Background studies for particle astrophysics experiments

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Abstract. Neutron background for the high-sensitivity underground particle astrophysics experiments, in particular for dark matter searches, is discussed with an emphasis on the neutrons from rock and from cosmic-ray muons.

1. Introduction
The background radiations can restrict the sensitivity of large-scale underground detectors searching for WIMP dark matter, double-beta decays or other rare processes. Knowledge of the background and ability to suppress or reject background events are essential for estimating the detector sensitivity, interpreting experimental results and designing future experiments. A new opportunity for background studies has been offered by I LIAS – Integrated Large Infrastructures for Astroparticle Science – a European Programme within Framework 6.

Neutrons underground arise from two sources: i) local radioactivity, and ii) cosmic-ray muons. Neutrons associated with local radioactivity are produced mainly via spontaneous fission of $^{238}$U and $(\alpha,n)$ reactions initiated by $\alpha$-particles from U and Th traces in the rock and detector components. The neutron yield from cosmic-ray muons depends strongly on the site depth.

2. Neutron background from rock
To reach a sensitivity down to about $10^{-10}$ pb to the WIMP-nucleon spin-independent cross-section at the minimum of the sensitivity curve the background should not exceed a few events per tonne of target per year in the energy range of interest. This requires a suppression of neutron background from rock by about 6 orders of magnitude.

The neutron yields and energy spectra from spontaneous fission and $(\alpha,n)$ reactions can be calculated with the code SOURCES [1]. A few changes have been done [2] to the original code. More cross-sections have been added [2, 3] to the code library using either experimental data or calculations [3] using the EMPIRE code (version 2.19) [4]. The modified code SOURCES has been used to simulate neutron production in NaCl [2, 5] and in the Modane rock [3].

The neutron propagation can be done using MCNP(X) or GEANT4 simulation codes. Recently a comparison between MCNPX-2.5 [6] and GEANT4.7.0.p01 [7] (with the corrected inelastic cross-section on chlorine) has been carried out [3]. Starting with the neutron production spectra provided by the SOURCES code, the neutrons have first been propagated to the rock boundary and then through different configurations of shielding which included lead and hydrocarbon in simple geometries.
The neutron spectra originated in NaCl and propagated through 30 cm of Pb and different thicknesses of CH₂ shielding are shown in figure 1 [3]. The agreement is satisfactory for the purpose of the shielding design. After 50 g/cm² of CH₂, MCNPX gives the differential flux 50% higher than the GEANT4 flux, translating into an additional 1-2 cm thick CH₂ layer.

3. Neutrons from cosmic-ray muons

At deep underground sites (3 km w. e. or more), the neutron production rate from muons is about 3 orders of magnitude lower than the rate of neutrons arising from rock activity, depending strongly both on the depth and the U/Th contamination. Muon transport through the large thickness of rock can be done with general particle physics codes such as GEANT4 [7] or FLUKA [8], or with specially developed, simple, fast and widely used muon propagation codes such as MUSIC [9]. In most cases the muon transport through the rock is not needed and can be substituted with a code which simulates muon energy spectra and angular distributions underground, for example MUSUN [10] which is widely used for muon simulations [10, 2, 5, 11].

Two general-purpose codes GEANT4 and FLUKA have been used for production, transport and detection of muon-induced neutrons. The validation of the codes has been done through their comparison with each other [12, 13] and with available experimental data [10, 14, 12]. Several models for neutron production in GEANT4 have been tested and compared to FLUKA predictions [13] allowing one to choose the most accurate model. The results of the simulations with the most accurate model agree reasonably well with most available experimental data [12]. Good agreement has been found for the neutron yields, spectra and lateral distributions in light materials. There are, however, some problems discussed in detail in Refs. [12, 15].

For high-energy muons (>100 GeV) and most targets the neutron yield from GEANT4 has been found to be less (by up to a factor of 2) than that from FLUKA [12, 13]. The neutron production in electromagnetic cascades always dominates in GEANT4 over that in hadronic cascades. In FLUKA hadronic cascades play more important role at high muon energies (>10 GeV) in most materials [10]. Despite these differences, the simulated total fluxes of fast neutrons (>1 MeV) from salt rock entering the underground cavern and after being transported through the lead and hydrocarbon shielding were found to agree within 20% [12].
The spectrum of energy depositions in a xenon-based WIMP detector has been found to be very similar in GEANT4 and FLUKA [12] (see figure 2). Some fraction of the events below 10 keV electron equivalent energy is due to nuclear recoils, assumed to have a quenching factor of 0.2. Both codes predict similar rate of neutron-induced events and similar rejection factor for most of these events due to coincidences between nuclear recoils and energy depositions from other particles in muon-induced cascades. In fact, only a few percent (5-8%) of nuclear recoils in a large-scale xenon detector are ‘pure’ nuclear recoils without other energy depositions. Note that such coincidences will be missed if the simulation of production, propagation and detection are done for neutrons only but not for all other particles. For accurate simulations of neutron-induced effects it is very important to produce, transport and detect neutrons and all other particles associated with muons with a single Monte Carlo code.

The rate of single nuclear recoils from muon-induced neutrons is expected to be about \((9 \pm 3)\) events/tonne/year at 10-50 keV Xe recoil energies [12]. This is the rate of events not accompanied by any other energy deposition due to muons or muon-induced secondaries. With an active veto around the detector this rate can be reduced by a factor of 10 [12].

4. Conclusions
A reasonably good agreement between MCNPX and GEANT4 is found for propagation of low-energy neutrons in rock, lead and hydrocarbon material. A neutron shielding equivalent to about 55 g/cm\(^2\) of CH\(_2\) (for instance 20 cm of Pb + 45 g/cm\(^2\) of CH\(_2\)) would be suitable for a one tonne-scale experiment aiming at reaching the sensitivity of \(10^{-10}\) pb to spin-independent interactions. The simulations show that muon-induced neutrons at the depth of about 3 km w. e. will not limit the sensitivity of large-scale dark matter detectors down to \((1 - 3) \times 10^{-10}\) pb (depending on the detector configuration) at the minimum of the sensitivity curve.

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