Neutron background in underground particle astrophysics experiments

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Outline

- **Introduction.**
- **Neutrons from radioactivity and their suppression by passive shielding.**
- **Neutrons from cosmic-ray muons.**
- **Summary.**

See also presentations and other documentation related to ILIAS activities on background studies: links available from ilias.in2p3.fr

Background studies in ILIAS

- **ILIAS - FP6 European Programme: Integrated Large Infrastructures for Astroparticle Science.**
- **A working group on background studies within N3 (Direct Dark Matter Detection - DMD) and JRA1 (Low Background Techniques for Deep Underground Science - LBT-DUSL) activities.**
- **Active participants from: France - Saclay, LSM, Lyon, Grenoble; Germany - Tuebingen, Munich-Garching, Karlsruhe, Heidelberg; Spain - Zaragoza, Canfranc; Italy - Milan, LNGS; UK - Imperial College, RAL, Sheffield.**
- **One of the objectives of ILIAS: to disseminate a new knowledge as widely as possible through the participation in international workshops and conferences, publication of scientific papers.**

Aims of the working group

- **Simulations of various types of background in underground laboratories (in particular, for dark matter detectors), comparing the results from different MC codes with each other and with available experimental data (testing MC codes) - N3, JRA1.**
- **Investigation of methods of background suppression and rejection (passive shielding, active vetoes etc.); formulation of requirements for shieldings and veto systems - mainly N3.**
- **Calculation of background rates in dark matter detectors - N3.**
- **Another working group in JRA1: measurements of neutron and gamma fluxes (and spectra) in underground laboratories (Gran Sasso, Modane, Canfranc, Boulby) - can be used to check Monte Carlo codes.**

Backgrounds for dark matter experiments

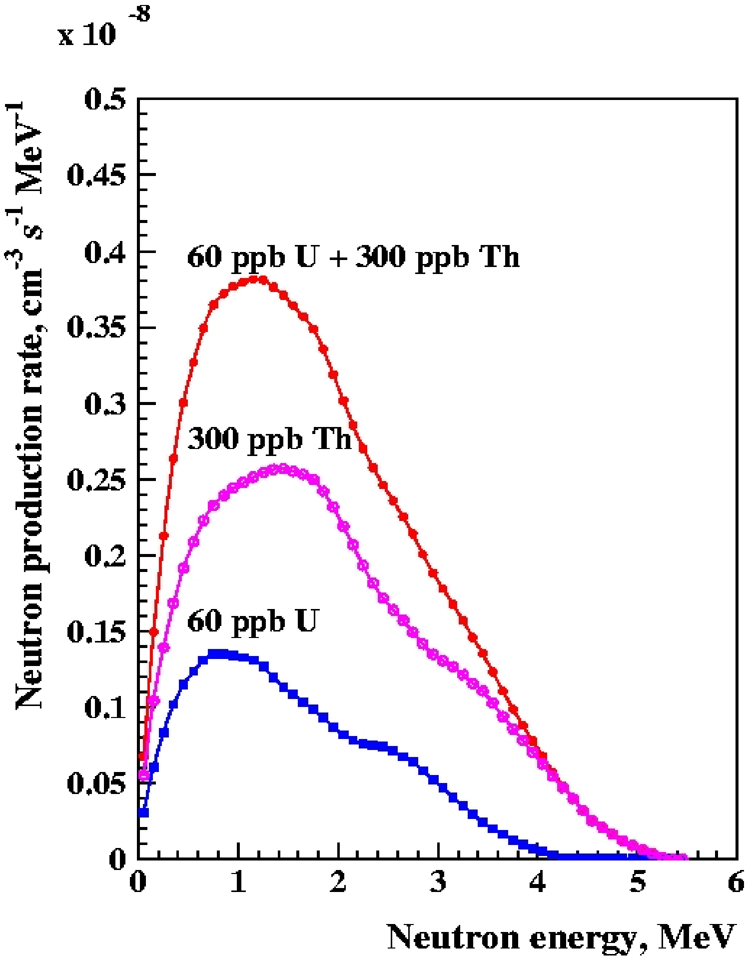
- **Several large-scale (~ 1 tonne) experiments are discussed for WIMP dark matter searches down 10^{-10} pb: SuperCDMS (Ge), EURECA (EDELWEISS + CRESST), XMASS (Xe), XENON (Xe), ZEPLIN IV/MAX (Xe), CLEAN (Ne), DRIFT, WARP(Ar), ArDM (Ar), DEAP (Ar) etc.**
  - **Tolerated (non-discriminated) background - no more than a few events per tonne of target per year (< 5 ev/tonne/year in Xe at 10-50 keV recoil energies to reach 10^{-10} pb);**
  - **Neutrons and gammas from rock - suppression of >10^{6} should be achieved for neutrons - passive shielding;**
  - **Neutrons, gammas, alphas and betas from detector components - ultra-pure materials, veto, discrimination;**
  - **Neutrons from cosmic-ray muons - large depth, veto;**
  - **Radon - gammas, neutrons and alphas (?) - radon removal, gas-tight sealing and ventilation with radon-free air, careful treatment at the surface;**
  - **Cosmogenically produced isotopes - underground storage, large depth.**

Neutron production in U/Th decay chains

- **SOURCES-4A (Wilson et al. SOURCES4A, Technical Report LA-13639-MS, Los Alamos, 1999) - code to calculate neutron flux and energy spectrum arising from U/Th contamination in various materials.**
- **Modifications to SOURCES (Carson et al. Astropart. Phys. 21 (2004) 667; Lemrani et al., NIMA 560 (2006) 454; hep-ex/0601030):**
  - **Alpha energy range extended beyond 6.5 MeV upper limit;**
  - **Cross-sections already present in the code library extended to higher energies using available experimental data;**
  - **Some cross-sections updated according to recent experimental results;**
  - **A code EMPIRE-2.19 (http://www.nndc.bnl.gov/empire219) is used to calculate the cross-sections to different excited states (excitation functions can be extracted) if there are no measurements;**
  - **New cross-sections added (^{35}Cl, Fe, Cu, Ca, Ti etc.).**
- **Main feature in SOURCES, absent (probably) in most other calculations:**
  - **Accounting for transitions of the final nucleus to the excited states (GNASH calculations of transition probabilities - excitation functions, or EMPIRE) - reduces neutron energies.**

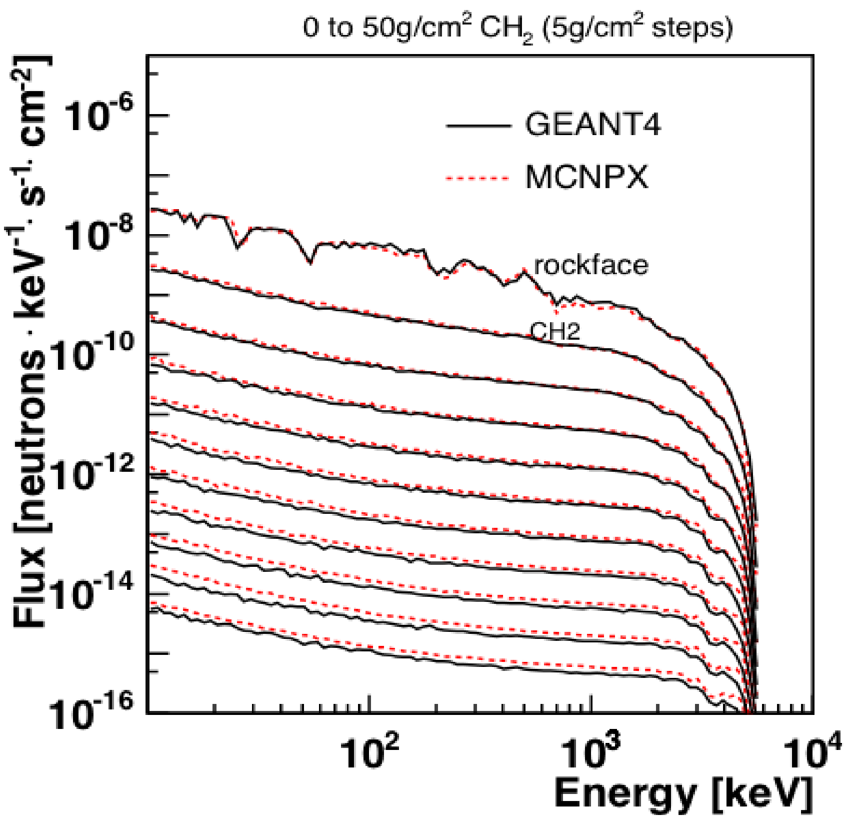
Neutron spectra and yields

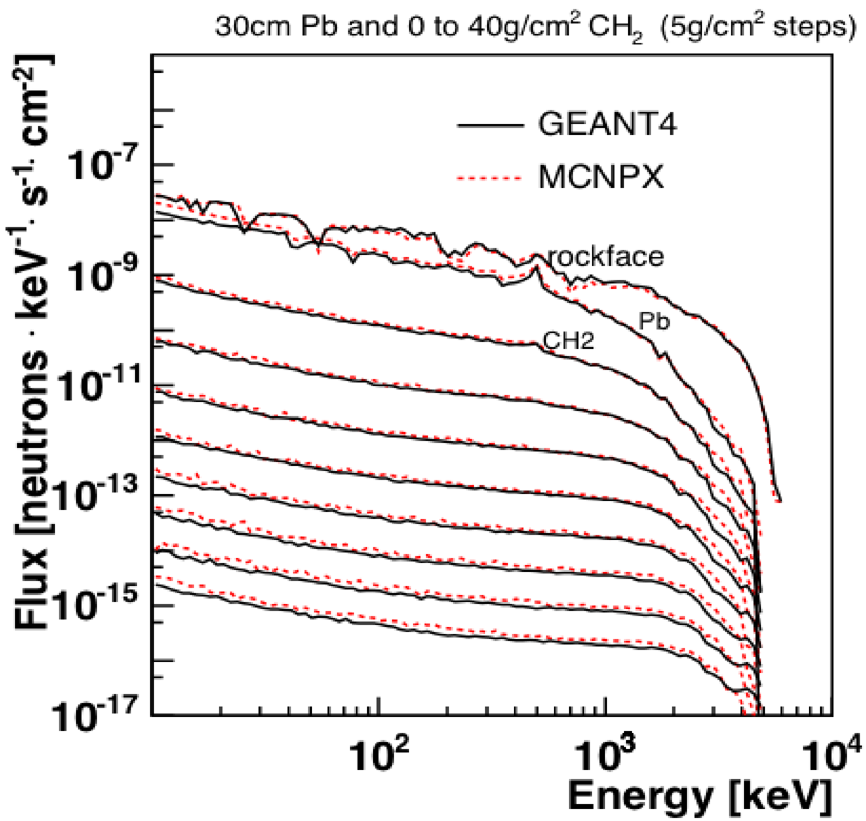
- Neutron production rate in NaCl - 1.05×10^{-7} cm^{-3} s^{-1} agrees with other calculations.
- The peak in the spectrum is usually at ~1-1.5 MeV which is lower than obtained in other calculations due to transitions to the excited states in SOURCES - less energy transferred to neutrons.
- Coulomb barrier suppresses the cross-sections for high-Z elements even if the energy threshold (calculated from the Q-value of the reaction) is small; for Fe-Cu the Coulomb barrier is about 7.0-7.2 MeV → for higher-Z targets spontaneous fission of U-238 dominates.
- Similar approach when calculating neutron production rate in detector components (including shielding).
- Similar spectrum for Modane rock (Lemrani et al., NIMA (2006); hep-ex/0601030).



Neutron production spectrum in NaCl -60/300 ppb U/Th (SOURCES-4A): mainly (α,n) - Carson et al. Astropart. Phys. 21 (2004) 667.

Neutron propagation through the shielding





Neutron spectra after various shielding thicknesses (CH_2) - Lemrani et al, NIMA, 560 (2006) 454; simulations by Lemrani, Robinson, De Jesus (see also Carson et al. Astropart. Phys. 21 (2004) 667).

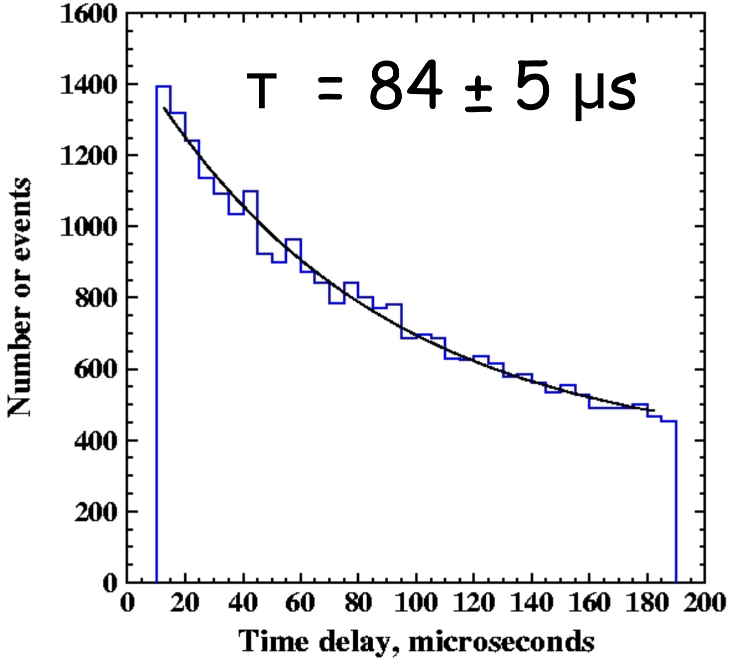
Neutron spectra after various shielding thicknesses (lead + CH_2) - Lemrani et al, NIMA, 560 (2006) 454; simulations by Lemrani, Robinson, De Jesus (also Carson et al. Astropart. Phys. 21 (2004) 667).

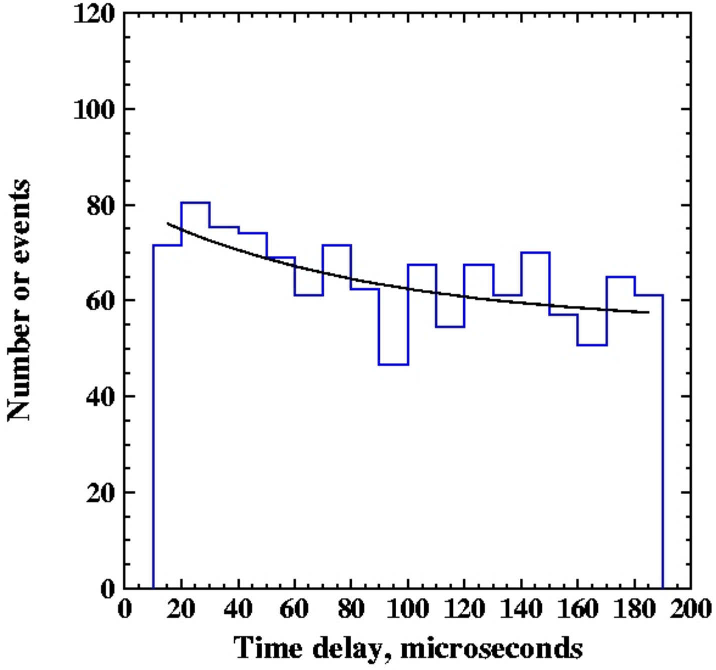
Comparing different rocks

- **Boulby - NaCl; Modane - O - 50% , Ca - 31%, C - 6%, Si - 7%, Mg - 1%, Al - 2%, H - 1%, Fe - 2% (Chazal et al. Astroparticle Physics (1998)).**
- **Higher U/Th concentrations in the Modane rock.**
- **Similar neutron yields due to lower thresholds of (alpha,n) reactions in Na and Cl - in Modane rock (alpha,n) reactions give 77% of neutron yield, in NaCl - 98%.**
- **Smaller neutron flux in the Modane lab - due to the presence of H: suppression by a factor of 1.8 above 1 MeV compared to the case without H.**
- **Details in Lemrani et al. NIMA 560 (2006) 454.**

Checking MC

- Measurements of neutron flux in underground labs.
- Boulby: Gd-loaded liquid scintillator; signature: two pulses (proton recoils and gammas from neutron capture) in delayed coincidences.
- Neutron flux at Boulby (>0.5 MeV): $(2.05 \pm 0.72) \cdot 10^{-6}$ n/cm^{2}s (preliminary) - in agreement with MC assuming measured concentrations of U/Th





Muon-induced neutrons

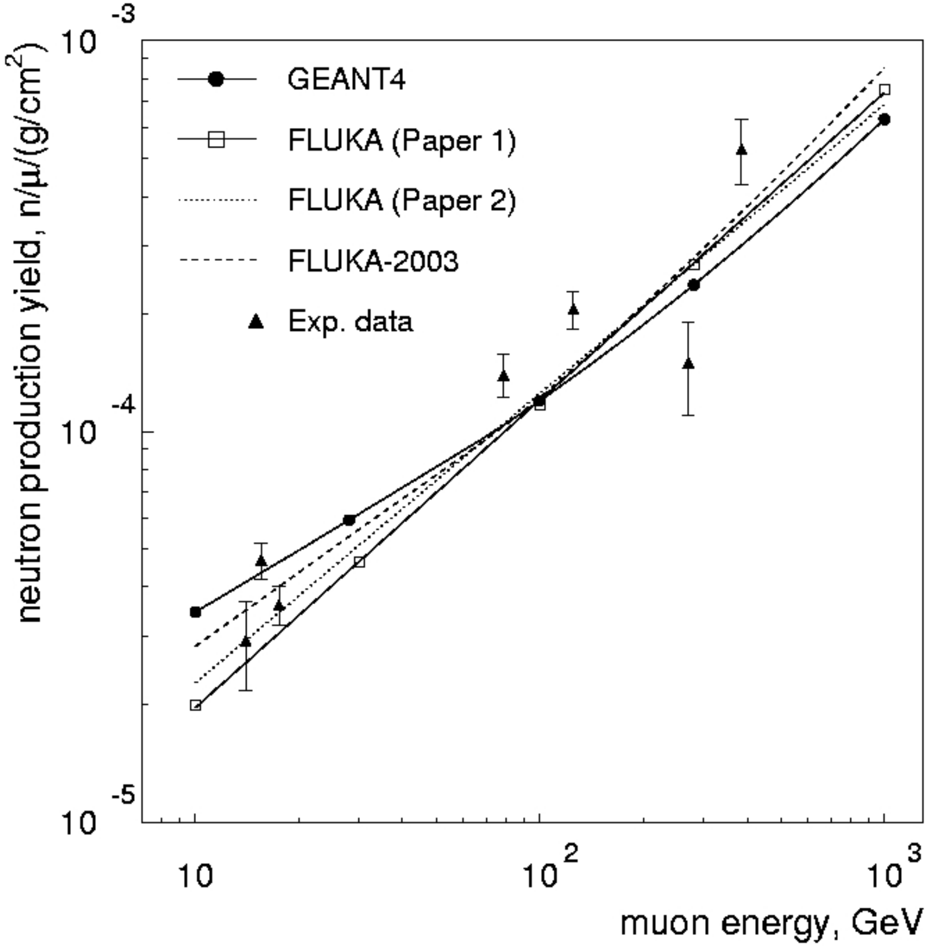
- **Inputs:**
  - **Muon rate - measurements at a particular underground site.**
  - **Muon spectrum and angular distribution (normalised to the total rate) - simulations or measurements (if available) - not a problem (for example, MUSIC code for muon propagation - Antonioli et al., Astrop. Phys. 7 (1997) 357, Kudryavtsev et al. Phys. Lett. B 471 (1999) 251 or MUSUN code for muon simulations underground - Kudryavtsev et al. NIMA, 505 (2003) 688).**
  - **Neutrons from muons - production, propagation, detection together with all other particles (muon-induced cascades): GEANT4 (GEANT4 Coll. NIMA, 506 (2003) 250) or FLUKA (Fasso et al. Proc. MC2000 Conf., Lisbon, 2000, p. 159; ibid. p. 995).**
- **Important: all particles should be produced, propagated and detected with one code to look for simultaneous detection of neutrons and other particles, such as photons, electrons, muons, hadrons.**
- **FLUKA calculates kerma factors as average energy depositions from nuclear recoils - not very accurate treatement on event-by-event basis.**

Total neutron yield

- Total neutron yield is used to check Monte Carlo codes which can then be used to simulate fast neutrons.
- Usually expressed as the average number of neutrons produced by a muon crossing 1 g/cm^2 of target material.
- It is measured or simulated by counting neutrons produced by many muons along long tracks.
- Dark matter experiments should worry about fast neutrons

  (> 0.5-1 MeV) but it is difficult to measure the yield of fast neutrons because their energy degrades during transport in matter.
- The flux of fast neutrons can be measured by scintillators or dark matter detectors but it is possible to do so only at certain (quite big) distances from the muon track. At small distances neutron signal may coincide with the muon signal if they are detected by the same detector.
- Delayed signal from neutron capture is usually used to detect neutrons. It provides information about neutrons with all energies which were thermalised and captured. (Also DM and DBD detectors but small signal).

Dependence on muon energy



- **Neutron production rate in $(CH_2)_n$ (liquid scintillator):**

Araujo et al., NIMA 545 (2005), 398; hep-ex/0411026;

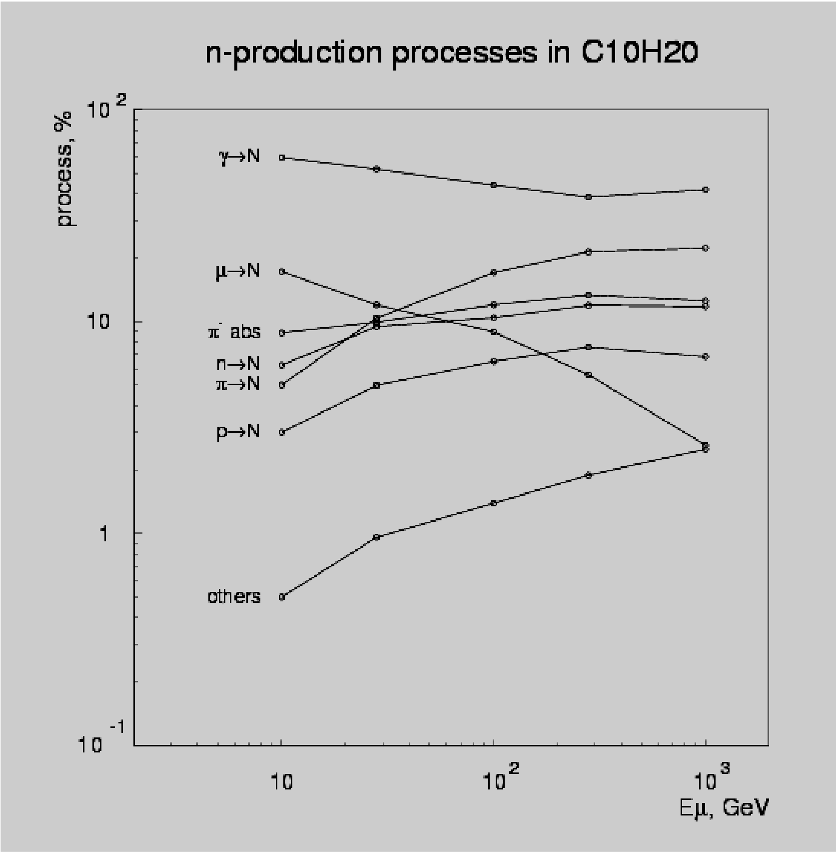
FLUKA (Paper 1) - Kudryavtsev et al. NIMA, 505 (2003) 688;

FLUKA (Paper 2) - Wang et al. Phys. Rev. D, 64 (2001) 013012;

Experimental data - see Papers 1 and 2 for the full list of references for experimental data.

- **No accurate simulations of the detector geometry and response for any of the experiments at large depths.**

Muon-induced neutrons: processes



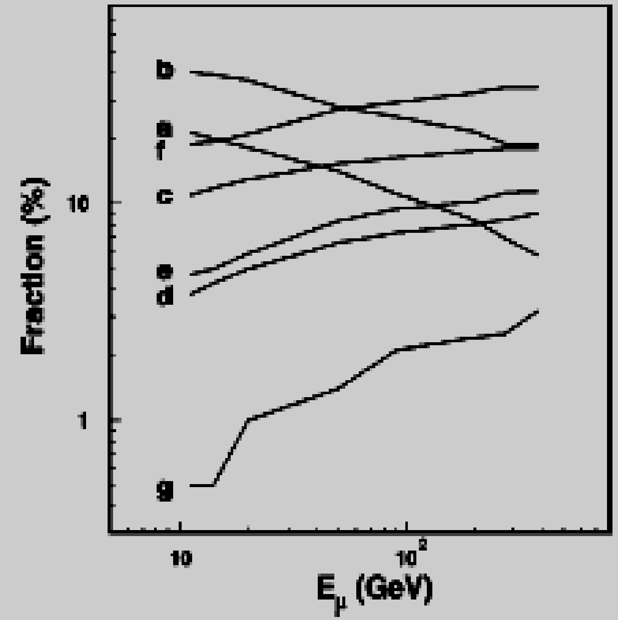


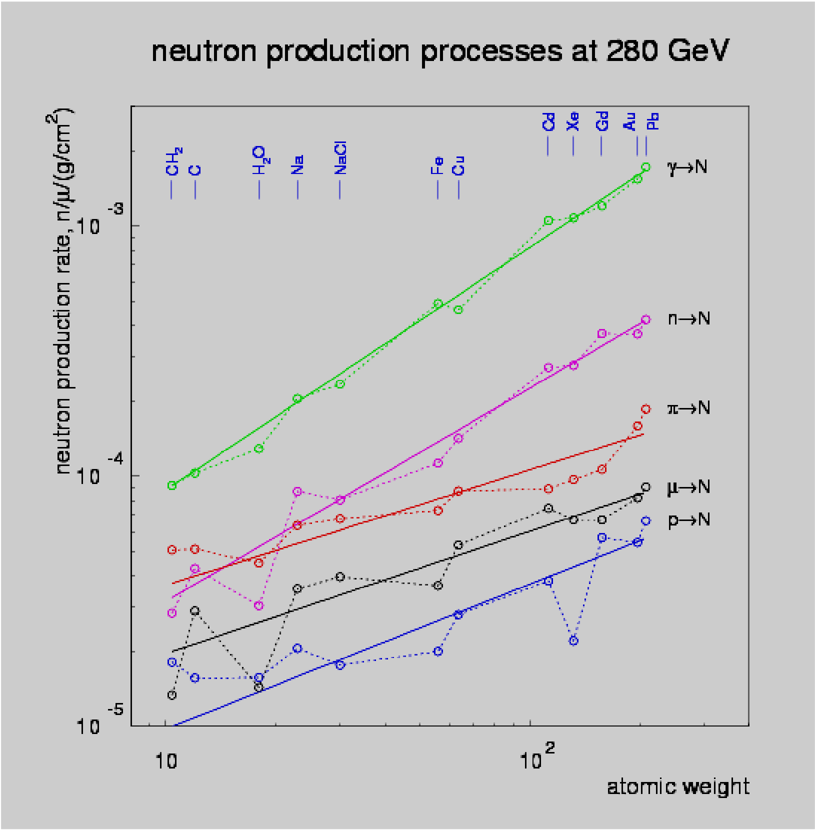
FIG. 3. Origin of neutrons: (a) direct muon spallation, (b) real photonuclear disintegration, (c) neutron spallation, (d) proton spallation, (e) π^+ spallation, (f) π^- spallation and capture, and (g) others.

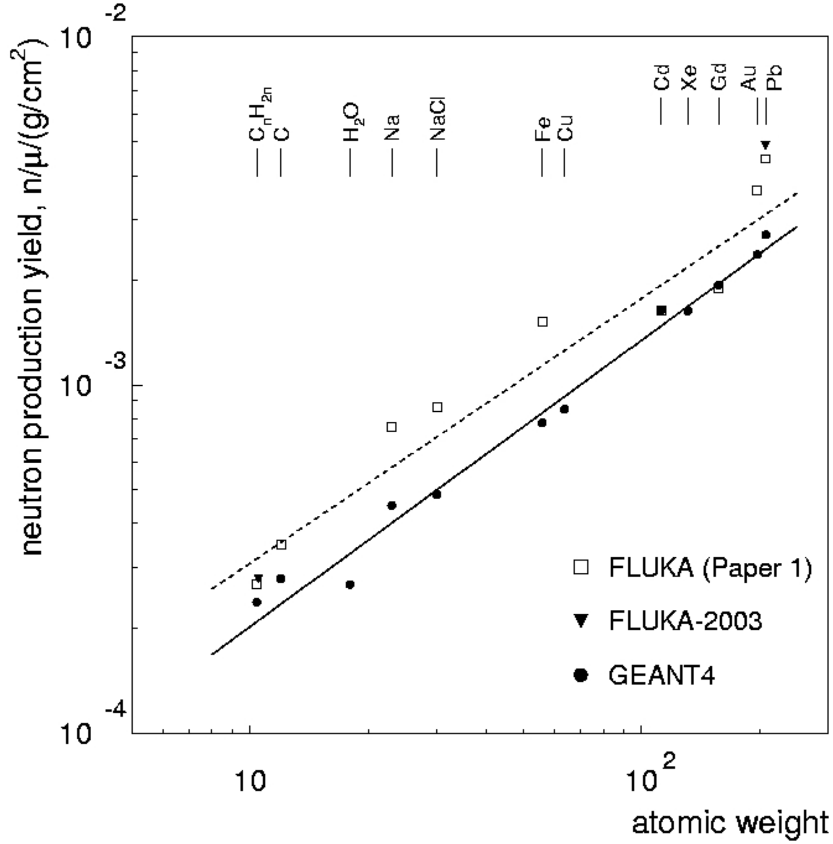
GEANT4: Araujo et al. NIMA 545 (2005), 398 **FLUKA: Wang et al. PRD, 64 (2001) 013012**

- **Contribution of different processes: real photonuclear disintegration dominates in GEANT4 at all energies and for (almost) all materials.**

Muon-induced neutrons: A-dependence

GEANT4 Coll. NIMA, <u>506</u> (2003) 250. **Fasso et al. Proc. MC2000 Conf., p. 159; p. 995.**

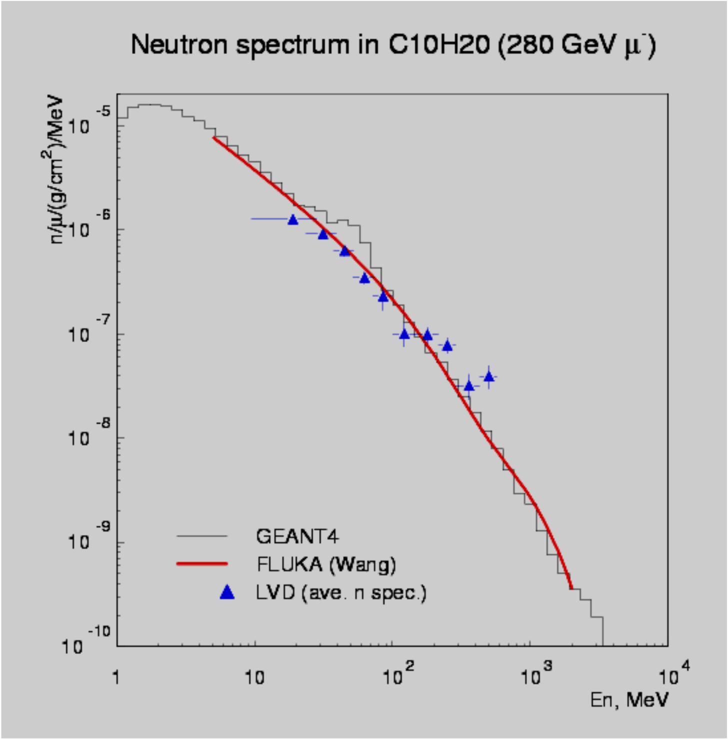


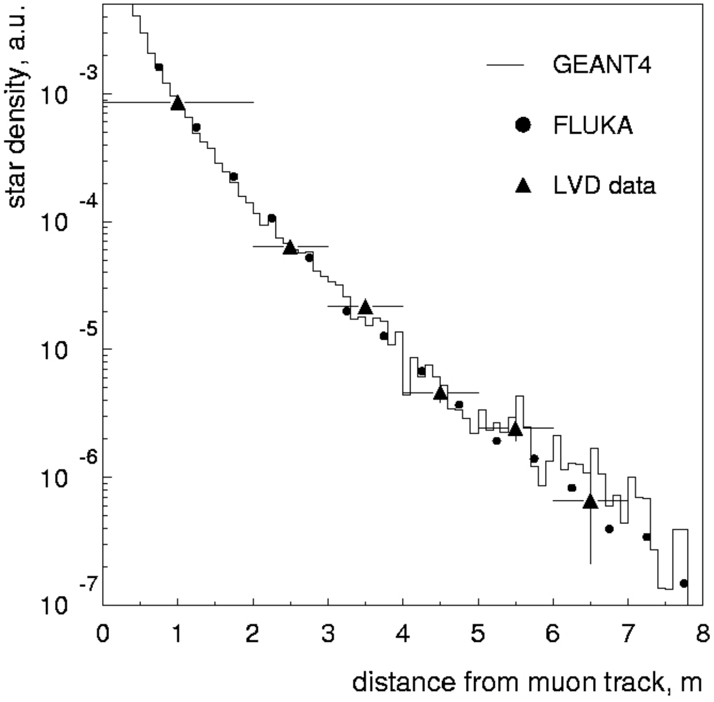


Contribution of different processes in various materials - GEANT4: Araujo et al. NIMA <u>545</u> (2005), 398.

A-dependence of neutron production rate - GEANT4: Araujo et al., FLUKA: Kudryavtsev et al. FLUKA gives twice as many neutrons compared to GEANT4 in most materials tested.

Energy spectrum and lateral distribution



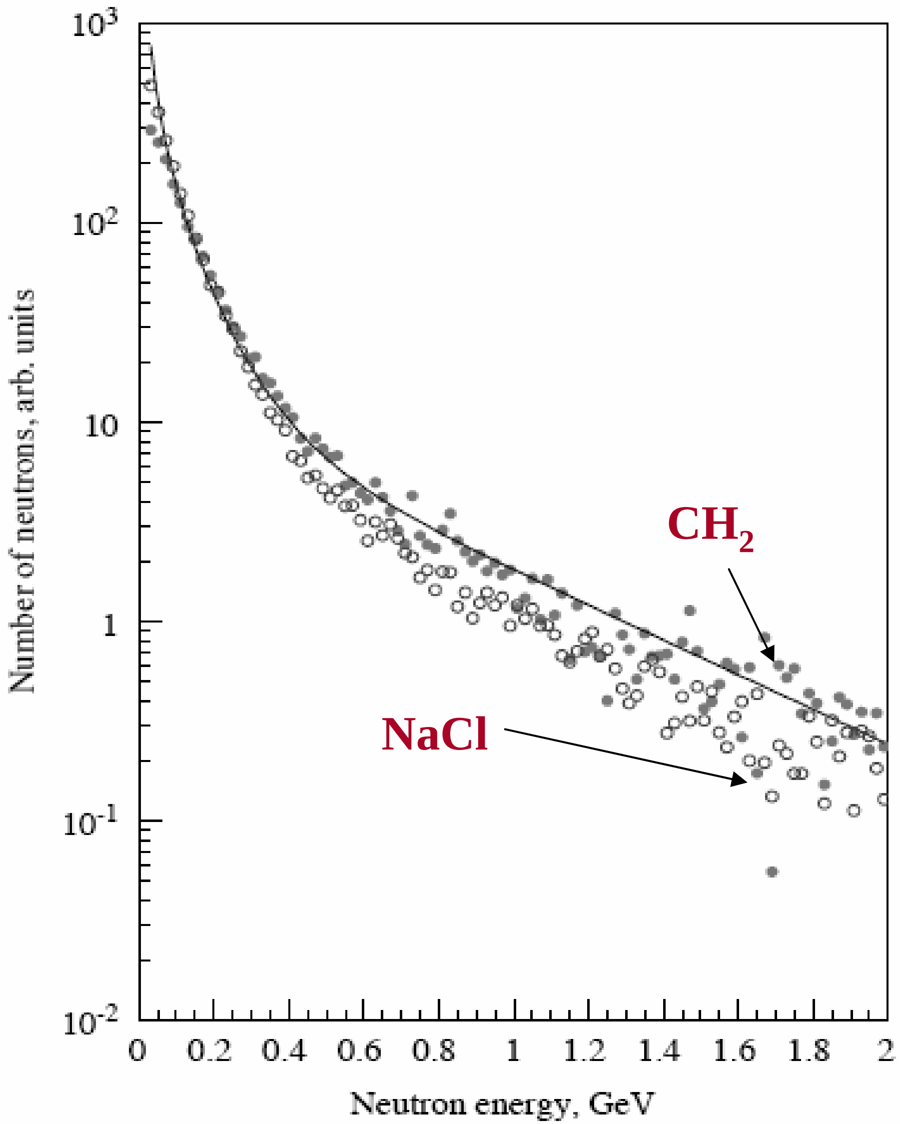


Neutron production spectrum - GEANT4: Araujo et al., FLUKA: Wang et al. ; data - LVD: LVD Collab., Proc. 26 ICRC (1999), vol. 2, p. 44; hep-ex/9905047. LVD and FLUKA spectra are in arbitrary units and are normalised to the GEANT4 simulations.

Neutron lateral distribution (from muon track) - GEANT4, FLUKA and LVD data. Simulations did not include detector specific features. LVD data are in arbitrary units normalised to the simulations. See also Menghetti et al. Proc. IDM2004, for more LVD data and another analysis technique.

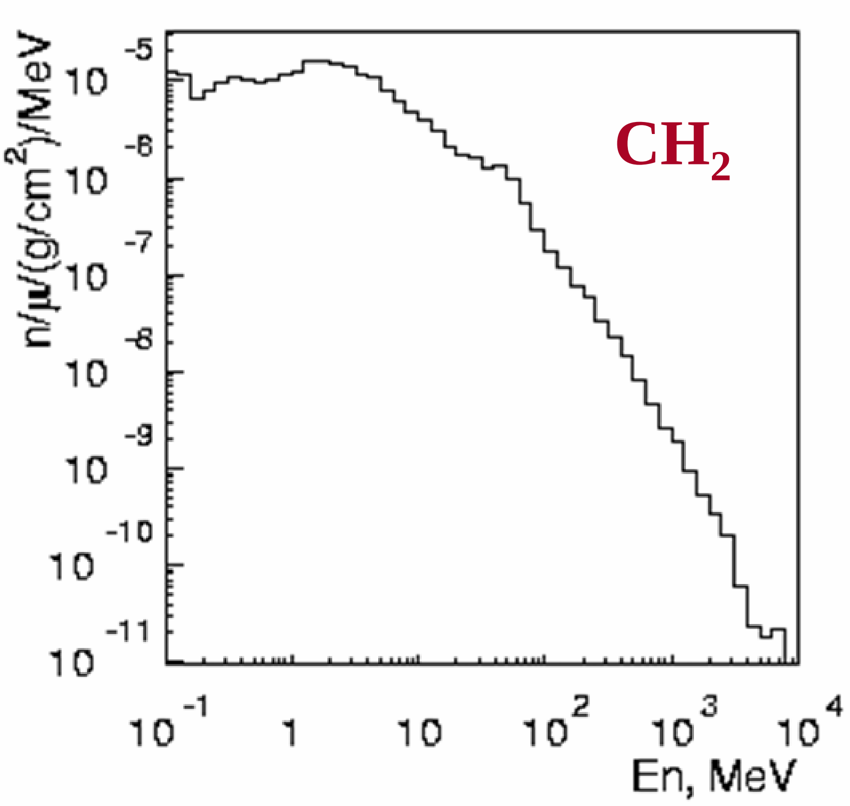
Neutron energy spectra

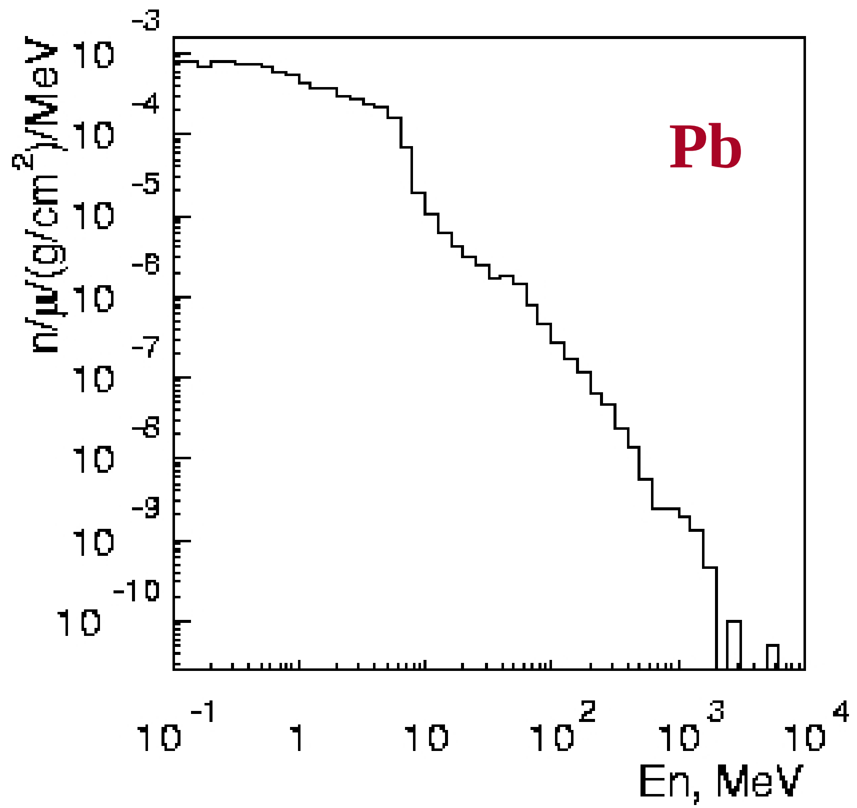
- **Neutron energy spectra are different in different materials.**
- **Typically higher neutron yield result in softer spectrum (less high energy neutrons).**
- **Should be checked for all our labs and other materials.**



From V. A. Kudryavtsev et al., NIMA, 505 (2003) 688.

Neutron energy spectra: GEANT4





- Neutron production spectra from 270 GeV muons in CH_2 (left) and lead (right) - GEANT4: Araujo and Kudryavtsev (talk at IDM2004).
- Energy spectra are different for different materials but the main difference is at low energies: fast neutron yield (> 20 MeV) is not much different for CH_2 and lead.
- Neutron yield (per muon) at >1 MeV in NaCl is 50% lower than in Gran Sasso rock (FLUKA: Carson et al., Wulandari et al., hep-ex/0401032).

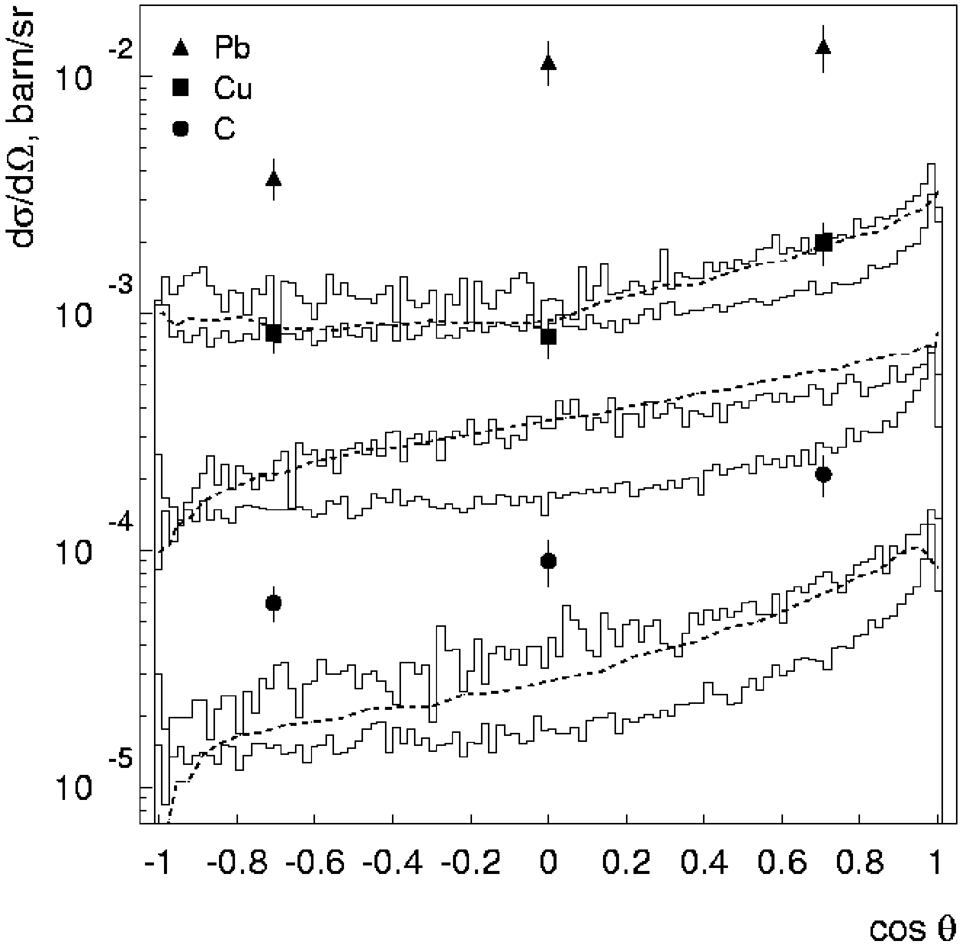
Fast neutron fluxes

Neutron fluxes coming from rock at different energies in units of 10^{-9} cm^{-2} s^{-1}. All results are from simulations with FLUKA:

Carson et al. Astropart. Phys. 21 (2004) 667;
Wulandari et al., hep-ex/0401032;
D.-M. Mei and A. Hime, Phys. Rev. D 73 (2006) 053004.

Site		Total	> 1 keV	> 1 MeV	> 10 MeV	> 100 MeV
Boulby	Mei&Hime	4.86		1.34	1.11	0.277
Boulby	Carson et al.		5.61	0.87	0.25	0.064
Gran Sasso	Mei&Hime	2.72		0.81	0.73	0.201
Gran Sasso	Wulandari et al.			0.43		

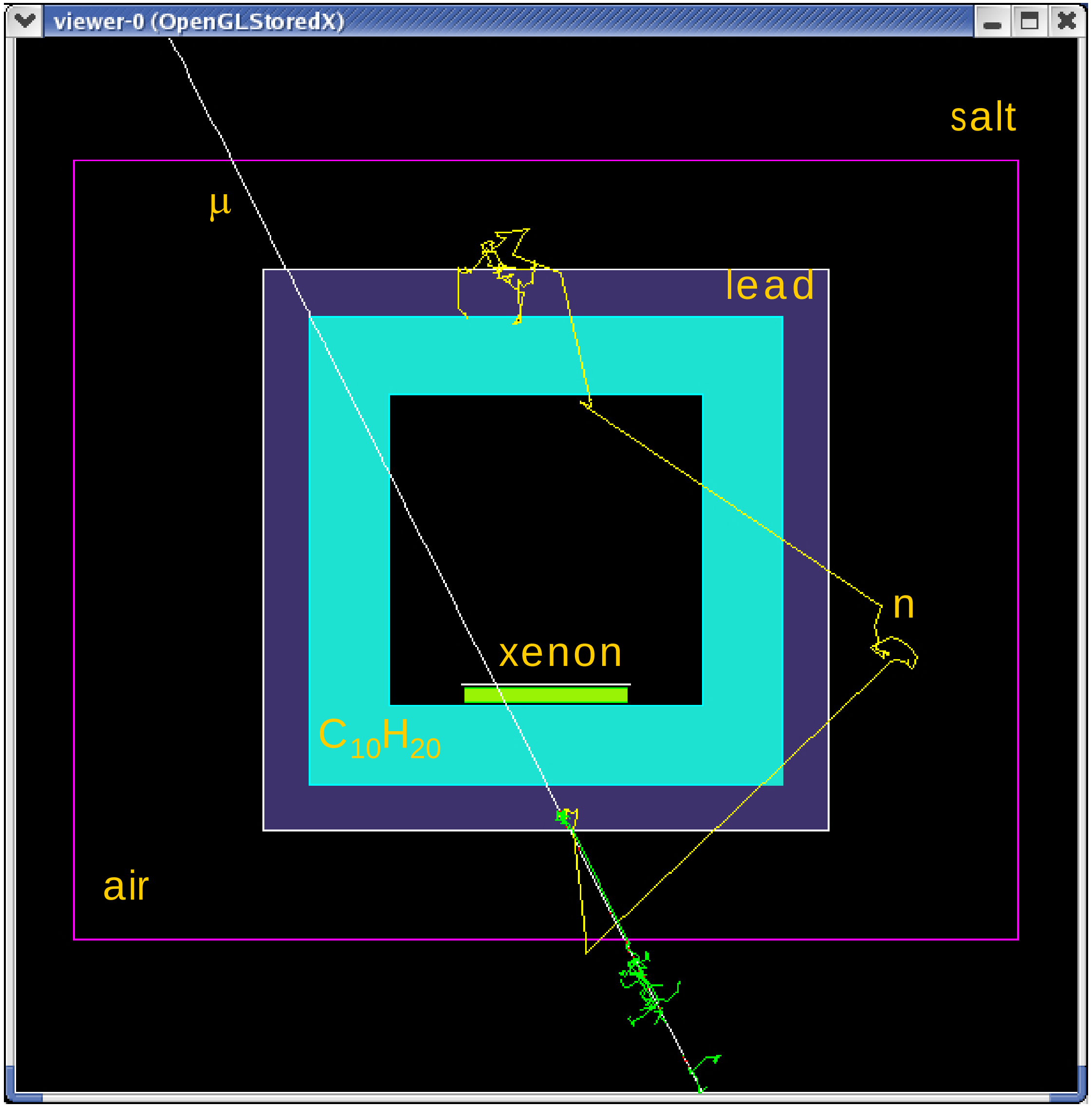
Muon-induced neutrons: problems



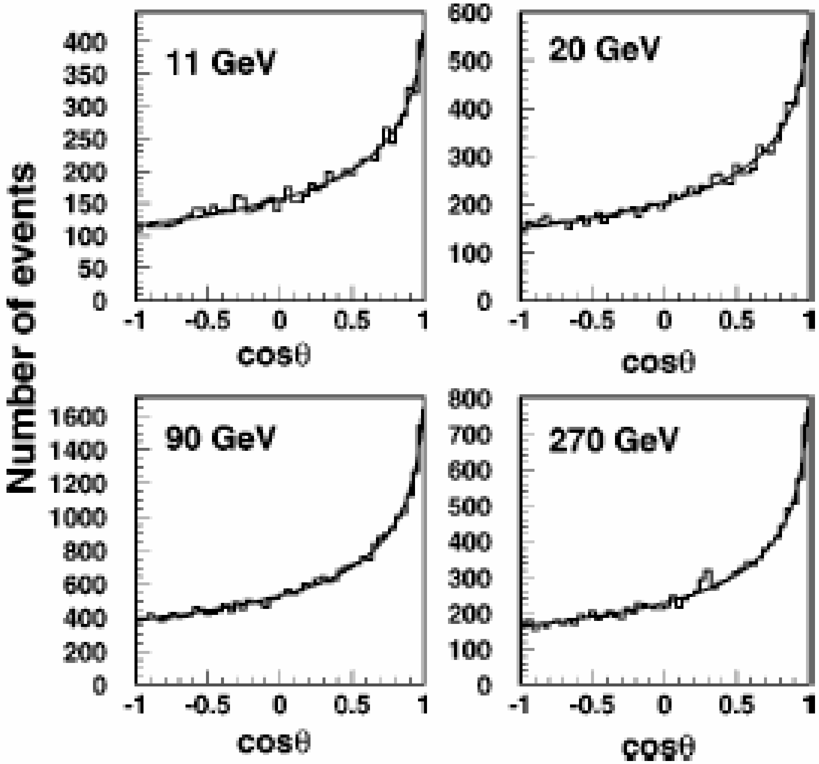
- Differential cross-section of neutron production in thin targets for 190 GeV muons (E_n>10 MeV). Upper (thick) histograms - GEANT4; dashed line - FLUKA (Araujo et al.); data - NA55 (Chazal et al. NIMA, 490 (2002) 334).
- Other data for lead (Bergamasco et al. Nuovo Cim. A, 13 (1973) 403; Gorshkov et al. Sov. J. Nucl. Phys., 18 (1974) 57) are old and controversial but also show significantly higher neutron production compared with simulations.
- Lead is important since it is used as a shield in DM experiments.
- Measurements using dark matter detectors or active veto systems.

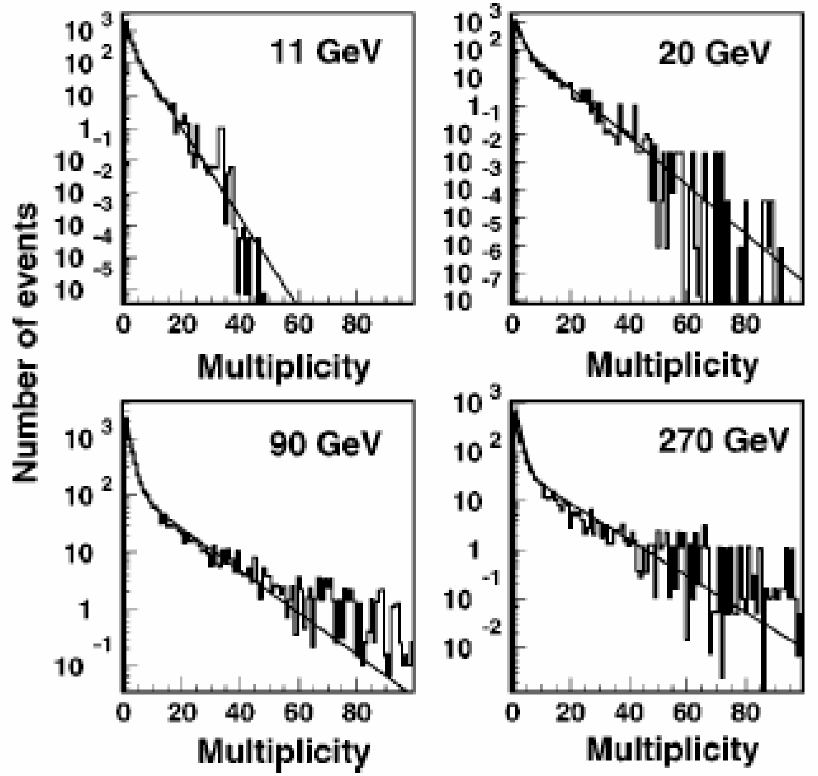
Site specific simulations

- **Site specific (detector specific) simulation.**
- **Sampling muons according to angular distribution and energy spectrum at specific site, propagating muons, generating secondaries, propagating secondaries, everything is detected.**
- **Sampling neutrons: where? Around the detector? Or on sides only? It is not known where the tracks of muons and secondaries are and whether they will be detected by the target or veto?**



Angular distribution and multiplicity

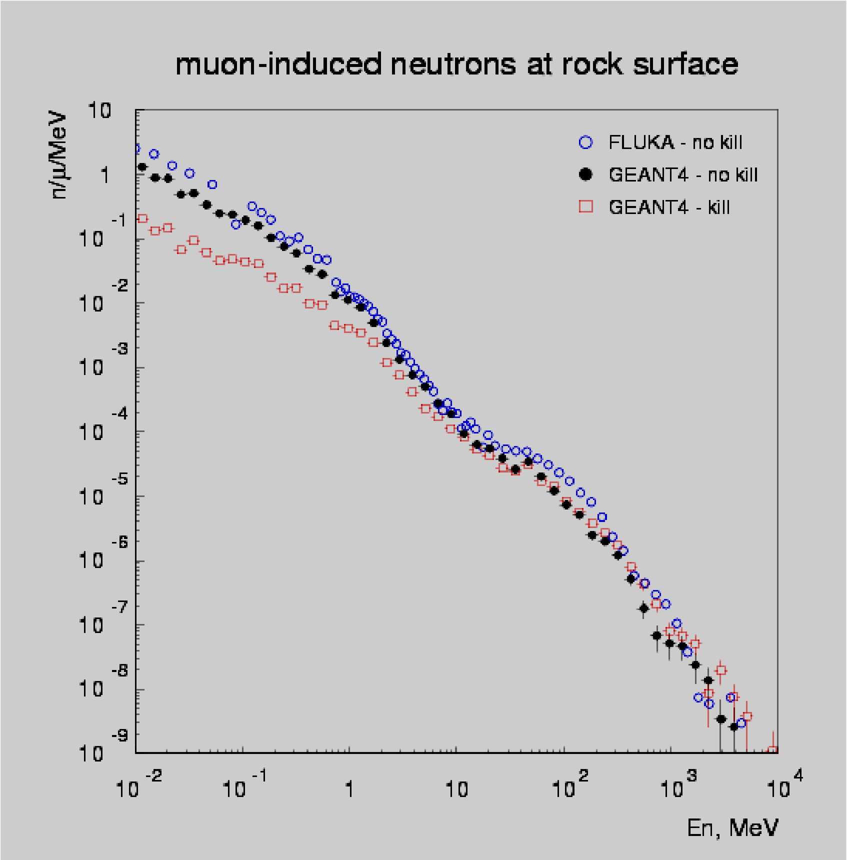


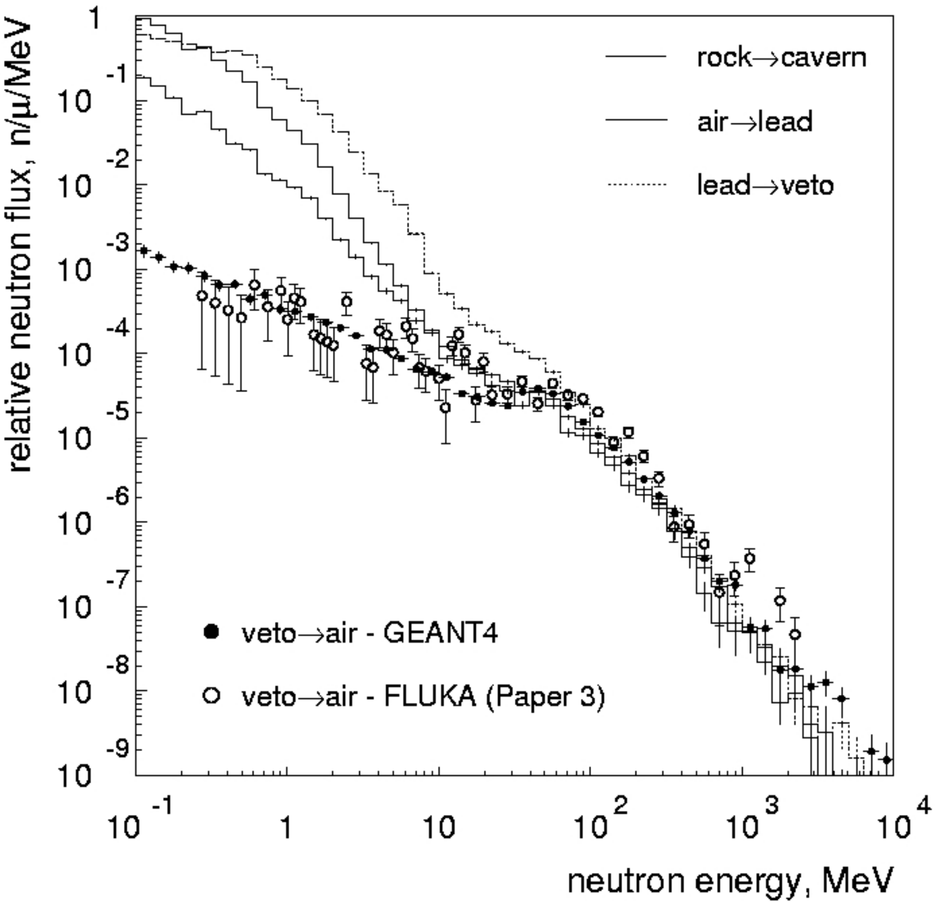


From Wang et al. (2001)

- Distributions peaked at 0º relative to the muon track. To sample correctly the direction of a neutron, the muon track should be known.
- Total neutron yield includes different neutron multiplicities. This should be simulated correctly for each muon interaction.

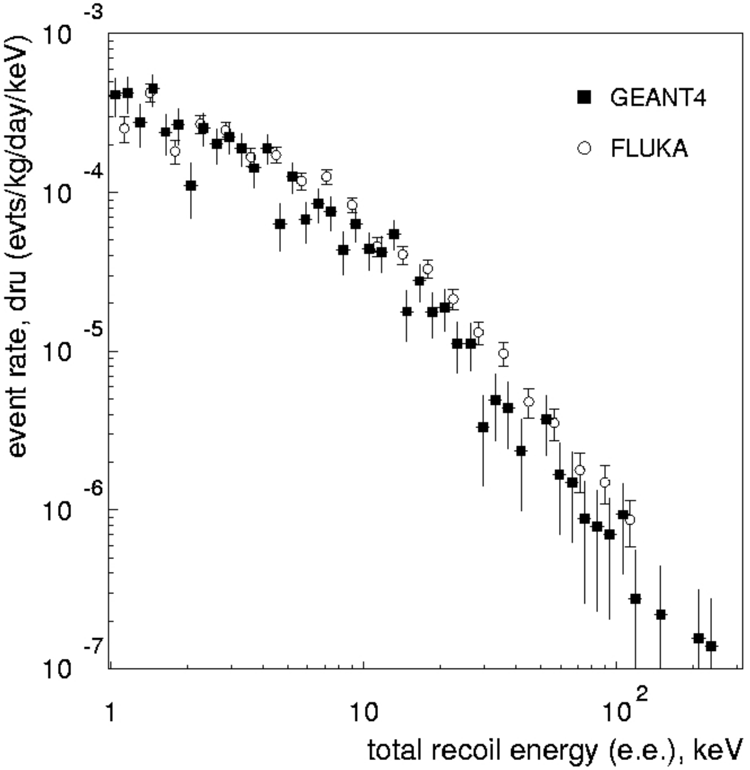
Spectra in the laboratory

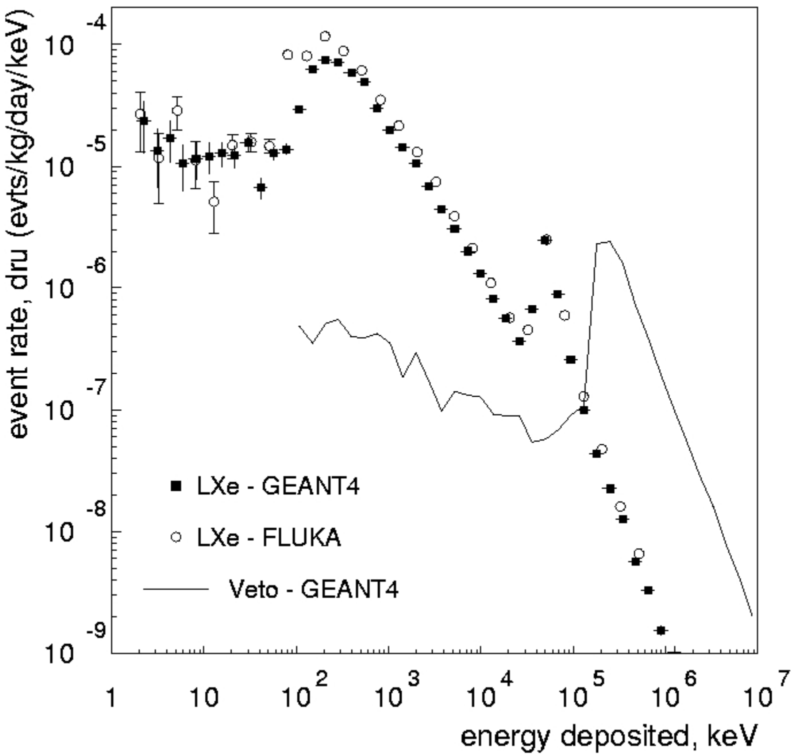




Neutron spectra in the lab before and after shielding - GEANT4: Araujo et al.; also Araujo&Kudryavtsev, talk at IDM2004; FLUKA: Kudryavtsev et al. - good agreement for all energies of interest (within 50%).

Events in xenon detector





Nuclear recoil event rate as a function of measured energy (quenching = 0.2 for xenon) - GEANT4 and FLUKA: Araujo et al. - good agreement (within 30%).

Energy spectrum of all events - GEANT4 and FLUKA: Araujo et al.

Only <10% of nuclear recoil events contain nuclear recoils only; others have larger energy deposition from other particles. To estimate the background from nuclear recoils only, all particles should be produced, propagated and detected.

Events in xenon detector

TABLE I: Muon-induced neutron background (nuclear recoil (NR) events per year) in 250 kg xenon target for several detection thresholds

Event type	E_{ee}, keV	FLUKA	GEANT4
All NR events	>0	234±8	217±9
Pure NR events	>0	13.6±1.9	10.3±1.9
	>2	7.3±1.4	4.0±1.2
	2–10	3.9±1.0	3.3±1.1
Pure single NR events	>0	6.6±1.3	6.6±1.6
	2–10	2.1±0.7	2.6±1.0
Anti-coincidence with veto	>0	0	0

From Araujo et al. NIMA 545 (2005), 398; hep-ex/0411026.

Neutron signal will be in time coincidence with 'electromagnetic' signal (fast neutrons) - no big delays.

If there is an active veto (100 keV threshold, 4π geometry) - no signal in anticoincidence with veto - a limit of <0.5 ev/year.

Summary - I

- **Low-energy neutron production:**
  - **Modified code SOURCES is probably OK for this job - tested.**
  - **Softer spectrum compared to earlier calculations.**
  - **Missing cross-sections and excitation functions can be calculated with EMPIRE: the accuracy is about 20% if you choose right model.**
- **Low-energy neutron propagation and detection:**
  - **Accurate measurements underground (and simulations of the whole experiment) are needed to test neutron yields and spectra - not easy.**
  - **MCNP vs GEANT4 - good agreement: 50% difference after 6 orders of magnitude suppression by shielding.**
- **Designing dark matter detector:**
  - **55 g/cm^2 of CH_2 (or 20 cm of lead + 45 g/cm^2 of CH_2) should suppress the neutron flux below 1 event/ton/year at 10-50 keV nuclear recoil energies;**
  - **the required thickness of CH_2 depends on the fraction of H, density, use of lead (10 cm of Pb is equivalent to 5 g/cm^2 of CH_2), holes, neutron spectrum;**
  - **detector components (+ shielding) will become the dominant background.**

Summary - II

- **Muon-induced neutrons:**
  - FLUKA and GEANT4 (also modified GEANT3) agree within a factor of 2 (even better for some materials and energies).
  - Most experimental data (although with large uncertainties) are also in agreement with simulations within a factor of 2; some data show significantly higher neutron yield in heavy materials;
- **Designing dark matter detector:**
  - 40 g/cm^2 of CH_2 (after lead) suppress the muon-induced neutron flux down to a few events/year/tonne at a depth of about 3 km.w.e.;
  - self-vetoing is important: most neutron events have accompanying particles - gammas, electrons, muons;
  - $(3\div5)\times10^{-10}$ ($(1\div2)\times10^{-10}$) pb is reachable at ~2.5 (~3.0) km w. e. even without active veto (tested for a large xenon detector and NaCl as a rock). However, active veto is good for diagnostic and against neutrons (gammas) from the detector components.