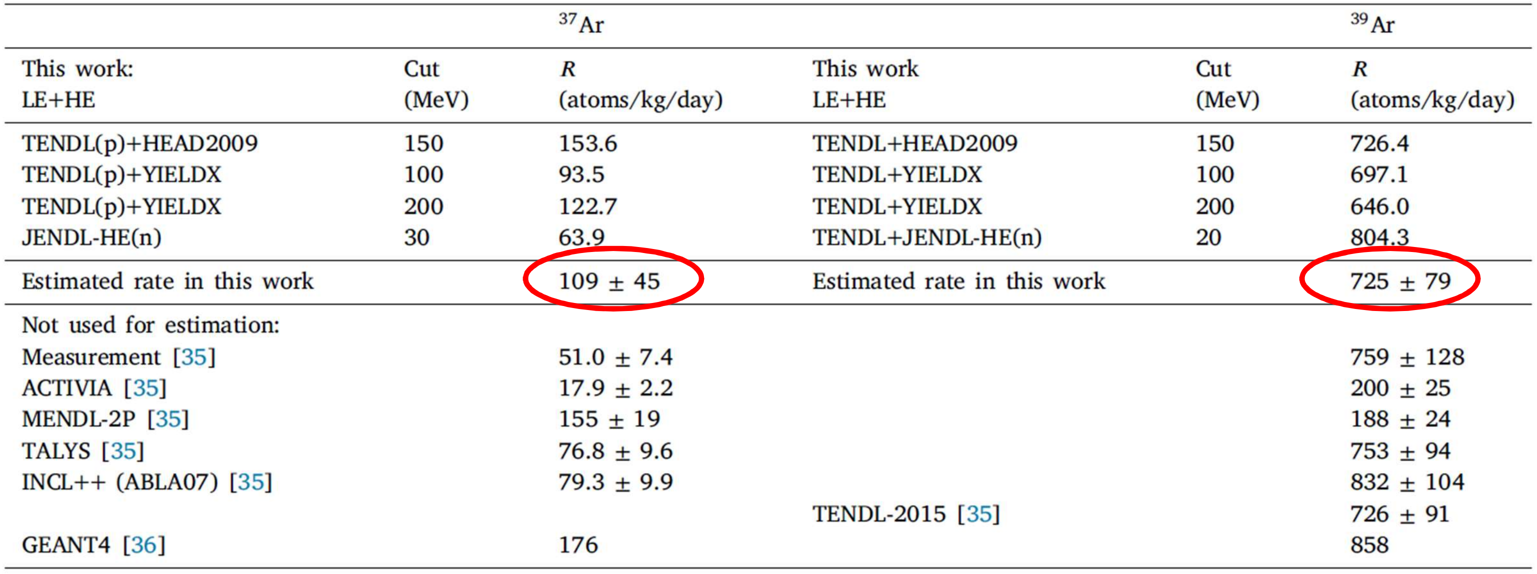
Activation studies: Ar

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

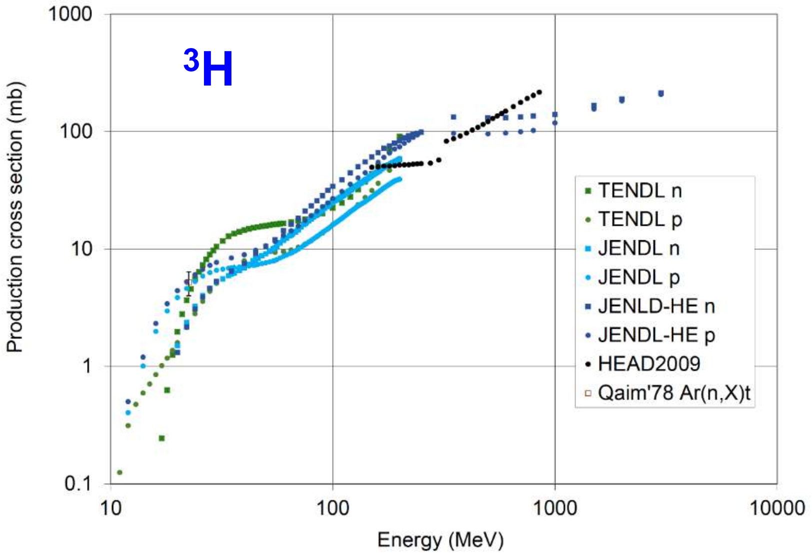
^{39}Ar: fully compatible with measured value and several calculations

^{37}Ar: larger discrepancies

Activation studies: Ar

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

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



	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

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

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

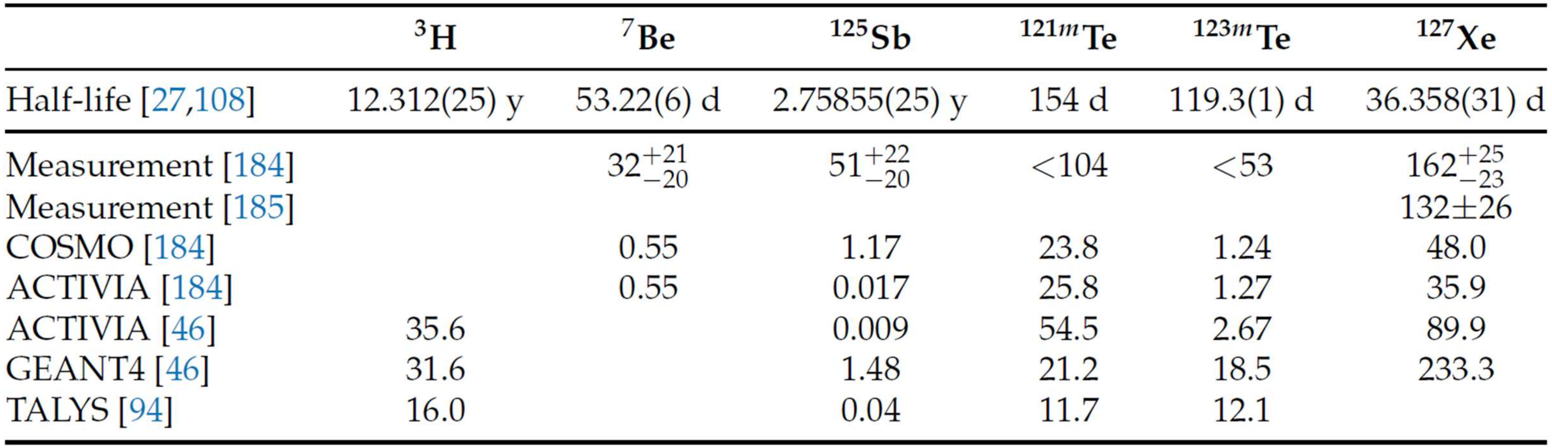
- Tolerable residual level of 2.8% of quantified activity of ^{39}Ar in DarkSide-50

  Each additional month at sea level would add 2.6 μBq/kg
- Purification reduces activity of ^{3}H by a factor 25

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

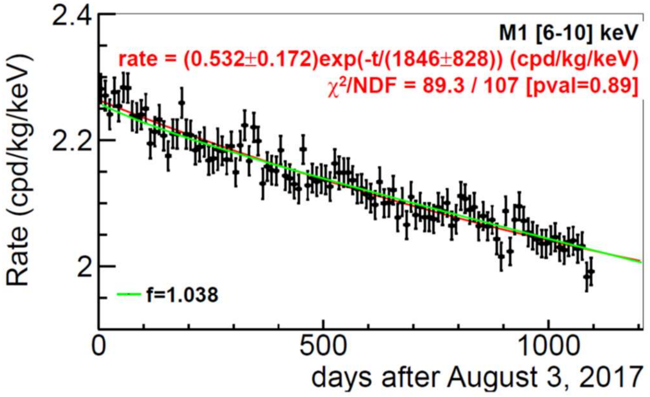
Activation studies: NaI

- Cosmogenics found to make a very relevant contribution, according background models, in anual modulation DM experiments **ANAIS-112** and **COSINE-100**

J. Amaré et al, Eur. Phys. J. C 79 (2019) 412; G. Adhikari et al, Eur. Phys, J. C 81 (2021) 837; G.H. Yu et al, arXiv:2408.09806

Reproducing decaying cosmogenics (and ^{210}Pb) in time evolution of data is essential for robust annual modulation search

Exponential fit
Background estimated evolution

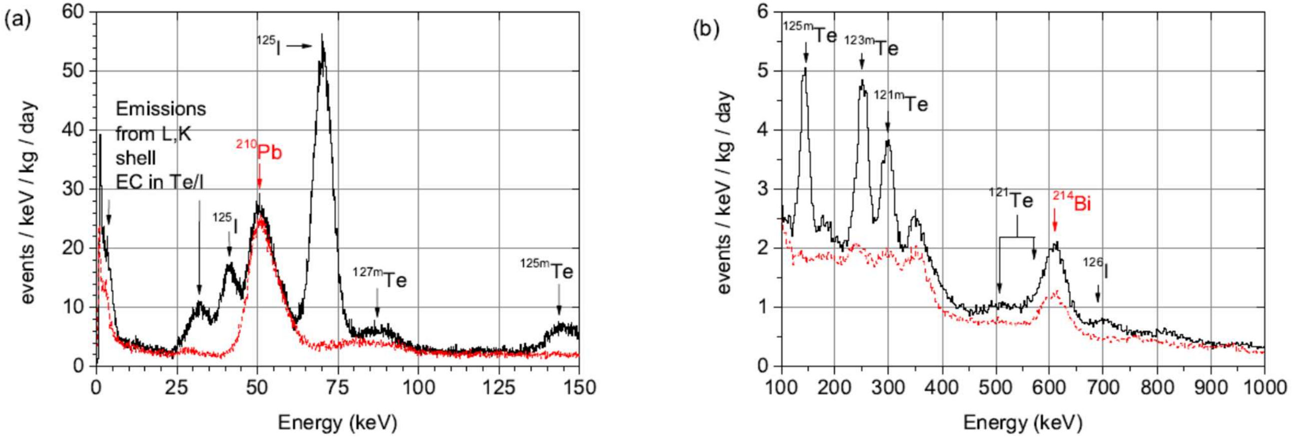


- Detailed studies using **data from experiments** to quantify production of **I**, **Te** isotopes, **^{22}Na, ^{109}Cd, ^{113}Sn** in NaI(Tl) crystals

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

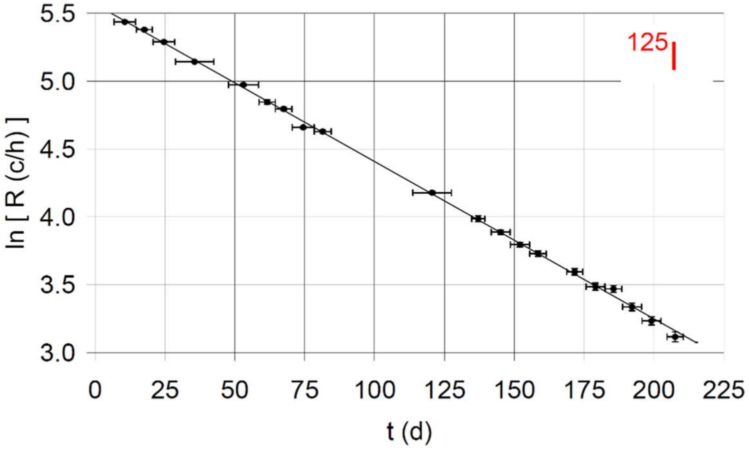
Start of data taking (December 2012)

Data 15 months later

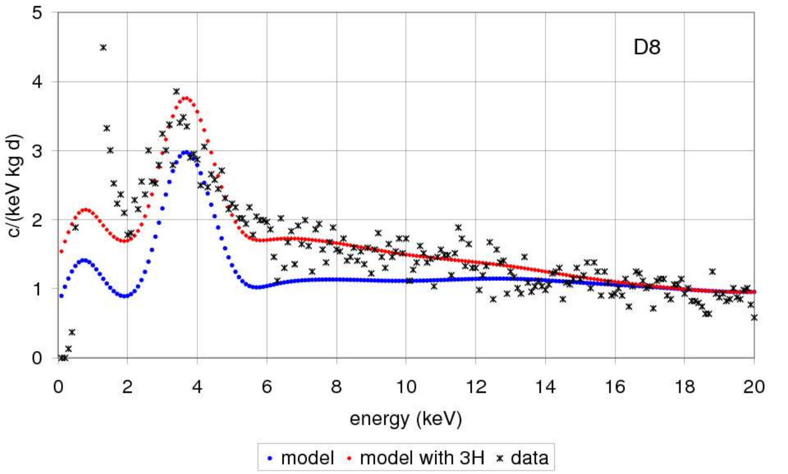


Activation studies: NaI

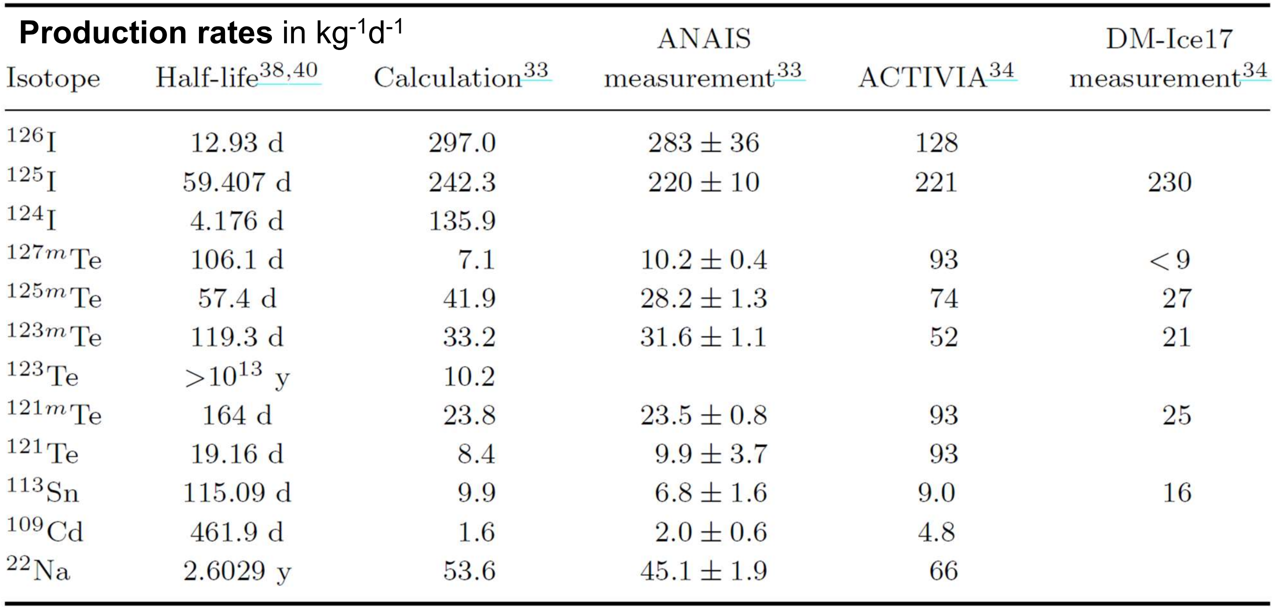
Production rates from known exposure and analysis of decaying signals



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



Measured rates compared with different calculations



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

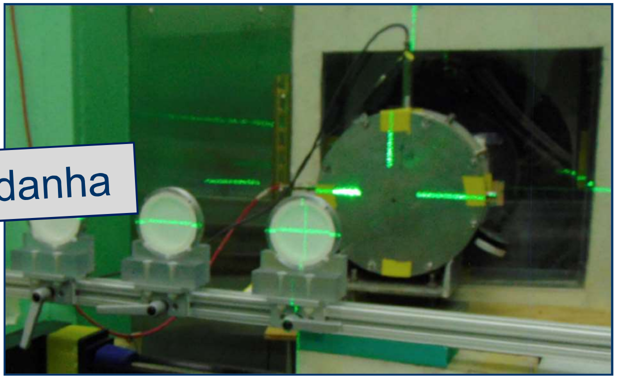
Isotope	Half-life[38,40]	Calculation[33]	ANAIS measurement[33]	ACTIVIA[34]	DM-Ice17 measurement[34]
^{126}I	12.93 d	297.0	283 ± 36	128	
^{125}I	59.407 d	242.3	220 ± 10	221	230
^{124}I	4.176 d	135.9			
^{127m}Te	106.1 d	7.1	10.2 ± 0.4	93	<9
^{125m}Te	57.4 d	41.9	28.2 ± 1.3	74	27
^{123m}Te	119.3 d	33.2	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	

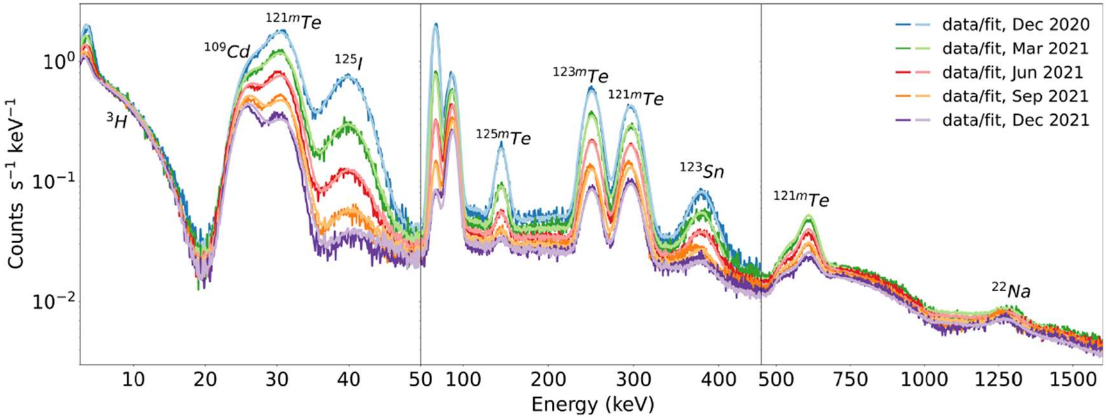
Activation studies: NaI

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

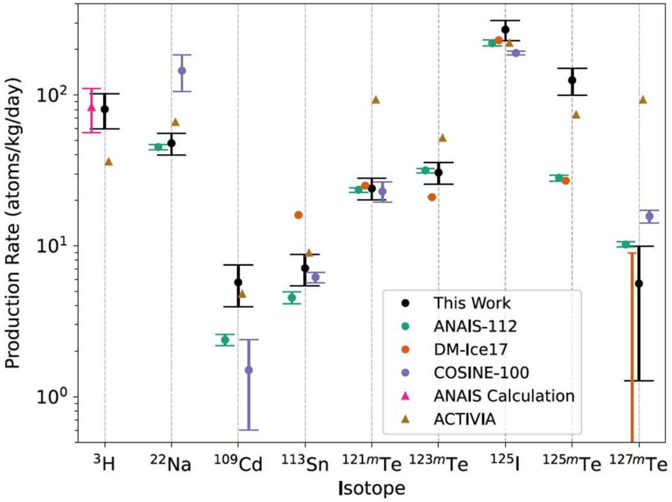
R. Saldanha et al, Phys. Rev. D 107 (2023) 022006

Talk by Richard Saldanha





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

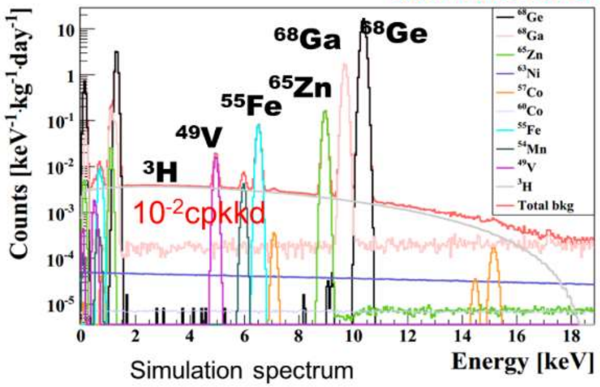


Reasonable agreement between different estimates of **production rates** except for ^{125m}Te

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

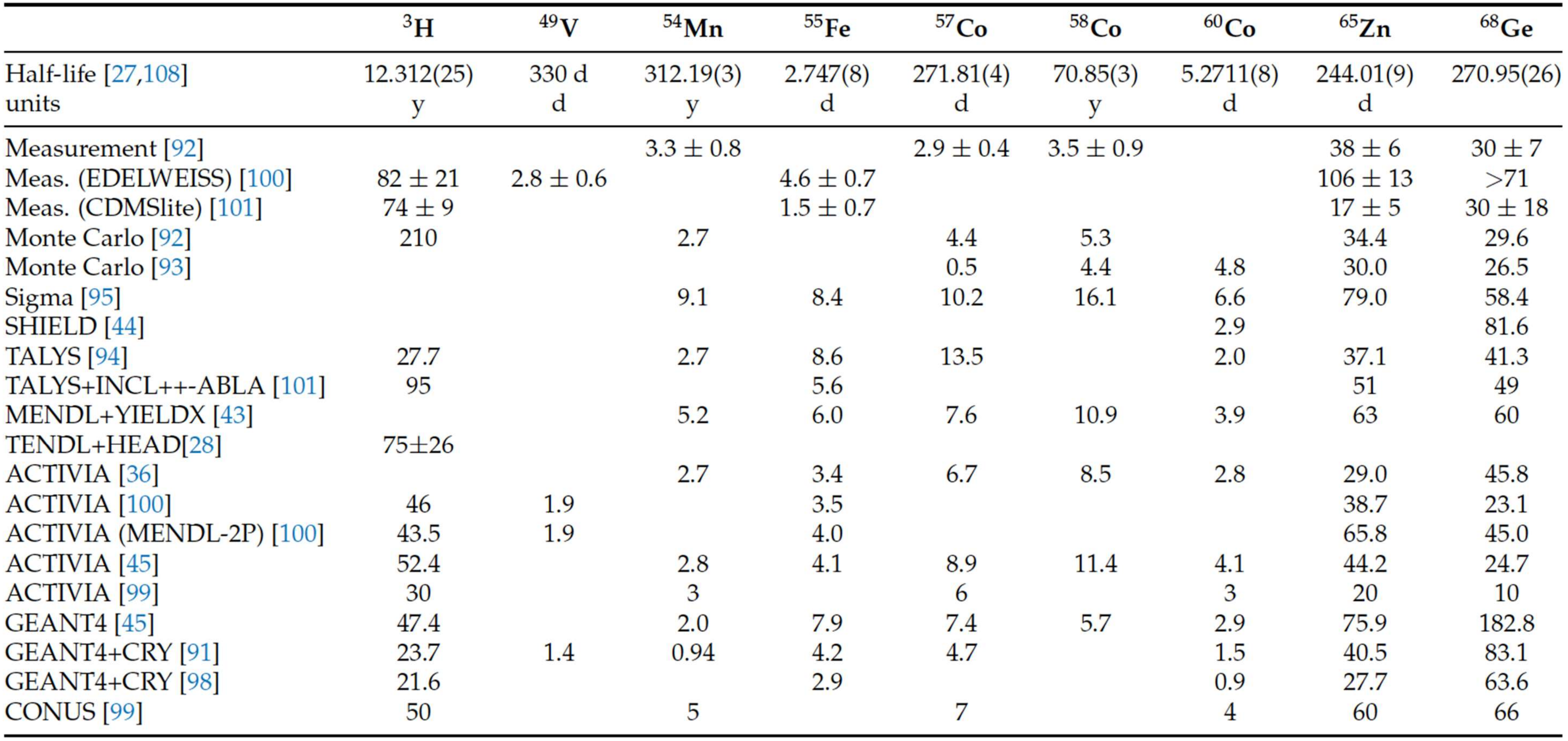
Production rates in kg^{-1}d^{-1}

	^{3}H	^{54}Mn	^{55}Fe	^{57}Co	^{58}Co	^{60}Co	^{65}Zn	^{68}Ge
Half-life [27]	12.312(25)	312.19(3)	2.747(8)	271.81(4)	70.85(3)	5.2711(8)	244.01(9)	270.95(26)
units	y	d	y	d	d	y	d	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

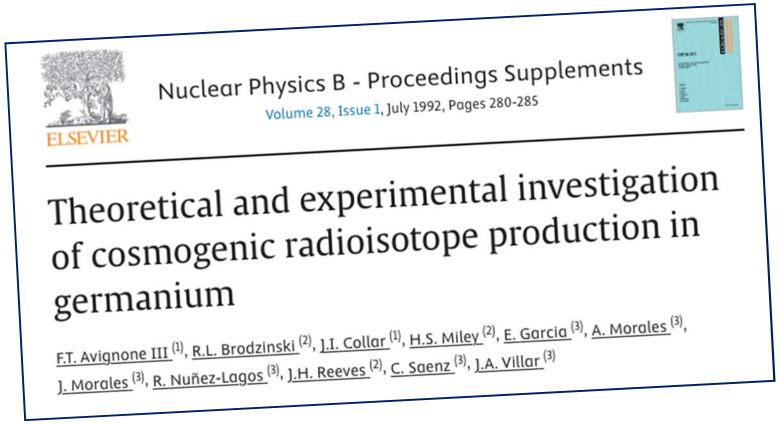
Natural Ge

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

Activation studies: Ge



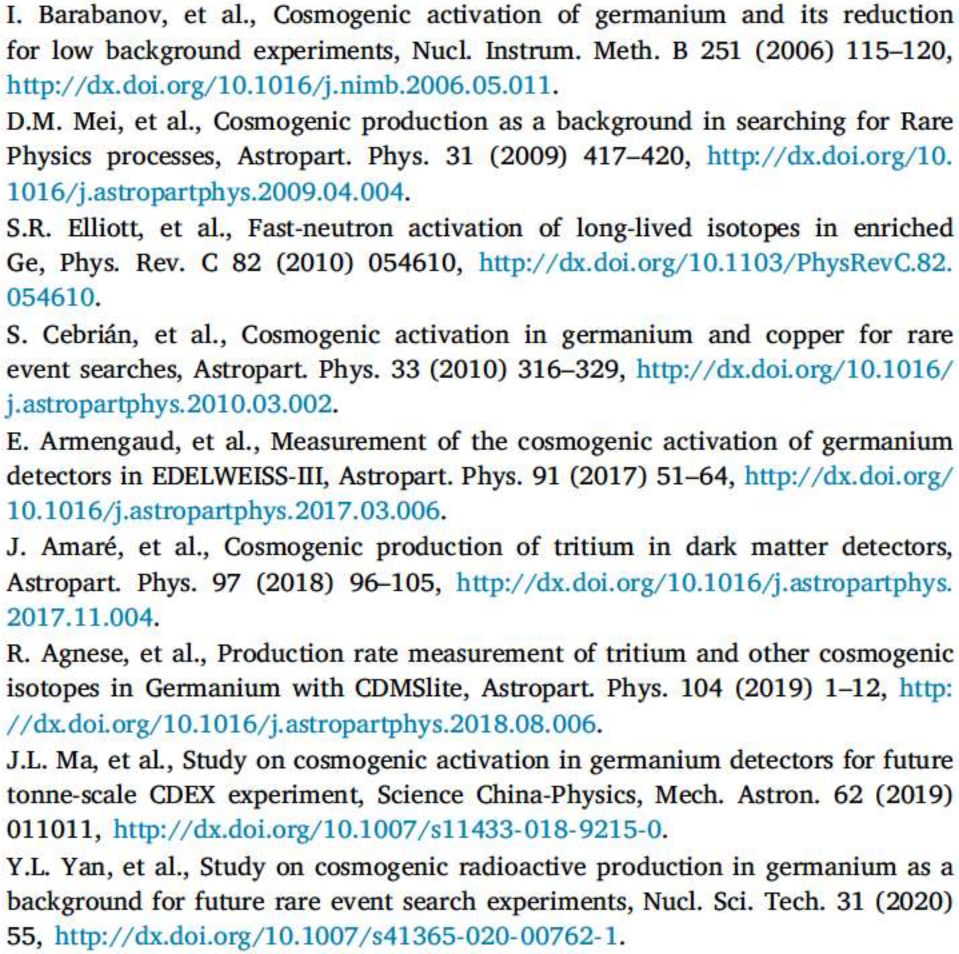
ELSEVIER

Nuclear Physics B - Proceedings Supplements

Volume 28, Issue 1, July 1992, Pages 280-285

Theoretical and experimental investigation of cosmogenic radioisotope production in germanium

F.T. Avignone III (1), R.L. Brodzinski (2), J.I. Collar (1), H.S. Miley (2), E. Garcia (3), A. Morales (3), J. Morales (3), R. Nuñez-Lagos (3), J.H. Reeves (2), C. Saenz (3), J.A. Villar (3)



I. Barabanov, et al., Cosmogenic activation of germanium and its reduction for low background experiments, Nucl. Instrum. Meth. B 251 (2006) 115–120, http://dx.doi.org/10.1016/j.nimb.2006.05.011.

D.M. Mei, et al., Cosmogenic production as a background in searching for Rare Physics processes, Astropart. Phys. 31 (2009) 417–420, http://dx.doi.org/10.1016/j.astropartphys.2009.04.004.

S.R. Elliott, et al., Fast-neutron activation of long-lived isotopes in enriched Ge, Phys. Rev. C 82 (2010) 054610, http://dx.doi.org/10.1103/PhysRevC.82.054610.

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.

E. Armengaud, et al., Measurement of the cosmogenic activation of germanium detectors in EDELWEISS-III, Astropart. Phys. 91 (2017) 51–64, http://dx.doi.org/10.1016/j.astropartphys.2017.03.006.

J. Amaré, et al., Cosmogenic production of tritium in dark matter detectors, Astropart. Phys. 97 (2018) 96–105, http://dx.doi.org/10.1016/j.astropartphys.2017.11.004.

R. Agnese, et al., Production rate measurement of tritium and other cosmogenic isotopes in Germanium with CDMSlite, Astropart. Phys. 104 (2019) 1–12, http://dx.doi.org/10.1016/j.astropartphys.2018.08.006.

J.L. Ma, et al., Study on cosmogenic activation in germanium detectors for future tonne-scale CDEX experiment, Science China-Physics, Mech. Astron. 62 (2019) 011011, http://dx.doi.org/10.1007/s11433-018-9215-0.

Y.L. Yan, et al., Study on cosmogenic radioactive production in germanium as a background for future rare event search experiments, Nucl. Sci. Tech. 31 (2020) 55, http://dx.doi.org/10.1007/s41365-020-00762-1.

W.Z Wei, et al., Cosmogenic Activation of Germanium Used for Tonne-Scale Rare Event Search Experiments. Astropart, Phys. 96 (2017) 24, http://dx.doi.org/10.1016/j.astropartphys.2017.10.007.

R. Breier, et al., Monte-Carlo calculation of production rates of cosmogenic radionuclides in a HPGe detector operating in the Modane underground laboratory, Nucl. Instrum. Meth. A 978 (2020) 164355, http://dx.doi.org/10.1016/j.nima.2020.164355.

H. Bonet et al, Full background decomposition of the CONUS experiment, Eur. Phys. J. C (2023) 83:195, https://doi.org/10.1140/epjc/s10052-023-11240-4

Q. Nie et al., Study of cosmogenic activation in ^{76}Ge enriched germanium detectors during fabrication and transportation above ground, 2024 JINST 19 P03002, https://doi.org/10.1088/1748-0221/19/03/P03002

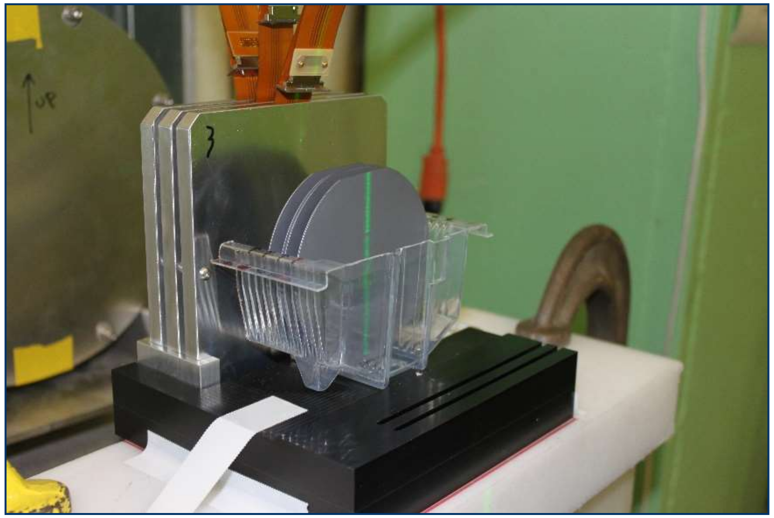
Activation studies: other detector targets

Silicon: ^{32}Si, ^{3}H

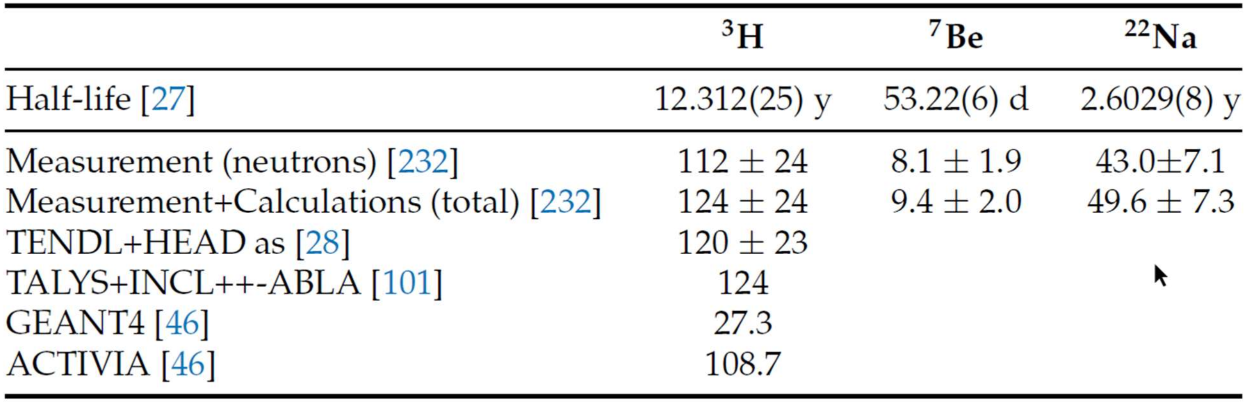
Controlled irradiation of silicon CCDs at Los Alamos

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

Talk by Richard Saldanha



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



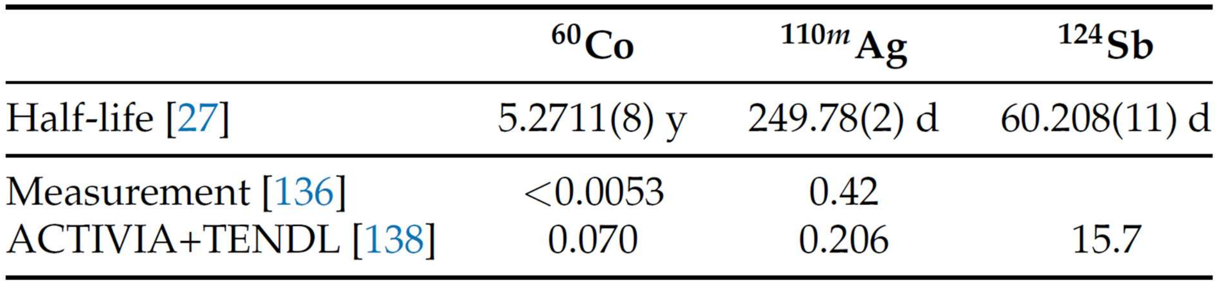
	^{3}H	^{7}Be	^{22}Na
Half-life [27]	12.312(25) y	53.22(6) d	2.6029(8) y
Measurement (neutrons) [232]	112 ± 24	8.1 ± 1.9	43.0±7.1
Measurement+Calculations (total) [232]	124 ± 24	9.4 ± 2.0	49.6 ± 7.3
TENDL+HEAD as [28]	120 ± 23		
TALYS+INCL++-ABLA [101]	124		
GEANT4 [46]	27.3		
ACTIVIA [46]	108.7		

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:

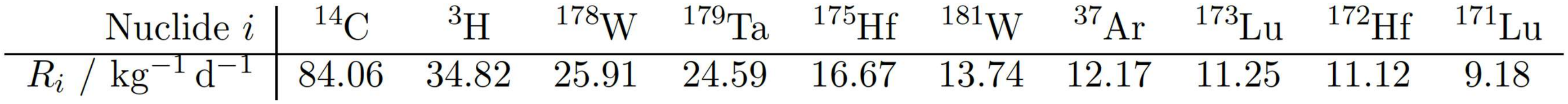
Production rates in LMO of ^{88}**Y,** ^{82}**Rb** affecting double beta decay of ^{100}Mo
Simulation based on **Geant4** + **CRY** for n, p, μ and γ spectra

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



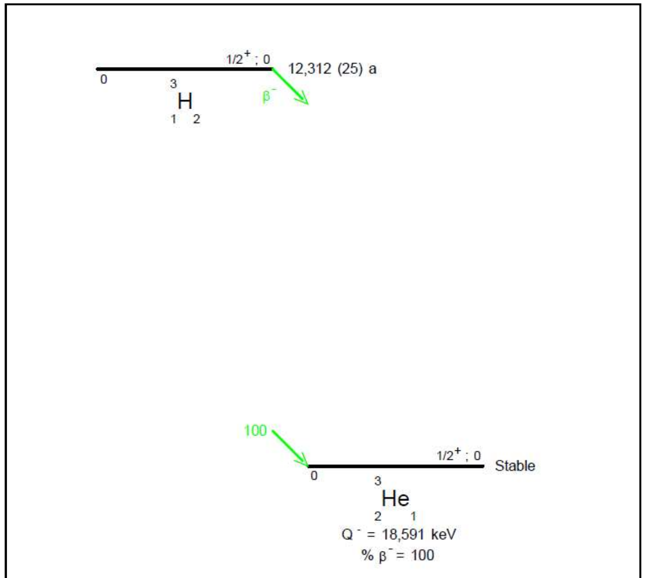
Nuclide i	^{14}C	^{3}H	^{178}W	^{179}Ta	^{175}Hf	^{181}W	^{37}Ar	^{173}Lu	^{172}Hf	^{171}Lu
R_i / kg^{-1} d^{-1}	84.06	34.82	25.91	24.59	16.67	13.74	12.17	11.25	11.12	9.18
TALYS		45.5								

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

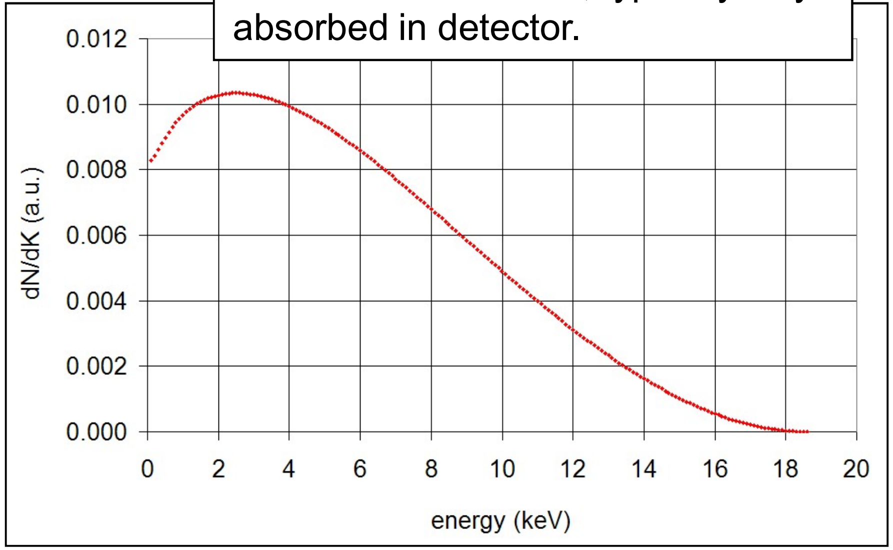
Activation studies: Tritium

Tritium can be a very relevant background in the detector medium of DM experiments due to its decay properties.

Talk by Sagar Sharma Poudel



Pure β^- emitter, difficult to tag, with very low **transition energy (18.591 keV)** and a long **half- life (12.312 y).**



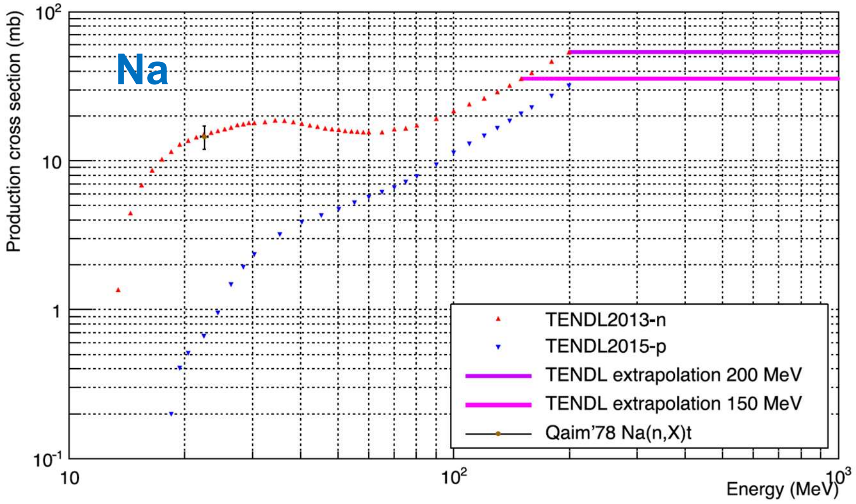
Super-allowed beta spectrum: **57% electrons in 1-7 keV**, typically fully absorbed in detector.

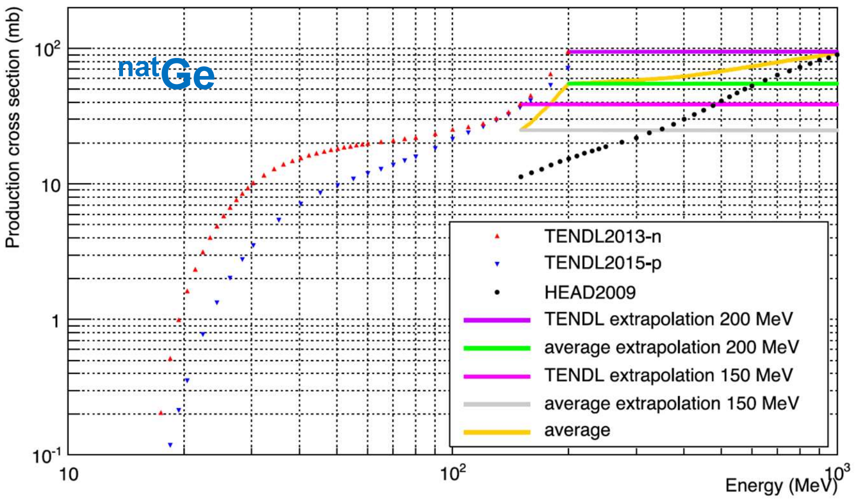
→ Specific study to quantify **production rates** induced in **targets** used in different **dark matter detectors: Ge, Si, NaI, Ar, Ne**

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

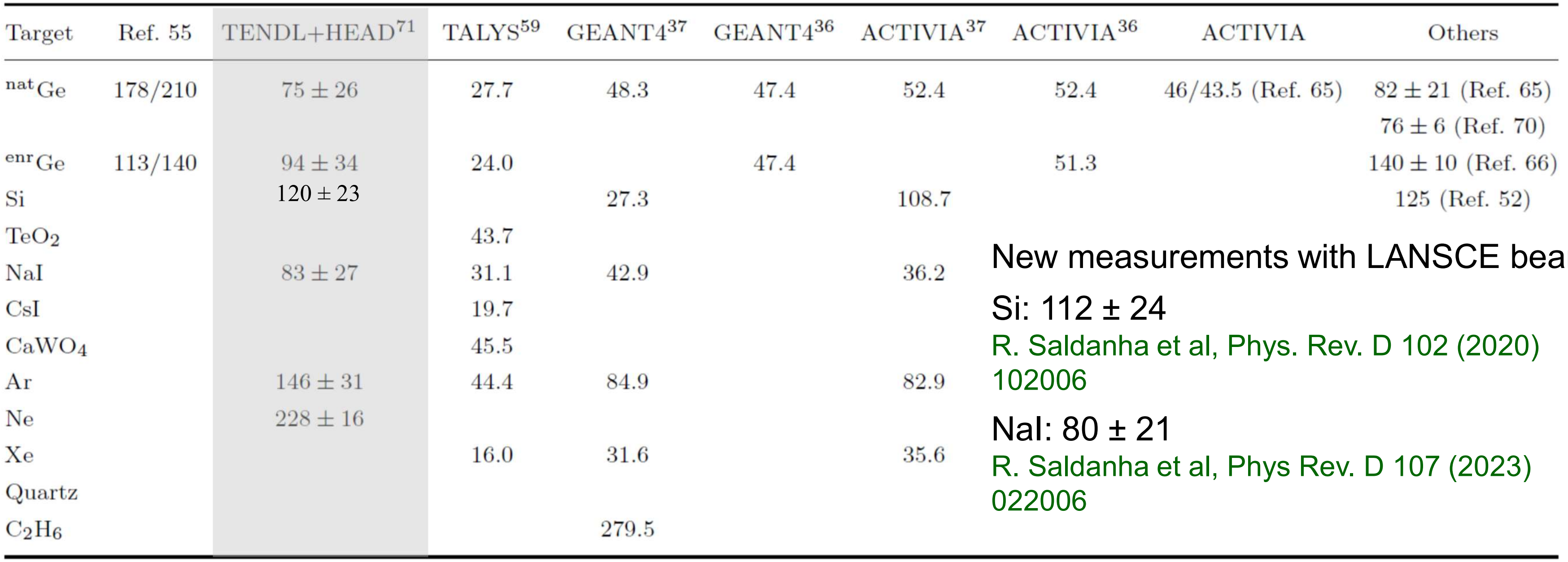
$$R = N_t \int \sigma(E)\phi(E)dE$$

Activation studies: Tritium





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$_2$H$_6$				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

Cosmogenic activation in materials used in low background experiments

- Cosmogenic activation: origin and quantification
- Examples of activation studies:
  - Detector targets: Ar, Xe, NaI, Ge, others; ^{3}H
  - **Other materials: Cu, Pb, others**
  - Underground activation

Susana Cebrián, scebrian@unizar.es

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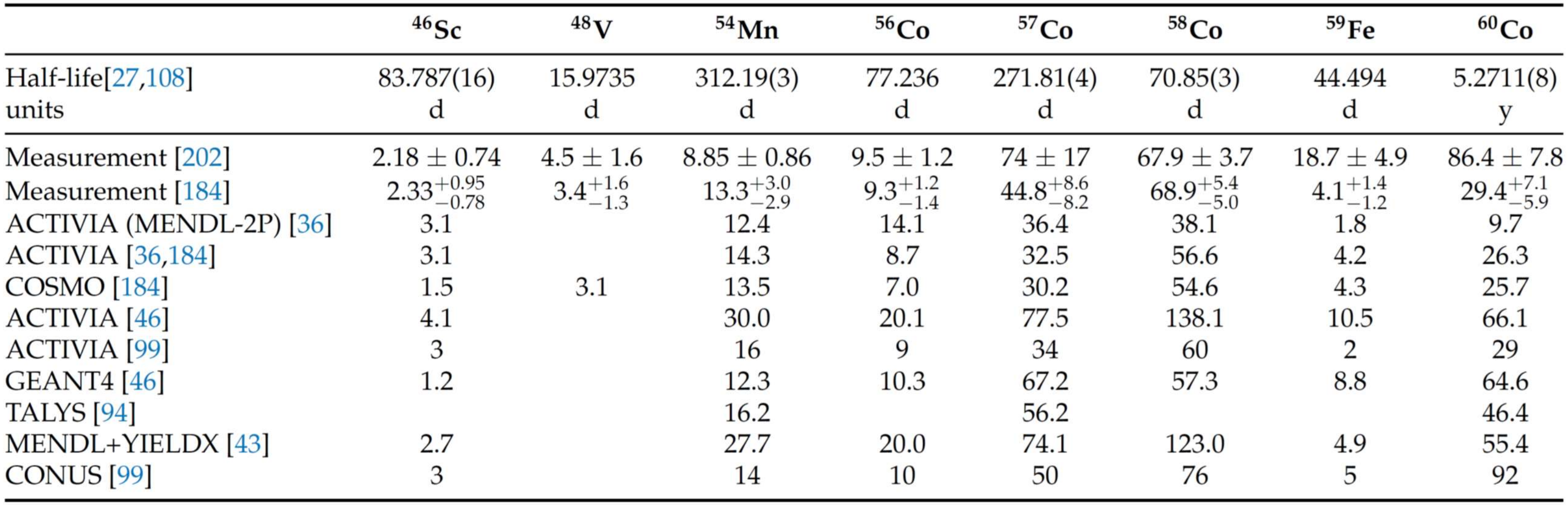
Universidad Zaragoza 1542

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] units	83.787(16) d	15.9735 d	312.19(3) d	77.236 d	271.81(4) d	70.85(3) d	44.494 d	5.2711(8) 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.

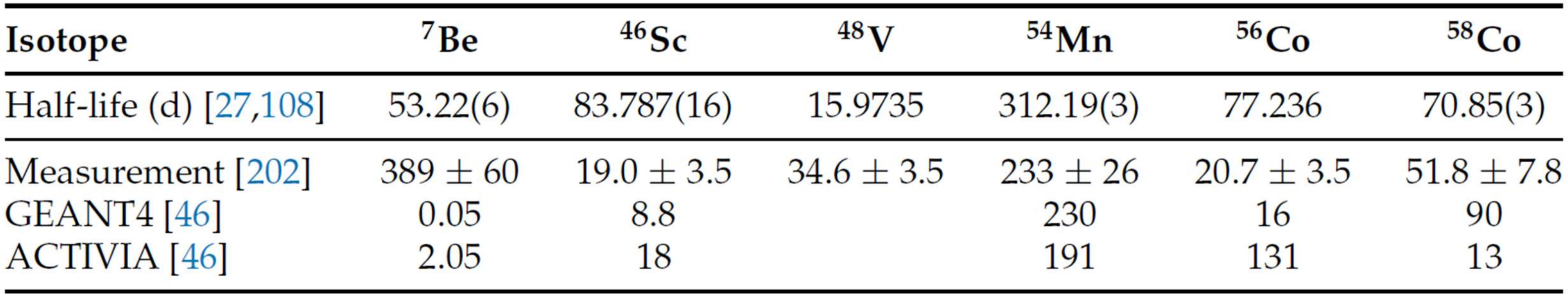
Z. She, et al., Study on cosmogenic activation in copper for rare event search experiments, Eur. Phys. J. C 81 (2021) 1041, http://dx.doi.org/10.1140/epjc/s10052-021-09827-w.

Activation studies: Steel, Ti

Stainless steel

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

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



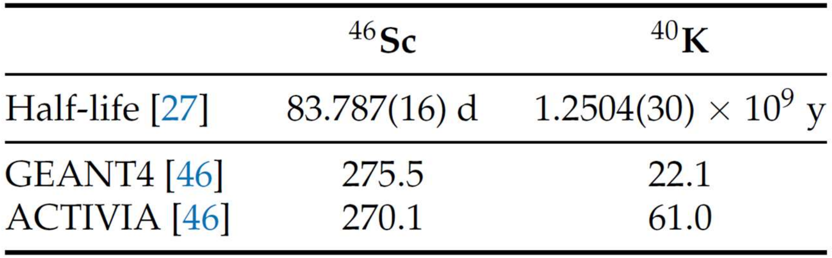
Isotope	^{7}Be	^{46}Sc	^{48}V	^{54}Mn	^{56}Co	^{58}Co
Half-life (d) [27,108]	53.22(6)	83.787(16)	15.9735	312.19(3)	77.236	70.85(3)
Measurement [202]	389 ± 60	19.0 ± 3.5	34.6 ± 3.5	233 ± 26	20.7 ± 3.5	51.8 ± 7.8
GEANT4 [46]	0.05	8.8		230	16	90
ACTIVIA [46]	2.05	18		191	131	13

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) × 10^{9} y
GEANT4 [46]	275.5	22.1
ACTIVIA [46]	270.1	61.0

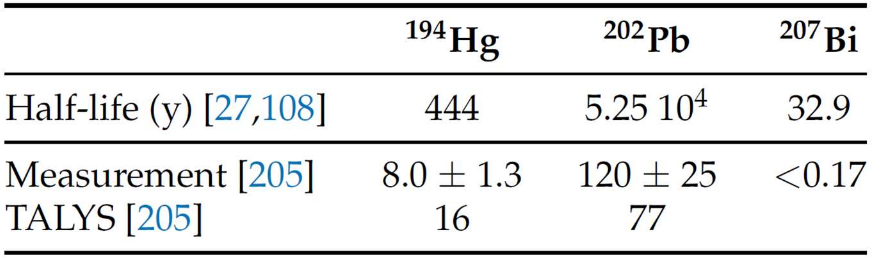
C. Zhang et al, Astropart. Phys. 84 (2016) 62

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	

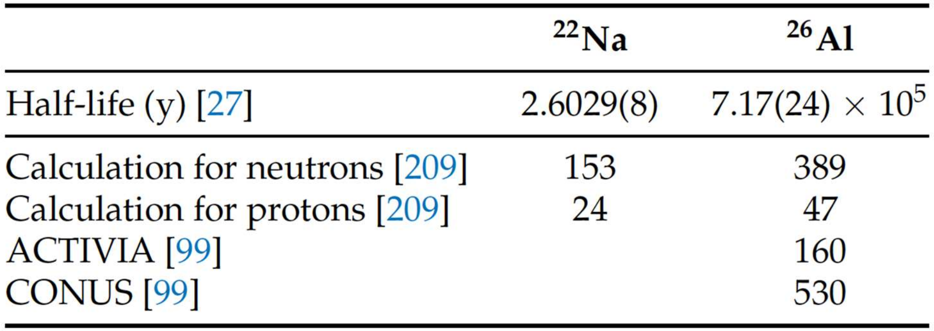
V. E. Giuseppe et al, Astropart. Phys. 64 (2015) 34

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) × 10^5
Calculation for neutrons [209]	153	389
Calculation for protons [209]	24	47
ACTIVIA [99]		160
CONUS [99]		530

Activation deep underground

Muons can produce by spallation radioisotopes inside the detector volume

Effect of short-lived isotopes can be mitigated by time correlation with μ

^{11}C in **liquid scintillator:** three-fold coincidence between the crossing muon, the ejected neutron from ^{12}C, and the ^{11}C decay (EC, β+, $T_{1/2}$= 20.4 m), allows a reduction of this background at the cost of a reduction of the life-time

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

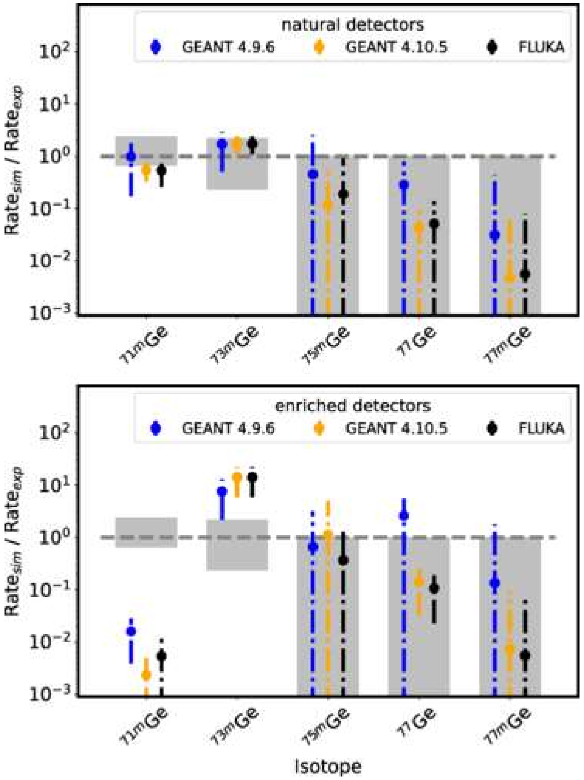
$^{77(m)}$Ge in **Ge detectors:** decays of ^{77}Ge (β-, Q = 2.7 MeV, $T_{1/2}$ = 11.2 h) and metastable state ^{77m}Ge ($T_{1/2}$ = 53.7 s) affect ^{76}Ge DBD experiments

Delayed coincidence cuts allow also to reduce this background.

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

Production of other metastable Ge isotopes quantified from Majorana data and simulations

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



Activation deep underground

Xe detectors: production rates of ^{3}**H**, ^{137}**Xe** and other unstable **Xe** isotopes evaluated due to muon-induced neutron fluxes and spallation

- For four underground labs LNGS, SURF, LSM and SNOLAB for site selection of the **DARWIN** observatory
- Based on **MUSIC-MUSUN + Geant4** simulation

M. Adrover et al, arXiv:2306.16340

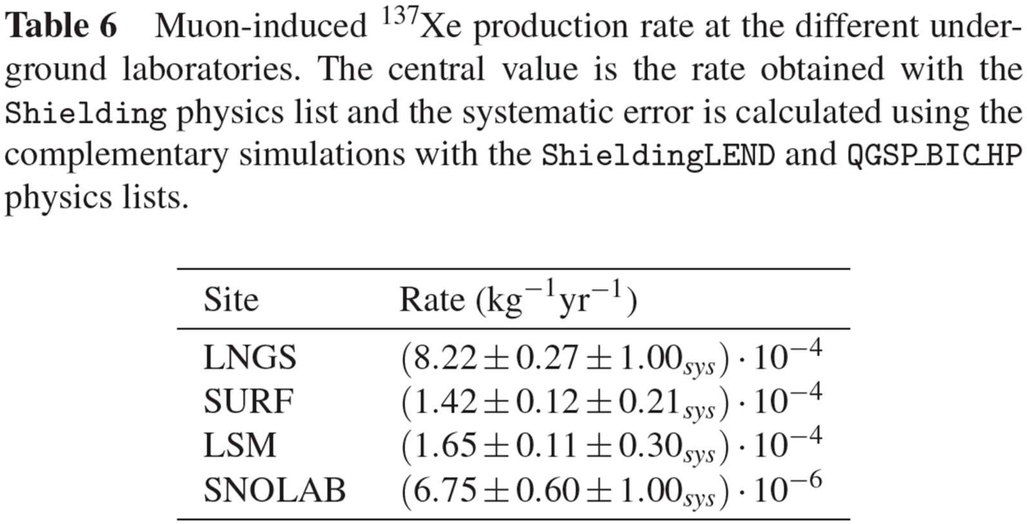


Table 6 Muon-induced ^{137}Xe production rate at the different underground laboratories. The central value is the rate obtained with the `Shielding` physics list and the systematic error is calculated using the complementary simulations with the `ShieldingLEND` and `QGSP_BIC_HP` physics lists.

Site	Rate (kg^{-1}yr^{-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	$(1.65 \pm 0.11 \pm 0.30_{sys}) \cdot 10^{-4}$
SNOLAB	$(6.75 \pm 0.60 \pm 1.00_{sys}) \cdot 10^{-6}$

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

- From **KamLAND-Zen**: (1.42 ±0.73) 10^{-3} kg^{-1} yr^{-1}
- Production rate at WIPP lab for **EXO-200** from measured μ flux and **Geant4 (FLUKA)** simulations 439±17 (403±16) atoms per year

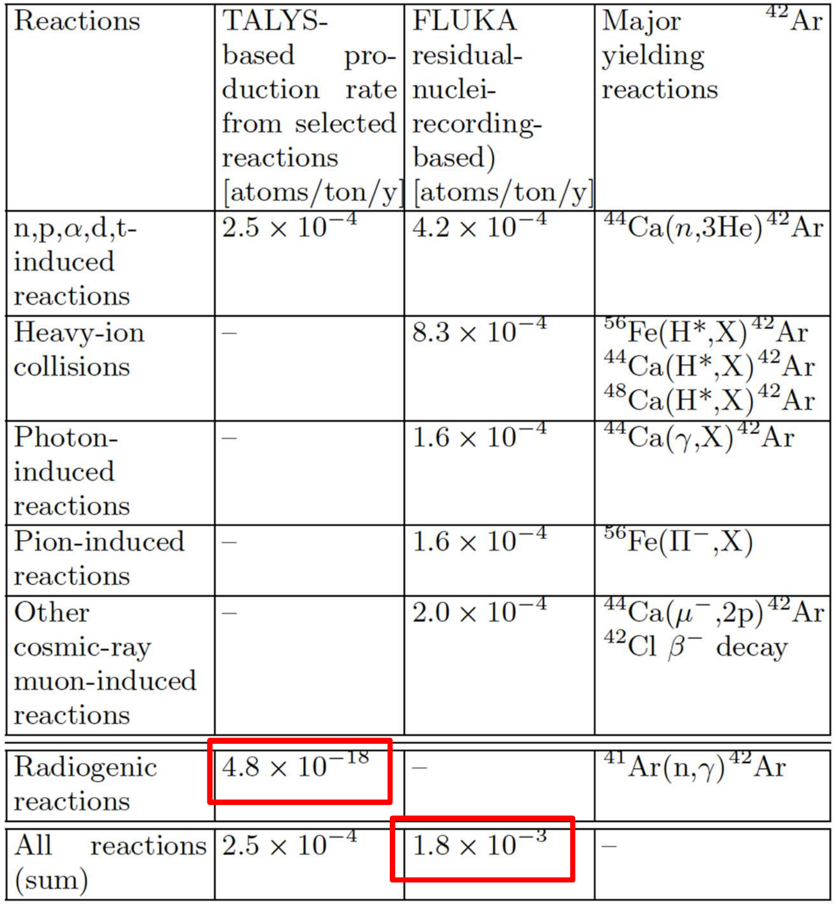
  J. Albert et al, JCAP 04 (2016) 029
- Mitigation proposed by adding to Xe a small quantity of ^{3}He to capture thermal n

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

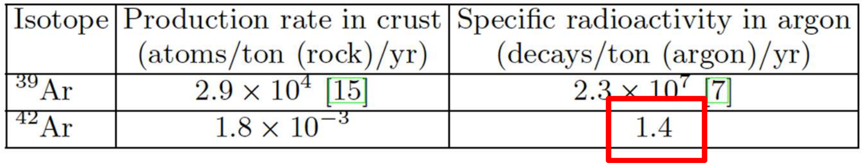
Activation deep underground

^{42}Ar in **Ar:** subsurface cosmogenic and radiogenic production carefully evaluated

S. Poudel et al, arXiv:2309.16169



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}	–



Isotope	Production rate in crust (atoms/ton (rock)/yr)	Specific radioactivity in argon (decays/ton (argon)/yr)
^{39}Ar	2.9×10^{4} [15]	2.3×10^{7} [7]
^{42}Ar	1.8×10^{-3}	1.4

- Standard continental crust, 3000 mwe
- **Radiogenic** contribution, based on **TALYS** cross sections, totally negligible
- **Cosmogenic** production **in crust** based on **FLUKA** simulation of μ's from **MUSIC**
- **Activity in UAr gas** evaluated from ^{39}Ar results, pointing to a suppression factor respect to AAr of at least 10^7, much higher than for ^{39}Ar

Summary

Cosmogenic activation of materials can jeopardize the sensitivity of ultra-low background experiments, being increasingly important as background requirements get more stringent

- production of **long-lived isotopes** at Earth's **surface** due to **nucleons**
- continuous generation of **short-lived nuclides** deep **underground** due to fast **muons**

Production rates and yields for several materials have been evaluated in the context of DBD, neutrino and DM experiments from direct **measurements** (with beams or from controlled, long exposure to cosmic rays) and from **calculations** based on different approaches

Mitigation is presently based on **limiting exposure** to cosmic rays but active suppression and removal of activation products can be considered:

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

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Cosmogenic activation of materials

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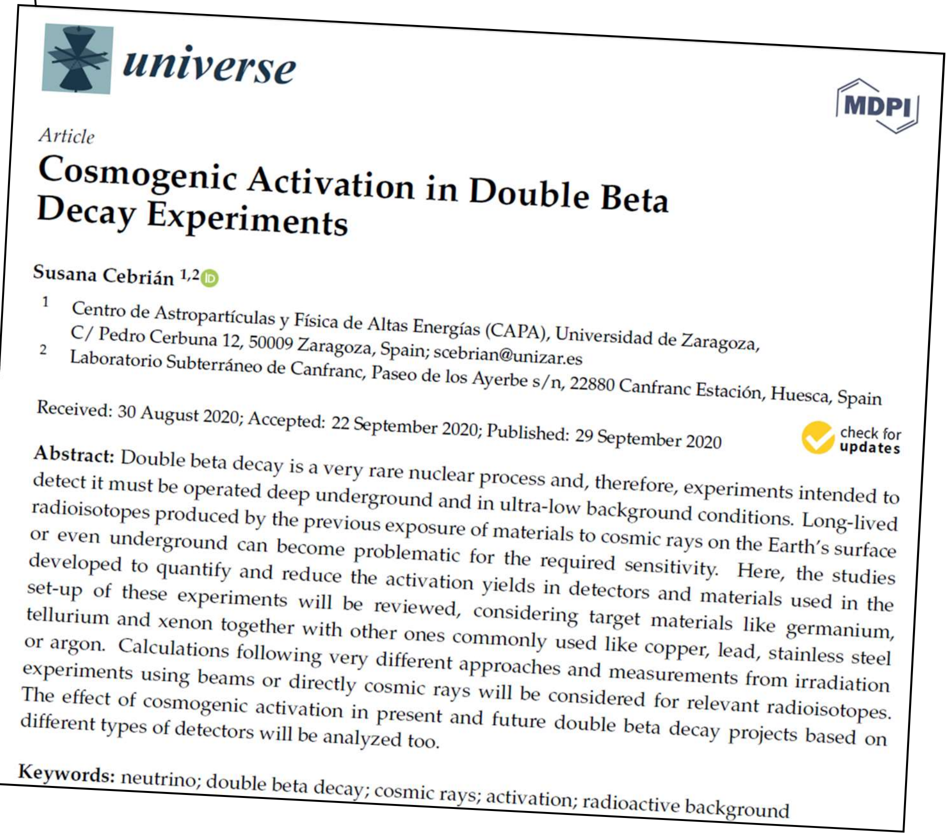
Experiments looking for rare events like the direct detection of dark matter particles, neutrino interactions or the nuclear double beta decay are operated deep underground to suppress the effect of cosmic rays. But, the production of radioactive isotopes in materials due to previous exposure to cosmic 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

https://doi.org/10.1142/S0217751X17430060



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Article

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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