Cosmogenic production of tritium in dark matter detectors

- Motivation
- Calculations
- Results: Ge, NaI, Ar, Ne
- Summary

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RENATA thematic meeting on Dark Matter @ LSC

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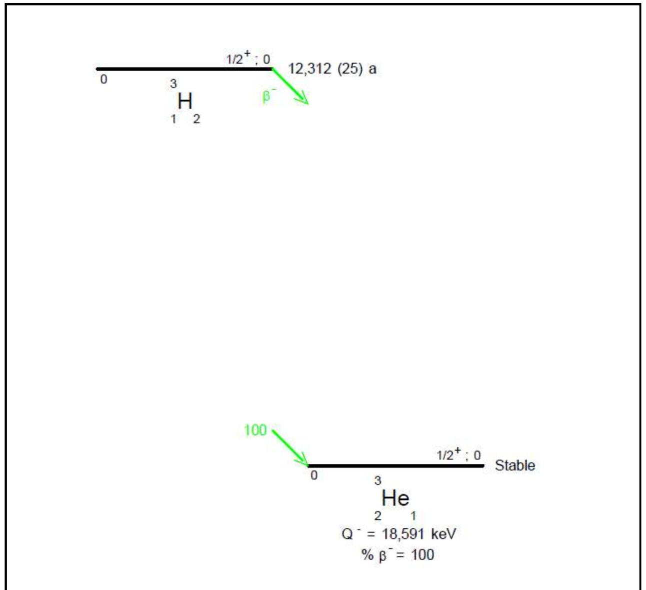
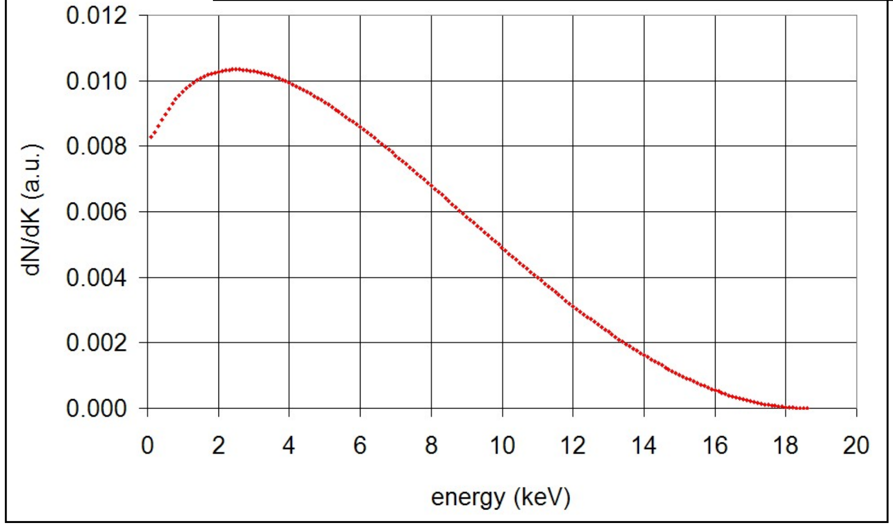
Motivation

- **Ultra-low background** conditions are a must in dark matter direct detection.
- Long-lived **radioactive impurities** in the materials of the set-up induced by the exposure to **cosmic rays** at sea level may become very problematic.
- **Tritium** can be a very relevant background in the detector medium of dark matter experiments due to its decay properties.



Pure β^- emitter 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.



Motivation

- **Quantification** of tritium cosmogenic production is not straightforward, neither **experimentally** (beta emissions are hard to disentangle from other background contributions) nor by **calculations** (it can be produced by different reaction channels).

  − In **Ge:** recently identified and production quantified in EDELWEISS, MAJORANA and CDMSlite detectors.

  Highlighted as one of the relevant background sources in future experiments like SuperCDMS.

  E. Armengaud et al., Measurement of the cosmogenic activation of germanium detectors in EDELWEISS-III, Astropart. Phys. 91 (2017) 51–64.

  R. Agnese et al., Projected sensitivity of the SuperCDMS SNOLAB experiment, Phys. Rev. D 95 (2017) 082002.

  − In **NaI:** hints of tritium in ANAIS detectors.

  J. Amaré et al., Assessment of backgrounds of the ANAIS experiment for dark matter direct detection, Eur. Phys. J. C 76 (2016) 429.

The *aim of this work* has been to find a reliable **method** to quantify the **production rate of tritium** in several **detector media** used in WIMP direct detection.

– **Production cross sections** have been selected over the entire relevant energy range of **cosmic nucleons.**
– Calculations have been compared with available data.

Calculations

- **Induced activity *A*** and **production rate *R*** of an isotope

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

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

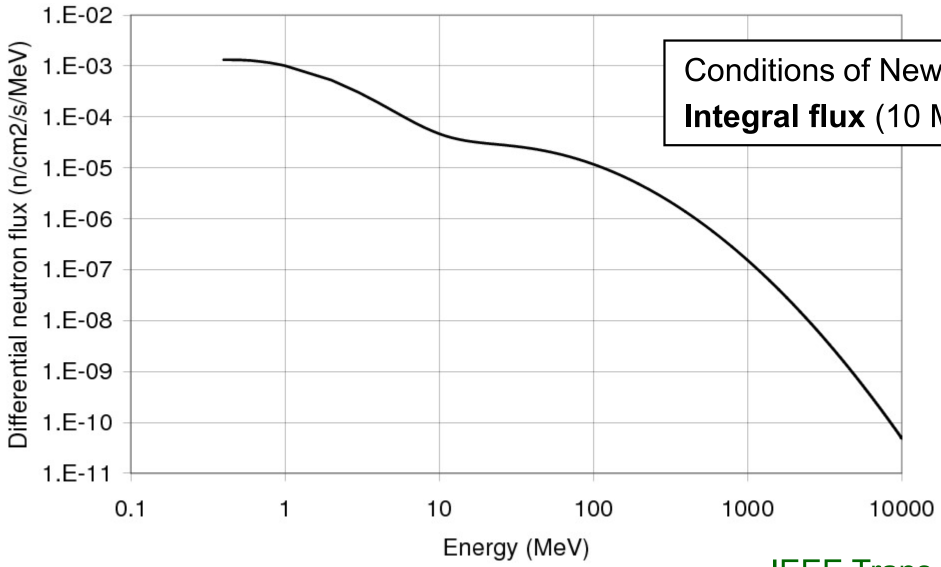
t_{exp} = exposure time
t_{cool} = cooling time underground

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

- **Flux of cosmic rays**

At the Earth's surface nuclide production is dominated by **neutrons** because of the absorption of charged particles in the atmosphere.

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



Conditions of New York City at sea level
Integral flux (10 MeV-10 GeV): 3.6×10^{-3} cm^{-2} s^{-1}

M.S. Gordon et al,
IEEE Trans. Nucl. Sci. 51 (2004) 3427–3434 .

Calculations

- **Production cross sections**

1. Collect information from different sources of data, taken into account both measurements and calculations using computational codes.

   Considered targets: ^{nat}Ge, ^{enr}Ge, Na, I, Ar, Ne

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

   EXFOR database: **experimental data** from irradiation experiments.

   Only one experimental point for Ar, Na and Ne at 22.5 MeV.

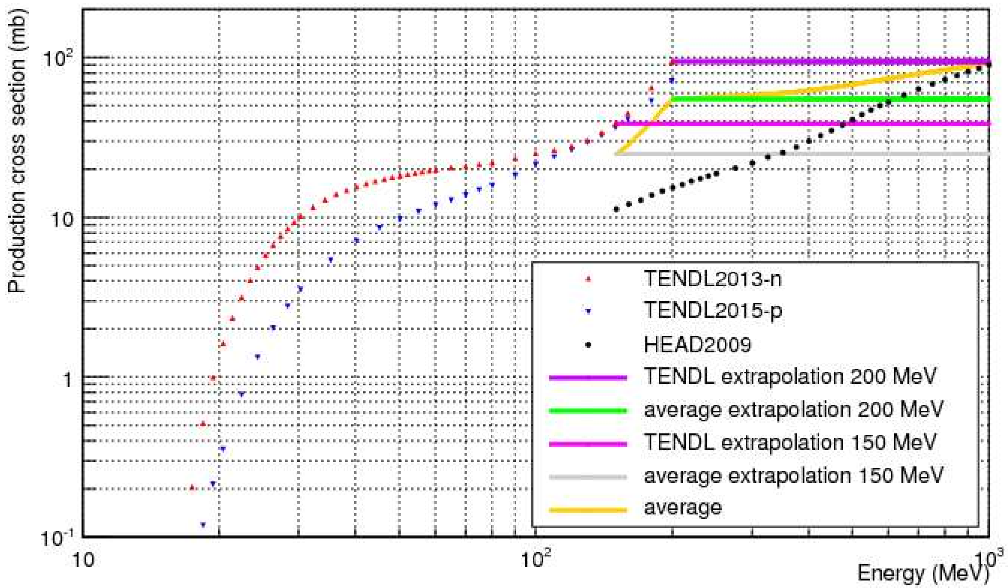
   TENDL (TALYS-based Evaluated Nuclear Data Library):

   - Using the TALYS nuclear model code system.
   - For **neutrons and protons up to 200 MeV.**

   HEAD-2009 (High Energy Activation Data) library:

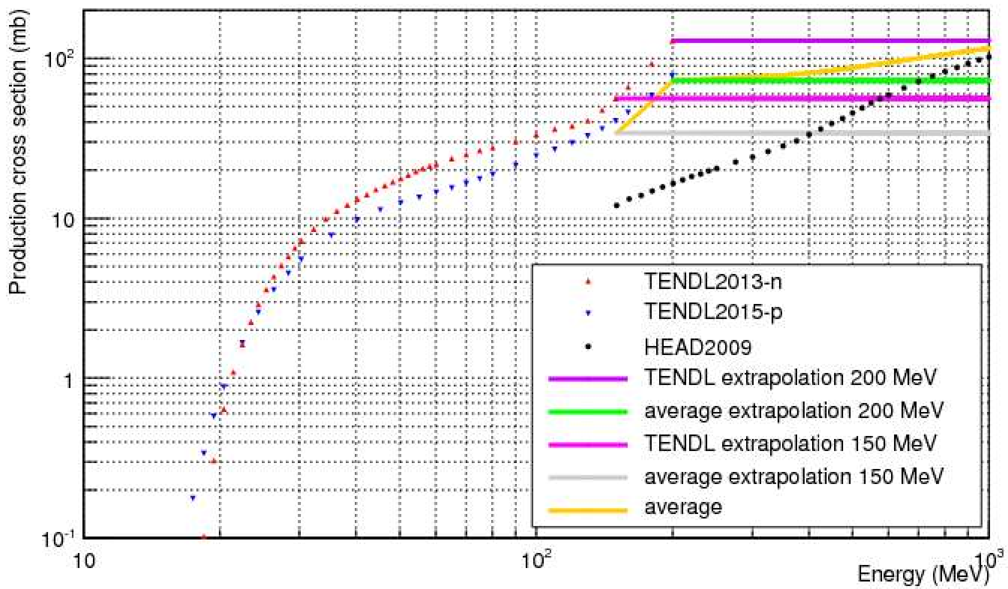
   - Using a selection of models and codes (CEM, CASCADE/INPE, MCNP, ...) dictated by an extensive comparison with EXFOR data.
   - For **protons from 150 MeV to 1 GeV.**
   - Only for Z≥12.

Calculations



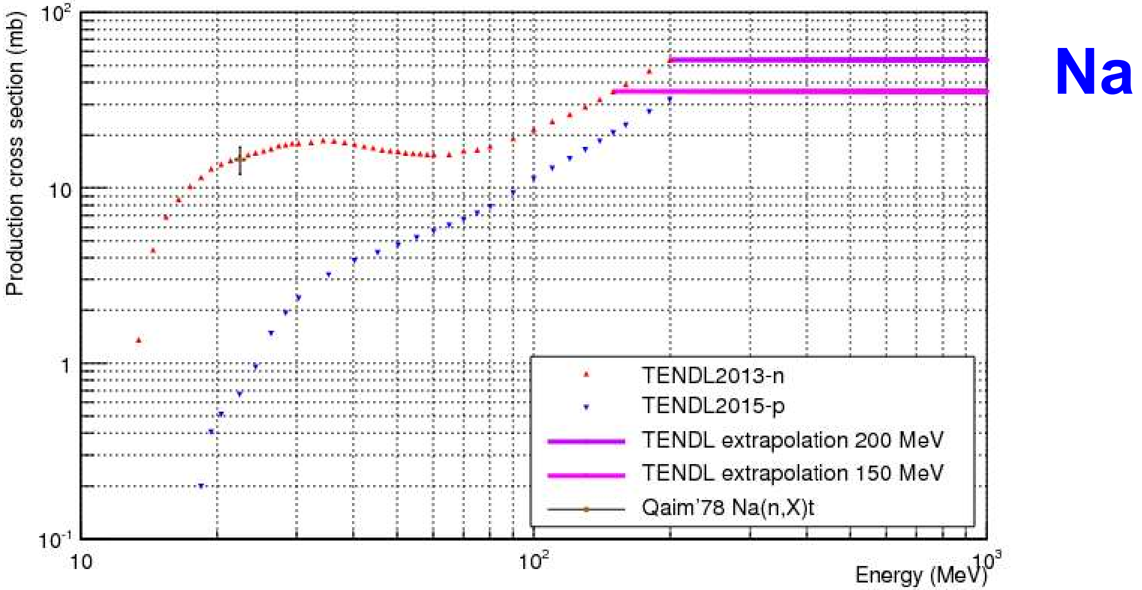
^{nat}Ge

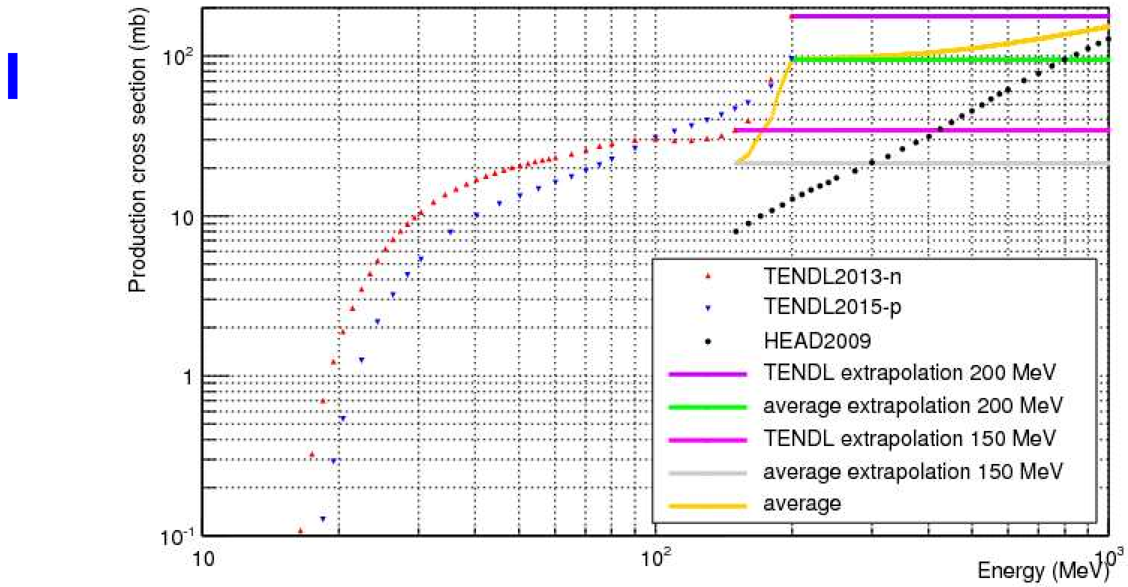
^{enr}Ge



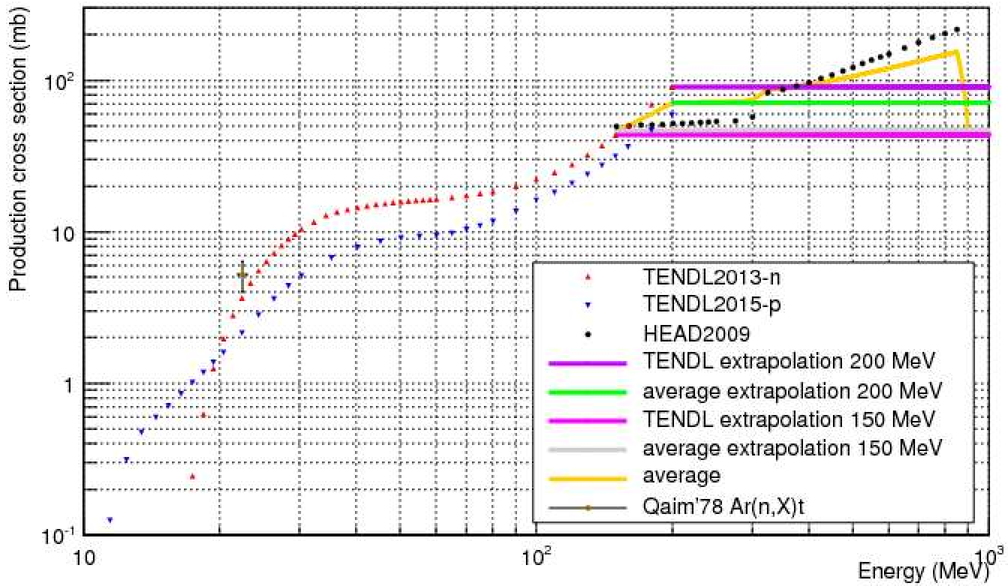
Important mismatch between excitation functions from the two different libraries available at low and high energies
→ the whole process of calculating the production rate made twice, considering the cut between low and high energy either at 150 or at 200 MeV.

Calculations





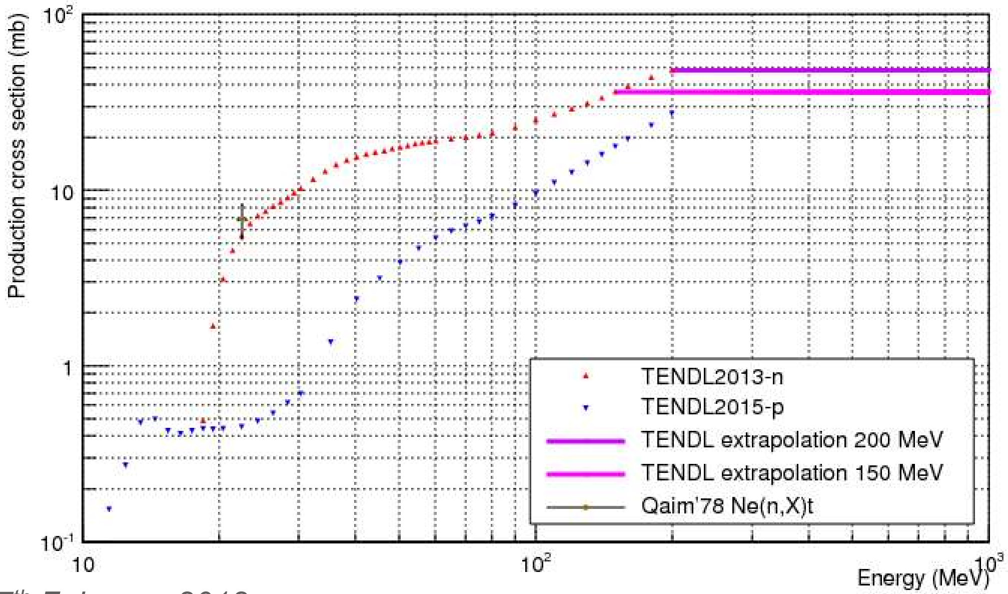
Calculations



Ar

- TENDL data for neutrons reproduce well all the three measurements.
- No experimental data to validate the cross section selection at high energy.
- Above 1 GeV, a constant production cross-section from the last available energy has been assumed.

Ne



Results

- **Production rates** derived for different conditions

  LE (below 150/200 MeV): TENDL data.

  HE: 1) **HEAD-2009** cross sections, if available.

  2) **TENDL extrapolation:** the available highest energy cross-section from TENDL considered as a constant value at higher energies.

  3) **Average extrapolation:** the average between the available highest energy cross-section from TENDL and the corresponding results from HEAD-2009 considered also as a constant value at higher energies.

  4) **Average:** the average at each energy between TENDL data (and its extrapolation) and HEAD-2009 cross sections taken into consideration.

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

(kg^{-1} d^{-1})	^{nat}Ge	^{enr}Ge	Na	I	Ar	Ne
LE TENDL	28.2/40.7	31.6/48.8	14.3/18.7	15.4/22.9	47.7/71.8	101.5/133.1
HE (1)	26.6/23.9	28.5/25.6		14.6/13.6	111.5/92.3	
HE (2)	32.8/60.5	45.8/79.5	14.6/16.6	8.7/55.2	67.4/105.4	110.6/111.5
HE (3)	21.2/35.2	27.8/44.8		14.2/29.6	71.9/82.9	
HE (4)	49.8/42.2	62.6/52.6		38.6/34.4	120.5/98.9	
total (1)	54.8/64.6	60.1/74.5		30.0/36.5	159.3/164.1	
total (2)	61.0/101.3	77.4/128.3	28.8/35.2	29.6/78.1	115.1/177.2	212.1/244.6
total (3)	49.4/75.9	59.4/93.6		24.1/52.5	119.7/154.7	
total (4)	78.0/83.0	94.2/101.4		54.0/57.3	168.2/170.7	
estimated rate	75 ± 26	94 ± 34	32.0 ± 3.2	51 ± 27	146 ± 31	228 ± 16

The maximum and minimum rates define an interval, whose central value and half width are considered as the final results and their uncertainties

NaI: (83 ± 27) kg^{-1} d^{-1}

Results

- **Comparison** with available production rates from the literature:

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				27.3		108.7			125 (Ref. 52)
TeO_2			43.7						
NaI		83 ± 27	31.1	42.9		36.2		26 (Ref. 90)	
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								46 (Ref. 90)	
C_2H_6				279.5					

TALYS code: excitation functions from simulation of nuclear reactions below 200 MeV.

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

GEANT4: Shielding physics list for electromagnetic and hadronic processes.

ACTIVIA calculations: based on semiempirical formulae for cross sections.

37. C. Zhang *et al.*, *Astropart. Phys.* **84**, 62 (2016).
36. W.Z. Wei *et al.*, *Astropart. Phys.* **96**, 24 (2017).

Results: Ge

- First **measurements** of production rates:

Target	Ref. 55	TENDL+HEAD[71]	TALYS[59]	GEANT4[37]	GEANT4[36]	ACTIVIA[37]	ACTIVIA[36]	ACTIVIA	Others
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Ar		146 ± 31	44.4						
Ne		228 ± 16							
Xe			16.0						
Quartz									
C_2H_6				[illegible]					

The range derived in this work is well compatible with the measured rates by EDELWEISS and CDMSlite.

According to measured rates, production is higher in enriched than in natural Ge.

55. F. T. Avignone *et al.*, *Nucl. Phys. B* (*Proc. Suppl.*) **28**, 280 (1992).

65. E. Armengaud *et al.*, *Astropart. Phys.* **91**, 51 (2017).

EDELWEISS: long measurement, many Ge detectors

66. B. White *et al.*, Presentation at *Low Radioactivity Techniques 2017 Workshop*, Seoul, Korea, http://indico.ibs.re.kr/event/46/session/7/contribution/13.

MAJORANA

70. E. Fascione and W. Rau, Cosmogenic background in CDMSlite, *Poster at the XV Int. Conf. on Topics in Astroparticle and Underground Physics* (*TAUP 2017*), Sudbury, Canada, https://indico.cern.ch/event/606690/contributions/2591554/.

CDMSlite

Results: NaI

- Only calculations of production rates:

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)
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Ar		146 ± 31	44.4						
Ne		228 ± 16							
Xe			16.0						
Quartz								46 (Ref. 90)	
C_2H_6				279.5					

The range derived in this work gives higher values than those of the other estimates.

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

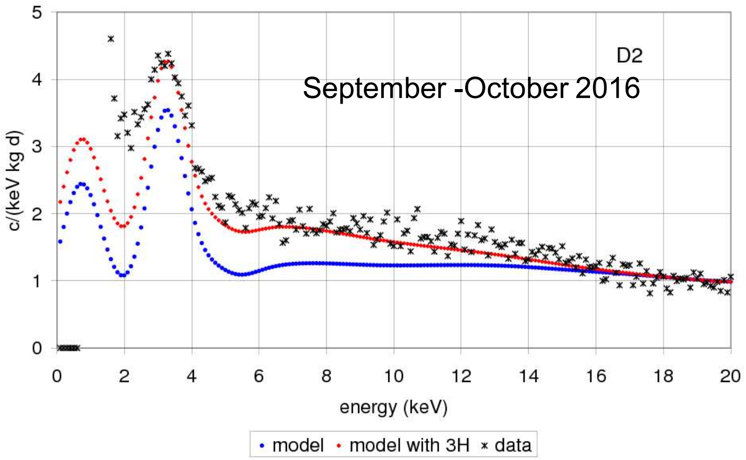
37. C. Zhang *et al.*, *Astropart. Phys.* **84**, 62 (2016).

90. W. C. Pettus, Cosmogenic activation in NaI detectors for dark matter searches, Ph.D. thesis, University of Wisconsin-Madison, 2015.

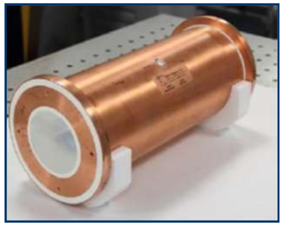
DMIce

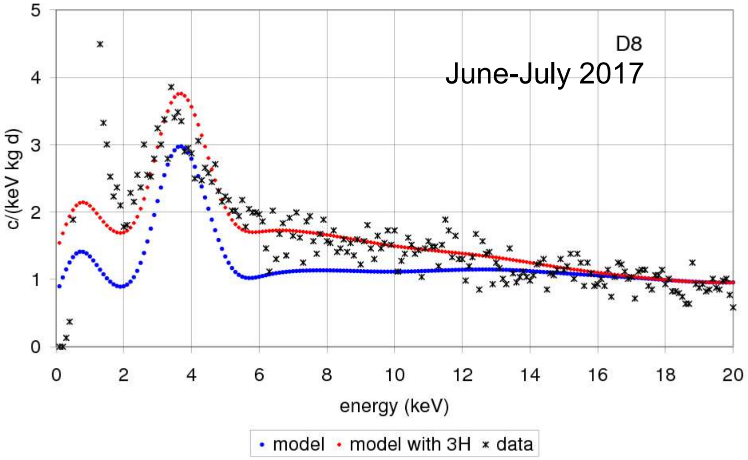
Results: NaI

- Only calculations of production rates, but hints of presence of ^3H in ANAIS detectors:

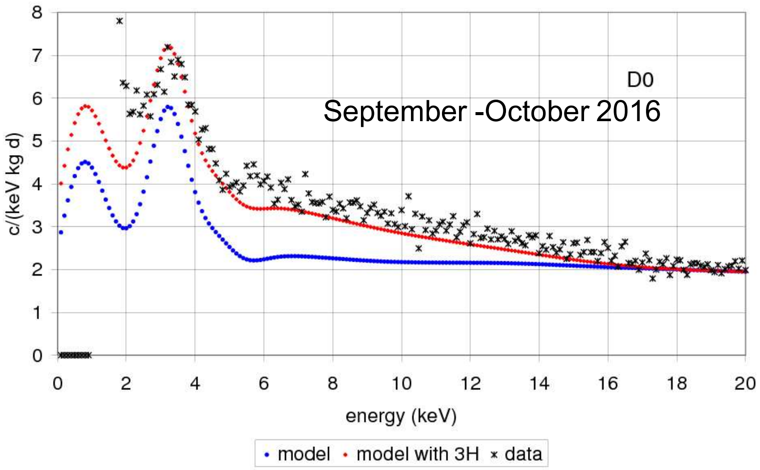


Detailed **background models** (based on simulation of quantified components) point to the need of an additional background source contributing only in the very low energy region, which could be tritium.





D0: 0.20 mBq/kg
D2,D8: 0.09 mBq/kg (upper limit set by DAMA/LIBRA)



- No attempt to derive production rates, as the exposure history is not precisely known.
- *Cross-check:* the required **exposure times** to get the deduced activities from the estimated rate roughly agree with time between material purification and shipment: 0.8-1.6 y for D0, 4.2-8.4 months for D2.

Results: Ar, Ne

- Only calculations for Ar and no information for Ne:

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

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

Effect on the TREX-DM experiment:

- For these rates, if saturation activity was reached, tritium would dominate the background rate.
- However, tritium is expected to be suppressed by **purification** of gas and minimizing exposure to cosmic rays of the purified gas should avoid any problematic tritium activation.

Summary

- ✓ **Cosmogenic production of tritium** has been studied for several detector media (**Ge, NaI, Ar** and **Ne**) as it may be dangerous for **dark matter** experiments.
- ✓ **Production rates at sea level** have been calculated from a common parametrization of the neutron spectrum and a selection of production cross sections:
  - From TENDL-2013 library for neutrons <200 MeV, in agreement with the scarce experimental data.
  - At higher energies production cannot be neglected and has been estimated from HEAD-2009 library data and extrapolating available cross sections.
  - Uncertainties in the excitation functions are very important and have been taken into account.
- ✓ Production rates estimated in this work are in general higher than previous calculations and, if saturation was reached, would produce background levels of ~10 c/keV/kg/d.
- ✓ The acceptable agreement of calculated production rates with available experimental results can be considered as a validation of the method.
  - For **Ge**, it is in very good agreement with the measured rate by EDELWEISS and CDMSlite.
  - For **NaI**, it can produce the observed possible tritium activity in ANAIS detectors in reasonable exposure times.

J. Amaré et al., Cosmogenic production of tritium in dark matter detectors, Astropart. Phys. 97 (2018) 96-105