PROCEEDINGS OF SCIENCE

Calculations of background for dark matter searches

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Gamma-rays and neutrons are the most important backgrounds in high-sensitivity experiments for direct dark matter searches. They are produced in the decays of the radioactive isotopes in the detector materials and surroundings. Neutrons are originated in the spontaneous fission and (α,n) reactions from the decays of uranium and thorium and their daughters. Gamma-rays and neutrons can be attenuated and suppressed by passive and active shielding (including self-shielding). Cosmic-ray muons are responsible for producing high-energy neutrons that can travel from large distances avoiding active veto systems, hitting the target and giving a signal similar to the WIMPs' one. Gamma-rays can be discriminated from the WIMP-like interactions using different methods. This paper briefly discusses the status of background studies for direct WIMP dark matter searches. Major sources of background, such as radioactivity and cosmic rays, are considered. Special emphasis is given to high-energy muon-induced neutrons able to mimic the expected signal from WIMPs.

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1. Introduction

The sensitivity of future large-scale underground detectors for direct WIMP searches can be restricted by various types of backgrounds, high-energy gamma-rays and neutrons being among them. High-energy gamma-rays produce electron recoils via Compton scattering on target electrons. These electron recoils, although rarely, can have low energies similar to nuclear recoils from WIMP-nucleon interactions. Fortunately, electron recoils can be discriminated from nuclear recoils using specially developed techniques. Such a discrimination is characterised by a discrimination factor – the average fraction of non-discriminated electron recoils relative to the total rate at the energy range of interest. Non-discriminated electron recoils are those passing all cuts and mimicking nuclear recoils from WIMP interactions. The most sensitive current dark matter experiments have reached discrimination factors as low as $10^{-3}-10^{-4}$. Neutrons are more dangerous since single nuclear recoils from neutron interactions are indistinguishable from WIMP-induced events.

Both neutrons and gamma-rays are originated in the decays of radioactive isotopes. Neutrons associated with local radioactivity are produced via spontaneous fission of ^{238}U and (α,n) reactions initiated by α-particles from U/Th traces in the rock and detector components. Gamma-rays are coming from U/Th decay chains, as well as from the decays of ^{40}K, ^{60}Co and some other long and short-lived isotopes generated by cosmic rays, nuclear reactors or nuclear explosions.

Neutrons can also be produced by cosmic-ray muons pushing dark matter and some other particle astrophysics experiments deep underground where the muon flux is attenuated by a large thickness of rock above the laboratory. However, even at a few km w.e. underground, the muon flux can be high enough to cause severe problems for high-sensitivity detectors. An active veto system around the main detector target is an efficient way of rejecting muon-induced events but proper estimate of the residual neutron background should be done.

Knowledge of background fluxes and ability to suppress or reject background events are essential for estimating detector sensitivity, interpreting experimental results and designing future experiments. Background studies have been initiated by many collaborations to evaluate the potential of large-scale experiments in the area of astroparticle physics, design their shielding and active veto systems. A coordinated approach for such studies, an opportunity to share the Monte Carlo codes, test them and exchange all relevant information have been offered by ILIAS – Integrated Large Infrastructures for Astroparticle Science – a European Programme within Framework 6.

In this paper we briefly discuss gamma-ray and neutron backgrounds that may limit the sensitivity of future large-scale experiments. We concentrate on the gamma-ray background and neutrons from muons. More on gamma-ray backgrounds and neutrons from radioactivity can be found in Ref. [1] and references therein.

2. Gamma-rays from radioactivity

Gamma-rays from radioactivity in rock and concrete walls can be attenuated by a sufficiently thick layer of shielding. Usually high-Z material such as lead, steel or copper is used. As was shown in Ref. [2] $\approx 20-25$ cm of lead can attenuate the gamma-ray flux from rock by about 5-6 orders of magnitude (depending on the energy). This will allow the rejection of practically all remaining gamma-induced background events at low energies providing a gamma-ray discrimination factor of about 10^4 is achieved. If a thick (≈30 cm) layer of concrete is put on the rock walls, then the gamma-ray flux is dominated by that from concrete walls (more than 90% contribution).

Several proposals for high-sensitivity detectors rely on the water shielding against both neutrons and gamma-rays. For instance, a proposal for an extension of the Modane Underground Laboratory (LSM) contains a water shielding around the laboratory walls in one of the halls [3]. Fig. 1 [1] shows the simulated spectra of gamma-rays and electrons originated from the measured concentration of Th in concrete of LSM beyond different layers of water. The GEANT4 toolkit [4] has been used for particle transport and detection. The single electron recoil spectra in Ge crystals (≈ 104 kg of Ge) beyond 2 m of water are presented in Fig. 2. The back-scatter peak is clearly seen between 100 and 200 keV. The spectrum below 30 keV is essentially flat, being dominated by the Compton electrons from high-energy gamma-rays. After 2 m of water the event rate at 10-50 keV in 104 kg Ge detector can be about 10^5 events/year assuming the measured concentrations of U/Th/K in the LSM rock and concrete. After 3 m of water the rate is reduced down to about 1200 events/year that can be suppressed by discrimination techniques. Neutrons from rock/concrete can be efficiently attenuated by about 60 cm of water [1].

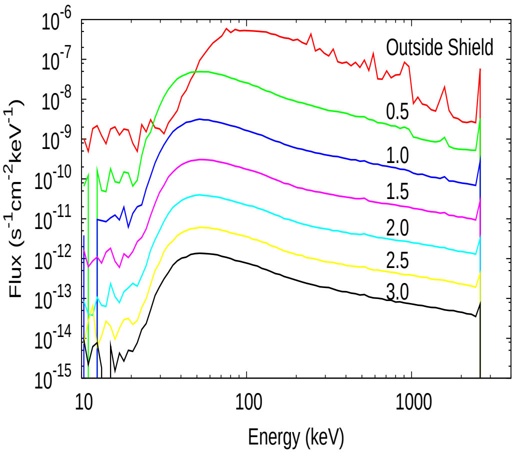

Figure 1: Gamma-ray and electron fluxes beyond different layers of water (thickness in metres is shown above the curves). The source is ^{232}Th in equilibrium in 30 cm thick concrete walls.

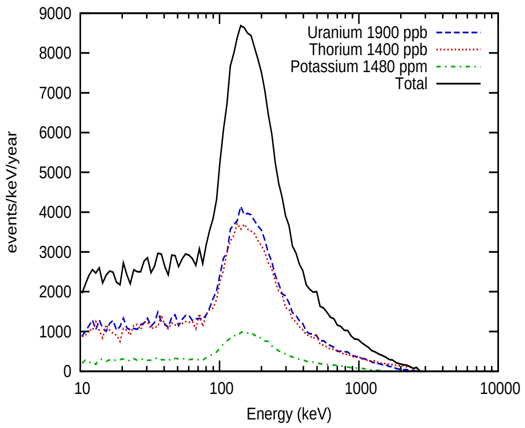

Figure 2: Electron recoil rate in 104 kg of Ge from gamma-rays originated in concrete. Measured concentrations of U/Th/K in the LSM rock are indicated on the graph.

Placing the water shielding around the walls of the laboratory results in the additional gamma-ray and neutron fluxes coming from the water tank vessel(s). Equipment located in the lab inside the water shielding will also contribute to the background in the detector. This will require additional shielding to be placed around the sensitive volume of the detector. Gamma-ray and neutron backgrounds from detector components in connection with the large-scale Ge experiment are described in Ref. [1].

3. Muon-induced neutrons

At deep underground sites (≥ 3 km w. e.) the neutron production rate from muons is at least 3 orders of magnitude lower than the rate of neutrons from U/Th traces in rock. Muon-induced neutron flux can be important, however, for experiments planning to reach high sensitivity to WIMPs or other rare events. This flux is proportional to the muon flux but also increases with the mean muon energy underground (see, for example, Ref. [5] for discussion). As neutrons are produced not only in rock but also in all materials in and around a detector, the total neutron flux is strongly affected by the composition of the detector and its surroundings. It can be enhanced significantly by the presence of high-A target close to the detector. It can also be significantly reduced at energies below 10 MeV by the presence of hydrogen in the shielding. All these effects complicate simulations of the muon-induced neutron background. To make accurate predictions full Monte Carlo of the experimental setup is needed.

Two general-purpose codes GEANT4 [4] and FLUKA [6] have been used so far for production, transport and detection of muon-induced neutrons. The validation of the codes has been done through the comparison of them with each other [7, 8] and with available experimental data [9, 5, 7]. The results of the simulations agree within a factor of 2 with most available experimental data [7, 11]. However, most experiments that measured muon-induced neutrons, did not present accurate Monte Carlo simulations which would include their setups together with production, transport and detection of all particles produced by muons. This makes the interpretation of experimental results difficult. Muon-induced neutron production in lead has recently been measured at the Boulby Underground Laboratory [10] and found to be 1.7 times smaller than the predicted rate. Accurate simulations of the setup and all physical processes allowed direct comparison between measured and simulated event rates.

For high-energy muons ($>$100 GeV) and most targets the neutron yield from GEANT4 has been found to be less (by up to a factor of 2) than that from FLUKA [7]. Despite this difference, the simulated total fluxes and spectra of fast neutrons ($>$1 MeV) at different surfaces within an experimental setup are found to be in agreement within 20%. Fig. 3 [11] shows energy spectra of neutrons at production in different materials as generated by GEANT4. Energy spectra of neutrons coming from different processes are presented in Fig. 4 [11] (see also Ref. [12]).

Total neutron yields in light and heavy materials are very much different and the spectra of neutrons are different too (see Fig. 3). In heavy materials the enhancement of the neutron flux occurs mainly at low and intermediate energies ($<$ 20 MeV), whereas the spectra above 20 MeV are not much different (in shape and absolute fluxes) from those in light targets [5, 7, 11].

When simulating muon-induced neutrons, it is important to generate, transport and detect all particles produced by muons. Neutrons, and especially fast neutrons, are emitted preferentially along the muon path leading to a high probability that a neutron will be detected together with a muon or cascade (possibly in an active veto system).

4. Conclusions

Recent simulations of gamma-rays from rock/concrete show that their flux can be efficiently attenuated by about 25 cm of lead or 3 m of water. Inner shielding around the sensitive volume of the detector may be needed if the outer shielding is thinner than required. Muon-induced neutrons and their background event rate can be simulated with sufficient accuracy (within a factor of 2) using GEANT4 if all particles produced by muons are transported and detected in a precisely modelled setup.

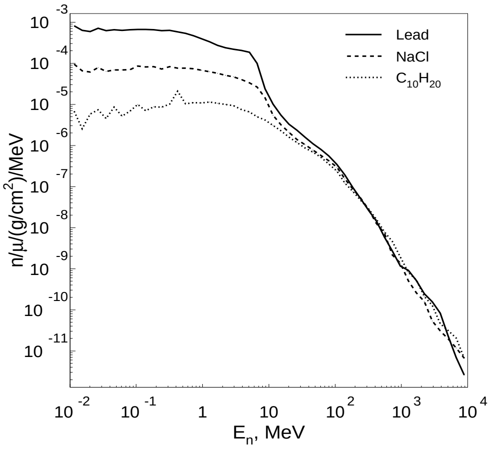

Figure 3: Differential energy spectra of neutrons produced in Pb (thick curves), NaCl (dashed curves) and C_nH_{2n} (dotted curves) for 280 GeV incident muons. Mean energies of these distributions are 8.8 MeV, 23.4 MeV and 65.3 MeV for Pb, NaCl and C_nH_{2n} respectively [11].

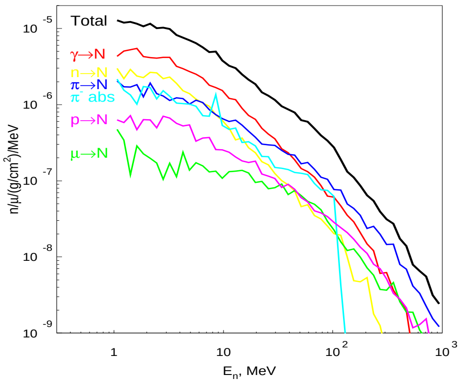

Figure 4: Differential energy spectrum of neutrons produced in C_nH_{2n} by 280 GeV muons (thick black curve). Also shown are the contributions of the most important individual processes: photonuclear interaction of γ-rays ($\gamma \rightarrow$ N), neutron inelastic scattering (n $\rightarrow$ N), pion spallation ($\pi \rightarrow$ N) and absorption (π *abs*), and proton (p $\rightarrow$ N) and muon ($\mu \rightarrow$ N) spallation [11].

5. Acknowledgements

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