Neutron- and muon-induced background in underground physics experiments

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Background studies in ILIAS

A working group in **ILIAS** is devoted to **background studies** within N3 and JRA1 activities

Goals:

1) **Simulations** of various types of **background** in underground laboratories; **comparison** of the **results** from MC codes with each other and with experimental data (MC validation)

2) Investigation of methods of **background suppression** and rejection (passive shielding, active vetoes etc.); formulation of requirements for shieldings and veto systems (optimisation).

Both items require **detailed Monte Carlo simulations**, including detector-related effects (geometry, response)

Active groups: **France** - Saclay, LSM, Lyon, Grenoble; **Germany** - Tuebingen, Munich-Garching, Karlsruhe, Heidelberg; **Spain** - Zaragoza, Canfranc; **Italy** - Milan, LNGS; **United Kingdom** - Imperial College, RAL, Sheffield

Neutron and muon-induced background

Neutrons are a relevant **background source** for most underground experiments through different reactions:

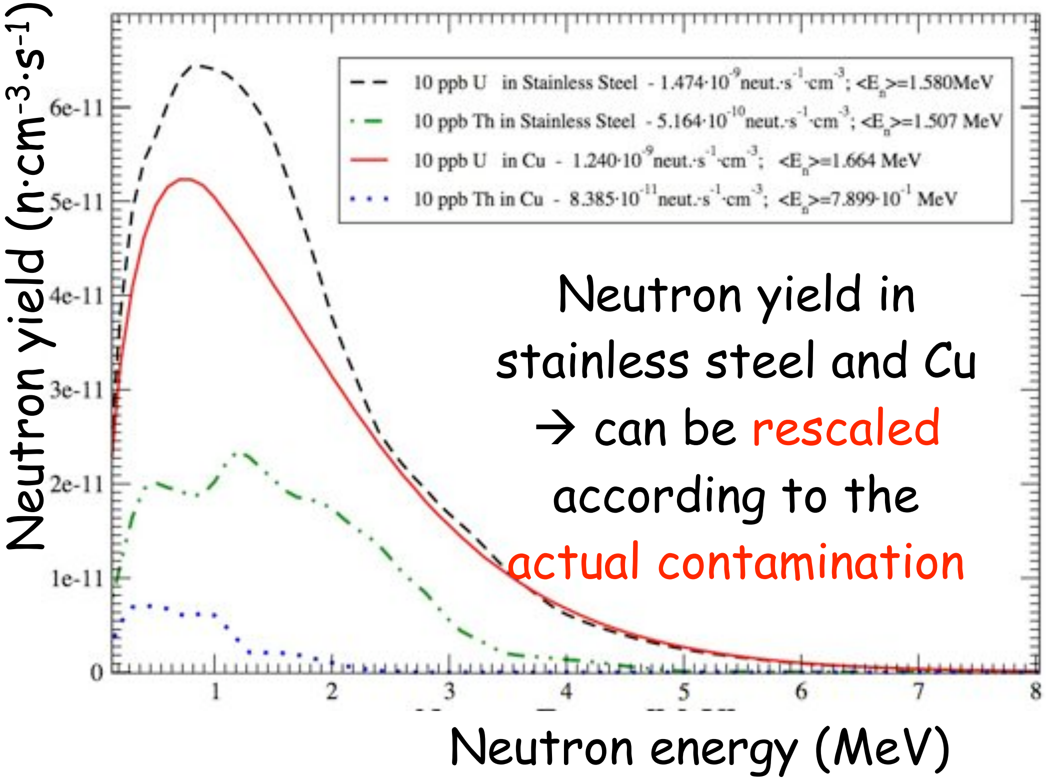
- **Dark Matter:** elastic interactions of **fast neutrons** have the same signature as WIMPs
- **Double beta decay:** γ-rays emitted in $(n,n'\gamma)$ or (n,γ) interactions may mimic DBD signature. Unstable isotopes can be created via (n,X) → possible background

Neutrons in deep underground labs are **produced** by:

- Natural radioactivity (rocks, setup materials), via spontaneous fission (^{238}U) and (α,n) reactions on light nuclei. $\mathbf{E_n < 10}$ **MeV**
- Reactions induced by cosmic ray muons (in rock or setup materials), as photo-disintegration, spallation. $\mathbf{E_n}$ **up to 100's of MeV**.

Unstable nuclei can be also produced (bck for DBD)

Neutron yield from radioactivity



Neutron yield in stainless steel and Cu → can be rescaled according to the actual contamination

Ingredients for the recipe:

- chemical composition of the material (rock, detector component)
- contamination in ^{238}U and α emitters (U and Th chains)
- cross section of (α,n) interactions and SF half-life
- propagation and detection of the produced neutrons in the materials (MCNP, Geant4)

Calculation of neutron yield per unit volume → code SOURCES-4A

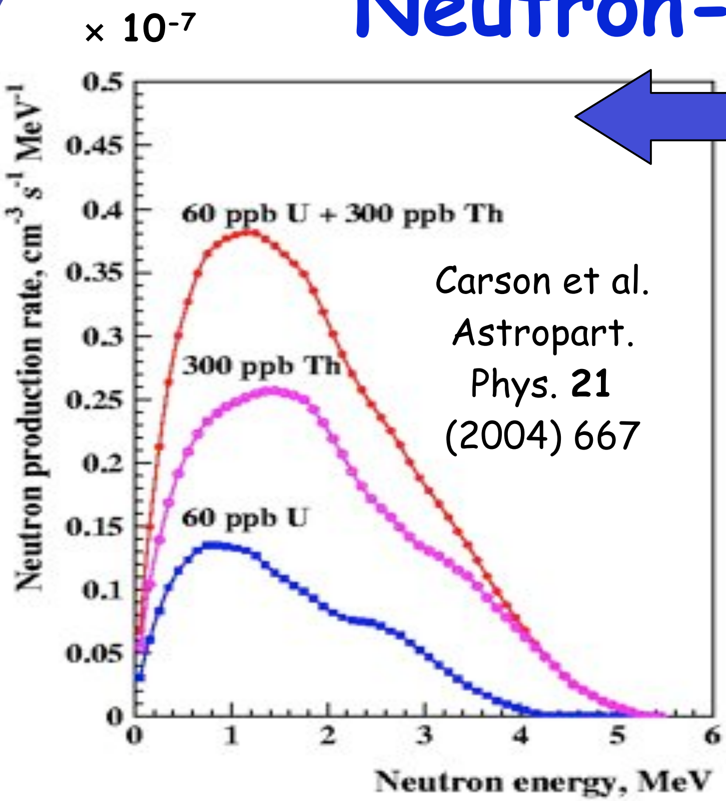
(Wilson et al. SOURCES4A, Technical Report LA-13639-MS, Los Alamos, 1999).

Substantially improved within ILIAS in order to increase energy range, to extend libraries of cross-sections (from codes or data) and of branching ratios to excited states.

Carson et al. Astrop. Phys. **21** (2004) 667

Lemrani et al., NIM A **560** (2006) 454

Neutron-induced background



Carson et al. Astropart. Phys. **21** (2004) 667

Neutron yield in NaCl → neutron production is dominated by (α,n)

Neutron yield due to the rock radioactivity and effective flux depend on **chemical composition** → absorption by H

Typical neutron flux in underground laboratories: a few 10^{-6} n/(cm^2·s). Peak energy between 1 and 2 MeV

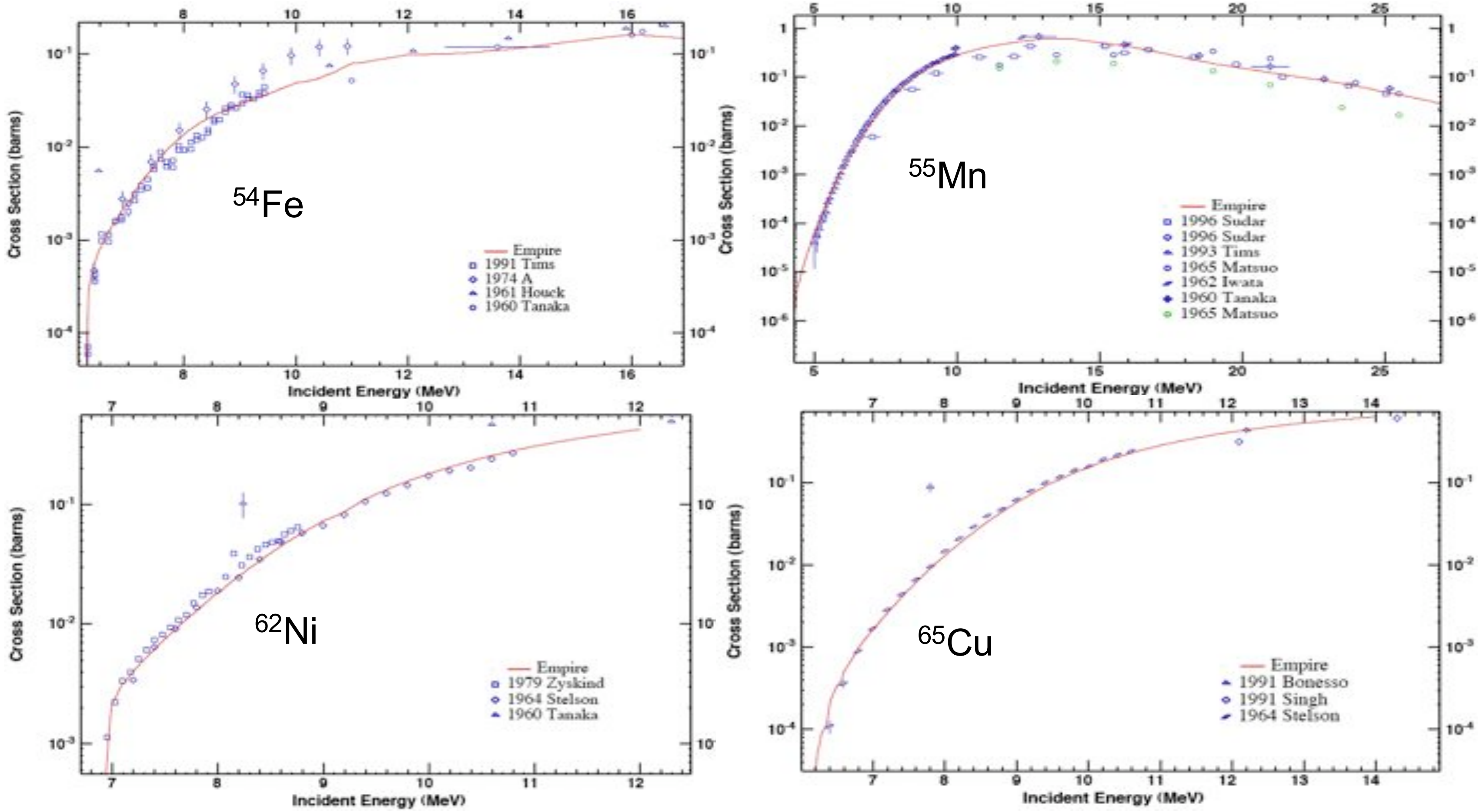
Neutron flux from the **rock** can be **effectively suppressed** by thick neutron passive shieldings → e.g. 55 g/cm^2 of CH_2 give < 1 event/(ton·year) for direct search DM experiments

The dominant source of neutron background are **detector components** and **shielding** → attention to be paid to radiopurity of the internal components and to the optimization of passive shielding

Ingredient: (α,n) cross sections

Experimental data are scarce or unavailable for some target isotopes of interest → calculated using the EMPIRE 2.19 code.

Good agreement with available experimental data (≈ 20%)

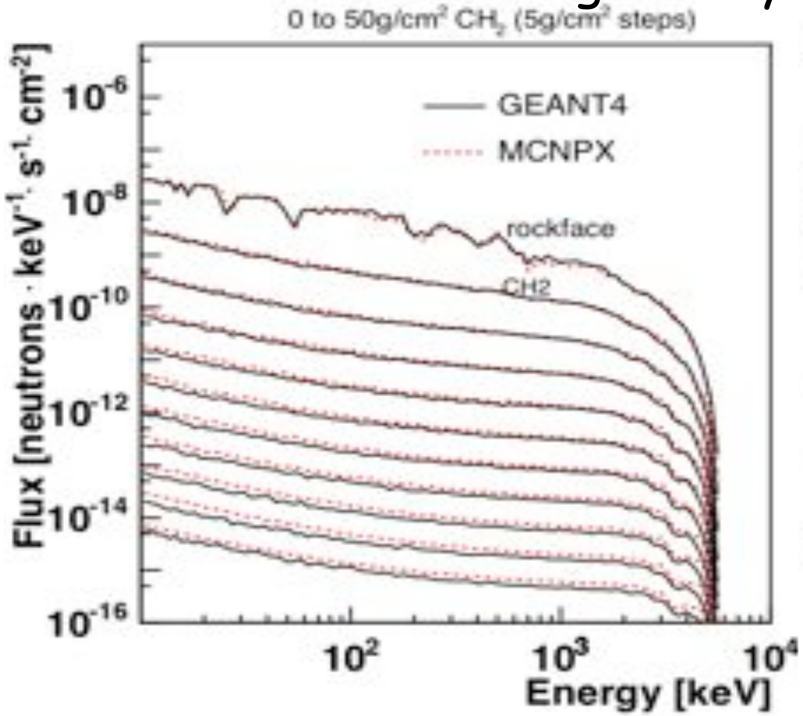


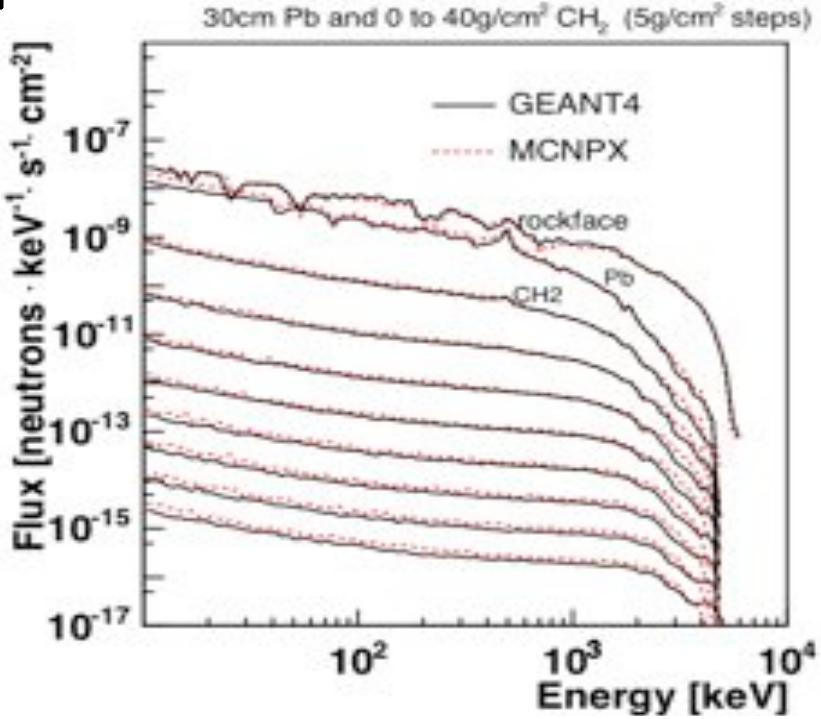
(α,n) interactions in high-Z targets (> Fe) suppressed by Coulomb barrier

Intercomparison and validation

Estimates of neutron background depend on neutron propagation in the source material (e.g. rock) and in the passive shielding.

Neutron tracking usually performed with Geant4 or MCNPX



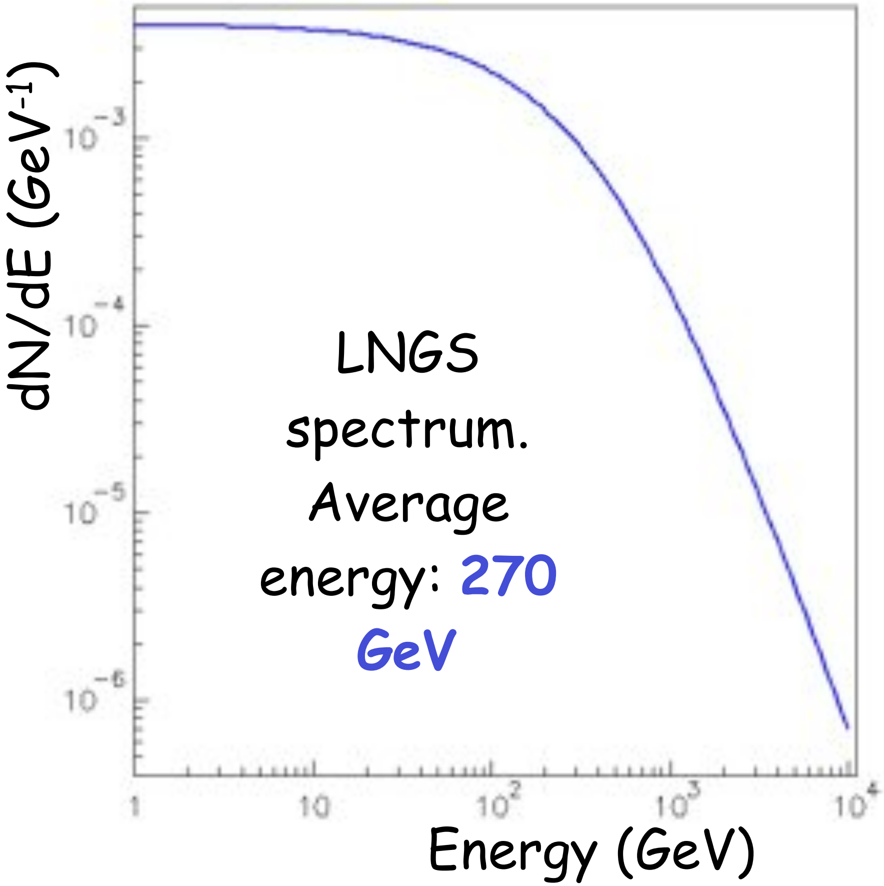


Lemrani et al, NIM A, **560** (2006) 454

MCNP vs. GEANT4 - good agreement: 50% difference after 6 orders of magnitude suppression by shielding

Measurements of environmental neutron flux performed or ongoing within **ILIAS-JRA1** (Tziaferi talk) → require detailed MC

Muon-induced neutrons



<u>Ingredients for the recipe:</u>

- Muon rate (measurements at a the underground site), e.g. 1 $\mu/(m^2 \cdot h)$ at Gran Sasso
- Muon spectrum and angular distribution. Simulations or measurements (if available) - not a problem (for example, MUSIC code - Kudryavtsev et al. Phys. Lett. B **471** (1999) 251 or MUSUN code - Kudryavtsev et al. NIMA, **505** (2003) 688).
- Interaction, production, propagation, detection of muons and secondaries (Geant4 or FLUKA)

<u>Notice:</u> all particles should be produced, propagated and detected with one code to look for **simultaneous detection** of neutrons and other particles → background identification in the detector

Integral neutron yield

Among MC outputs: integral neutron yield (normalized per muon and per g/cm^2 of target material) → can be compared to experimental data for cross-check and validation

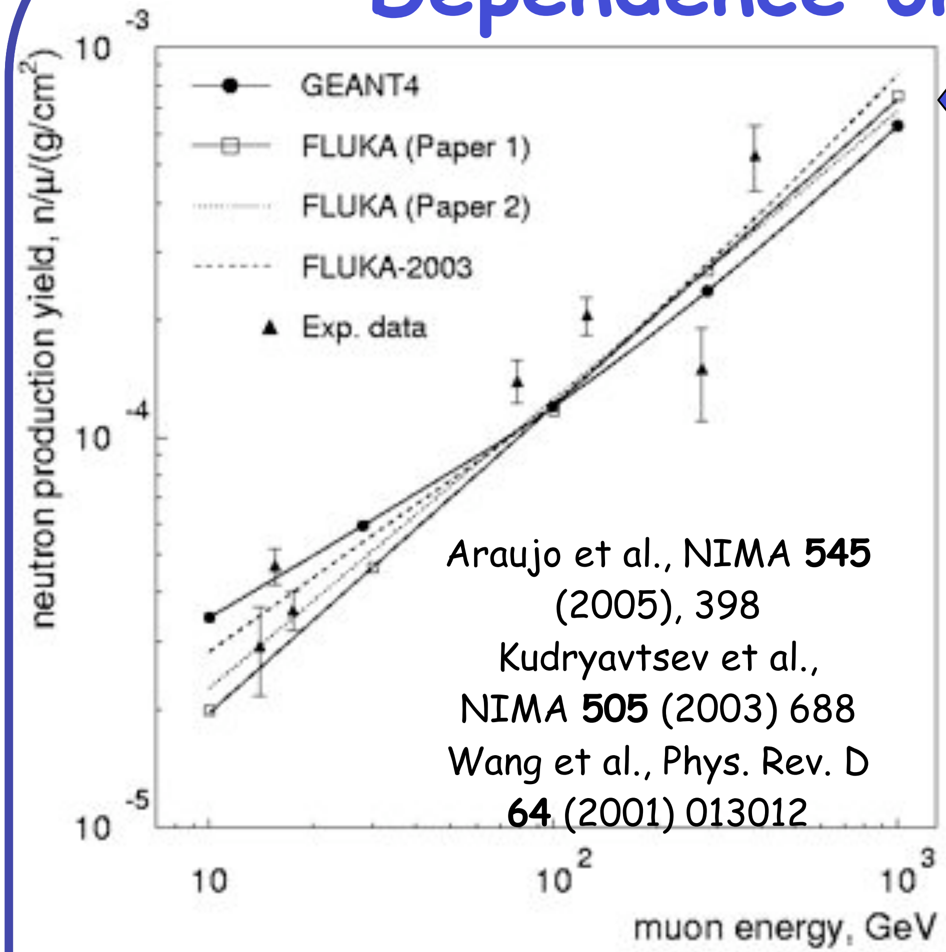
Fast neutrons (> 0.5-1 MeV) may be measured by scintillators or dark matter massive detectors → possible only at large distances from the muon track (one should not see the muon). Delayed capture signal may be used for neutron tagging (e.g. Gd-loaded scintillators or ^{3}He neutron counters)

Yield difficult to measure because energy degrades during transport in matter → data analysis needs a precise MC simulation. Ongoing TA-DUSL project (P2006-13-IUS) to measure muon-induced neutron flux at Boubly using ZEPLIN-II veto

Typical flux of fast muon-induced neutrons in deep underground Labs (LNGS, Boulby) ≈ 10^{-9} cm^{-2}s^{-1} (> 1 MeV) → 1000 times smaller than neutrons from rock radioactivity

Depends on depth (μ flux, μ energy) and rock composition

Dependence on muon energy



Araujo et al., NIMA **545** (2005), 398
Kudryavtsev et al., NIMA **505** (2003) 688
Wang et al., Phys. Rev. D **64** (2001) 013012

Neutron production rate in $(CH_n)_n$ (liquid scintillator)
Fluka and Geant4 simulations compared with experimental data

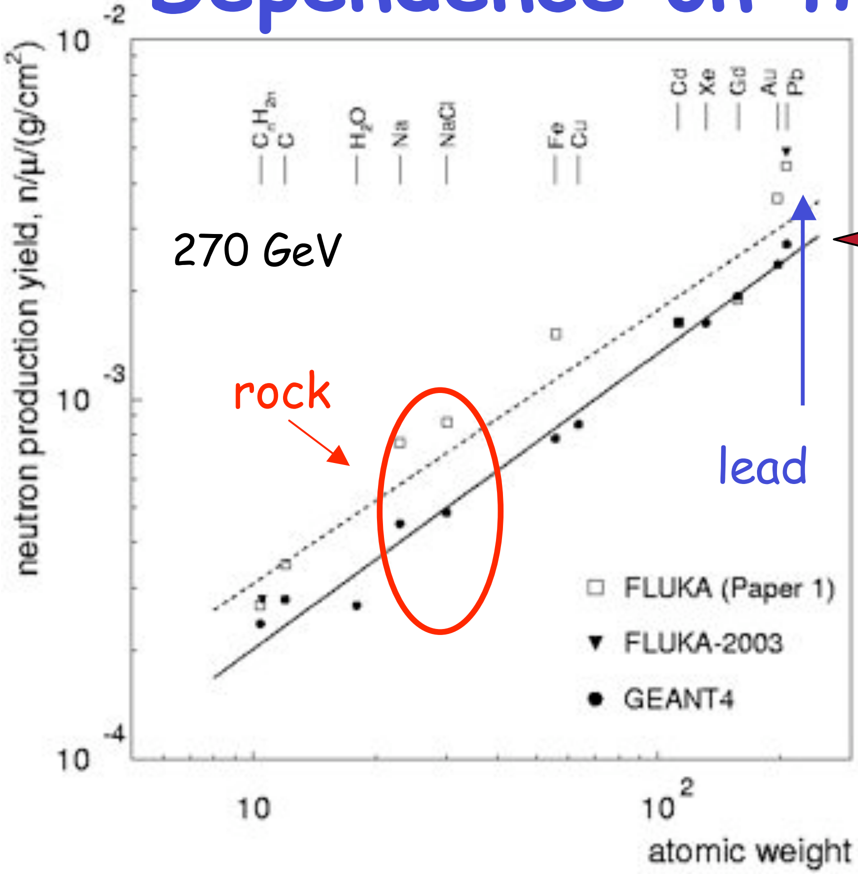
→ good qualitative agreement, but there is **no precise simulations** of detector geometry and response for any of the experiments at large depths

detector-related effects have to be taken into account for a full comparison

Different processes contribute to the neutron production: photonuclear disintegration, nucleon spallation, $\pi^{\pm}$ spallation

For Geant4 nuclear disintegration by real photons is dominant at all energies and pratically for all materials

Dependence on the A of the target



Comparison of FLUKA vs. Geant4 for different targets

GEANT4: Araujo et al. NIMA **545** (2005), 398
FLUKA: Kudryavtsev et al. NIM A **505** (2003) 688

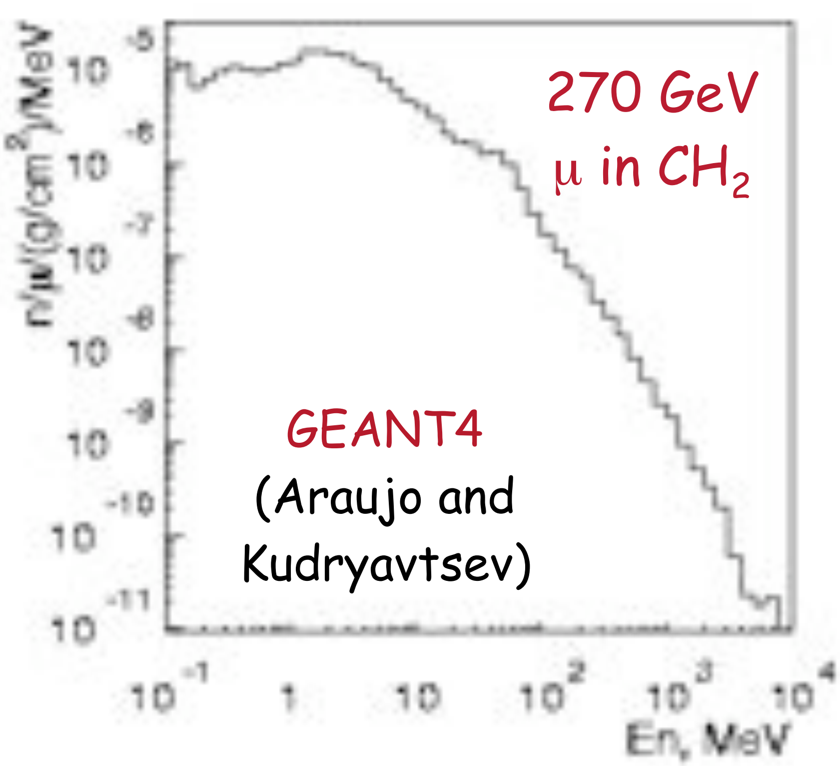
FLUKA → **twice as many neutrons** as GEANT4 for high-A material. Better agreement for **lower-A**

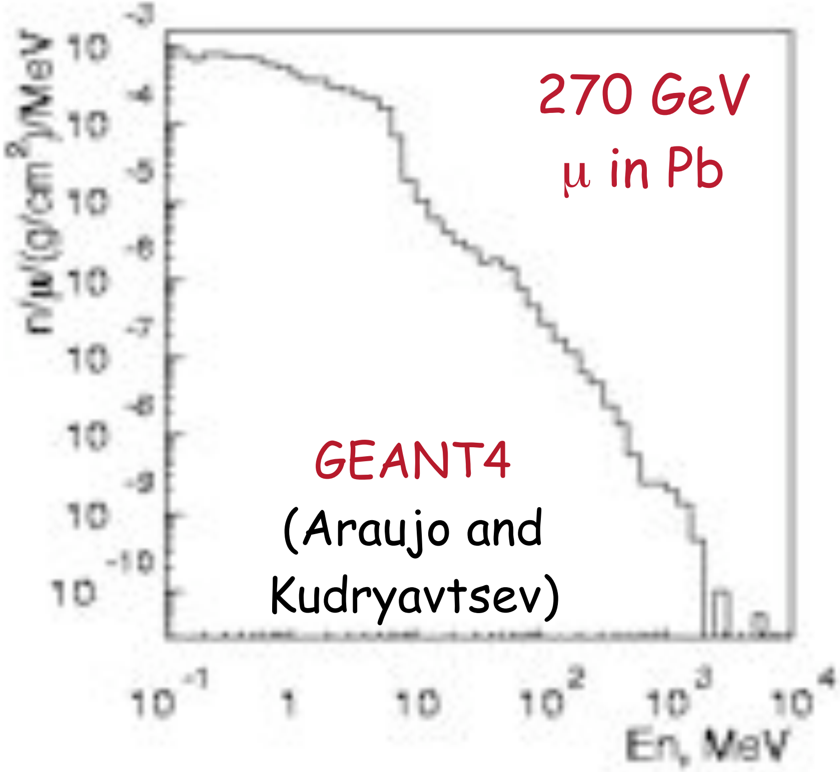
$$\boxed{Y \propto A^{0.8} \cdot \rho}$$

High-Z targets (= Pb used for passive γ-ray shielding) have a higher neutron yield → **inner** (low-Z) **neutron shielding** (CH_2, H_2O, LN_2) to reduce muon-induced neutron flux

Notice: neutrons produced in the shielding can be identified if the primary μ or other secondaries interact in the detector and/or in the veto

Neutron energy spectra

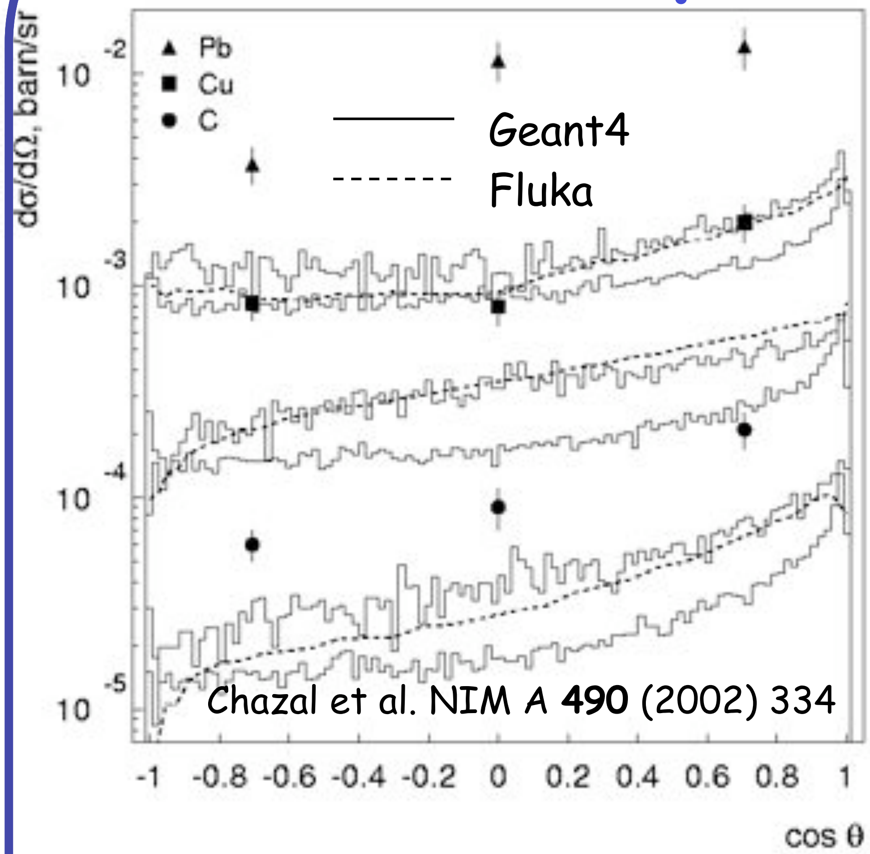




Energy spectra are **different** for different materials:

- main difference is at low energy: fast neutron yield (> 20 MeV) is not much different for CH_2 and Pb
- typically higher neutron yield (= high-A materials) → softer spectrum

Intercomparison and validation



Differential cross section of neutron production in **thin targets** (C, Cu and Pb) for 190-GeV muons (E_n > 10 MeV) NA55 at CERN

While Geant4 and FLUKA agree within a factor of two, they both seem to **underestimate substantially** the neutron production

Difficult to draw conclusions, because precise MC simulations are **not available** for these experiments

Other data for Pb are old and controversial but also show significantly higher neutron production

Bergamasco et al. Nuovo Cim. A, **13** (1973) 403; Gorshkov et al. Sov. J. Nucl. Phys., **18** (1974) 57

Pb is important since it is a common **shielding material**!

New measurements using dark matter detectors or active veto systems, associated with precise Monte Carlo simulations → **ILIAS**

Reduction of neutron background

Neutrons produced by natural radioactivity (rock & materials)

Passive neutron shielding

50 g/cm^2 of CH_2 reduce neutron flux from the rock by 6 orders of magnitude

Material selection for radiopurity

Neutron flux from the **detector components** (and shielding) **dominant**

Neutrons produced by muon interactions (rock & materials, especially Pb)

Internal neutron shielding

shield μ-induced neutrons from Pb

Simultaneous detection of μ or of other secondaries in the detector (**self-veto**) and/or in active veto

self-veto is effective because neutrons are accompained by many other secondaries

Detector design (optimization of high-Z passive materials)

Neutron-induced background → below a few events/(year·ton) for DM (10^{-10} pb sensitivity) and 10^{-3} counts/(keV·kg ·y) for DBD at the **depth** of the **ILIAS laboratories** (2-4 km w.e.)

Site-specific simulations

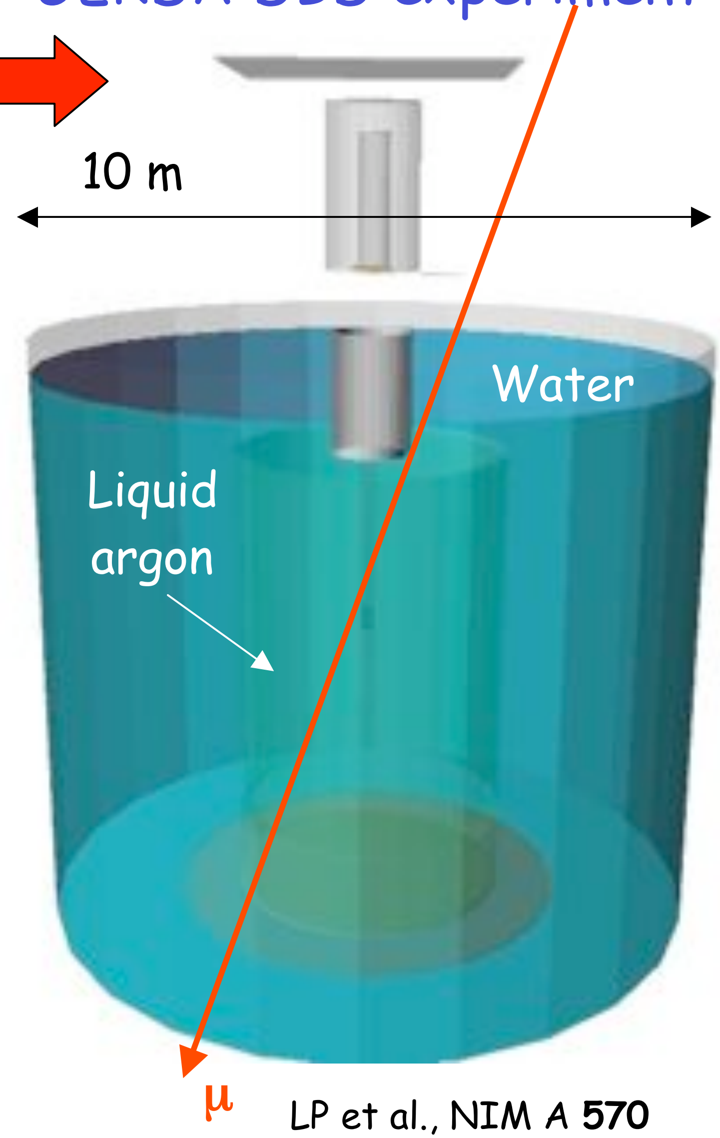
Example of site specific (and detector specific) simulation

Sampling μ according to the proper angular and energy distribution at specific site, propagating muons, generating secondaries, propagating secondaries, everything is detected

Muon-induced background is strongly **dependent** on the experimental design → material properties and placement around the detectors are important (affects muon showering and propagation of secondaries)

Shielding design has to be **optimized**: compromise between suppression of the external radiation and reduction of muon-induced background in the setup

GERDA DBD experiment



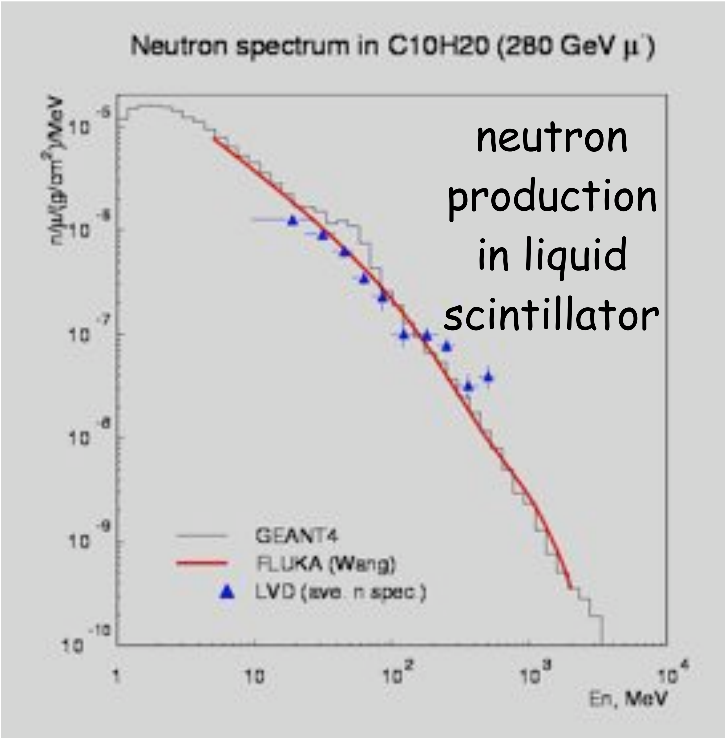
LP et al., NIM A **570** (2007) 149

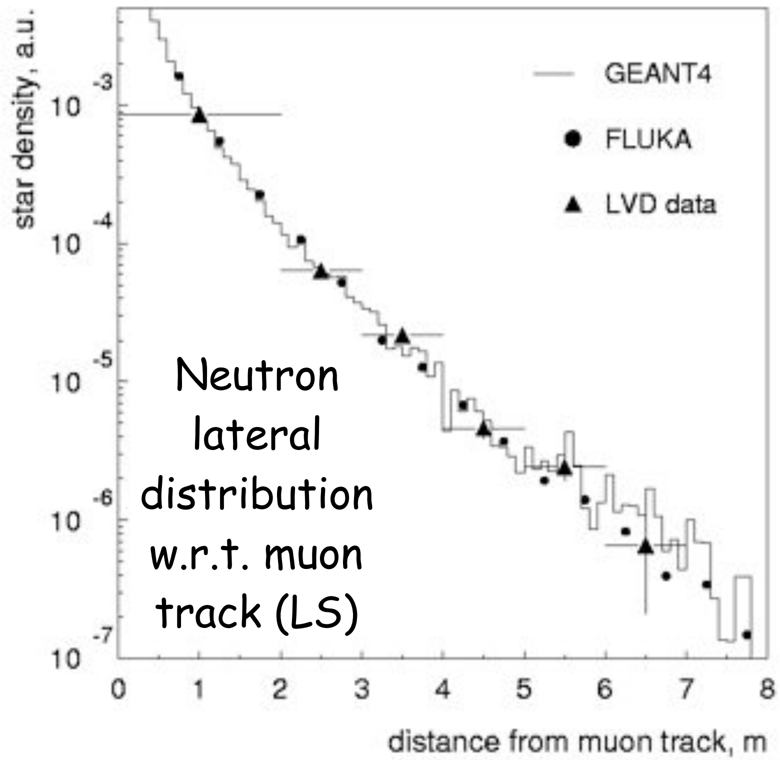
Conclusions

- Neutrons produced by natural radioactivity and by muons (in rock or detector setup) can give **background** for underground experiments
- Monte Carlo simulations (including detector-specific effects) are critical to define sensitivity and optimize rejection strategy
- Neutron flux from radioactivity → reliably **predicted** (SOURCES4A and Geant4/MCNP). Detector components may be the main contribution to neutron background → **radiopurity** issue
- Muon-induced background **strongly dependent** on the **experimental design** (material properties and placement) → neutron shielding inside Pb. **Self-vetoing** effects are relevant
- Geant4 and FLUKA agree within a **factor** of **2** for μ-induced neutrons. Needed new data, associated with precise MC simulations (→ ILIAS)
- Neutron background can be **suppressed** so that it **does not limit sensitivity** for DM or DBD at the depth of the ILIAS DULs

Backup slides

Energy spectrum & lateral distribution



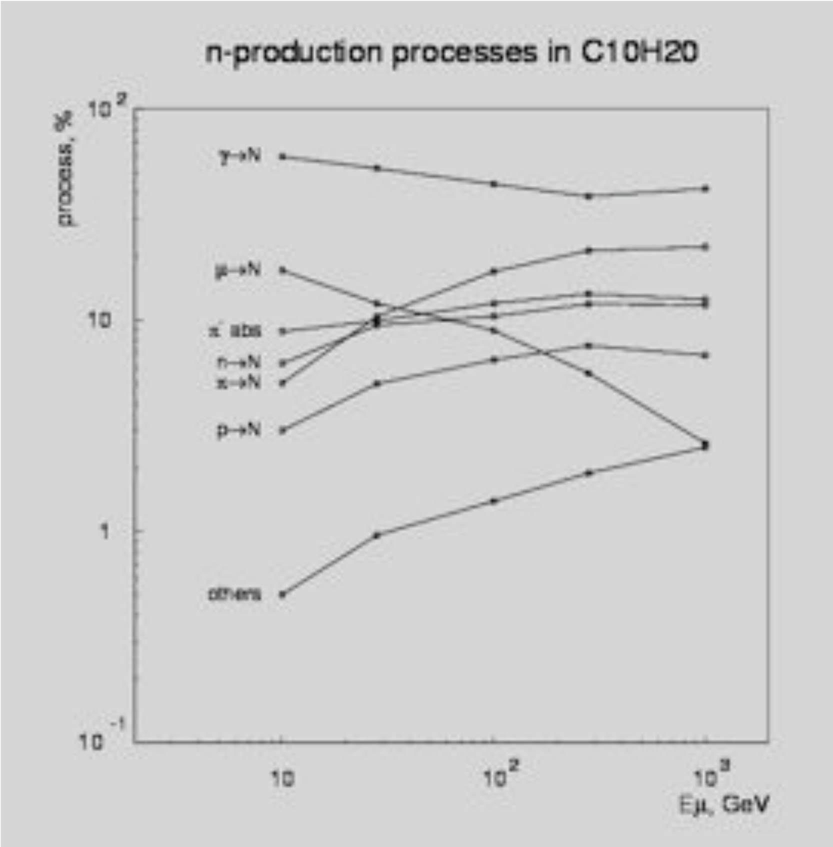


LVD and FLUKA normalised to GEANT4. Spectral **shapes** are in good agreement

Simulations do not include detector specific features. **Good agreement**

Lateral distribution is important for estimating **background rejection capability** → simultaneous detection of the parent muon or other secondary radiation (in main detector or veto)

Muon-induced neutrons: processes



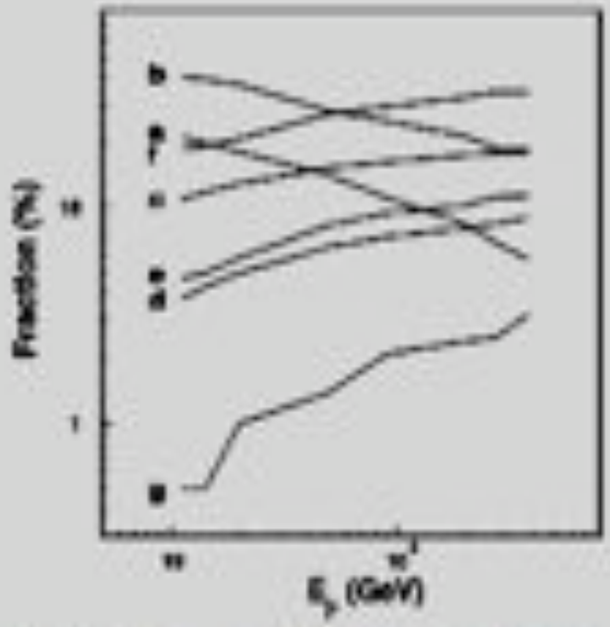


FIG. 3. Origin of neutrons: (a) direct muon spallation, (b) real photonuclear disintegration, (c) neutron spallation, (d) proton spallation, (e) π^+ spallation, (f) π^- spallation and capture, and (g) others.

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

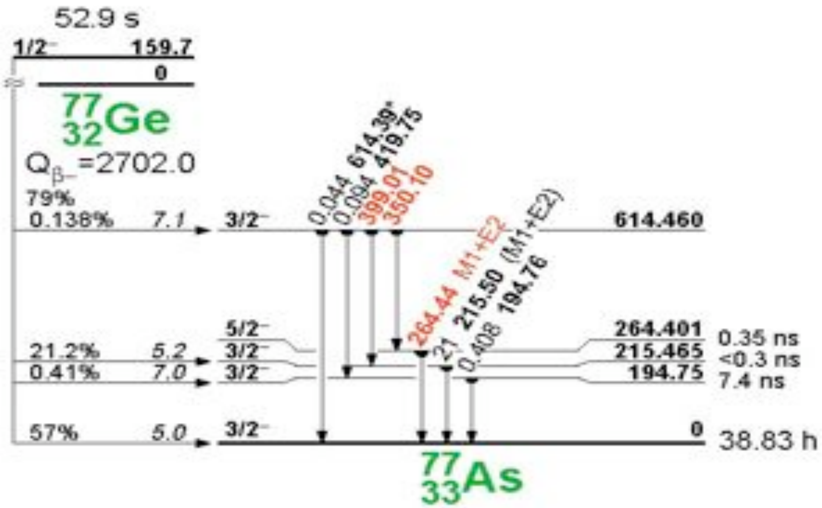
Real photonuclear disintegration dominates in **Geant4** at all energies and for (almost) all materials

Isotope production & delayed background

n or μ interactions can produce long-lived ($T_{1/2}$ > 1 s) unstable isotopes.

Their decay (**not vetable** because delayed) is a background for DBD experiments if Q > $Q_{\beta\beta}$ (not for DM because of γ/n discrimination)

For ^{76}Ge-based DBD experiments (= GERDA), the most dangerous are ^{77}**Ge** (Q=2.7 MeV, $T_{1/2}$ = 11.3 h) and ^{77m}**Ge** (Q=2.8 MeV, $T_{1/2}$ = 53 s)



Thermal neutron capture, high cross section (0.14 barn), **scales with enrichment**

Muon veto and self-veto are **uneffective**: specific cuts (delayed coincidence using prompt γ-rays) required to reduce background

The production rate in GERDA changes by a **factor of 10** using LAr or LN_2