A comprehensive comparison for simulations of cosmic-ray muons underground

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Abstract. The two leading simulation frameworks used for the simulation of cosmic-ray muons underground are FLUKA and Geant4. There have been in the past various questions raised as to the equivalence of these codes regarding cosmogenically produced neutrons and radioactivity in an underground environment. Many experiments choose one of these frameworks, and because they typically have different geometries or locations, the issues relating to code comparison are compounded. We report on an effort to compare the results of each of these codes in simulations which have simple geometry that is consistent between the two codes. It is seen that in terms of integrated neutron flux and neturon capture statistics the codes agree well in a broad sense. There are, however, differences that will be subject of further study. Comparisons of the simulations to available data are considered and the difficulties of such comparisons are pointed out.

Keywords: cosmogenics, neutrons, low background
PACS: 96.50.S-,25.30.Mr,25.20.-x,25.30.-c

INTRODUCTION

Cosmogenically produced prompt radiation or residual radioactivity are sources of backgrounds for deep-underground experiments which can have impacts up to and beyond depths of 3 km.w.e if the experimental sensitivity is not limited first by some other background [1]. One approach which is typically taken to quantify these backgrounds is to propagate surface muon energy and angular distributions [2] to the depth of the experimental installation where a full simulation of the surviving muons through underground cavern material is performed. Different experimental collaborations typically perform these simulations with various generalized simulation packages, FLUKA and Geant4 being two examples [3, 4, 5]. It is important to fully understand the physics included in these simulation packages, how their implementations differ, and how the key results compare to data. Because of these facts an effort to comprehensively characterize important physics for cosmogenically induced radiation with both FLUKA and Geant4 in a simple geometrical environment is underway and first results are reported here.

FLUKA is a particle physics Monte Carlo simulation package which traditionally has been applied to cosmogenic background problems. Its predictions are predominantly based on original and well-tested microscopic models. The physics models are fully integrated in the code and can not be modified by the user. Details about the implemented muon-nucleus interactions and hadronic models relevant to the production of cosmogenic neutrons can be found in [6, 7, 8, 9, 10]. Low-energy neutrons with kinetic energies < 20 MeV are treated in the multi-group approach in FLUKA which requires a careful interpretation of results at the single event level. FLUKA 2011.2.17 from December 2012 was used for the simulation with the FLUKA default setting PRECISIO(n). Photonuclear interactions were enabled through the user option PHOTONUC and a more detailed treatment of nuclear de-excitation was requested with the options EVAPORAT(ion) and COALESCE(nce). In addition, the treatment of nucleus-nucleus interaction was turned on for all energies via the option IONTRANS.

Geant4 is in general a particle tracking Monte Carlo code which has been predominantly used in high-energy particle physics and radiation protection. The code attempts to explicitly include all relevant interactions to a simulation in a modular, user-defined way and then use the selected models and stored relative probabilities (usually cross sections) of each interaction in a given material to decide the course of the tracked particle at the next simulation step. The simulation of a particle proceeds on a microscopic basis (interaction-by-interaction) until it is absorbed, an energy limit is reached or it decays. While the code includes well-tested microscopic models for many processes, details of the physics models used can in general be modified by the user and in principle the user has access to the entire source code of Geant4. The Shielding physics list is used for the Geant4 simulations in this study [11]. The Shielding list is a composition of hadronic, leptonic and radioactive decay physics which previously had to be

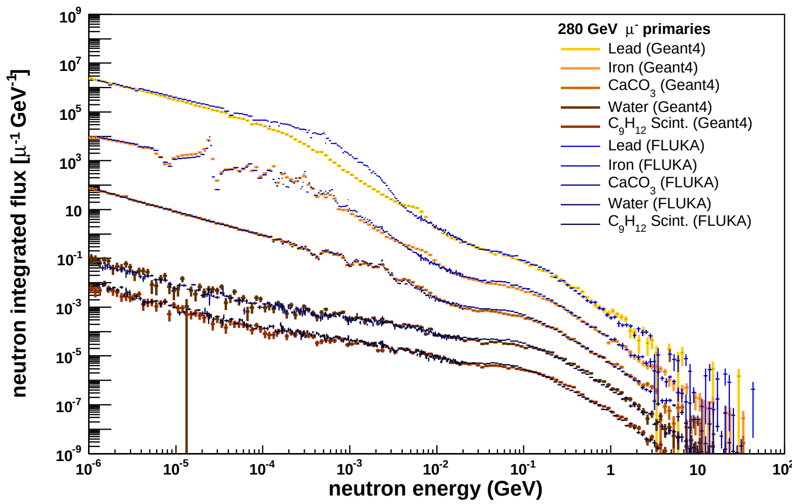

FIGURE 1. Integrated neutron fluxes across perpendicular planes for all materials down to neutron energy of approximately 1 keV. Each material is scaled by a power of 10 for plotting purposes, lead by 10^{0}, iron by 10^{-1}, $CaCO_3$ by 10^{-2}, water by 10^{-3} and liquid scintillator by 10^{-4}. The FLUKA simulations are shown in blue shades while the Geant4 simulations are shown in yellow/orange shades. The neutron fluxes are integrated over a plane in the geometrical center of the cylindrical slab perpendicular to the muon momentum. The central plane is located after the muon shower has fully developed in all materials.

included one-by-one. In particular, the Shielding list includes muon nucleus interactions and hadronic models relevant to the production of cosmogenic neutrons [12, 13]. One of the original uses for this list was underground or low-background experiments, so it includes high precision neutron transport physics. The version of Geant4 used in this study is currently Geant4.9.5p01, but the Shielding list has been available since Geant4.9.4.

In order to get the greatest access to the physics of the cosmogenic cascades a simple cylindrical geometry is used with five materials. The materials were selected to be some of those that are present in currently operating underground laboratories and to give a broad range of nuclei. Each material is taken with a density-weighted thickness equal to 3200 g/cm^2 and a radius of 10 m so that the captured neutrons can range out and the capture statistics can be allowed to probe the low energy diffusion properties of the material in each simulation package. Liquid scintillator (C_9H_{12}, density 0.887 g/cm^3), water (density 0.997 g/cm^3), calcium carbonate ($CaCO_3$, density 2.710 g/cm^3), iron (density 7.874 g/cm^3) and lead (density 11.342 g/cm^3) are used. All isotopic abundances are those which appear naturally. In addition the primary muon or anti-muon energies of 30, 100, 280 GeV and 1 TeV are used in this study. In the following sections we specialize to the 280 GeV energy setting when examining the integrated neutron flux and to the liquid scintillator material for examination of the neutron capture statistics. In all cases we present data for only muon primaries, not anti-muons. These specializations are made to keep the length of this article tractable and focus discussion.

NEUTRON FLUX VS. ENERGY

The one-directional neutron flux integrated over the detector cross section perpendicular to the momentum of the muon primary is a good parameter to summarize the neutron production behavior over a wide range in neutron energies. This integrated flux is plotted in Fig. 1, normalized to the number of generated primaries. The integrated fluxes compare favorably between the FLUKA and Geant4 simulations in general. The liquid scintillator and water seem to be within 30% over most of the energy range with the largest discrepancies near 100 MeV neutron energy. Other materials follow this general agreement in the region between 100 MeV and the highest energies plotted. Below 10 MeV $CaCO_3$ has several resonant structures which are well tracked and an indication of successful implementation in the nuclear physics regime (and similar cross sections). The case is similar for iron with the exception of a structure around 3-7 MeV which appears in the Geant4 simulation but not the FLUKA. The lead material has a similar structure in the same energy region not reproduced by FLUKA and furthermore Geant4 begins to register dramatically less neutrons than FLUKA between 10 keV and 5 MeV. This is the largest discrepancy revealed so far and is not yet understood. Lead is, however, an important material for many low background experiments and so investigation of this discrepancy and correlation to data, if possible, is important.

THERMALIZATION AND MULTIPLICITY

In a simple geometry such as the one being utilized in this study, it is typically easy to keep track of the number of neutrons that are produced in a given event in total. Further, since the cylindrical material slabs have such a large lateral distance, it is likely that almost all of the produced neutrons will remain inside the detection volume. To this end Fig. 2 shows plots which analyze various properties of neturons captured on hydrogen inside the fiducialized detector volume (the innermost 1600 g/cm^2). The capture time spectrum in the rightmost panel of Fig. 2 shows that FLUKA produces

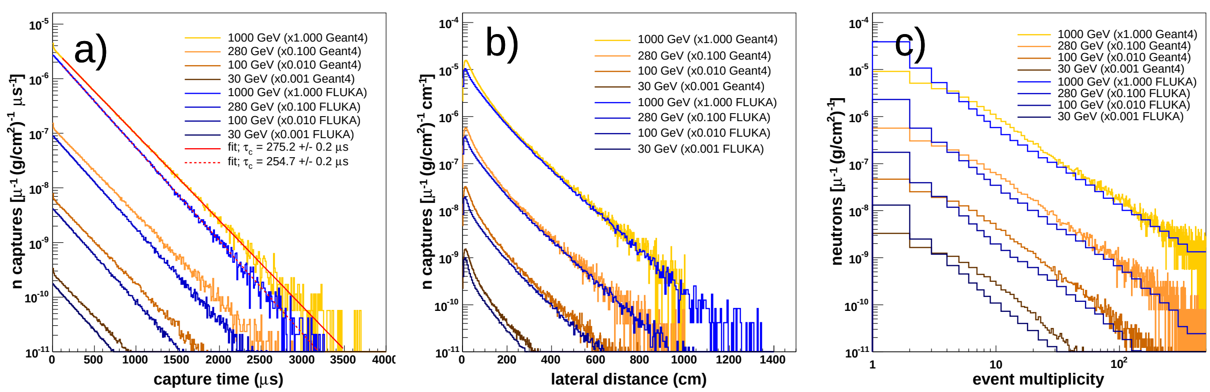

FIGURE 2. a) Capture time distributions for all neutrons which capture on hydrogen in liquid scintillator b) Perpendicular distance to the muon tracks (lateral distance) distributions for those same neutrons. c) Multiplicity distributions with each entry counting all captures which result from a single thrown muon primary.

slightly less neutrons than Geant4 does and additionally the capture time constant for FLUKA is 254.7$\pm$0.2 μs whereas the time constant for Geant4 is 275.2$\pm$0.2 μs. The difference in these is interesting and indicates a slight difference in the low-energy neutron transport physics, which warrants further study. It is also interesting to note that a Borexino analysis finds that Geant4.9.6p01 and the version of FLUKA used here also show a similar capture-time discrepancy [14]. In that analysis, however, it is noted that their previous analysis using Geant4.9.2p02 *does not* show the discrepancy. The other distributions look qualitatively similar but there are several discrepancies. Firstly there is slight normalization discrepancy as it is often the case that the FLUKA curves are bounded below the Geant4 curves. There is also a discrepancy in the lateral distance distributions which appears to be worse toward lower distance and with lower-energy muon primaries. Finally the multiplicity distributions show a large discrepancy often a factor of 2-4 in the multiplicity-one bin. These discrepancies may be linked, and understanding their origins is important in order to vet the transport physics of each of the simulations.

Some experiments like Borexino can measure very analogous quantities at depth [14]. Experimental conditions should be used to match simulation to experiment, like the amount of deadtime after a muon traversal before being able to detect neutron captures. After these corrections, however, the capture time, lateral distance and multiplicity distributions should be quantitatively similar to the ones displayed in Fig. 2. Quantitative comparisons of that type have not been undertaken for these simulation data but will be in the future. The Borexino collaboration has, however, produced its own simulation data for comparison to the data [14].

CONCLUSIONS

A common way to summarize the quality of the agreement of data and simulations has been to plot the total neutron yields for a given material and energy [1]. The energy is usually quoted as the average energy of an underground muon spectrum but here in this simple study we use the energy of the muon primaries. Figure 3 displays this yield for the liquid scintillator material. Though the values for each simulation track, the Geant4 simulation produces 30-50%

more neutrons in total than FLUKA. An understanding of these values could be related to the discrepancies noted in previous sections.

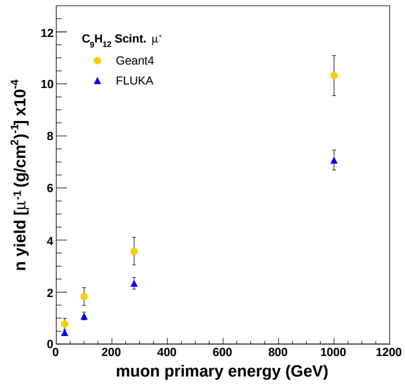

FIGURE 3. Normalized neutron yield for the liquid scintillator material at energies 30, 100, 280 GeV and 1 TeV primary muon energy. Geant4 produces about 30-50% more neturons on average with the settings used here.

While there is good qualitative agreement in much of the simulation work presented here, there are discrepancies which need to be understood in the context of the physics models being used and in the context of agreement with data. The analysis included here looks at some rough quantifiers of production (flux vs. energy) and transport (capture distributions) physics. Our analysis serves as the starting point for understanding the interplay of these types of variables and the investigation of new variables which can be utilized for benchmarking both between various Monte Carlo codes and between those codes and measured data. In the end, the ideal result from these studies will be a detailed understanding of which observables constrain the important microscopic processes involved in cosmogenic studies, and a framework which can be used to benchmark any code which is put to use for deep-underground cosmogenic simulations.

ACKNOWLEDGMENTS

We gratefully acknowledge the guidance of Vitaly Kudryavtsev in suggesting this study. This work is supported in part by the National Science Foundation (Grant No. PHY-1242640).

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