Cosmogenic activation of materials

- ✓ **Activation at sea level:**
  - Production cross sections: codes and libraries
  - Cosmic ray spectrum
  - Results: **Ge, Te, Xe, NaI, Mo, Cu, Steel, Pb**
- ✓ **Activation underground:**
  - Results: **liquid scintillator, Ge**
- ✓ **Summary**

Low Radioactivity Techniques 2013

S. Cebrián

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Activation at sea level

- **Activity A** induced on a material taking into account history of exposure and cooling:

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

R = production rate

λ = decay constant of product

t_{exp} = exposure time

t_{cool} = cooling time

- **Production rate R** of induced isotopes:

$$R \propto \int \sigma(E)\phi(E)dE$$

E = energy

σ = production cross section

ϕ = flux of cosmic rays

Cross sections: codes and libraries

Determination of production cross sections

- Compilation of experimental data: **EXFOR**
- Silberberg&Tsao semiempirical formulae
  → codes: **COSMO, YIELDX, ACTIVIA**
- Monte Carlo simulation of hadronic interaction
  → **MC codes**
- Libraries combining calculations with experimental information: **MENDL**, **RNAL, HEAD**…

Deviation factor:

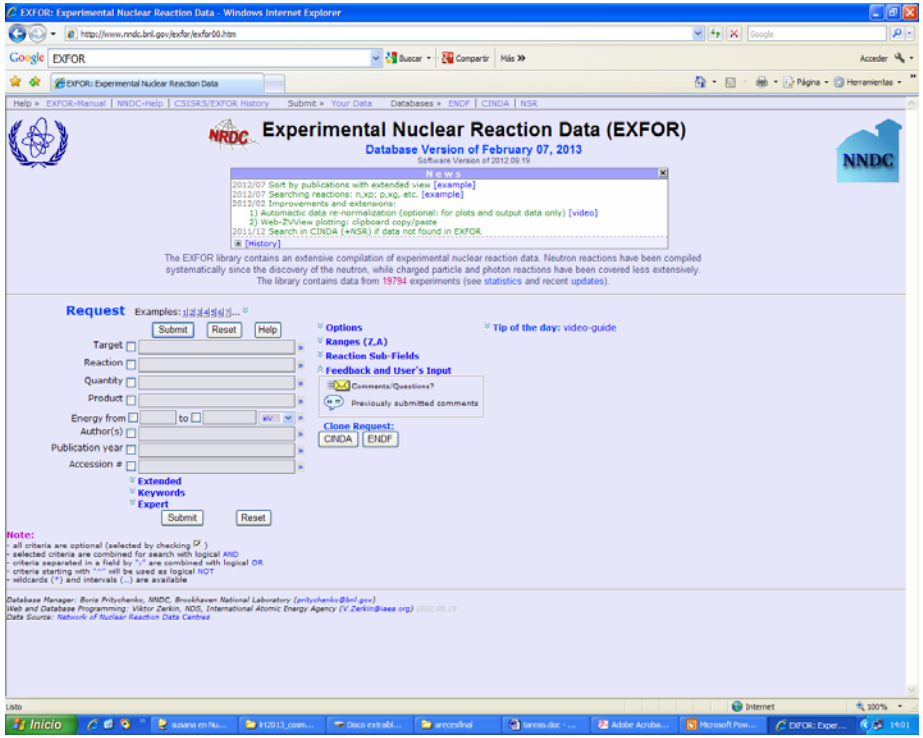
$$F = 10^{\sqrt{d}}$$

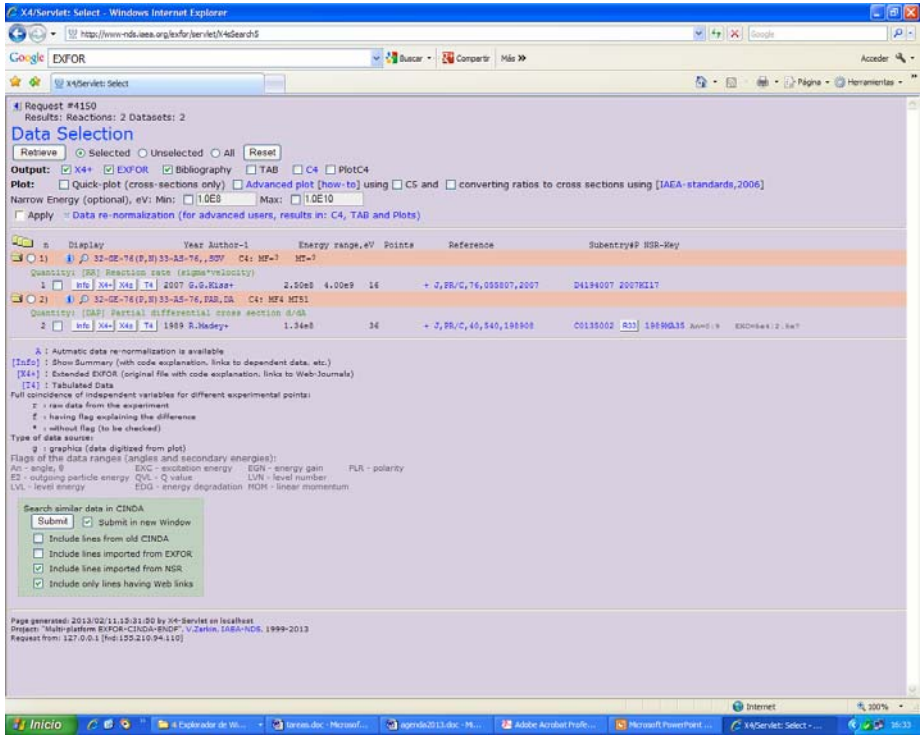
$$d = \frac{1}{n}\sum_i (log(\sigma_{exp,i}) - log(\sigma_{cal,i}))^2$$

Cross sections: codes and libraries

✦ EXFOR / CSISRS (in USA)

Experimental Nuclear Reaction Data database





http://www.nndc.bnl.gov/exfor/exfor00.htm
http://www-nds.iaea.org/exfor/exfor.htm

Cros aries

✦ **Semiempirical**

- **Silberberg & Ts**
  - give nucleon ctions (break-up, spallation, fi es and tuning parameters
  - for light and
  - for a wide ra
  - at energies

R. Silberberg an 25 (1973) 335.

R. Silberberg an 58 (1985) 873, Phys. Rep. 191 (1990) 351.

R. Silberberg an

☹ Based only on p

☺ Very fast calcula

TABLE 1B

PARAMETERS OF EQUATION (1) FOR TARGETS $6 \le Z_t \le 16$ AND PRODUCTS $Z \ge 6$

σ_0	$\dfrac{28(A_t^{2/3} - 1)[1 - 0.3 \ln (\frac{1}{20}A_t)]PR^{1/2}}{1 - \exp(-PA_t)}$	...
P	$2.6E^{-0.5}$	$E < 1250$*
	0.075*	$E \ge 1250$*
R	$10.2E^{-0.26}$	$E < 1250$
	1.6	$E \ge 1250$
S	$0.502 - 0.26\left(\frac{A_t}{Z_t} - 2\right)^{1.4}$	...
T	0.0005	...
ν	2	...
η	1.15, 1.15, 0.9, 0.8	...

* When $E_0 > 1250$ MeV, replace 1250 by E_0 and 0.075 by $0.77A_t^{-2/3}$.

TABLE 1C

PARAMETERS OF EQUATION (1) FOR TARGETS $17 \le Z_t \le 20$ AND PRODUCTS $Z \ge 6$

σ_0	$\dfrac{28f'_2(A_t^{2/3} - 1)[1 - 0.3 \ln (\frac{1}{20}A_t)]PR^{1/2}}{1 - \exp(-PA_t)}$	...
P	$20E^{-0.77}$	$E < E_0$
	$0.77A_t^{-2/3}$	$E \ge E_0$
R	$10.2E^{-0.26}$	$E < 1250$
	1.6	$E \ge 1250$
S	$0.502 - 0.08\left(\frac{A_t}{Z_t} - 2\right)$	...
T	0.0005	...
ν	2	...
η	1.25, 0.9, 1, 0.85	...

TABLE 1D

PARAMETERS OF EQUATION (1) FOR TARGETS $21 \le Z_t \le 28$ AND PRODUCTS $Z \ge 6$ AND FOR SPALLATION OF TARGETS WITH $63 \le A_t \le 209$

σ_0	$\dfrac{144f_1f_2PA_t^{0.367}}{1 - 0.3/PA_t - (0.7 - 0.3/PA_t)\exp(-PA_t)}$	...
P	$20E^{-0.77}C_p$	$E < E_0$
	$0.77A_t^{-2/3}$	$E \ge E_0$
R	$1.29A^{0.15}$	$A < 40$
	$11.8A^{-0.45}$	$A \ge 40$
S	$0.486 - 0.06(A_t - \bar{A}_t)/Z_t$	...
T	0.00038	...
ν	1.5	...
η	1.25, 0.9, 1, 0.85	...

$$C_p = \begin{cases} 1 - 0.32 \exp\left[-\left(\frac{E - 100}{100}\right)^2\right] & \text{for } 21 \le Z_t \le 30^* \\ 1 - 1.5 \times 10^{-5}(A_t - 100)\left(\frac{E_0 + 150}{E + 150}\right) & \text{for } A_t > 100 \\ 1 & \text{otherwise} \end{cases}$$

* The restriction to $Z_t \le 30$ is not firmly established; it is largely based on the spallation cross-sections of ^{75}As, measured by Rudstam (1956) at 100 MeV.

Cross sections: codes and libraries

✦ Semiempirical formulae and codes

- **COSMO code**:
- Computer program 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
- Complete treatment for targets with A<210, Z<83

COSMO- a program to estimate spallation radioactivity produced in a pure substance by exposure to cosmic-radiation on the Earth
C. J. Martoff, P. D. Lewin, Computer Physics Comm. 72 (1992) 96

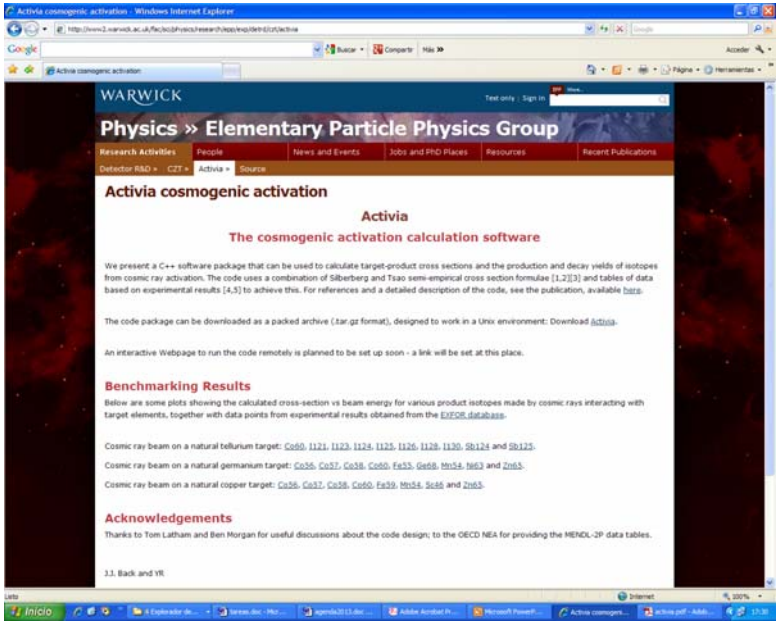
- **YIELDX routine**:
- FORTRAN routine to calculate the **production cross-section** of a nuclide in a particular target at a certain energy.
- Including the most recent updates of the Silberberg & Tsao equations (1998)
- Offered by the authors

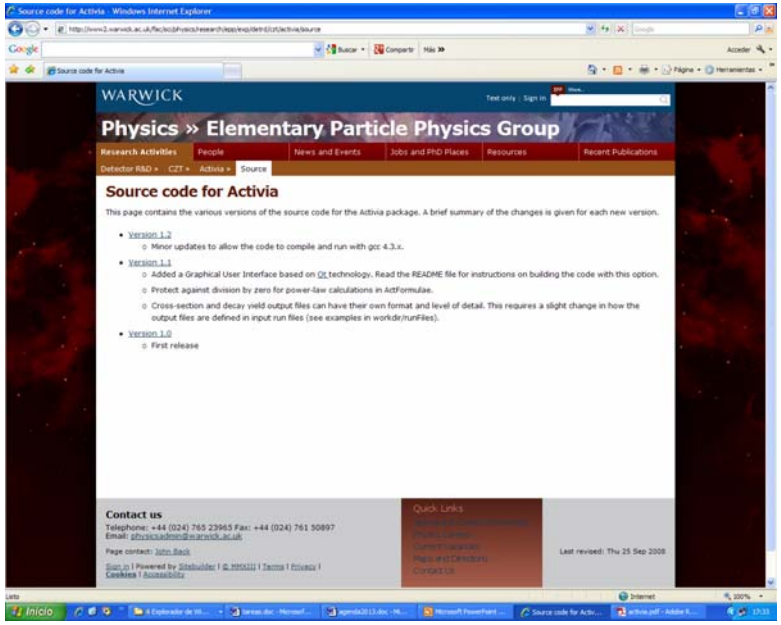
Cross sections: codes and libraries

✦ Semiempirical formulae and codes

- **ACTIVIA code**:
- 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

ACTIVIA: calculation of isotope production cross-sections and yields
J. J. Back, Y. A. Ramachers, Nucl. Instrum. Meth. A 586 (2008) 286-294



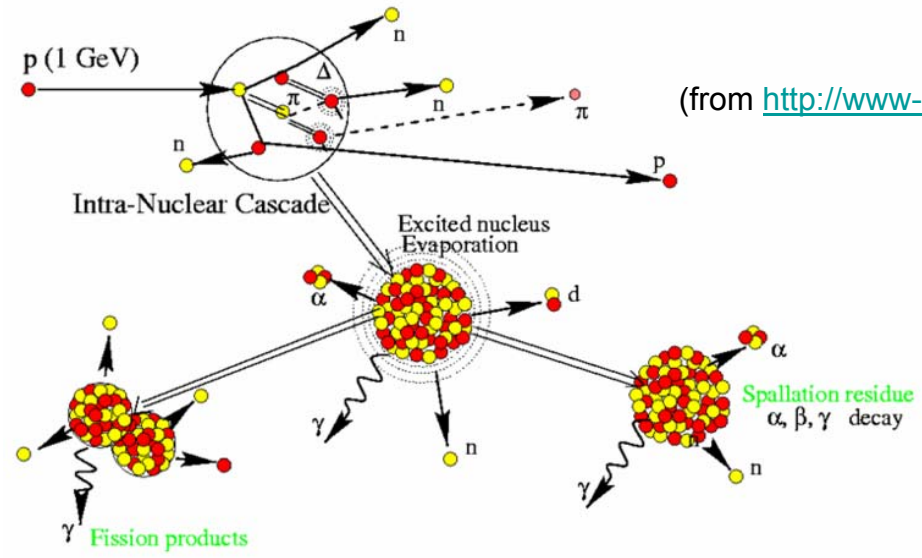


http://www.warwick.ac.uk/go/activia

Cross sections: codes and libraries

✦ MC simulation of hadronic interaction nucleon-nuclei

- 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, fission**, …



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

GEM TALYS HMS-ALICE INUCL LAQGSM CEM ISABEL LAHET
INCL+ABLA CASCADE MARS SHIELD BERTINI …

Analysis of existing codes for n/p activation, ILIAS-IDEA Cosmogenic Induced Activity WG
http://idea.dipscfm.uninsubria.it/frontend/docs/reports/cosmogenics-task2.pdf

Cross sections: codes and libraries

✦ MC simulation of hadronic interaction nucleon-nuclei

Nuclear Instruments and Methods in Physics Research A 624 (2010) 20–26

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journal homepage: www.elsevier.com/locate/nima

High energy activation data library (HEAD-2009)

Yu.A. Korovin [a], A.A. Natalenko [a], A.Yu. Stankovskiy [b], S.G. Mashnik [c], A.Yu. Konobeyev [d,*]

Models recommended on the basis of our statistical analysis and used in the IEAF-2005 and HEPAD-2008 libraries calculations.

Target mass range	Models used for the IEAF-2005 calculations	Models used for the HEPAD-2008 calculations
1-H-1–2-He-4	MCNPX interpolation tables	Bertini INC
3-Li-6–10-Ne-22	ISABEL/Dresner	CEM03.01
11-Na-23–13-Al-27	INCL4/Dresner	INCL4/Dresner
12-Mg-28–27-Co-55	CASCADE	CASCADE
29-Cu-56–28-Ni-59	Bertini/Dresner	Bertini/Dresner
26-Fe-60–40-Zr-89	CASCADE	CASCADE
38-Sr-90–54-Xe-124	INCL4/Dresner	INCL4/Dresner
50-Sn-125–75-Re-181	CEM2K	CASCADE
72-Hf-182–84-Po-210	CASCADE	CEM03.01

PHYSICAL REVIEW C **84**, 064612 (2011)

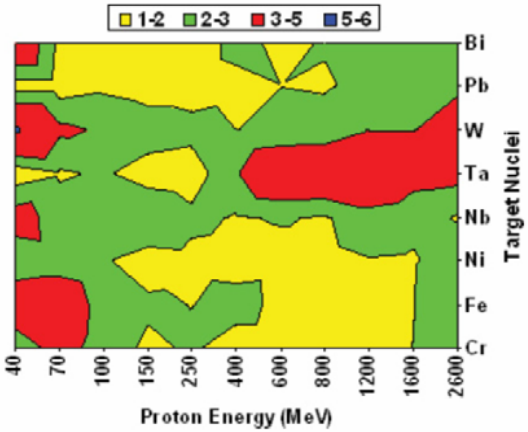
Verification of high-energy transport codes on the basis of activation data

Yu. E. Titarenko,[1] V. F. Batyaev,[1] M. A. Butko,[1] D. V. Dikarev,[1] S. N. Florya,[1] K. V. Pavlov,[1] A. Yu. Titarenko,[1] R. S. Tikhonov,[1] V. M. Zhivun,[1] A. V. Ignatyuk,[2] S. G. Mashnik,[3] A. Boudard,[4] S. Leray,[4] J.-C. David,[4] J. Cugnon,[5] D. Mancusi,[5] Y. Yariv,[6] H. Kumawat,[7] K. Nishihara,[8] N. Matsuda,[8] G. Mank,[9] and W. Gudowski[10]

VI. CONCLUSIONS

The estimated predictive accuracy of the most popular HETC tested here indicates that all codes need further improvements. At the present time, the CEM03.02 (as developed during 2004–2006) and NCL4.5 + ABLA07 (as developed during 2008–2009) codes can be considered as the most accurate.

Predictive accuracy of CEM03.02 code



Cross sections: codes and libraries

✦ Libraries combining calculations and experimental data

- **RNAL** (Reference Neutron Activation Library)
http://www-nds.iaea.org/public/rnal/www/
  - Restricted to 255 reactions

- **MENDL-2** and **MENDL-2P** (Medium Energy Nuclear Data Library)
http://www-nds.iaea.org/publications/iaea-nds/iaea-nds-0136.htm
http://www.oecd-nea.org/tools/abstract/detail/iaea1376
  - Neutrons up to 100 MeV and protons up to 200 MeV
  - Calculation based on ALICE family codes

- Evaluated library
  - Neutrons and protons to 1.7 GeV

A computer study of radionuclide production in high power accelerators for medical and industrial applications
K. A. van Riper et al, Nucl. Instrum. Meth. A 463 (2001) 576-585

- **HEAD-2009** (High Energy Activation Data)
  - Neutrons and protons up to 1 GeV
  - Choice of models dictated by an extensive comparison with EXFOR data
  - Available upon request

High Energy Activation Data library (HEAD-2009)
Yu. A.Korovin et al, Nucl. Instrum. Meth. A 624 (2010) 20-26

Cosmic ray spectrum

✦ Neutron spectrum at sea level

- **Compilation of measurements,** including the historical Hess spectrum and relevant corrections

Terrestrial cosmic ray intensities, J. F. Ziegler, IBM Journal of Research and Development 42 (1998) 117-140.

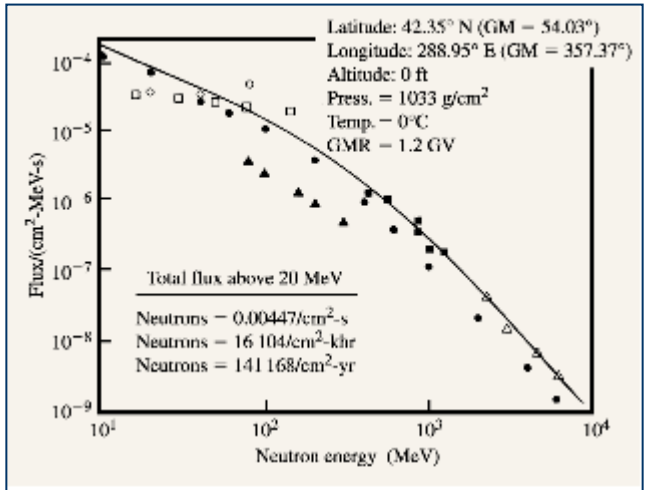


Figure 13

Experimental data on sea-level neutron spectrum. The absolute flux of neutrons above 10 MeV has been measured by six groups. These are shown on the plot and are discussed in detail in the text. All have been normalized to New York City, 1985, as a datum. The solid curve is the nominal sea-level neutron flux which best fits the data. Although the data were quoted as specific for neutrons, some of the experiments did not remove the contribution of other hadron particles. The curve is suggested as the total nucleon flux curve.

Analytic function valid from 10 MeV to 10 GeV **(Ziegler spectrum):**

$$\phi(E) = 1.5 \exp[F(E)]$$

$$F(E) = -5.2752 - 2.6043 \ln E + 0.5985 (\ln E)^2 - 0.08915 (\ln E)^3 + 0.003694 (\ln E)^4$$

E in MeV

ϕ in $cm^{-2}\ s^{-1}\ MeV^{-1}$

Cosmic ray spectrum

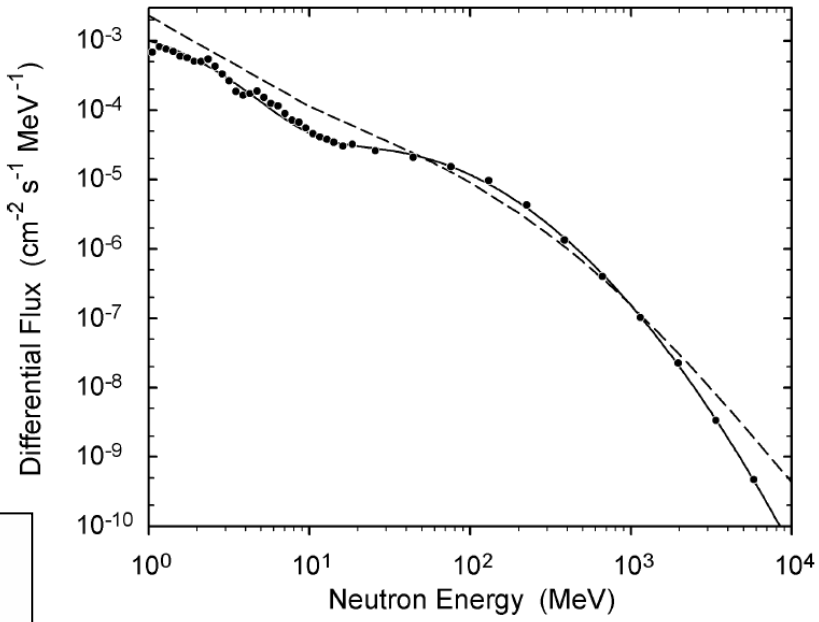
✦ Neutron spectrum at sea level

- Set of **measurements of cosmic neutrons** on the ground across the USA

Measurement of the Flux and Energy Spectrum of Cosmic-Ray Induced Neutrons on the Ground
M.S. Gordon et al., IEEE Trans. Nucl. Sci. 51 (2004) 3427.

Analytic expression fitting data
E>0.4 MeV (**Gordon spectrum**):

$$\phi(E) = 1.006 \times 10^{-6} e^{-0.35 \ln^2 E + 2.1451 \ln E} + 1.011 \times 10^{-3} e^{-0.4106 \ln^2 E - 0.667 \ln E}$$



Results: germanium

✦ Early estimates and measurements of production rates

- Excitation functions calculated with a spallation reaction code
- Hess and Lal and Peters neutron spectra used to calculate production rates
- Production rates also derived experimentally from Ge detectors in Homestake and Canfranc previously exposed

TABLE IV

Calculated and experimental isotopic production rates in natural germanium and germanium enriched to 86% ^{76}Ge and 14% ^{74}Ge (atoms per day per kilogram)

ISOTOPE PRODUCED	Natural Germanium			Enriched Germanium	
	Reference 1	Reference 2	Experiment	Reference 1	Reference 2
^{3}H	~178	~210	--	~113	~140
^{54}Mn	0.93	2.7	3.3 ± 0.8	0.37	1.4
^{57}Co	1.70	4.4	2.9 ± 0.4	0.28	1.0
^{58}Co	2.30	5.3	3.5 ± 0.9	0.59	1.8
^{65}Zn	24.6	34.4	38 ± 6	3.12	6.4
^{67}Ga	30.8	39.0	53 ± 15	2.26	4.1
^{68}Ge	22.9	29.6	30 ± 7	0.54	0.94

Ref.1 Lal and Peters

Ref. 2 Hess

New techniques and results in ^{76}Ge double-beta decay
H. Miley et al., Nucl. Phys. B (Proc. Suppl.) 28A (1992) 212-215.
Theoretical and experimental investigation of cosmogenic radioisotope production in germanium
F. T. Avignone III et al, Nucl. Phys. B (Proc. Suppl.) 28A (1992) 280-285

Results: germanium

✦ Estimates of production rates

- Excitation functions calculated using SHIELD code
- Production rates evaluated for ^{60}Co and ^{68}Ge including also proton contribution

^{68}Ge production rates (per day, per 1 kg), statistical standard deviations are shown in parentheses

Target	Total		By sea level protons	
	No shield	Shield	No shield	Shield
^{70}Ge	281.4 (0.5%)	33.0 (2%)	17.17 (1.1%)	4.90 (1.5%)
^{72}Ge	55.34 (1.4%)	6.20 (4%)	4.78 (2%)	0.96 (3%)
^{73}Ge	28.0 (1.3%)	2.94 (7%)	2.54 (3%)	0.45 (6%)
^{74}Ge	14.53 (2%)	1.46 (8%)	1.48 (4%)	0.24 (6%)
^{76}Ge	4.22 (4%)	0.4 (8%)	0.54 (6%)	0.06 (12%)

Cosmogenic activation of germanium and its reduction for low background experiments
I. Barabanov et al, Nucl. Instrum. Meth. B 251 (2006) 115–120

Results: germanium

✦ Estimates of production rates

- Excitation functions calculated using TALYS code
- Neutron spectrum considering the Gordon parameterization
- Production rates:

Cosmogenic isotope	Production rate (/(kg day))			$t_{1/2}$
	Natural Ge	Enriched Ge	Natural Cu	
^{68}Ge	41.3	7.2		270.8 days
^{60}Co	2.0	1.6	46.4	5.2714 years
^{57}Co	13.5	6.7	56.2	271.79 days
^{55}Fe	8.6	3.4	30.7	2.73 years
^{54}Mn	2.7	0.87	16.2	312.3 days
^{65}Zn	37.1	20.0		244.26 days
^{63}Ni	1.9	1.8		100.1 years
^{3}H	27.7	24.0		12.33 years

Checked against IGEX–DM data: <21 kg^{-1} d^{-1}

- Production rates of tritium in various targets:

Target	Ar	Xe	NaI	CsI	TeO_2	$CaWO_4$
Rate (/(kg day))	44.4	16.0	31.1	19.7	43.7	45.5

Cosmogenic production as a background in searching for rare physics processes
D. M. Mei et al, Astropart. Phys. 31 (2009) 417-420
Studies on cosmogenic production as a background for rare physics processes
Z.-B. Yin et al, Nucl. Phys. A 834 (2010) 823c–825c

Results: germanium

✦ Measurements of production rates

- A 11-g sample of enriched Ge and Ge detectors irradiated
- Exposed at Los Alamos Neutron Science Center (LANCE) to a wide-band pulsed neutron beam that resembles the cosmic-ray neutron flux
- After cooling, Ge gamma counting at WIPP for 49 d
- Cross section calculation performed with CEM03 code

➡ Nuclei production measured and predicted

Isotope	$\tau_{1/2}$ (days)	γ-ray energy (keV)	C	ϵ_γ	ϵ_c	B	N_0	N_0^{Pred}
^{57}Co	271.8	122.1	2916 ± 84	0.1663(7)	0.0280	0.856	$(7.31 \pm 0.21) \times 10^5$	$(2.97 \pm 0.06) \times 10^6$
^{57}Co	271.8	136.5	386 ± 63	0.163(2)	0.0280	0.107	$(7.89 \pm 1.3) \times 10^5$	$(2.97 \pm 0.06) \times 10^6$
^{54}Mn	312.1	834.9	1084 ± 43	0.0302(3)	0.0297	1.000	$(1.21 \pm 0.05) \times 10^6$	$(1.79 \pm 0.05) \times 10^6$
^{68}Ge	270.8	1077.4	198 ± 18	0.0207(5)	0.0280	0.032	$(1.06 \pm 0.10) \times 10^7$	$(2.92 \pm 0.02) \times 10^7$
^{65}Zn	244.25	1115.5	8541 ± 95	0.0232(5)	0.0262	0.506	$(2.77 \pm 0.03) \times 10^7$	$(5.03 \pm 0.06) \times 10^7$
^{60}Co	1923.6	1173.2	1342 ± 42	0.0200(6)	0.0146	0.999	$(4.61 \pm 0.14) \times 10^6$	$(7.50 \pm 0.01) \times 10^6$
^{60}Co	1923.6	1332.5	1176 ± 39	0.0167(3)	0.0146	1.000	$(4.83 \pm 0.16) \times 10^6$	$(7.50 \pm 0.01) \times 10^6$

Fast-neutron activation of long-lived isotopes in enriched Ge
S. R. Elliott et al, Phys. Rev. C 82 (2010) 054610
Neutron activation of long-lived isotopes in Ge, Pb, and other metals
V. E. Guiseppe, CAB Workshop (Berkeley 2011) https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141/Agenda/guiseppe_berkeley_apr11_V2.pdf

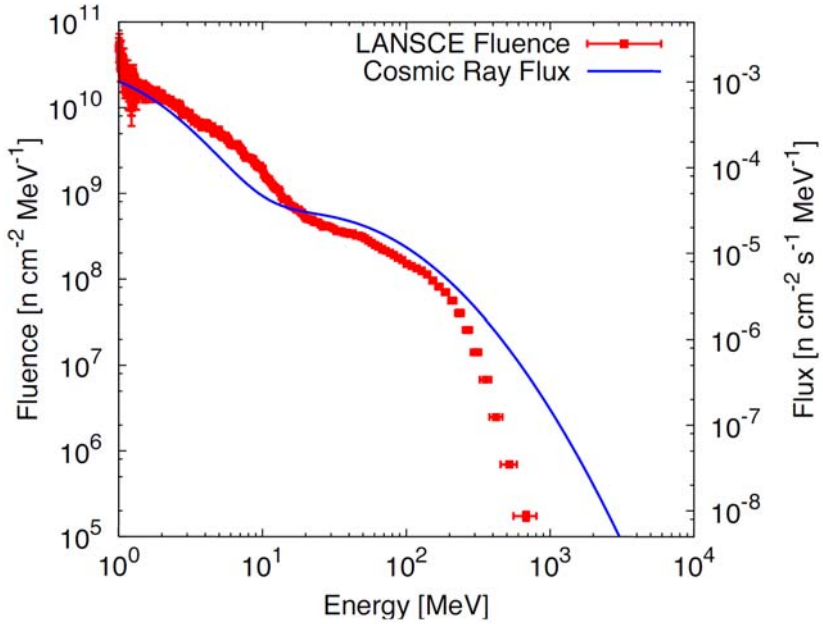
Results: germanium

✦ Measurements of production rates

- Measured yields converted to cosmogenic production rates considering the Gordon neutron spectrum

Isotope	Ratio $\left(\frac{N_0}{N_0^{\mathrm{Pred}}}\right)$	K_{Gordon} [atoms/(kg d)]	K_{scaled} [atoms/(kg d)]
^{57}Co	0.25 ± 0.01	2.93	0.72 ± 0.37
^{54}Mn	0.67 ± 0.03	2.91	1.96 ± 1.01
^{68}Ge	0.36 ± 0.03	5.83	2.12 ± 0.39
^{65}Zn	0.55 ± 0.01	16.24	8.94 ± 2.53
^{60}Co	0.63 ± 0.03	4.06	2.55 ± 1.20

Evaluated total uncertainties betwwen 20-50%



Fast-neutron activation of long-lived isotopes in enriched Ge
S. R. Elliott et al, Phys. Rev. C 82 (2010) 054610
Neutron activation of long-lived isotopes in Ge, Pb, and other metals
V. E. Guiseppe, CAB Workshop (Berkeley 2011) https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141/Agenda/guiseppe_berkeley_apr11_V2.pdf

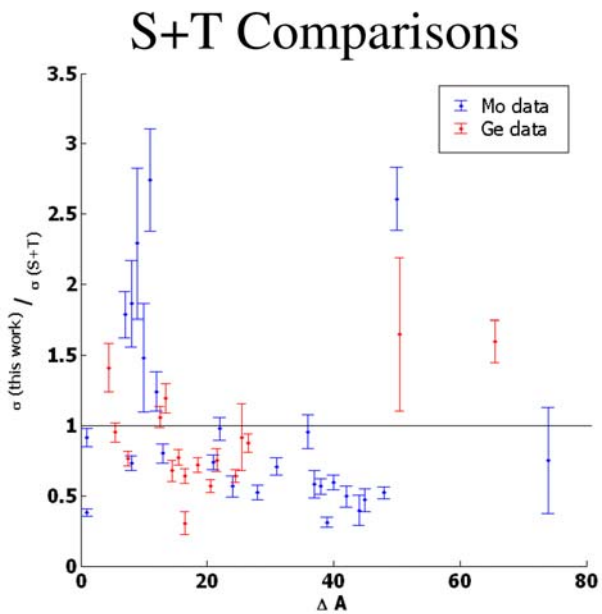
Results: germanium

✦ Measurements of production cross sections

- Natural Ge target
- Proton irradiation at Los Alamos Neutron Science Center (LANCE): **E=0.8 GeV**
- Screening with germanium detectors at Berkeley intermittently from 2 weeks to 5 years after irradiation.

^{A}Z	σ(mb)	± (mb)
^{7}Be	1.74	0.16
^{22}Na	**0.28**	0.092
^{44m}Sc	1.69	0.16
^{46}Sc	3.13	0.23
^{47}Sc	1.19	0.13
^{47}Ca	0.055	0.014
^{48}V	4.29	0.30
^{51}Cr	12.5	1.3
^{52}Mn	4.18	0.32
^{54}Mn	12.75	0.9

^{A}Z	σ(mb)	± (mb)
^{56}Co	4.21	0.32
^{56}Ni	0.055	0.014
^{57}Co	16.0	1.1
^{58}Co	18.0	2.0
^{59}Fe	2.3	0.20
^{60}Co	**8.3**	0.59
^{65}Zn	31.0	2.2
^{67}Ga	33.9	2.4
^{68}Ge	**12.2**	1.5
^{74}As	19.4	2.2

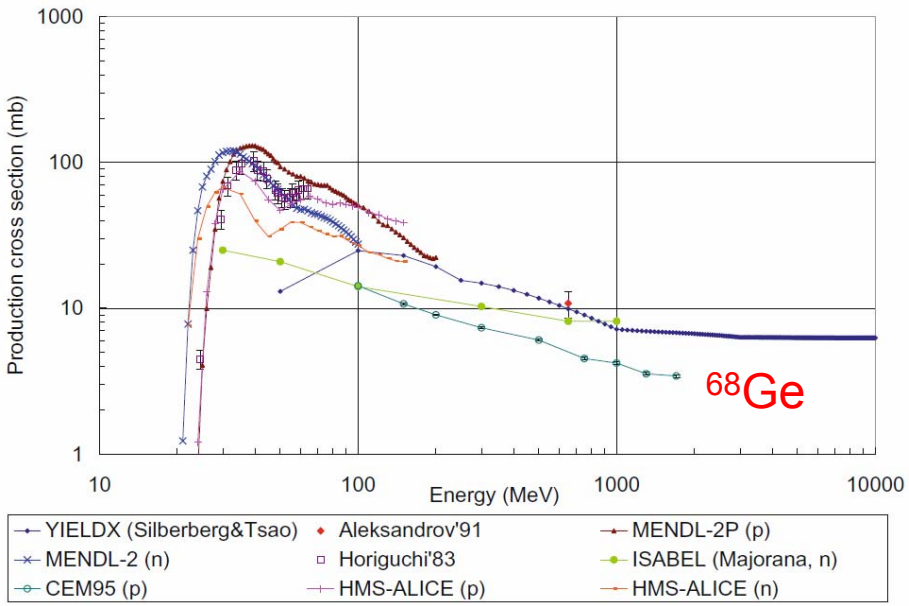


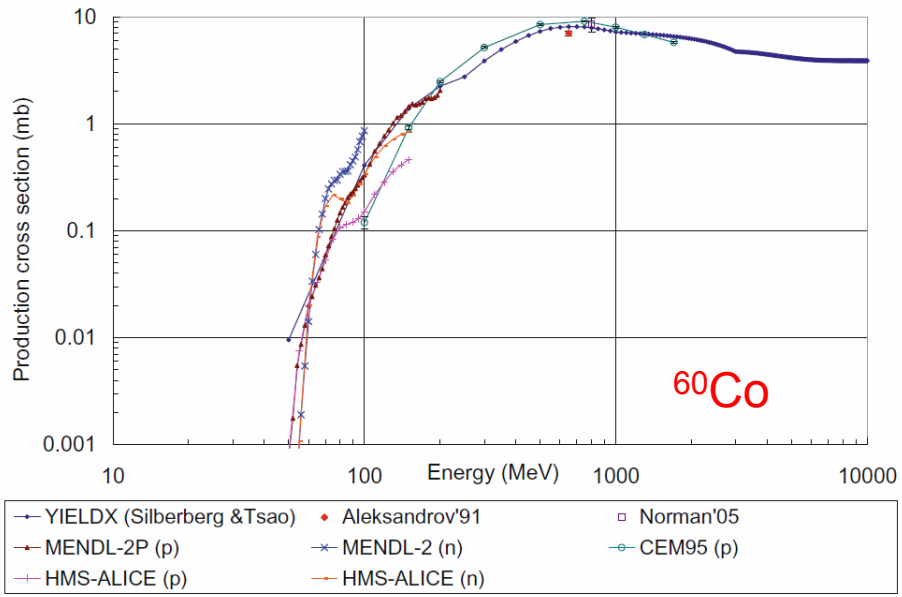
Cosmic-ray production of 60Co in double-beta decay source materials
E. B. Norman et al, Nucl. Phys. B (Proc. Suppl.) 143 (2005) 508
Measurements of Radioisotope Production Cross Sections from p-induced Reactions on Ge, Mo and Te
E. B. Norman et al, CAB Workshop (Berkeley 2011) https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141/Agenda/Radionuclide%20Production%20from%20%20Proton%20Interactions%20in%20Ge,Mo,Te.pdf

Results: germanium

✦ **Evaluation of excitation functions and estimate of production rates**

- Information collected on **excitation functions** for each relevant isotope
  - experimental data: only for protons
  - available calculations (MENDL libraries and other ones based on different codes) and new calculations (YIELDX)





Cosmogenic activation in germanium and copper for rare event searches
S. Cebrián et al, Astropart. Phys. 33 (2010) 316-329

Results: germanium

✦ **Evaluation of excitation functions and estimate of production rates**

- **Deviation factors** evaluated

Deviation factors between measured production cross-sections by Horiguchi'83 from 25 to 64 MeV and calculations of HMS-ALICE and MENDL-2P, and between measured production cross-sections at 660 MeV by Aleksandrov'91 and calculations of CEM95 and YIELDX. Last column indicates the number *N* of pairs of data considered in the comparison between measurements and calculations.

	MENDL-2P	HMS-ALICE	CEM95	YIELDX	*N*
^{68}Ge	1.4	1.2			19
^{65}Zn	3.7	1.6			18
Average (^{68}Ge, ^{65}Zn)	2.6	1.4			37
Average (various isotopes)			1.7	1.4	7

Cosmogenic activation in germanium and copper for rare event searches
S. Cebrián et al, Astropart. Phys. 33 (2010) 316-329

Results: germanium

✦ **Evaluation of excitation functions and estimate of production rates**

- **Production rates** at sea level (kg^{-1} d^{-1})

Natural Ge

	This work (Ziegler)	This work (Gordon et al.)	Mei 2009 TALYS	Barabanov 2006 SHIELD	Klapdor-K 2002 SIGMA	Miley 1992	Avignone 1992 MC	Avignone 1992 exp	Black 2008 ACTIVIA
^{68}Ge	77 + 12 = 89	50 + 10 = 60	41.3	81.6	58.4	26.5	29.6	30 ± 7	45.8
^{60}Co	0.3 + 4.5 = 4.8	0.3 + 3.6 = 3.9	2	2.9	6.6	4.8			2.8
^{65}Zn	36 + 41 = 77	27 + 36 = 63	37.1		79	30	34.4	38 ± 6	29.0
^{58}Co	0.5 + 13.3 = 13.8	0.4 + 10.5 = 10.9			16.1	4.4	5.3	3.5 ± 0.9	8.5
^{57}Co	0.3 + 9.4 = 9.7	0.3 + 7.3 = 7.6	13.5		10.2	0.5	4.4	2.9 ± 0.4	6.7
^{56}Co	0.09 + 2.9 = 3.0	0.1 + 2.3 = 2.4							2.0
^{54}Mn	0.01 + 7.2 = 7.2	0.01 + 5.2 = 5.2	2.7		9.1		2.7	3.3 ± 0.8	2.7
^{63}Ni	1.7 + 3.5 = 5.2	1.4 + 2.9 = 4.3	1.9		4.6				1.6
^{55}Fe	0.06 + 7.9 = 8.0	0.1 + 5.9 = 6.0	8.6		8.4				3.4

Enriched Ge (86% ^{76}Ge, 14% ^{74}Ge)

	This work (Ziegler)	This work (Gordon et al.)	Mei 2009 TALYS	Barabanov 2006 SHIELD	Miley 1992	Avignone 1992	Elliot 2010	Black 2008 ACTIVIA
^{68}Ge	2.8 + 10 = 13	2.5 + 9.1 = 12	7.2	5.8	1.2	0.94	2.1 ± 0.4	7.6
^{60}Co	0.02 + 6.7 = 6.7	0.02 + 5.1 = 5.1	1.6	3.3	3.5		2.5 ± 1.2	2.4
^{65}Zn	2.9 + 21 = 24	2.6 + 17.8 = 20	20		6	6.4	8.9 ± 2.5	10.4
^{58}Co	0 + 6.2 = 6.2	0 + 4.6 = 4.6			1.6	1.8		5.5
^{57}Co	0 + 2.3 = 2.3	0 + 1.7 = 1.7	6.7		0.08	1	0.7 ± 0.4	2.9
^{56}Co	0 + 0.7 = 0.7	0 + 0.5 = 0.5						
^{54}Mn	0 + 5.4 = 5.4	0 + 3.7 = 3.7	0.87			1.4	2.0 ± 1.0	2.2
^{63}Ni	0.5 + 5.5 = 6.0	0.4 + 4.5 = 4.9	1.8					1.4
^{55}Fe	0 + 2.3 = 2.3	0 + 1.6 = 1.6	3.4					1.6

Cosmogenic activation in germanium and copper for rare event searches
S. Cebrián et al, Astropart. Phys. 33 (2010) 316-329

Results: tellurium

✦ **Measurements of production cross sections by protons**

- **Measurements in USA**
  - Te target
  - Proton irradiation at Los Alamos Neutron Science Center: **E=0.8 GeV**
  - Ge gamma screening measurements in Berkeley for one year
- **Measurements in Europe**
  - TeO_2 targets
  - Proton irradiations at CERN: **E=1.4, 23 GeV**
  - Ge gamma screening measurements at CERN for several months and in Milano 4.6 and 2.8 years after irradiation

Results for activation of isotopes with half-life >100 days.

Isotope	Half-life (d)	Gamma ray energy (keV)	Decay mode	σ Expt. 0.8 GeV (mb)	σ S&T 0.8 GeV (mb)	σ Expt. 1.4 GeV (mb)	σ S&T 1.4 GeV (mb)	σ Expt. 23 GeV (mb)	σ S&T 23 GeV (mb)
^{54}Mn	312	1377	EC	0.04 ± 0.02	0.11		0.40	1.5 ± 0.3	4.0
^{57}Co	272	836	EC	0.05 ± 0.01	0.20	0.15 ± 0.05	0.73	0.87 ± 0.09	1.1
^{60}Co	1923.6	2824	β^-	0.09 ± 0.04	0.22	0.20 ± 0.04	0.77	0.75 ± 0.08	1.15
^{65}Zn	244	1352	EC, β^+	0.11 ± 0.02	0.46	1.2 ± 0.3	1.5	1.8 ± 0.2	2.4
^{75}Se	120	864	EC	0.26 ± 0.08	1.1	3.2 ± 0.3	2.7	3.1 ± 0.3	4.3
^{88}Y	107	3623	EC, β^+	3.1 ± 1.2	1.3	4.6 ± 0.8	5.0	4.2 ± 0.6	3.1
^{102}Rh	207	2323 1151	EC, β^+ β^-	4.9 ± 1.2	7.9	1.5 ± 0.3	11		5.8
^{102m}Rh	1058.5	2323	EC, β^+	4.0 ± 0.6	1.3	2.4 ± 0.5		1.5 ± 0.2	
^{110m}Ag	250	2892	β^-	24.6 ± 3.7	16.0	1.9 ± 0.3	1.2	0.88 ± 0.59	0.64
^{113}Sn	115	1036	EC	12.4 ± 1.9	19.5	27 ± 5	19		11

Measurements of p-induced radionuclide production cross sections to evaluate cosmic-ray activation of Te, A.F. Barghouty et al, Nucl. Instrum. Meth. B 295 (2013) 16–21

Results: tellurium

✦ Measurements of production cross sections by neutrons

- Several TeO_2 crystals as targets (including one 5x5x5 cm^3)
- Irradiation at Los Alamos Neutron Science Center (LANCE) with a **neutron spectrum** that mimics that of the cosmic ray neutrons, from 1.5 to 800 MeV
- First Ge gamma screening 17 d after irradiation

Energy-averaged production cross sections:

Isotope	Half-life (d)	σ (mb) (neutrons on TeO_2)	σ (mb) (800 MeV protons on Te)
Rh-101m	4.34	0.18±0.08	--
Ag-105	41.29	0.36±0.12	10.1±1.0
In-111	2.8047	0.95±0.27	16.4±3.0

Isotope	Half-life (d)	σ (mb) (neutrons on TeO_2)
Be-7	53.12	0.76±0.30

Isotope	Half-life	σ (mb) (neutrons on TeO_2)
Sb-124	60.2 d	8.7±4.0
Sb-125	2.76 y	10.3±3.8

Cross-section Measurements for Neutron Activation of Radioactive Isotopes in TeO_2
B. Wang, CAB workshop (Berkeley 2011) https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141/Agenda/Cross-sectionMeasurementsTeO2_4_13_2011.pdf

Results: Sodium Iodide

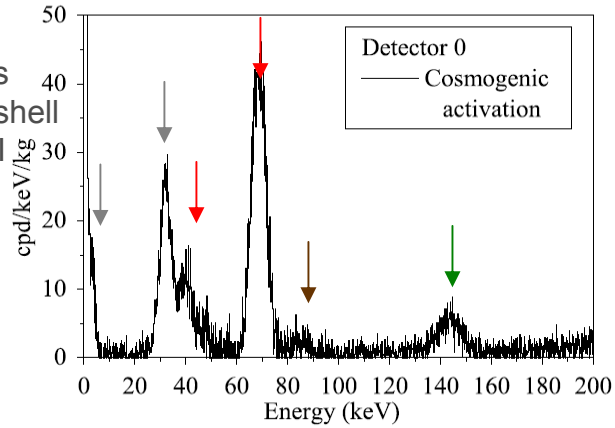
✦**PRELIMINARY measurement of production rates**

- Two new 12.5 kg NaI(Tl) detectors for the ANAIS experiment are taking bakground data since December 2012, just three days after going underground

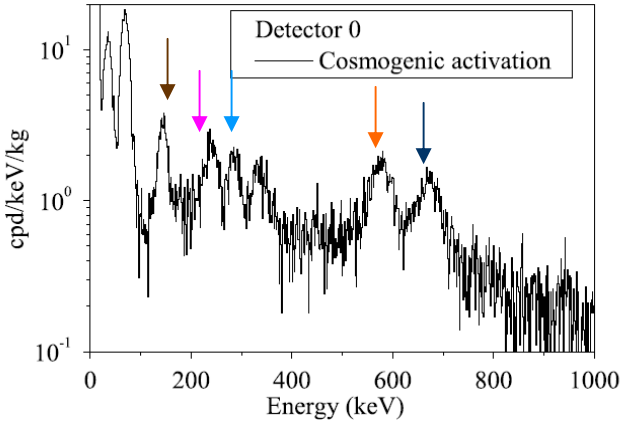
See Poster "Background studies for NaI(Tl) detectors in the ANAIS dark matter project", J. Amaré et al

- Emissions from several cosmogenic isotopes identified and decay observed

Emissions from L,K shell EC in Te/I



Differences between first data and data taken 75 days later



	$T_{1/2}$ (d)	Decay	Emissions (keV)
^{125}I	59.4	CE	35.5
^{125m}Te	57.4	IT	144.8
^{127m}Te	109	IT	88.3

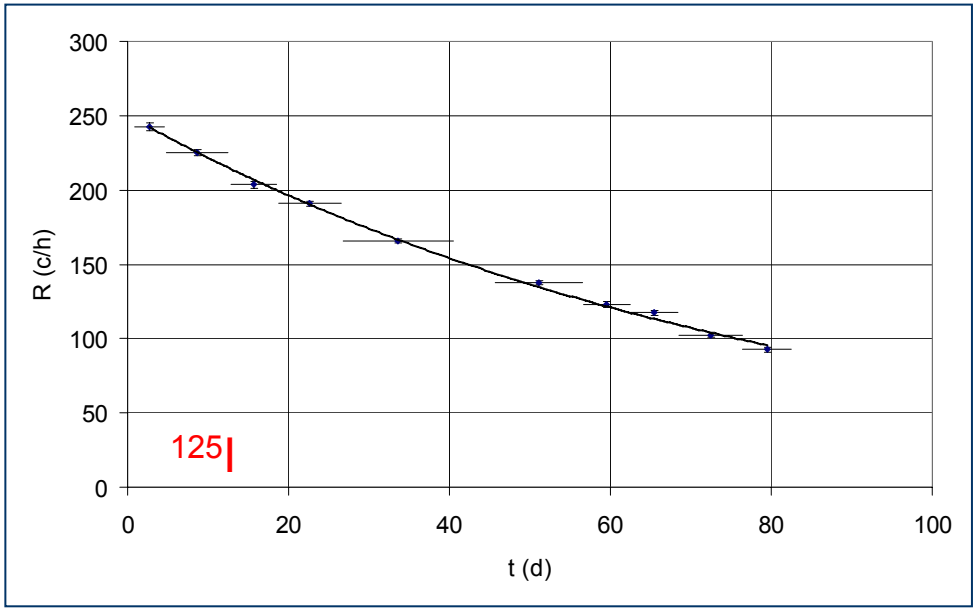
	$T_{1/2}$ (d)	Decay	Emissions (keV)
^{126}I	13.11	CE, β-	666
^{121m}Te	154	IT	294.0
^{121}Te	16.8	CE	507.6, 573.1
^{123m}Te	119.7	IT	247.6

ANAIS-0: Feasibility study for a 250 kg NaI(Tl) dark matter search experiment at the Canfranc Underground Laboratory, C. Cuesta, PhD thesis, March 2013

Results: Sodium Iodide

✦**PRELIMINARY measurement of production rates**

- Production rates (kg^{-1} d^{-1}):



	$T_{1/2}$ (d)	Data	Calculation MENDL2N+YIELDX
^{125}I	59.4	615.5 ± 7.3	600
^{125m}Te	57.4	82.2 ± 2.1	79

Results: copper

✦ Direct measurement of production rates

- Seven plates made of NOSV grade copper from Nord-deutsche Affinerie AG (Germany), with total weight 125 kg
- Exposed for 270 d at an outside hall of the LNGS (altitude 985 m) under a roof
- Screening with GeMPI detector at Gran Sasso for 103 d

Production rates

Radionuclide	Half-life[a]	(Saturation) activity (μBq kg^{-1})	
		Exposed	Unexposed
Cosmogenic			
^{56}Co	77.236 d	230 ± 30	
^{57}Co	271.80 d	1800 ± 400	
^{58}Co	70.83 d	1650 ± 90	
^{60}Co	5.271 a	2100 ± 190	< 10
^{54}Mn	312.13 d	215 ± 21	
^{59}Fe	44.495 d	455 ± 120	
^{46}Sc	83.788 d	53 ± 18	
^{48}V	15.9735 d	110 ± 40	
Primordial			
^{226}Ra (U)	1600 a	< 35	< 16
^{228}Th (Th)	698.60 d	< 20	< 19
^{40}K	1.265×10^9 a	< 110	< 88

Cosmogenic radionuclides in metals as indicator for sea level exposure history
M. Labustenstein, G. Heusser
ARI 67 (2009) 750-754

Results: copper

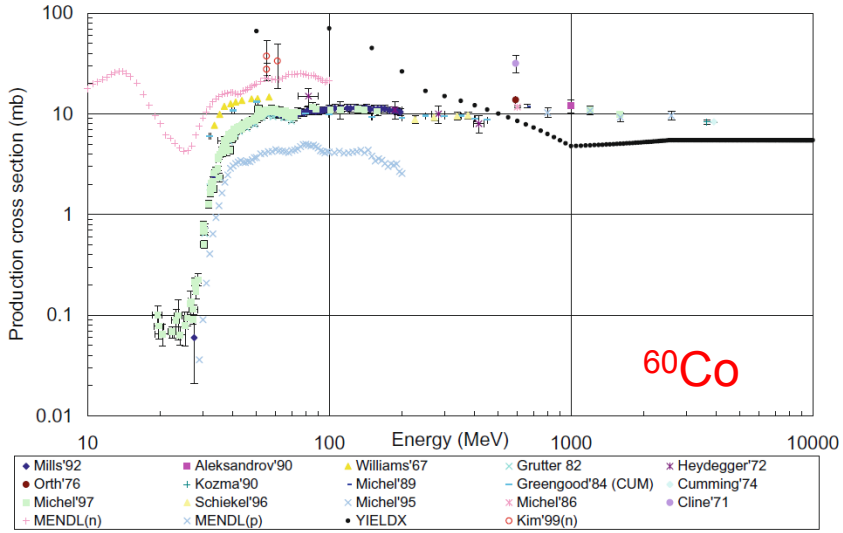
✦ **Evaluation of excitation functions and estimate of production rates**

- Information collected on **excitation functions** for each relevant isotope
  - experimental data: even for neutrons!
  - available calculations (MENDL libraries) and new calculations (YIELDX)

- **Deviation factors** evaluated

Deviation factors between measured production cross-sections and calculations from MENDL and using YIELDX, averaged on different energy intervals. Numbers in brackets indicate the number *N* of pairs taken into consideration in the comparison between measurements and calculations.

	MENDL(n) <100 MeV	MENDL(p) <200 MeV	YIELDX 200–300 MeV	YIELDX >300 MeV
^{56}Co	3.6 (4)	1.8 (40)	1.1 (2)	1.2 (10)
^{57}Co	1.4 (3)	1.3 (48)	1.4 (3)	1.1 (7)
^{58}Co	1.3 (7)	1.8 (61)	6.8 (4)	2.9 (10)
^{60}Co	1.4 (2)	2.6 (184)	2.0 (6)	1.6 (15)
^{54}Mn		1.5 (123)	1.5 (3)	1.5 (11)
^{59}Fe	2.5 (4)	5.0 (43)	3.6 (3)	1.7 (11)
^{46}Sc			1.8 (8)	1.3 (6)
^{65}Zn		1.7 (72)	1.3 (2)	1.9 (5)
Average	2.1 (20)	2.2 (571)	2.5 (31)	1.8 (75)



Cosmogenic activation in germanium and copper for rare event searches
S. Cebrián et al, Astropart. Phys. 33 (2010) 316-329

Results: copper

✦ **Evaluation of excitation functions and estimate of production rates**

- **Production rates** at sea level (kg^{-1} d^{-1})

	This work (Ziegler)	This work (Gordon et al.)	Laubenstein 2009 (LNGS)	Baudis 2002 COSMO	Mei 2009 TALYS	Black 2008 ACTIVIA
^{56}Co	2.6 + 18.0 + 2.3 = 22.9	2.1 + 16.4 + 1.5 = 20.0	19.9 ± 2.6			8.7
^{57}Co	29.7 + 55.8 + 2.8 = 88.3	22.2 + 50.5 + 1.4 = 74.1	155 ± 35	30.5	56.2	32.5
^{58}Co	90.4 + 65.7 + 3.5 = 159.6	61.7 + 59.5 + 1.8 = 123.0	142.6 ± 7.8			56.6
^{60}Co	81.8 + 14.2 + 1.4 = 97.4	41.9 + 12.8 + 0.7 = 55.4	181 ± 16	25.7	46.4	26.3
^{54}Mn	3.6 + 25.9 + 3 = 32.5	2.9 + 23.2 + 1.6 = 27.7	18.6 ± 1.8	134.2	16.2	14.3
^{59}Fe	4.3 + 1.9 + 0.3 = 6.5	3.0 + 1.7 + 0.2 = 4.9	39 ± 10			4.2
^{46}Sc	0 + 2.5 + 1.3 = 3.8	0 + 2.0 + 0.7 = 2.7	4.6 ± 1.6			3.1

Correction factor due to altitude and roof: 2.1

Cosmogenic activation in germanium and copper for rare event searches
S. Cebrián et al, Astropart. Phys. 33 (2010) 316-329

Results: stainless steel

✦ Direct measurement of production rates

- Samples of stainless steel (1.4571 grade) from different batches supplied by Nironit company (masses from 53 to 61 kg)
- First screening with GeMPI detector at Gran Sasso for 3 to 20 d

Measurements of extremely low radioactivity levels in stainless steel for GERDA.
W. Maneschg et al. Nucl. Instrum. Meth. A 593 (2008) 448–453.

Sample	(Saturation) activity (mBq kg^{-1})					
	^{7}Be 53.22 d	^{54}Mn 312.13 d	^{58}Co 70.83 d	^{56}Co 77.236 d	^{46}Sc 83.788 d	^{48}V 15.9735 d
G1	⩽3.9	1.3±0.4	0.67±0.34	⩽0.32	⩽0.35	0.30±0.11
G2	⩽3.0	1.5±0.1	0.99±0.12	0.17±0.06	0.24±0.06	0.36±0.07
G3	⩽5.7	0.92±0.24	0.56±0.23	⩽0.62	⩽0.54	0.27±0.11
G4	9.6±2.9	2.0±0.3	0.71±0.26	⩽0.71	⩽0.67	0.31±0.13
G5	4.8±1.7	1.7±0.2	0.69±0.16	0.28±0.10	0.47±0.14	0.22±0.09
G6	13.6±2.5	1.4±0.2	0.59±0.20	⩽0.42	⩽0.31	0.40±0.12
G7	⩽5.9	1.6±0.3	0.54±0.27	⩽0.6	0.61±0.26	0.39±0.13
$PR_{sea\ level}$	4.5±0.7	2.7±0.3	0.6±0.09	0.24±0.04	0.22±0.04	0.4±0.04
PR_{LNGS}	10.9±1.6	6.5±0.7	1.5±0.2	0.57±0.08	0.53±0.09	0.88±0.09

Correction factor due to altitude: 2.4

- G2 sample re-exposed for 314 d in open air at the LNGS outside laboratory (after a cooling time of 327 d underground)

Cosmogenic radionuclides in metals as indicator for sea level exposure history
M. Labustenstein, G. Heusser, ARI 67 (2009) 750-754

Results: xenon

✦ Estimates of production rates

- Excitation functions calculated using TALYS code
- Neutron spectrum considering the Gordon parametrization
- Production rates

Cosmogenic isotope	Production rate (/(kg day))	$t_{1/2}$
^{3}H	16.0	12.33 years
^{121m1}Te	11.7	154 days
^{123m1}Te	12.1	119.7 days
^{127m1}Te	5.0	109 days
^{101}Rh	0.04	3.3 years
^{125}Sb	0.04	2.7582 years
^{119m1}Sn	0.02	293.1 days
^{123}Sn	0.004	129.2 days
^{109}Cd	3.2	462.6 days
^{113m1}Cd	0.002	14.1 years

Cosmogenic production as a background in searching for rare physics processes
D. M. Mei et al, Astropart. Phys. 31 (2009) 417-420

Results: xenon

✦ Estimates of production rates

- Calculations using COSMO and ACTIVIA code

isotope	$T_{1/2}$	PR (saturation activities) [$kg^{-1}day^{-1}$]		
		ACTIVIA	COSMO	TALYS
^{3}H	12.3 y	36.0	35.1	16.0
^{22}Na	2.6 y	0.09	0.09	N/A
^{45}Ca	165 d	0.06	0.05	N/A
^{49}V	330 d	0.26	0.22	N/A
^{54}Mn	312 d	0.23	0.20	N/A
^{55}Fe	2.7 y	0.14	0.12	N/A
^{57}Co	271 d	0.15	1.69	N/A
^{60}Co	5.27 y	0.10	0.98	N/A
^{65}Zn	244.1 d	0.33	3.73	N/A
^{68}Ge	270.8 d	0.15	0.18	N/A
^{75}Se	118.5 d	0.39	4.17	N/A
^{88}Y	106.6 d	0.15	1.19	N/A
^{93m}Nb	13.6 y	0.19	1.09	N/A

isotope	$T_{1/2}$	PR (saturation activities) [$kg^{-1}day^{-1}$]		
		ACTIVIA	COSMO	TALYS
^{101}Rh	3.3 y	1.59	0	N/A
^{102}Rh	206 d	0.54	0	N/A
^{102m}Rh	2.9 y	0.54	0	N/A
^{110m}Ag	252 d	0.08	0	N/A
^{109}Cd	1.3 y	3.30	0	3.2
^{113m}Cd	14.0 y	0.07	0	0.02
^{113}Sn	115 d	4.59	0.01	N/A
^{119m}Sn	250 d	0.06	0.09	0.02
^{125}Sb	2.7 y	0.02	1.14	0.04
^{121m}Te	154 d	24.85	16.19	11.7
^{123m}Te	119.7 d	1.23	1.10	12.1
^{127m}Te	109 d	1.07	1.06	5.0
^{134}Cs	2.1 y	0.82	0.83	N/A

Cosmogenic background in XENON100 experiment, A. Kish, CAB workshop (Berkeley 2011)
https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141/Agenda/Berkeley2011_Xe100_Kish_red4.pdf

Results: lead

✦ Measurements of production rates

- Pb activation previously unknown
- Pb sample exposed at Los Alamos Neutron Science Center (LANCE) to the wide-band neutron beam that resembles the cosmic-ray neutron flux
- Counted on a low background, underground Ge detector at WIPP
- Preliminary production rates derived scaling the neutron flux
- Comparisons made calculating cross-sections with the TALYS code

Isotope	Prod. rate [atoms/kg/day]	
	this work	TALYS
^{194}Au (via ^{194}Hg)	~0.03	0.04
^{202}Tl (via ^{202}Pb)	~0.5	0.21
^{207}Bi	~0.001	N/A

Neutron activation of long-lived isotopes in Ge, Pb, and other metals
V. E. Guiseppe, CAB Workshop (Berkeley 2011) https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141/Agenda/guiseppe_berkeley_apr11_V2.pdf

Results: molibdenum

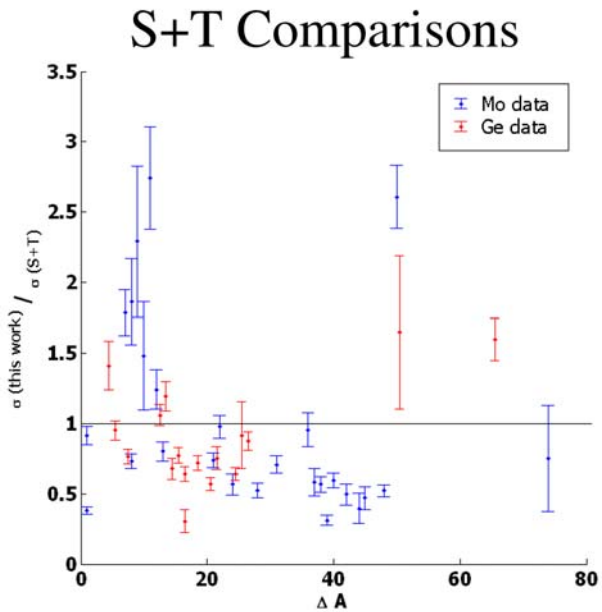
✦ Measurements of production cross sections

- Natural Mo target
- Proton irradiation at Los Alamos Neutron Science Center (LANCE): **E=0.8 GeV**
- Screening with germanium detectors at Berkeley intermittently from 2 weeks to 5 years after irradiation.

^{A}Z	σ(mb)	± (mb)
^{7}Be	2.24	0.19
^{22}Na	**0.06**	0.030
^{46}Sc	0.18	0.016
^{48}V	0.19	0.016
^{51}Cr	0.69	0.12
^{52}Mn	0.23	0.062
^{54}Mn	0.75	0.11
^{56}Co	0.33	0.029
^{57}Co	0.58	0.065
^{58}Co	1.45	0.14

^{A}Z	σ(mb)	± (mb)
^{60}Co	**0.86**	0.11
^{59}Fe	0.12	0.020
^{65}Zn	5.75	0.48
^{68}Ge	**4.07**	0.42
^{72}Se	4.30	0.59
^{74}As	3.29	0.27
^{75}Se	22.0	1.4
^{83}Rb	36.5	3.0
^{84}Rb	4.57	0.52
^{85}Sr	36.0	4.7

^{A}Z	σ(mb)	± (mb)
^{86}Rb	0.8	0.21
^{87}Y	44.7	10.5
^{88}Y	10.3	1.7
^{88}Zr	32.4	2.3
^{92m}Nb	10.9	1.1
^{95}Nb	15.5	1.1
^{95}Zr	1.22	0.09
^{95m}Tc	0.90	0.08
^{89}Zr	44.3	4.1



Measurements of Radioisotope Production Cross Sections from Proton-Induced Reactions on Ge, Mo, and Te
E. B. Norman et al, CAB Workshop (Berkeley 2011) https://docs.sanfordlab.org/docushare/dsweb/View/Wiki-141/Agenda/Radionuclide%20Production%20from%20%20Proton%20Interactions%20in%20Ge,Mo,Te.pdf

Activation at sea level

How can we estimate the cosmogenic production of radioactive isotopes?

1. To collect all the available **information on isotope production** cross sections, from both measurements (**EXFOR**) and calculations, either from libraries (**HEAP-2009**) or using codes (semiempirical: **YIELDX, ACTIVIA**, MC: **CEM**)

2. To choose the best description of the **excitation functions** of products over the whole energy range, by calculating deviation factors (F) between measurements and calculations

	Target	Projectile	Energy range	*F*	*N*
HMS-ALICE from Ref. [35]	Germanium	Protons	<100 MeV	1.4	37
MENDL2	Germanium	Protons	<100 MeV	2.6	37
MENDL2	Copper	Protons	<200 MeV	2.2	571
MENDL2	Copper	Neutrons	<100 MeV	2.1	20
CEM95 from Ref. [35]	Germanium	Protons	660 MeV	1.7	7
YIELDX	Germanium	Protons	660 MeV	1.4	7
YIELDX	Copper	Protons	200–300 MeV	2.5	31
YIELDX	Copper	Protons	>300 MeV	1.8	75

3. To calculate the **production rates (R)** of relevant products considering a particular cosmic ray spectrum and to compare them with previous estimates or measurements if available

Cosmogenic activation of materials

- ✓ **Activation at sea level:**
  - Production cross sections: codes and libraries
  - Cosmic ray spectrum
  - Results: **Ge, Te, Xe, NaI, Mo, Cu, Steel, Pb**
- ✓ **Activation underground:**
  - Results: **liquid scintillator, Ge**
- ✓ **Summary**

Low Radioactivity Techniques 2013

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Cosmogenic activation underground

• **Production rate R** of induced isotopes:

• By **stopped μ- capture**: Z→Z-1 transformation

$$R = I\mu \, Pc \, Pe$$

Iμ= stopping rate of μ-

Pc = capture probability

Pe = neutron emission probability

• By **fast muons**: direct muon spallation, photonuclear reactions, neutron capture, neutron inelastic scattering…

$$R \propto \int \sigma(E) \frac{dN}{dE} dE$$

E = muon energy

σ = production cross section

dN/dE = muon spectrum

Results underground

✦ Estimates of production rates

- Isotopes produced in materials used in neutrino experiments: **C, O, Ar**
- Considering inelastic scattering giving electromagnetic nuclear reactions
- At sea level and underground (2700 m.w.e.)

Isotope	$t_{1/2}$	Decay	Q (MeV)	Formation	σ_{-1} (μb)	R (d^{-1} kt^{-1}) Sea level	2700 (mwe)
^{7}Be	53.3 d	γ(10%)	0.48	$^{12}C(\gamma,\alpha n)$	500	4×10^{7}	
				$^{16}O(\gamma,2\alpha n)$	250	2×10^{7}	
				$^{40}Ar(\gamma,{}^{7}Be)$	250	1×10^{7}	
^{11}C	20.4 m	β^+	0.96	$^{12}C(\gamma,n)$	4500		150
^{15}O	122 s	β^+	1.72	$^{16}O(\gamma,n)$	6000		150
^{22}Na	2.60 y	β^+,γ	2.84	$^{40}Ar(\gamma,{}^{22}Na)$	100	1×10^{5}	
^{39}Ar	269 y	β^-	0.57	$^{40}Ar(\gamma,n)$	5×10^{4}	7×10^{7}	
^{39}Cl	56 m	β^-,γ	3.44	$^{40}Ar(\gamma,p)$	5×10^{4}		500

Muon-induced radioactivity in underground detectors
J. S. O'Connell and F. J. Schima, PRD 38 (1988) 2277-2279

Results underground

✦ Measurements of cross sections

- Irradiation with SPS muon beam at CERN at **E=100** and **190 GeV**
- Different kinds of ^{12}C targets behind concrete and water to build the muon shower
- Several detection techniques for measuring products of different half-lives

Isotopes	σ in μbarn for E_μ (GeV)		Energy dependence exponent α
	100	190	
^{11}C	576 ± 45	905 ± 58	0.70 ± 0.16
^{7}Be	127 ± 13	230 ± 23	0.93 ± 0.23
^{11}Be	<1.22 (68% CL)	<2.34 (68% CL)	
^{10}C	77.4 ± 4.9	115.4 ± 14.6	0.62 ± 0.22
^{8}Li	2.93 ± 0.80	4.02 ± 1.46	0.50 ± 0.71
^{6}He	10.15 ± 1.0	16.02 ± 1.60	0.71 ± 0.22
^{8}B	4.16 ± 0.81	7.13 ± 1.46	0.84 ± 0.45
^{9}C		4.83 ± 1.51	
$^{9}Li + {}^{8}He$		2.12 ± 0.35	

Muon-induced production of radioactive isotopes in scintillation detectors
T. Hagner et al, Astropart. Phys. 14 (2000) 33-47

Results underground

✦ Estimates of production rates

- Considering the measured cross-section and deduced energy dependence
- For the muon flux at Gran Sasso and BOREXINO detector (100 t)

$$\sigma_{\text{tot}}(E_\mu) \propto E_\mu^\alpha. \qquad \alpha = \frac{\ln\left(\sigma(190\ \text{GeV})/\sigma(100\ \text{GeV})\right)}{\ln\left(190\ \text{GeV}/100\ \text{GeV}\right)}. \quad \langle\alpha\rangle = 0.73 \pm 0.10$$

Isotopes	Muon-induced background rates in BOREXINO given in counts/(day × 100 tons) for the different energy regions			
	Full energy range	$250 < E < 800$ keV ^{7}Be-ν region	$0.8 < E < 1.4$ MeV pep-ν region	$2.8 < E < 5.5$ MeV ^{8}B-ν region
^{11}C	14.55 ± 1.49	0	7.36 ± 0.75	0
^{7}Be	0.34 ± 0.04	0.34 ± 0.04	0	0
^{11}Be	<0.034	$<4.3 \times 10^{-4}$	$<1.0 \times 10^{-4}$	<0.01
^{10}C	1.95 ± 0.21	0	0	0.56 ± 0.06
^{8}Li	0.070 ± 0.017	$(2.5 \pm 0.6) \times 10^{-4}$	$(8.0 \pm 2.0) \times 10^{-4}$	0.020 ± 0.005
^{6}He	0.26 ± 0.03	0.040 ± 0.004	0.07 ± 0.01	0.011 ± 0.001
^{8}B	0.11 ± 0.02	0	$(3.3 \pm 0.6) \times 10^{-5}$	0.020 ± 0.004
^{9}C	0.077 ± 0.025	0	0	0.016 ± 0.005
^{9}Li + ^{8}He	0.034 ± 0.007	$<6.8 \times 10^{-4}$	$<1.0 \times 10^{-3}$	<0.014

Muon-induced production of radioactive isotopes in scintillation detectors
T. Hagner et al, Astropart. Phys. 14 (2000) 33-47

Results underground

✦ Estimates of production rates

- Production rate of ^{11}C taking into account all relevant production channels
- Evaluation of cross sections from different sources combining data and calculations
- FLUKA simulation of monoenergetic muons in BOREXINO liquid scintillator to derive rates and paths of secondary particles (γ, e, n, p, π)

E_μ (GeV)	100	190	285	320	350
Process			Rate ($10^{-4}/\mu$ m)		
$^{12}C(p, p+n)^{11}C$	1.8	3.2	4.9	5.5	5.6
$^{12}C(p, d)^{11}C$	0.2	0.4	0.5	0.6	0.6
$^{12}C(\gamma, n)^{11}C$	19.3	26.3	33.3	35.6	37.4
$^{12}C(n, 2n)^{11}C$	2.6	4.7	7.0	8.0	8.2
$^{12}C(\pi^+, \pi+N)^{11}C$	1.0	1.8	2.8	3.2	3.3
$^{12}C(\pi^-, \pi^-+n)^{11}C$	1.3	2.3	3.6	4.1	4.2
$^{12}C(e, e+n)^{11}C$	0.2	0.3	0.4	0.4	0.4
$^{12}C(\mu, \mu+n)^{11}C$	2.0	2.3	2.4	2.4	2.4
Invisible channels	0.9	1.6	2.4	2.7	2.8
Total	28.3	41.3	54.8	59.9	62.2
1σ systematic	1.9	3.1	4.4	5.0	5.2
Measured	22.9	36.0			
1σ experimental	1.8	2.3			
Extrapolated			48.4	52.6	56.2

Cosmogenic ^{11}C production and sensitivity of organic scintillator detectors to pep and CNO neutrinos
C. Galbiatti et al, Phys. Rev. C 71 (2005) 055805

Results underground

✦ Measurements and estimates of production yields

- Analysis of KamLAND data (from 2002 to 2007)
  - Isotopes identified by their decay time relative to their creation and by their decay energy.
  - Isotopes quantified by fitting the $\Delta T = t - t_\mu$ distributions to exponential decays
- FLUKA simulation of monoenergetic muons (10-350 GeV range) on KamLAND liquid scintillator

Muon beam experiment at CERN scaled to KamLAND depth by extrapolation (assuming a power law of the muon energy)

	Lifetime in KamLAND LS	Radiation energy (MeV)	Yield ($\times 10^{-7} \mu^{-1}$ g^{-1} cm^2)		
			Ref. [10]	FLUKA calc.	This measurement
n	207.5 μs	2.225 (capt. γ)	–	2097 ± 13	2787 ± 311
^{12}B	29.1 ms	13.4 (β^-)	–	27.8 ± 1.9	42.9 ± 3.3
^{12}N	15.9 ms	17.3 (β^+)	–	0.77 ± 0.08	1.8 ± 0.4
^{8}Li	1.21 s	16.0 ($\beta^-\alpha$)	1.9 ± 0.8	21.1 ± 1.4	12.2 ± 2.6
^{8}B	1.11 s	18.0 ($\beta^+\alpha$)	3.3 ± 1.0	5.77 ± 0.42	8.4 ± 2.4
^{9}C	182.5 ms	16.5 (β^+)	2.3 ± 0.9	1.35 ± 0.12	3.0 ± 1.2
^{8}He	171.7 ms	10.7 ($\beta^-\gamma n$)	1.0 ± 0.3	0.32 ± 0.05	0.7 ± 0.4
^{9}Li	257.2 ms	13.6 ($\beta^-\gamma n$)		3.16 ± 0.25	2.2 ± 0.2
^{11}C	29.4 min	1.98 (β^+)	421 ± 68	416 ± 27	866 ± 153
^{10}C	27.8 s	3.65 ($\beta^+\gamma$)	54 ± 12	19.1 ± 1.3	16.5 ± 1.9
^{11}Be	19.9 s	11.5 (β^-)	<1.1	0.84 ± 0.09	1.1 ± 0.2
^{6}He	1.16 s	3.51 (β^-)	7.5 ± 1.5	12.08 ± 0.83	–
^{7}Be	76.9 day	0.478 (EC γ)	107 ± 21	105.3 ± 6.9	–

Production of radioactive isotopes through cosmic muon spallation in KamLAND
S. Abe et al, Phys. Rev. C 81 (2010) 025807

Results underground

✦ Estimates of production rates

- Isotopes produced in **enriched Ge** detectors and set-up materials (**cryogenic liquid**) for GERDA experiment
- GEANT4 MC simulation from muon spectrum at Gran Sasso

	Nitrogen		Argon	
	nuclei/(kg y)	counts/(kg keV y)	nuclei/(kg y)	counts/(kg keV y)
Isotopes produced in crystals				
^{74}Ga/^{75}Ga/^{76}Ga	<0.08	$<3 \times 10^{-5}$	<0.1	$<4 \times 10^{-5}$
^{68}Ge	0.07 ± 0.03	$(4 \pm 2) \times 10^{-6}$	0.08 ± 0.03	$(5 \pm 2) \times 10^{-6}$
^{69}Ge	0.38 ± 0.08	$(1.0 \pm 0.2) \times 10^{-6}$	1.8 ± 0.2	$(5.0 \pm 0.6) \times 10^{-6}$
^{77}Ge/^{77m}Ge	0.05 ± 0.03	$(1.0 \pm 0.6) \times 10^{-5}$	0.51 ± 0.09	$(1.1 \pm 0.2) \times 10^{-4}$
Isotopes produced in cryogenic liquid				
^{38}Cl	–	–	46 ± 1 nucl/day	$(3.3 \pm 0.1) \times 10^{-5}$
^{40}Cl	–	–	2.7 ± 0.1 nucl/day	$(4.0 \pm 0.2) \times 10^{-6}$

The background index is calculated for phase II. It does *not* take into account the additional rejection from the segment anticoincidence and from other tools (e.g. delayed coincidences). Isotopes giving a background index below 10^{-6} counts/(kg keV y) are not reported. Only statistical errors are quoted. Upper limits are quoted at 90% CL. Systematic uncertainties are discussed in the text.

Monte Carlo Evaluation of the muon-induced background in the GERDA double beta decay experiment
L. Pandola et al, NIMA 570 (2007) 149-158

Summary

Cosmogenic activation of materials can jeopardize the sensitivity of ultra-low background experiments

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

Direct **measurements** and **estimates** of **production rates** and yields for several materials have been made in the context of, for instance, double beta decay and neutrino experiments

The main sources of uncertainty in the calculations come from difficulties on

- precise evaluation of inclusive **production cross-sections**
- accurate description of **cosmic ray spectra**