Update on FLUKA

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Assay and Acquisition of Radiopure Materials Collaboration Meeting
SLAC, March 4th 2013

Overview

- FLUKA
- The FLUKA international collaboration
- The FLUKA code design
- Some important developments
- Spin-parity in Fermi Break-up
- Muon-induced neutron background
- Muon interactions in FLUKA
- Photonuclear interactions
- Muon-photonuclear interactions
- 11-C production
- Comments on measurement accuracy
- Comments on simulation accuracy
- Cosmogenic isotope production
- Electron activation benchmarks
- CONCLUSIONS

FLUKA

http://www.fluka.org

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>5000 users

Developed and maintained under an INFN-CERN agreement

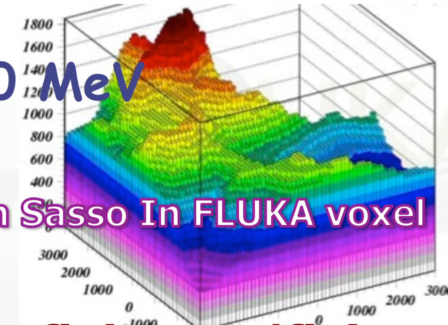
FLUKA is a general purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications:

Proton and electron accelerator shielding, Target design, Calorimetry, Activation, Dosimetry, Detector design, Accelerator Driven Systems, Cosmic rays, neutrino physics, radiotherapy, etc.

At SLAC widely used by radiation physics for LCLS, LCLS-II, etc.

FLUKA

- 60 different particles + Heavy Ions
  - h-h and h-N interactions from Coulomb barrier up to 10000 TeV/n
  - Electron and μ interactions 1 keV – 10000 TeV
  - Photon interactions 100 eV - 10000 TeV
  - Optical photons
  - Neutrino interactions
  - Charged particle transport including all relevant processes
  - Transport in magnetic fields
  - Neutron multigroup transport and interactions 0 – 20 MeV
  - Analog calculations, or with variance reduction
  - On-line evolution of radioactivity and dose
  - Combinatorial (Boolean) and Voxel geometries



- FLAIR advanced graphical interphase http://www.fluka.org/flair
  - front-end interface: edit and validate input file
  - interactive geometry editor and debugger – overlay cad designs
  - compile, run, monitor execution status and post-process output files
  - geometry and histogram plot generation including 3D photo-realistic
  - library of materials and geometrical objects
  - I/E to various formats (Dicom, mcnp, povray, dxf, bitmap)

The FLUKA international collaboration

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The FLUKA Code design

- Sound and updated physics models
  - Based, as far as possible, on original and well-tested microscopic models
  - Optimized by comparing with experimental data at single interaction level: ***"theory driven, benchmarked with data"***
  - Final predictions obtained with minimal free parameters fixed for all energies, targets and projectiles
  - Basic conservation laws fulfilled "a priori"

  → ***Results in complex cases, as well as properties and scaling laws***, arise naturally from the underlying physical models

  → ***Predictivity where no experimental data are directly available***

FLUKA is a "condensed history" MC code, however with the possibility to use single instead of multiple scattering

The FLUKA Code design

- Self-consistency
  - Full cross-talk between all components: hadronic, electromagnetic, neutrons, muons, heavy ions
  - Effort to achieve the same level of accuracy:
    - for each component
    - for all energies
  - → Correlations fully preserved within interactions and among shower components
  - → ***FLUKA is NOT a toolkit, its physical models are fully integrated***

Only **total** hadronic cross sections are used explicitly, to sample the next interaction point.

Partial cross sections are never explicitly available, but are an implicit by-product of the models.

Some important developments

- Inclusion of CR tools: atmospheric and geomagnetic models
- New treatment of the fragmentation of low mass quark chains:
  - *neutrino* interactions in the 0.5-5 GeV range
  - h-N particle production predictions in the 5-50 GeV range
- Alpha decays now simulated
- Low energy ion-ion interactions are built-in for current FLUKA version (by default) – BME
- Improvements in BME
  - Initial extension of BME to 3-H and 3-He induced reactions (E < 150 MeV/A)
  - Alpha-induced reactions (α,xn) at low energies
- Improvements in PEANUT for (p,d) and (n,d) reactions → strong improvement in the prediction of the excitation curves for 11-C and 15-O production at low energies
- Spin-parity in Fermi break-up

Some important developments

- Improvements in the AA reaction cross sections
- Major improvements in the (prompt) photon emission modeling:
  - Extended database of known levels and transitions taken from RIPL-3 (IAEA)
  - Discrete level treatment extended to evaporation stage
  - Account for discrete levels in BME (to be extended to rQMD and DPMJET)
  - Photon angular distribution according to multipolarity and spin
  - Special effort for 0→0 transitions
- The Landau-Pomeranchuk-Migdal (LPM) effect is added to pair production (was already in bremsstrahlung)
- Radiation damage to materials as NIEL and as DPA
- Reworked treatment of specific energy losses: Z3, Z4, Mott
- …and more…

Spin-parity in Fermi Break-up

In FLUKA, for $A \leq 16$, evaporation is replaced by Fermi break-up.

In cases where spin and parity of the residual nucleus are known, conservation laws, constraints on available configurations and centrifugal barrier (if L=0 is forbidden), are now enforced in the fragment production.

In the GDR region

until now:

$\gamma + {}^{12}C \rightarrow 3\,\alpha$ or $\rightarrow \alpha + {}^{8}Be$, ${}^{8}Be \rightarrow 2\,\alpha$ energetically favored, but impossible in L= 0

1^- 0^+ 0^+

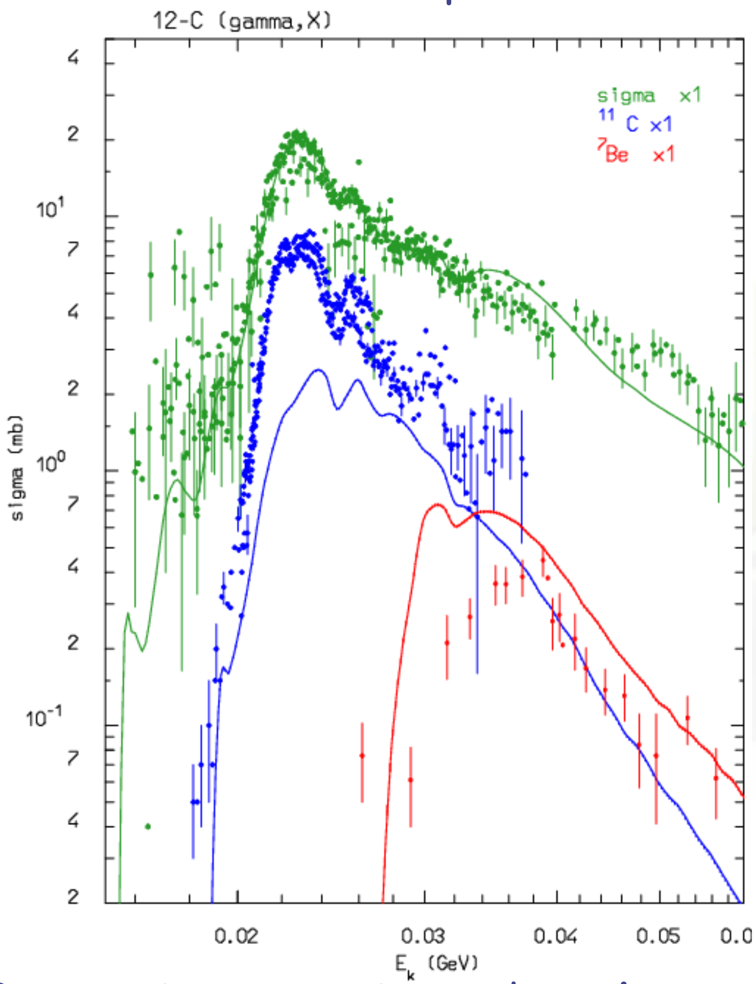
with the latest improvement:

$\gamma + {}^{12}C \rightarrow {}^{11}C + n$ or $\rightarrow {}^{7}Be + \alpha + n$ relative probability higher! (no centrifugal barrier)

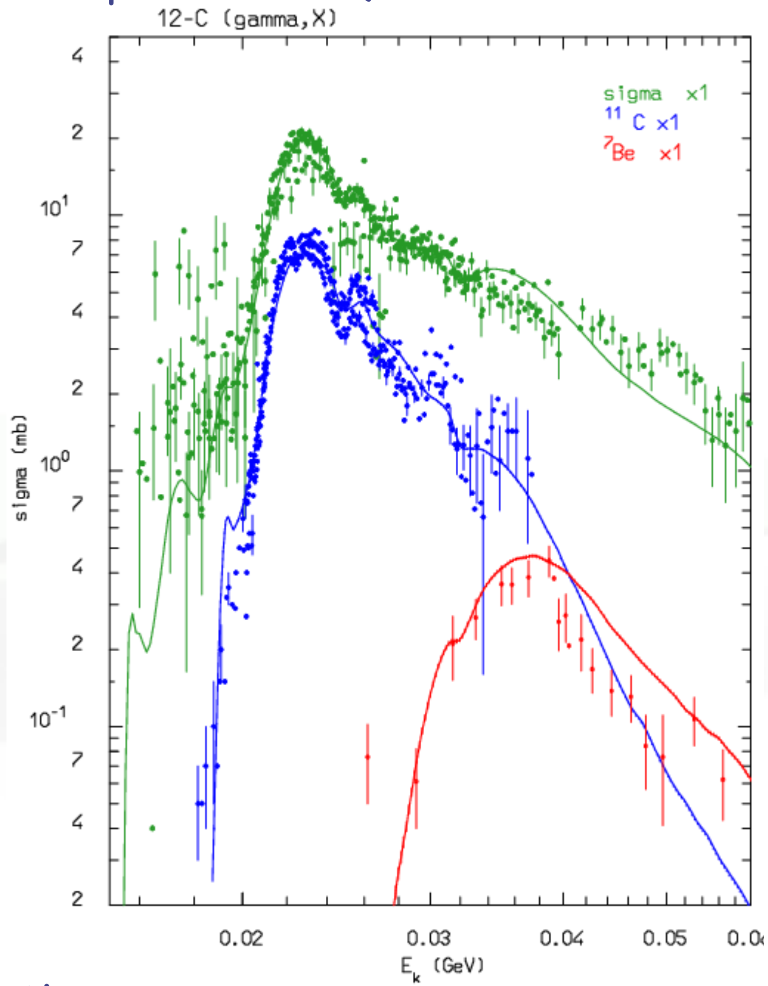
→ Factor 3 on ${}^{11}C$ production, and higher neutron yield

Spin-parity in Fermi Break-up

Before the improvement



Improvement (in the next release)



Green points: experimental **total** cross section
Green line: total cross section used by FLUKA to determine the interaction point

Muon-induced neutron background

Cosmogenic muon-induced neutrons are a serious background to rare physics experiments at underground sites.

Even though their rate is suppressed and small as compared to the radiogenic neutrons from the surrounding rock, they can have large kinetic energies and can not easily be shielded against.

To the direct search experiments for dark matter they are particularly dangerous since undetected neutrons can scatter inside the detector volume and generate recoil signals which can not be distinguished from the signal of a real dark matter interaction.

Special attention is given in literature to isolated high energy muon-induced neutrons far from the original muon track.

It is important to consider full events when evaluating cosmogenic (neutron) backgrounds and not just simulate the neutron component!

Muon interactions in FLUKA

Energy loss:

- continuous dE/dx
- delta-ray production
- bremsstrahlung
- pair production

→ e.m. showers → photonuclear reactions by real photons (GDR, QD, Δ Resonance, VMD)

↓

Direct nuclear interactions:

- virtual photonuclear reactions (VMD only)
- μ^- capture at rest

→ neutron production activation

Not directly related to background:

- decay
- multiple scattering
- motion in magnetic fields

Photonuclear reactions by real photons are the largest contributor to background

From Alberto Fassò, AARM workshop, June 2012

Photonuclear interactions

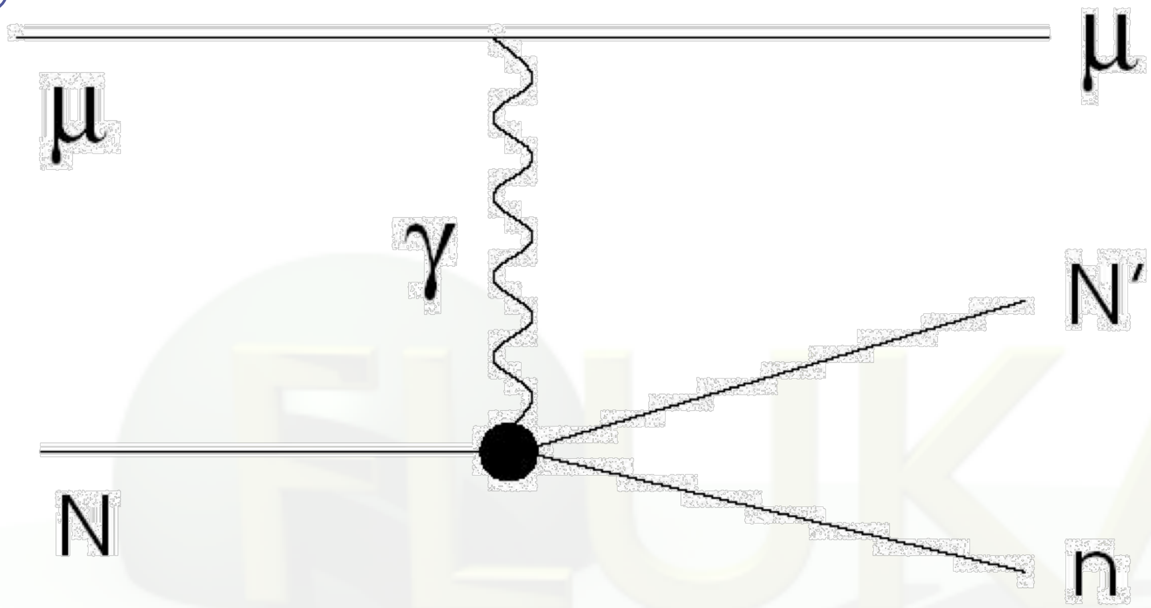
Photon-nucleus interactions in FLUKA are simulated over the whole energy range, through different mechanisms:

- Giant Resonance interaction
- Quasi-Deuteron effect
- Delta Resonance production
- Vector Meson Dominance ($\gamma \equiv \rho, \Phi$ mesons) at high energies

Nuclear effects on the *initial state* (i.e. Fermi motion) and on the *final state* (reinteraction / emission of reaction products) are treated by the FLUKA hadronic interaction model (PEANUT) ➔ INC + pre-equilibrium + evaporation/fission/Fermi breakup

From Alberto Fassò, AARM workshop, June 2012

Muon photonuclear interactions



Schematic view of a hadronic interaction.

The interaction is mediated by a *virtual photon*.

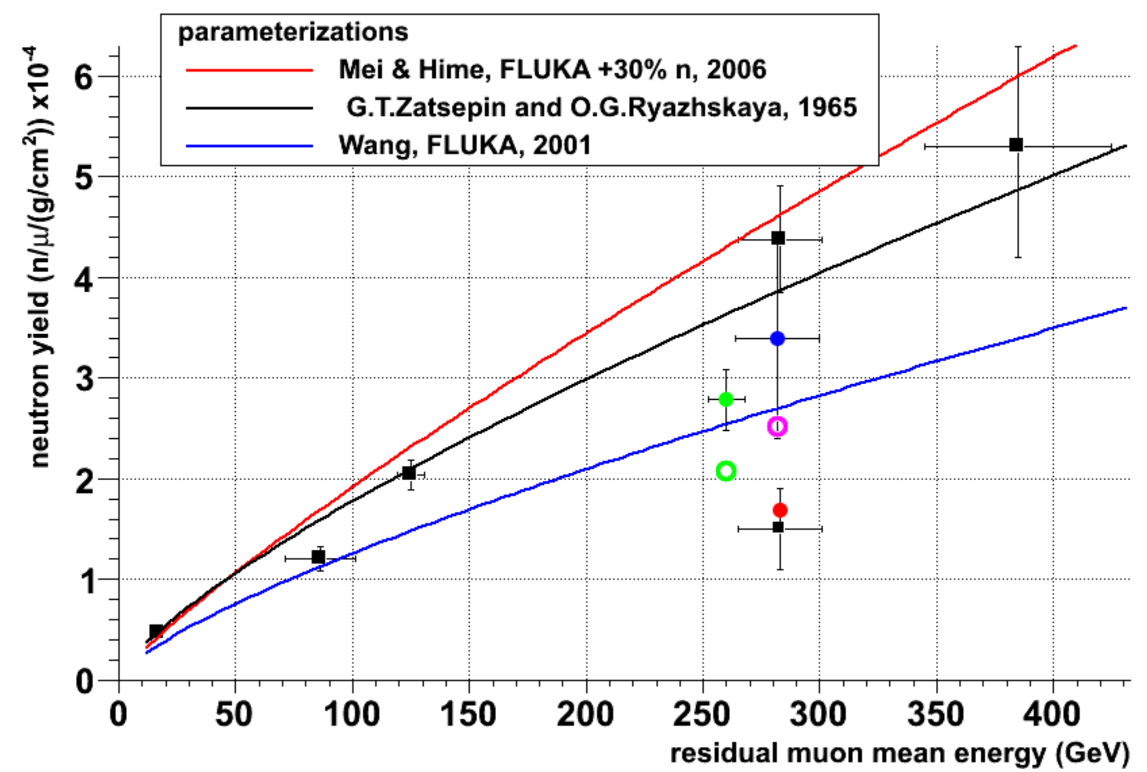
The final state can be more complex

- The cross section can be factorized (following Bezrukov-Bugaev) in virtual photon production and photon-nucleus reaction
- Nuclear screening is taken into account
- Virtual Meson Interactions are modeled, following the FLUKA meson-nucleon interaction models
- Nuclear effects are the same as for hadron-nucleus interactions

From Alberto Fassò, AARM workshop, June 2012

Muon-induced neutron background

blue symbol: new LVD measurement
red symbol: CTF measurement
solid green symbol: KamLAND measurement
open green symbol: KamLAND FLUKA calculation
open purple symbol: new Borexino FLUKA calculation
black symbols Malgin and Ryazhskaya, Yad. Fiz. 71, 1800 (2008), Phys. At. Nuclei 71, 1769 (2008)



11-C production

^{11}C production rate at LNGS liquid scintillator (pseudocumene, ρ=0.88 g/cm^3)

	[cts/day/100t]	date
Na54 (CERN μ-line)	14.55 ± 1.49	2000
CTF (1 m^3 LNGS)	13.0 ± 1.4	2006
KamLAND FLUKA	25.3 ± 4.5 12.2 ± 1.4	2010
Borexino FLUKA	27.4 ± 0.3 15.0 ± 2.2	2012

Early predictions (based on measurements extrapolated to Borexino) are about a **factor of 2 lower** for the production rate of ^{11}C in liquid scintillator at LNGS muon energies.

FLUKA calculations agree with these earlier results.

But recent improvements in FLUKA Fermi-Breakup are likely to increase predictions of ^{11}C and neutron production.

Comments on measurement accuracy

Measurements of neutron production:

Most experimental neutron production data which are regularly reported in various papers (Wang 2001, Araújo 2005, Malgin 2008, Kudryavtsev 2003, Mei and Hime 2006) **come actually from a same set**, which includes also some rather *old* measurements.

In these data there is a number of **unknowns**:

- What is the **energy** of the measured neutrons?
- What **materials** contribute? In general it is assumed that the values refer to *scintillators*, but in some cases the experimental apparatus was in great part made of steel or other *high-Z material*
- To which extent measurements made at an **accelerator** (NA54) or in a different configuration (CTF) can be "**extrapolated**" to the actual experiment?

Taking into account the above uncertainties, and the large spread of values referring to the same experiment (LVD) it looks that **the reported systematic experimental errors are often underestimated.**

Similar and stronger considerations can be made for ^{11}C production, whose measurement often entails intricate analyses.

From Alberto Fassò, AARM workshop, June 2012

Comments on simulation accuracy

A fair comparison of simulated quantities (neutron production, ^{11}C activation) with experimental values requires that:

- The muon source should be the **whole muon spectrum**, not muons of *average* energy. Most effects are *not linear* with energy!
- **Whole events** should be simulated: neutrons are not the only particles which can contribute, especially if a hadronic shower is created (p, $\pi^{\pm}$, secondary neutrons, heavier hadrons)
- The **actual geometry** of the experimental apparatus should be described, including the surrounding rock and the tank of the experiment
- The **actual composition** of the materials should be described (in particular that of the *scintillator*)

Respecting the above rules does not often require much additional time, but can affect the results in a *significant way*. However, many times this doesn't happen!

We can repeat for the simulations what we have said about the measurements:

taking into account the frequent unnecessary approximations, it looks that **the reported systematic simulation errors are often underestimated**.

From Alberto Fassò, AARM workshop, June 2012

Cosmogenic isotope production

Cosmogenic Isotopes rate per day per 100 ton	FLUKA	KamLAND
^{12}N	0.016 ± 0.006	0.053 ± 0.012
^{12}B	0.86 ± 0.06	1.26 ± 0.10
^{8}He	0.009 ± 0.004	0.020 ± 0.012
^{9}Li	0.09 ± 0.02	0.064 ± 0.006
^{8}B	0.20 ± 0.02	0.25 ± 0.07
^{6}He	0.52 ± 0.04	not reported
^{8}Li	0.86 ± 0.03	0.36 ± 0.08
^{9}C	0.027 ± 0.003	0.088 ± 0.035
^{11}Be	0.018 ± 0.004	0.032 ± 0.006
^{10}C	0.42 ± 0.03	0.48 ± 0.06
^{11}C	14.0 ± 0.7	25.4 ± 4.5

Comparison of production rates between experimental results from KamLAND (arXiv:0907.0066v1) and FLUKA predictions for Borexino. Both are large, unsegmented liquid scintillator detectors at about the same depth: mean muon energy for Kamioka site 260 GeV and about 283 GeV for LNGS. KamLAND results were scaled for the muon flux at LNGS and the Borexino scintillator.

Activation experiment at PAL

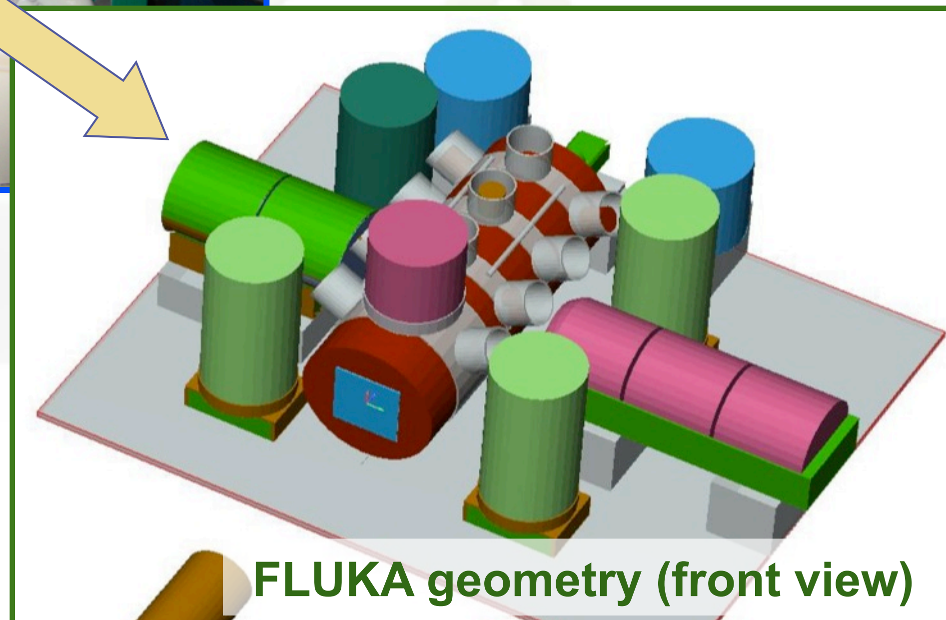

Dump and samples (rear view)

Irradiation at PAL with **2.5 GeV e^-**

Well measured initial compositions

Gamma spectroscopy and Liquid Scintillation Counter

Samples included metals, and shielding or environmental materials, including concrete, soil and water


FLUKA geometry (front view)

3D - rendering performed with SimpleGEO

3-H prediction in LCW

- The current experiment confirms the underestimation of ^3H production in water by ~50%
- FLUKA simulations to be repeated with latest version

Experiment	Measurements → Conditions ↓	FLUKA / $SLAC_{LSC}$	FLUKA / $CERN_{LSC}$	FLUKA / EBERLINE
2007 - T489 SLAC & CERN	28 GeV	0.50	0.46 (4.5%)	0.49 (4.5%)
Experiment	Measurements → Conditions ↓	FLUKA / $Busan_{LSC}$ t_c = 28 d	FLUKA / $SLAC_{LSC}$ t_c = 90 d	FLUKA / $SLAC_{LSC}$ t_c = 392 d
2010 - SLAC & PAL	**2.5 GeV**	**0.57 (9%)**	**0.46**	**0.55 (9%)**

M. Santana et Al, Publication pending with latest FLUKA version

SLAC soil activation (at PAL)

Fairly good agreement (FLUKA.2010) despite some uncertainties in beam intensity, jitter, composition...

			experimental result		FLUKA simulation		FLUKA/experiment	
nuclei	half life	Decay	[Bq/g]	%error	[Bq/g]	%error	average	%error
7Be	53 days	e	0.15	14.21	1.2E-01	0.97	0.8	15.18
22Na	2.6 years	e+b+	5.3E-02	3.16	2.7E-02	0.91	0.51	4.07
46Sc	83.9 days	b-	3.1E-02	6.7	1.2E-02	3.78	0.39	10.47
48V	16 days	e+b+	1.3E-03	26.52	8.3E-04	5.36	0.64	31.88
51Cr	27.8 days	e	2.1E-02	29.8	2.2E-02	4.01	1	33.81
54Mn	303 days	e+b+	8.6E-02	3.04	2.8E-02	1.43	0.32	4.47
56Co	77.3 days	e+b+	2.7E-04	19.4	4.4E-04	18.71	1.6	38.11
57Co	270 days	e	2.3E-03	24.3	3.0E-04	13.06	0.13	37.36
58Co	71.3 days	e+b+	4.0E-03	99.5	1.8E-03	5.5	0.45	105
59Fe	45 days	b-	1.2E-03	34.4	9.8E-04	29.5	0.81	63.9
60Co	5.26 years	b-	2.7E-04	36.7	2.9E-04	24.58	1.1	61.28
72Zn	46.5 hours	b-	3.5E-04	27.2	0.0E+00	0	0	27.2
88Y	107 days	e+b+	1.9E-03	8.35	8.7E-04	11.78	0.47	20.13
88Zr	83.4 days	e	6.5E-04	53.25	7.1E-04	14.5	1.1	67.75
95Nb	35 days	b-	2.2E-03	62.65	1.2E-03	5.59	0.53	68.24
TOTAL			**3.6E-01**	**11.6**	**2.2E-01**	**1.9**	**0.61**	**13.5**

0.8=<F/E=<1.2 **0.4=<F/E<0.8 1.2<F/E=<1.6** **0.2=<F/E<0.4** **F/E<0.2**

M. Santana et Al, Publication pending with latest FLUKA version

CERN metal activation (at PAL)

- **Lateral samples** t_{cool1}: 10d-13d t_{cool2}: 114d-149d

Isotope	$t_{1/2}$	FLUKA / Measurement	t_{cool}	sample
^{56}Co	77.3d	$1.2 \pm 9.8\%$	2	Cu4T
^{56}Co		$1.3 \pm 11\%$	1	Cu5T
^{56}Co		$1.5 \pm 14\%$	1	Cu8T
^{56}Co		$1.1 \pm 15\%$	1	Cu7L
^{56}Co		$1.3 \pm 15\%$	1	Cu10R
^{57}Co	271.79d	$0.72 \pm 12\%$	2	Cu4T
^{57}Co		$0.87 \pm 12\%$	2	Cu5T
^{57}Co		$1.0 \pm 13\%$	2	Cu8T
^{57}Co		$1.1 \pm 14\%$	2	Cu7L
^{57}Co		$1.0 \pm 13\%$	2	Cu10R
^{58}Co	70.82d	$0.69 \pm 9.0\%$	1	Cu4T
^{58}Co		$0.96 \pm 9.1\%$	1	Cu5T
^{58}Co		$1.3 \pm 9.4\%$	1	Cu8T
^{58}Co		$1.3 \pm 9.4\%$	1	Cu7L
^{58}Co		$1.3 \pm 9.6\%$	1	Cu10R
^{60}Co	5.27y	$0.38 \pm 7.4\%$	2	Cu4T
^{60}Co		$0.38 \pm 7.8\%$	2	Cu5T
^{60}Co		$0.45 \pm 9.2\%$	2	Cu8T
^{60}Co		$0.44 \pm 9.4\%$	2	Cu7L
^{60}Co		$0.44 \pm 9.4\%$	2	Cu10R
^{65}Zn	244.26d	$0.39 \pm 34\%$	2	Cu4T
^{65}Zn		$0.35 \pm 53\%$	2	Cu5T
^{65}Zn		$0.45 \pm 62\%$	2	Cu8T

- **Downstream Al sample**

Isotope	$t_{1/2}$	FLUKA / Measurement	t_{cool}
^{22}Na	2.6y	$1.1 \pm 8.6\%$	2
^{46}Sc	83.8d	$0.54 \pm 29\%$	1
^{48}V	16.0d	$1.1 \pm 32\%$	1
^{51}Cr	27.7d	$0.34 \pm 15\%$	1
^{52}Mn	5.6d	$1.7 \pm 21\%$	1
^{54}Mn	312.1d	$1.1 \pm 8.8\%$	2
^{57}Co	271.79d	$4.0 \pm 26\%$	2
^{58}Co	70.82d	$3.0 \pm 51\%$	1
^{65}Zn	244.26d	$3.3 \pm 27\%$	2

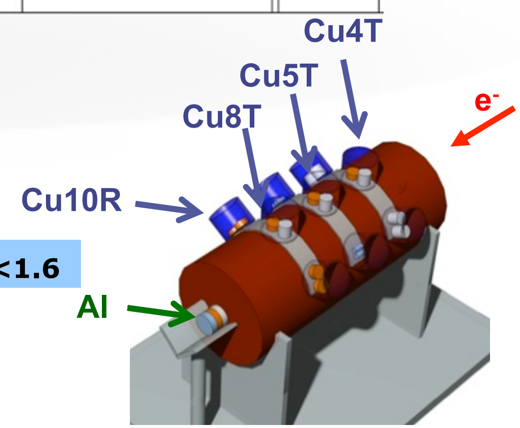
t_{cool1}: 18d 8h
t_{cool2}: 115d 15h

0.8=<F/E=<1.2

0.4=<F/E<0.8 1.2<F/E=<1.6

0.2=<F/E<0.4

F/E<0.2



Stefan Roesler et Al, *Activation benchmark study a 2.5 GeV electron accelerator*, To be published at ICRS12 conference proceedings

Conclusions

FLUKA is a widely used *general* purpose tool for calculations of particle transport and interactions with matter, covering an extended range of applications. FLUKA includes physics, tools and libraries for cosmic background studies in deep underground experiments.

Neutrons from 11C production in *liquid scintillator* at deep underground sites account for about 1/3 of the neutron yield. FLUKA predictions *underestimate* recent 11C measurements by little less than a factor of 2. This discrepancy impacts only low energy neutrons ($\leq$10 MeV).

New physics implemented in FLUKA are expected to increase both the estimate of neutron production in a scintillator and the production of 11C

Systematic electron activation experiments also show that isotope production predictions are typically within a factor two of measured data.

Are reported neutron yields a measure of the systematic uncertainties present in experimental results?

The End

FLUKA: the BME Model for nucleus – nucleus interactions below 150 MeV/n

The BME (Boltzmann Master Equation) in FLUKA

It works for $A_{proj}, A_{targ} \geq 4$, $E \leq 150$ MeV/A

1. COMPLETE FUSION

Fragment(s) : pre-equilibrium de-excitation according to the BME theory (where available) or to the PEANUT exciton model

evaporation/fission/fragmentation/ gamma de-excitation, same as for hadron-nucleus interactions

2. PERIPHERAL COLLISION

three body mechanism

with

incomplete fusion

one nucleon break-up and possibly transfer **(at high *b*)**

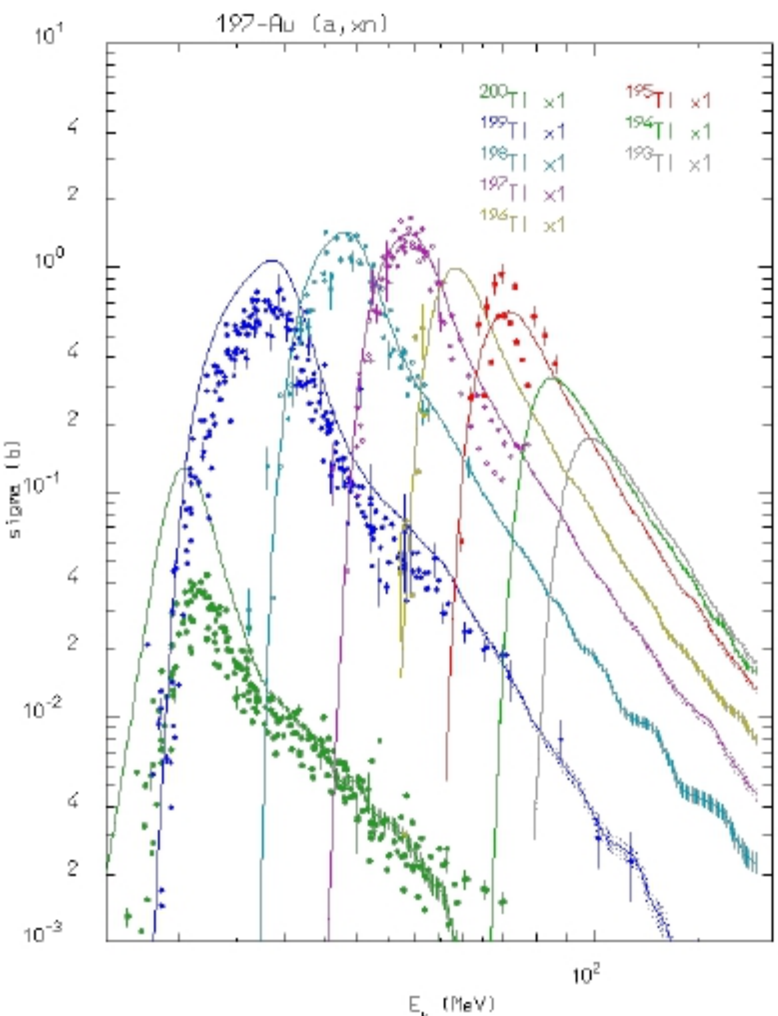
pickup/stripping **(for asymmetric systems at low *b*)**

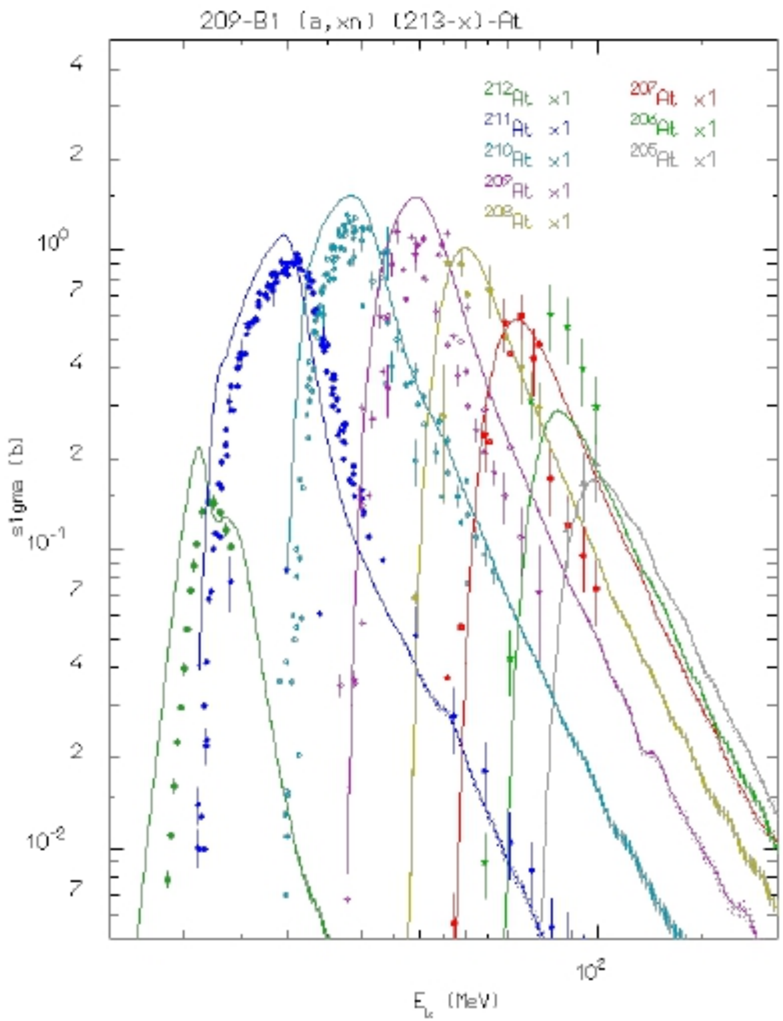
The kinematics is suggested by break-up studies.

BME : E. Gadioli group in Milano

BME in FLUKA: (α,xn) examples

Excitation functions for the production of radioisotopes from α interactions on Au (left) and Pb (right) (Data: CSISRS, NNDC)





Muon capture

Basic weak process: $\mu^- + p \rightarrow \nu_\mu + n$

μ^- at rest + atom → excited muonic atom → x-rays + g.s. muonic atom

Competition between μ decay and μ capture by the nucleus

In FLUKA: Goulard-Primakoff formula

$\Lambda_c \propto Z^4_{eff}$, calculated Z_{eff}, Pauli blocking from fit to data

$\frac{\Lambda_c}{\Lambda_d} = 9.2\times10^{-4}$ for H, 3.1 for Ar, 25.7 for Pb

Note that the effect is much more important for high-Z materials: but it is negligible in scintillators, as shown by several simulations.

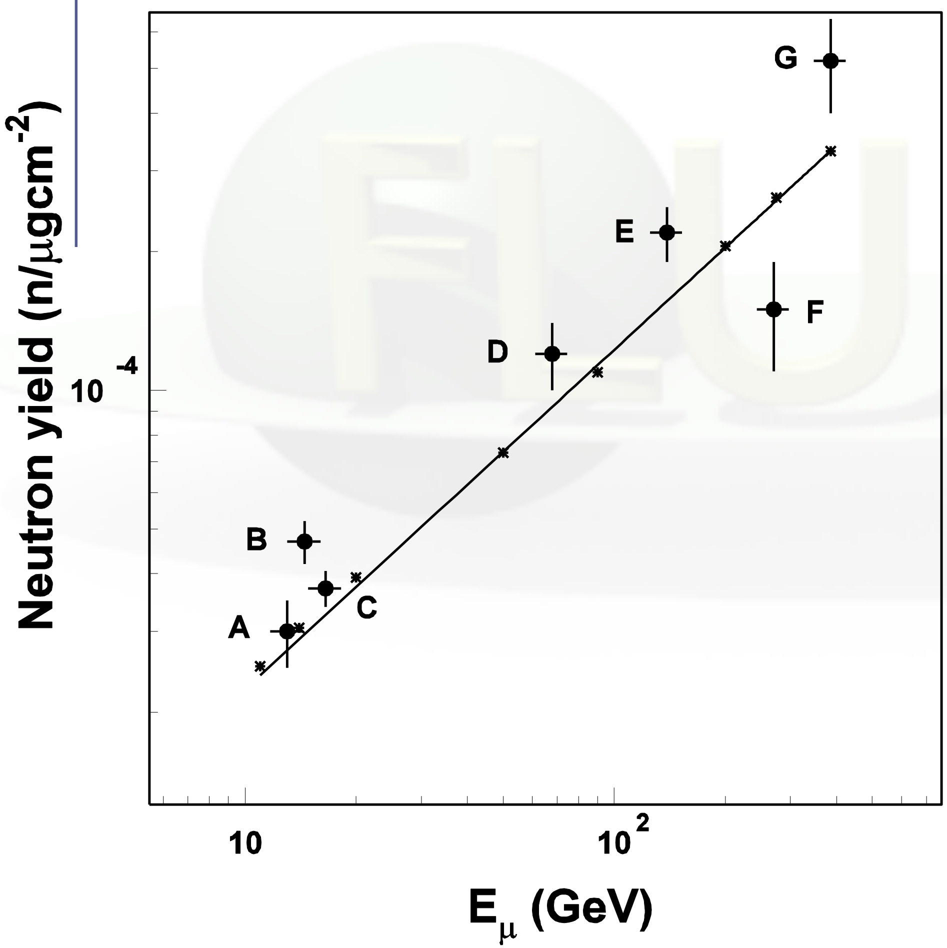
This is probably due also to the fact that in a wide muon spectrum only a few muons come to rest in a small region of interest.

Nuclear environment (Fermi motion, reinteractions, deexcitation...) from the FLUKA intermediate-energy PEANUT (INC + pre-equilibrium + evaporation/fission/Fermi breakup)

Beyond the simple one-body absorption, good results from addition of two-nucleon absorption.

Muon-induced neutron background

The first estimation, for the Palo Verde experiment:
Wang et al, PRD64 013012 (2001)



Neutron production rate as a function of muon energy

Stars+line : FLUKA simulation with a fit to a power law.

Exp. points:
abscissa → average μ energy at the experiment's depth:

A) 20 m.w.e.
B) 25 m.w.e.
C) 32 m.w.e. (Palo Verde)
D) 316 m.w.e.
E) 750 m.w.e. (should be 570?)
F) 3650 m.w.e. (LVD)
G) 5200 m.w.e. (LSD)

m.w.e. = meter of water equivalent

Muon-induced neutron background

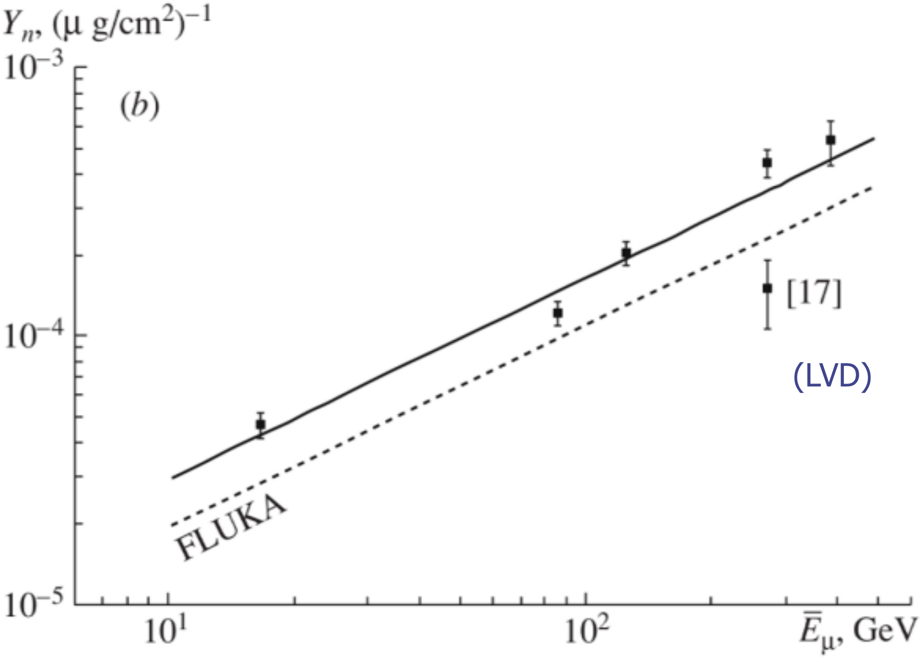
Malgin and Ryazhskaya, Yad. Fiz. 71, 1800 (2008)
Phys. At. Nuclei 71, 1769 (2008)

Measurements made by physicists of the Laboratory of Electron Methods for Neutrino Detection, Inst. for Nuclear Research, Moscow and by members of the LSD and LVD collaborations

Number of product neutrons as a function of the average energy of muons at different depths.

Points:
Experimental values 1970-2005
LVD point: 1999

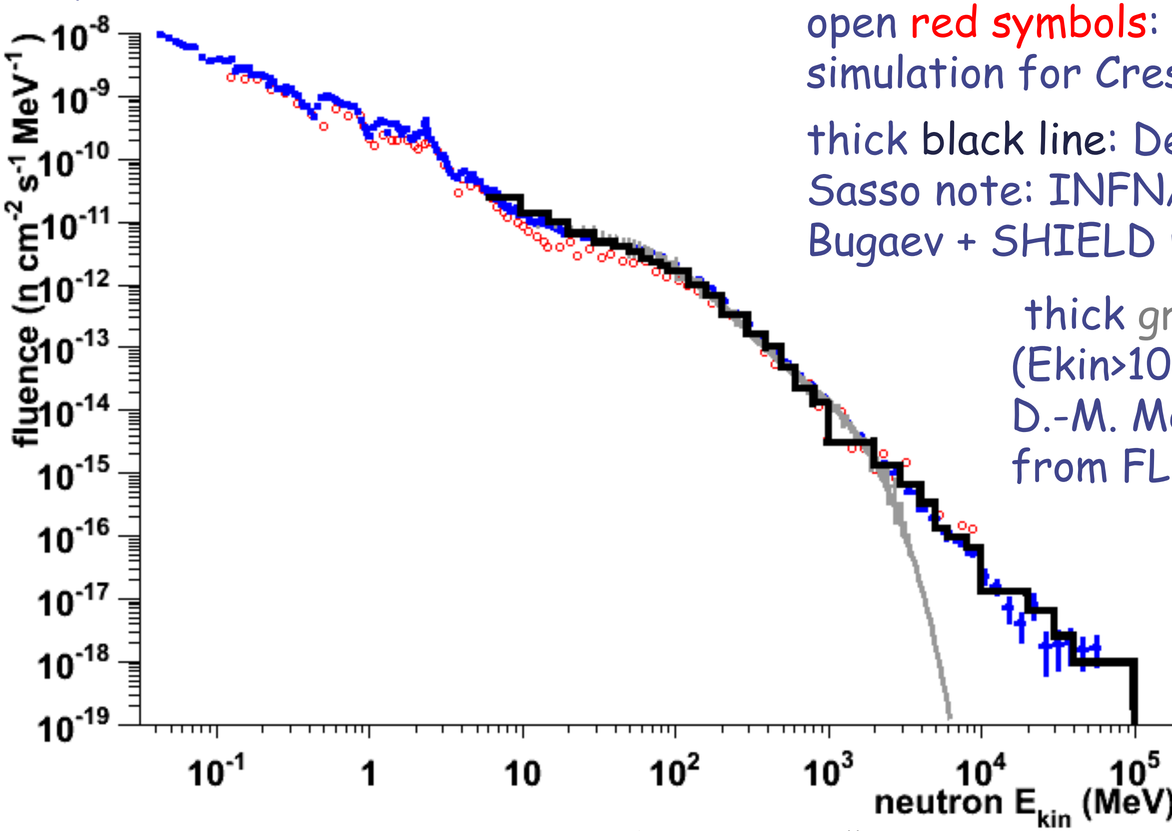
Solid curve:
Calculation by G.T. Zatsepin and O.G. Ryazhskaya 1965-1966 (!!!)
Not a fit, but an early prediction



"The yield for a liquid scintillator from a Monte Carlo calculation on the basis of the FLUKA code with allowance for all known processes was presented in Wang et al. 2001. The resulting expression... underestimates the effect in magnitude by a factor of about 1.5"

Calculated Neutron spectra

Predicted neutron kinetic energy spectrum for muon-induced cosmogenic neutrons emerging from a (LNGS) rock surrounding into a standard cavern. (Geometry: 20x20x20 m³ rock cube with centered 6x6x6 m³ cavern). Current FLUKA results are shown by the solid blue symbols with statistical uncertainties (back scattered neutrons are counted) and compared to earlier predictions:



open red symbols: Wulandari et al., 2004 FLUKA simulation for Cresst arXiv:hep-ex/0401032v1

thick black line: Dementyev et al, 1997 Gran Sasso note: INFN/AE-97/50. Bezrukov and Bugaev + SHIELD predictions for LVD

thick grey line: 2006 parameterization (Ekin>10MeV) suggested by A. Hime and D.-M. Mei, Phys. Rev. D 73, 053004 from FLUKA + 30% neutrons

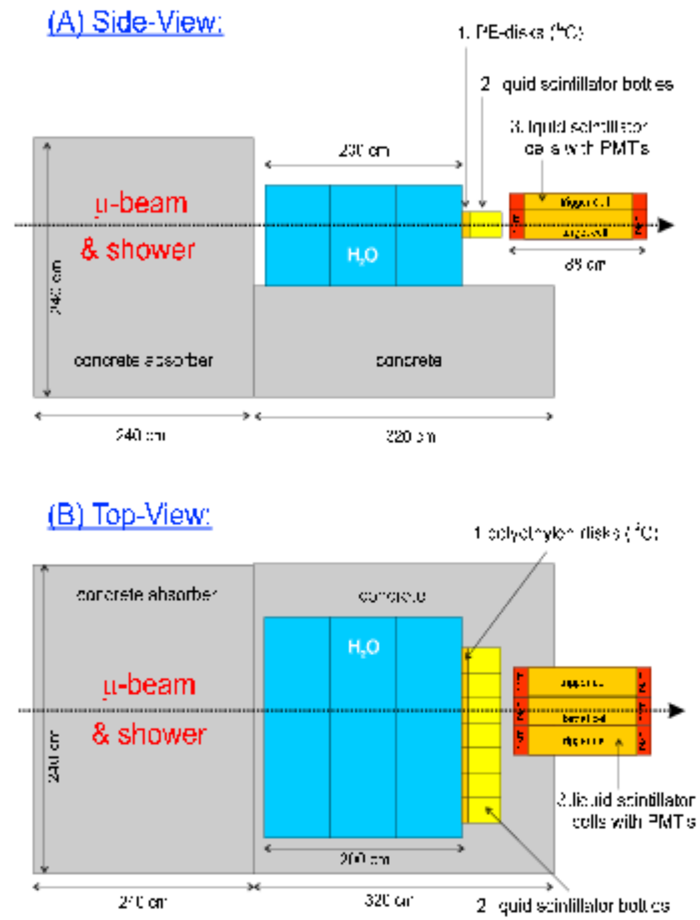
Activation experiments (NA54/Borexino 2000)

T. Hagner et al, 'Muon-induced production of radioactive isotopes in scintillation detectors', Astroparticle Physics, 14(1), 33-47 2000

CERN experiment NA54 measured the production of radioisotopes in liquid scintillator in order to estimate cosmogenic backgrounds to the Borexino experiment.

μ^+ beams of 100 and 190 GeV were directed through 240 cm of concrete and 200 cm of water to initiate muon interactions in front of a number of smaller liquid scintillation detectors.

The results were extrapolated to the ^{11}C production rate for Borexino.

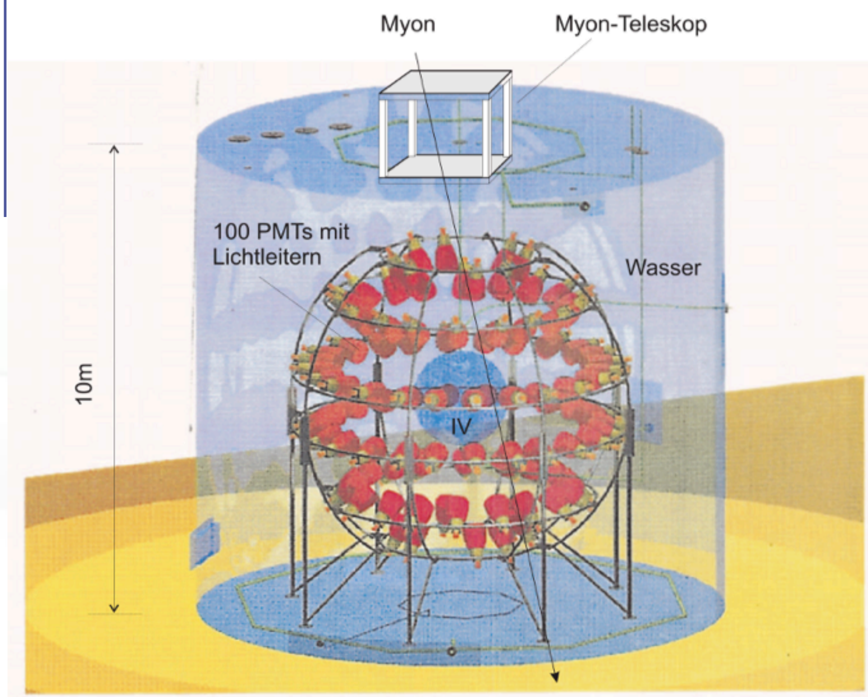


14.55 ± 1.49 (^{11}C counts per day per 100t of liquid scintillator)

(normalized to LNGS muon flux)

Activation experiments (CTF)

H. Back et al, 'CNO and pep neutrino spectroscopy in Borexino: Measurement of the deep-underground production of cosmogenic ^{11}C in an organic liquid scintillator' Phys. Rev. C 74, 045805 (2006)



The rate was then measured with the Borexino Counting Test Facility (CTF).

The CTF contains a 1 m^3 spherical volume of liquid scintillator shielded inside a water tank of 11 m diameter x 10 m height.

13.0 ±1.4 (^{11}C counts per day per 100t of liquid scintillator)
(normalized to LNGS muon flux)

Activation experiments (KamLAND)

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

The first result for the ^{11}C production rate from a larger volume liquid scintillator detector was reported by KamLAND along with FLUKA prediction.

Results were scaled to the 100t nominal Borexino liquid scintillator volume and the measured LNGS muon flux for comparison.

Scaled Measurements:

25.3 ± 4.5 (^{11}C counts per day per 100t of liquid scintillator)

FLUKA prediction:

12.2 ± 1.4

Activation experiments (Borexino 2012)

G. Bellini et al, 'First evidence of pep solar neutrinos by direct detection in Borexino', Phys. Rev. Lett. 108, 051302 (2012)

Borexino recently also reported a ^{11}C production rate. Also listed the predictions from a FLUKA simulation for Borexino.

27.4 ± 0.3 (^{11}C counts per day per 100t of liquid scintillator)
(normalized to LNGS muon flux)

FLUKA 2011.2 prediction:

15 ± 2.2

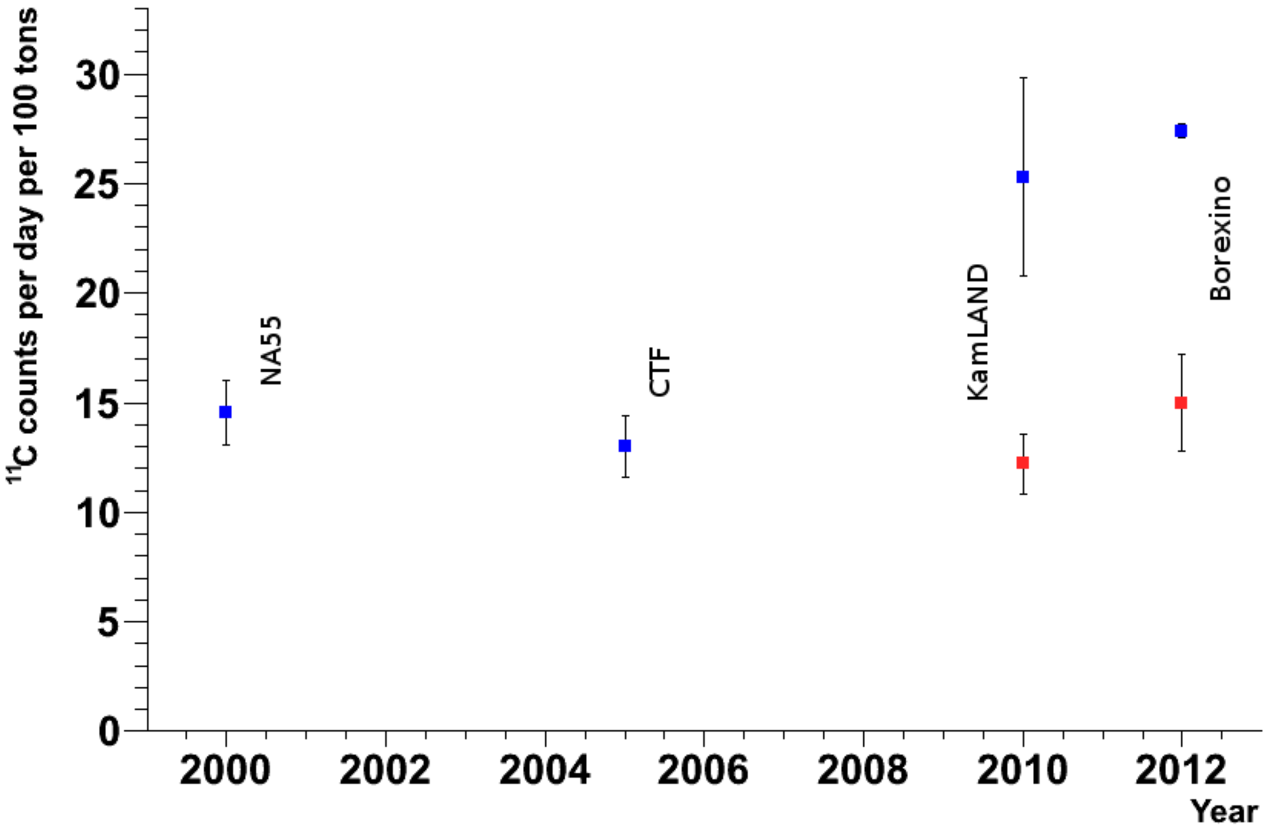
Note that ^{11}C is the dominant background in the 1-2 MeV region for low-energy neutrino electron scattering

Since ^{11}C is mostly produced through real photon interactions the production rate is expected to be less dependent on the muon mean energy.

Muon mean energy at	KamLAND	260 ± 8 GeV
	Borexino	283 ± 18 GeV

(MACRO Coll., Astropart. Phys. 19: 313-328, 2003)

^{11}C production estimates vs. time



Cosmogenic ^{11}C production per day for the nominal 100 ton fiducial volume of the Borexino detector. Rates derived by scaling from earlier available experimental data are compared to the recently published Borexino measured ^{11}C production rate (solid blue symbols). Error bars show the reported experimental uncertainties.
Also shown are 2 FLUKA predictions for the ^{11}C production rate (solid red symbols).