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# Direct measurement of neutrons induced in lead by cosmic muons at a shallow underground site

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## ABSTRACT

Neutron production in lead by cosmic muons has been studied with a Gadolinium doped liquid scintillator detector. The detector was installed next to the Muon-Induced Neutron Indirect Detection EXperiment (MINIDEX), permanently located in the Tübingen shallow underground laboratory where the mean muon energy is approximately 7 GeV. The MINIDEX plastic scintillators were used to tag muons; the neutrons were detected through neutron capture and neutron-induced nuclear recoil signals in the liquid scintillator detector. Results on the rates of observed neutron captures and nuclear recoils are presented and compared to predictions from GEANT4-9.6 and GEANT4-10.3. The predicted rates are significantly too low for both versions of GEANT4. For neutron capture events, the observation exceeds the predictions by factors of $1.65 \pm 0.02\,(\mathrm{stat.}) \pm 0.07\,(\mathrm{syst.})$ and $2.58 \pm 0.03\,(\mathrm{stat.}) \pm 0.11\,(\mathrm{syst.})$ for GEANT4-9.6 and GEANT4-10.3, respectively. For neutron nuclear recoil events, which require neutron energies above approximately 5 MeV, the factors are even larger, $2.22 \pm 0.05\,(\mathrm{stat.}) \pm 0.25\,(\mathrm{syst.})$ and $3.76 \pm 0.09\,(\mathrm{stat.}) \pm 0.41\,(\mathrm{syst.})$, respectively. Also presented is the first statistically significant measurement of the spectrum of neutrons induced by cosmic muons in lead between 5 and 40 MeV. It was obtained by unfolding the nuclear recoil spectrum. The observed neutron spectrum is harder than predicted by GEANT4. An investigation of the distribution of the time difference between muon tags and nuclear recoil signals confirms the validity of the unfolding procedure and shows that GEANT4 cannot properly describe the time distribution of nuclear recoil events. In general, the description of the data is worse for GEANT4-10.3 than for GEANT4-9.6.

## 1. Introduction

Muon-induced neutrons are an important background for underground experiments searching for rare events such as neutrinoless double beta decays [1,2], direct dark matter interactions [2,3] or neutrino interactions in oscillations experiments [2,4]. Experiments can sufficiently shield against neutrons from the radio-impurities in the rock surrounding the laboratories, because the kinetic energy of these neutrons is usually below 10 MeV and, thus, they are efficiently thermalized by low Z materials such as water or polyethylene. It is more difficult to shield against neutrons induced by cosmic muons because the high-energy muons that penetrate deep into the ground can produce neutrons with much higher energies.

A particular case are experiments using high-Z materials like lead, steel and copper for shields [5] close to the active detector. The cross sections for muons to generate neutrons in these materials are large and the neutrons can reach kinetic energies up to several GeV. These high energy neutrons have a large penetration power and can create secondary showers with many neutrons reaching the vicinity of the active detectors. In addition, the active detector itself can be made out of a high-Z material, like in the case of Germanium based experiments to search for neutrinoless double beta decay [1,5] or dark matter [6]. The experiments usually have a muon veto, which is used to reject signals following the passage of a muon. However, the neutrons from the showers can create meta-stable states in the inner structures or active parts of an experiment which can decay minutes or hours later and cannot be vetoed easily. An example is the creation of $^{77m}$Ge from $^{76}$Ge,

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**Table 1**
Underground experiments on neutrons induced by cosmic muons in lead.

| Depth (mwe) | Lead thickness (cm) | Reference |
|---|---|---|
| 12 | 15 | Gorshkov et al. [10] |
| 16 | 50 | Abt [11] and this work |
| 20 | 7.6 | Crouch and Sard [12] and Annis [13] |
| 40 | 10 | Gorshkov et al. [14] |
| 58 | –[a] | Short [15] |
| 60 | 10 | Bergamasco [16] |
| 80 | 10 | Gorshkov et al. [14] |
| 110 | 10 | Bergamasco [16] |
| 150 | 10, 16 | Gorshkov and Zyabkin [17], 18] |
| 800 | 10 | Gorshkov et al. [14] |
| 2850 | –[b] | Araújo [8] and Reichhart [19] |
| 4300 | 35 | Bergamasco et al. [20] |
| 4800 | 10 | Kluck [9] |

[a] The lead was mixed with rock and the neutron spectrum was measured with low statistical significance.

[b] The target was the whole lead shielding system of the ZEPLIN-II and ZEPLIN-III experiments.

for which the decay scheme includes a beta decay with a half-life of 12 h [7].

There are four main processes how muons generate neutrons inside matter:

- muon-nuclear deep inelastic scattering;
- photo-nuclear reactions, i.e. Bremsstrahlung photons induce photo-disintegration;
- hadronic inelastic scattering, i.e. muon-induced secondary hadrons cause hadron-induced spallation;
- $\mu^-$ capture, i.e. nuclei excited by $\mu^-$ capture release neutrons.

Muon capture is only relevant in shallow underground sites with a depth of $\lesssim 100$ m water equivalent (mwe) [8].

The production of muon-induced neutrons has been investigated for different materials and at different depths for many years [9]. In this paper, the focus is on lead as a target material. Details about some selected experiments on lead are listed in Table 1.

Of the experiments previous to this work listed in Table 1, only the experiment at the Holborn underground laboratory [15] has published a measurement of the spectrum of the neutrons induced by cosmic muons, albeit with low statistical significance. In addition, the target was composed of a mixture of lead and rock and no corresponding simulation was available. Complementary to the underground experiments on neutrons induced by cosmic muons, two accelerator based experiments measured muon-induced neutron spectra in lead. These were the E665 experiment at Fermilab using a 470 GeV muon beam [21] and the NA55 experiment at CERN using a 190 GeV muon beam [22]. The results of the NA55 experiment were compared to GEANT4-8.0 simulations and significant discrepancies in neutron multiplicities and angular distributions were found [23]. An updated experiment using a 160 GeV muon beam has recently been performed [24].

In this paper, a detailed investigation of neutrons induced by cosmic muons in lead is presented. The experiment was performed in the shallow underground laboratory at the University of Tübingen. Thus, the results cannot be directly used to predict the background in deep underground laboratories. They can, however, be used to evaluate the Monte Carlo (MC) programs used to make such predictions.

To measure the spectrum of muon-induced neutrons, a 28-liter Gadolinium doped (0.5% in weight) liquid scintillator (Gd–LS) detector was installed next to the MINIDEX (Muon-Induced Neutron Indirect Detection EXperiment) [11] setup. The details of the experimental setup and the detector concept are introduced in Section 2. The energy calibration is described in Section 3. The selections of events and their processing are presented in Section 4. The details of the MC simulations are described in Section 5. The results are given in Section 6. A discussion on the MC performance and a summary are presented in the last two Sections.

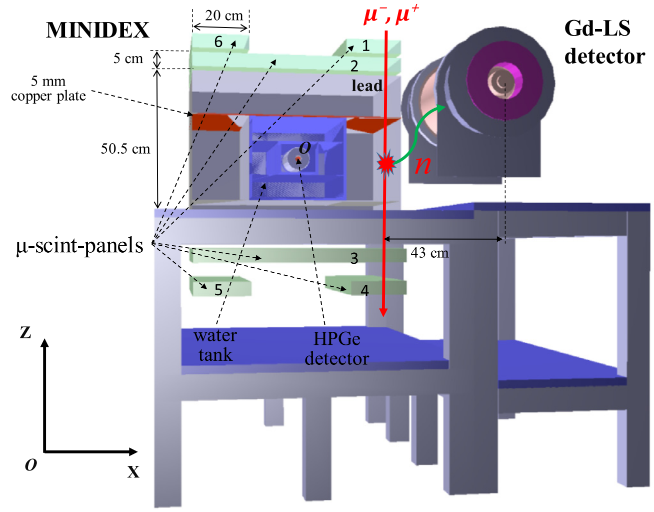

**Fig. 1.** The MINIDEX setup together with the Gadolinium doped liquid scintillator (Gd–LS) detector. The six muon scintillator panels (μ-scint-panels) were used to independently identify cosmic muons passing through the left-side and right-side lead walls. Signals in the four muon scintillator panels labeled 1, 2, 3 and 4 were required to select muon-induced signals in the Gd–LS detector. A steel box enclosing the Gd–LS detector is not shown.

## 2. Experimental setup and detector concept

The Gd–LS detector was placed next to one of the lead walls of the MINIDEX in the underground laboratory in Tübingen. The nominal vertical depth of the site was given [25] as 16 mwe; the cover consists predominantly of soil. According to simulation, which is described in Section 5, the average energy of the cosmic muons entering the laboratory was ≈7 GeV.[2] The geometry of the MINIDEX setup plus the Gd–LS detector is shown in Fig. 1. A detailed description of MINIDEX is given in [11]. Here, only components relevant for the analysis of the data from the Gd–LS detector data are described.

In the standard MINIDEX analysis, neutrons were identified with two high-purity germanium (HPGe) detectors embedded in a water tank. These were used to detect 2.2 MeV γ-rays emitted after neutron capture in water. The dimensions of the water tank were $35 \times 55 \times 30$ cm$^3$ with a $15 \times 55 \times 10$ cm$^3$ central cavity in which the HPGe detectors were inserted. The water tank and the HPGe detectors were fully surrounded by a lead castle, used both as a shield for the HPGe detectors and as the target for muons to generate neutrons. The thickness of the lead castle was 15 cm at the top supported by a 5 mm thick copper plate, 5 cm at the bottom and 5 cm for the two side walls at right angle to the HPGe and Gd–LS detectors which are not shown in Fig. 1. The two lead walls parallel to the Gd–LS detectors were 20 cm thick. These two walls are hereafter referred to as the left-side and right-side lead walls where the right-side wall is next to the Gd–LS detector.

A schematic of the Gd–LS detector is shown in Fig. 2. Organic liquid scintillator (EJ-335) was held inside a 8 mm thick tempered

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[2] The technical drawings and the result of the simulation indicate that the value of 16 mwe is an overestimate and that the overburden more closely corresponds to 12 mwe, see also Section 5.