Astroparticle Physics 73 (2016) 28–33

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropartphys

A simulation-based study of the neutron backgrounds for NaI dark matter experiments

E.J. Jeon [a,*], Y.D. Kim [a,b]

[a] Center for Underground Physics, Institute for Basic science (IBS), Daejeon 305-811, Republic of Korea
[b] Department of Physics, Sejong University, Seoul 143-747, Republic of Korea

ARTICLE INFO

Article history:
Received 31 March 2015
Revised 23 July 2015
Accepted 28 July 2015
Available online 4 August 2015

Keywords:
Simulations
Neutron backgrounds
DAMA modulation

ABSTRACT

Among the direct search experiments for weakly interacting massive particle (WIMP) dark matter, the DAMA experiment observed an annual modulation signal interpreted as WIMP interactions with a significance of 9.2σ. Recently, Jonathan Davis claimed that the DAMA modulation may be interpreted on the basis of the neutron scattering events induced by the muons and neutrinos together. We tried to simulate the neutron backgrounds at the Gran Sasso and Yangyang laboratory with and without the polyethylene shielding to quantify the effects of the ambient neutrons on the direct detection experiments based on the crystals.

1. Introduction

Numerous astronomical observations have led to the conclusion that the majority of the matter in our universe is invisible, exotic, and nonrelativistic dark matter [1,2]. However, it is still unknown what the dark matter is. Weakly interacting massive particles (WIMPs) are one of the most attractive dark matter particle candidates [3,4]. The lightest supersymmetric particle (LSP) is a possible WIMP candidate theoretically hypothesized beyond the standard model of particle physics. There have been a number of experiments that directly search for WIMPs in our galaxy by looking for WIMP–nucleus scattering through nuclear recoil [5,6].

For last decades, there were a few experiments (DAMA [8,9], CoGeNT [14,15], CRESST [18], CDMS [20]) claimed indications that could be interpreted as being due to low mass WIMP interactions. However, the recent CoGeNT analysis shows that the excess events have been shown to be due to a previously underestimated background from surface events, and the significance of the claim became very weak, 1–2.7 sigma [17]. CRESST group also excluded their previous claim for a possible signal which turned out to be alpha backgrounds [19]. Recent SuperCDMS data gave a limit which is almost an order below their own CDMS-II (Si) best-fit point [21]. Except for the DAMA experiment, the indications of WIMP-like signals are not significant at the $<3\sigma$ confidence level, and the same experimental groups or independent groups are planning to confirm these signals. However, the result from the DAMA experiment has attracted attention because the observation of an annual modulation of WIMP-like signals with a significance of 9.2σ has been reported. This finding has spurred a continuing debate concerning the observation of WIMPs over the past 15 years. The WIMP–nucleon cross sections inferred from the DAMA modulation are in conflict with limits from other experiments that directly measure the nuclear recoil signals, such as XENON100 [22], LUX [23], and SuperCDMS [24]. However, it is still possible to explain the DAMA data without conflict with other experiments in a specific model such as in ref. [12]. Therefore it is still very important to (de)confirm the DAMA experiment by other experiment using NaI crystal.

Recently Jonathan Davis of Durham University has proposed a new model for the DAMA annual modulation, which is a sum of two annually modulating components with different phases. More specifically, the events are composed of neutrons, which are liberated in the material surrounding the detector by a combination of 8B solar neutrinos and atmospheric muons [7]. The DAMA group disagreed with Davis's claim because the induced modulation amplitudes from neutrons induced by muons and by neutrinos are less than 9×10^{-6} cpd/kg/keV (2×10^{-5} cpd/kg/keV for neutrons produced in the lead shield) and less than 2×10^{-6} cpd/kg/keV, respectively from the simulation, and they are less than 0.1% of the modulation amplitude measured by DAMA/LIBRA [11]. Further, Barbeau et al. criticized Davis's claim because a seven order of magnitude discrepancy in the neutron contribution was required [16].

2. Method of simulation

To understand the neutron backgrounds for NaI dark matter experiments, we have performed simulations with the GEANT4 Toolkit [29]. The hadronic models of muon nucleus interaction and muon

---

[*] Corresponding author. Tel.: +821033213449.
E-mail addresses: ejjeon@ibs.re.kr (E.J. Jeon), ydkim@ibs.re.kr (Y.D. Kim).

http://dx.doi.org/10.1016/j.astropartphys.2015.07.004
0927-6505/

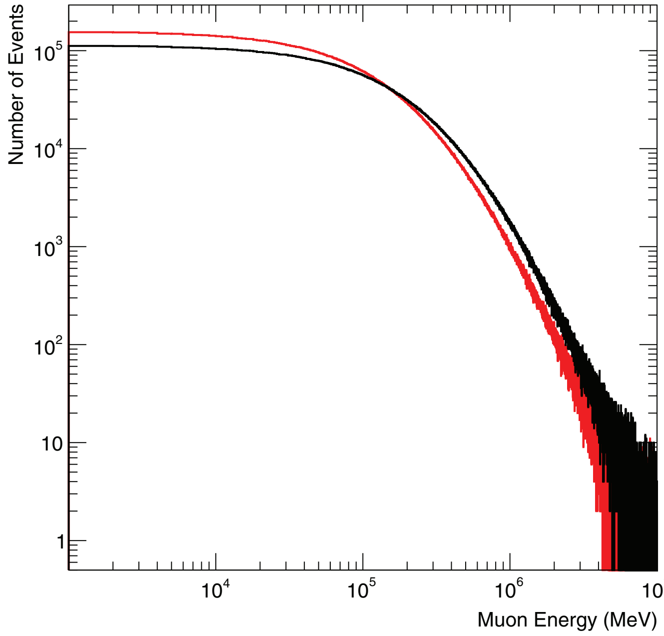

Fig. 1. Muon energy spectrum at Gran Sasso (black) and at Yangyang (red). (For interpretation of the references to color in this figure legend and in text, the reader is referred to the web version of this article.)

decay at rest were used in the GEANT4 simulation, version of 9.6.p02 (G4MuonVDNuclearModel and G4MuonMinusCaptureAtRest).

We have simulated the cosmic muons and the neutrons induced by simulating muons passing through the rock directly. We did not simulate the scintillation and light collection processes inside the crystals because it is not required for the conclusion derived in this study. Further, we did not simulate the environment neutrons underground because presumably these neutrons will not have annual modulation signals.

3. Analysis

3.1. Muon energy spectrum

Neutrons are produced primarily by the muons in the rock and materials in the detection system. These neutrons generate secondary neutrons via hadronic interactions in the materials. We simulated all the primary and secondary processes using GEANT4 simulation program starting with muons passing through the rock.

We used the muon energy spectrum provided by Mei and Hime [25], which is given by

$$\frac{dN}{dE_\mu} = Ae^{-bh(\gamma_\mu - 1)} \cdot (E_\mu + \epsilon_\mu(1 - e^{-bh}))^{-\gamma_\mu} \qquad (1)$$

where h is the rock slant depth in km.w.e and we used a set of parameters provided by Groom et al. for ϵ_μ, b, and γ_μ.

For two different depths at Gran Sasso and at Yangyang laboratory (Y2L) we assumed that $h = 3.1$ km.w.e and $h = 1.8$ km.w.e, respectively. Fig. 1 shows muon energy spectra generated at Gran Sasso (black line) and at Y2L (red line). Muon average energies are 276 GeV and 201 GeV for Gran Sasso and Y2L, which are consistent with the measured values [25].

3.2. Schematic layout of simulation geometry

Inside the rock of a thickness of 20 m × 20 m × 20 m there is an air-filled cavern whose dimensions are 4 m × 4 m × 4 m. A hemisphere with a radius of 10 m is assumed and generated muons are incident onto the shielded detector with an angle randomly selected according to an angular distribution proportional to $\cos^2\theta$, as shown in Fig. 2. The vertex of the muons is generated uniformly inside the square of 20 m × 20 m area at the surface of the hemisphere. The size of the square is determined to cover the whole volume of the rock for all the angles of the generated muons. Fig. 1 shows the energy spectrum of generated muons at the hemisphere. The muon flux at Gran Sasso is considered as 2.7×10^{-8} muons/cm^2/s or 2×10^7 muons/(20 m × 20 m)/2144 days and it is 2.7×10^{-7} muons/cm^2/s or 2×10^7 muons/(20 m × 20 m)/214 days at Y2L.

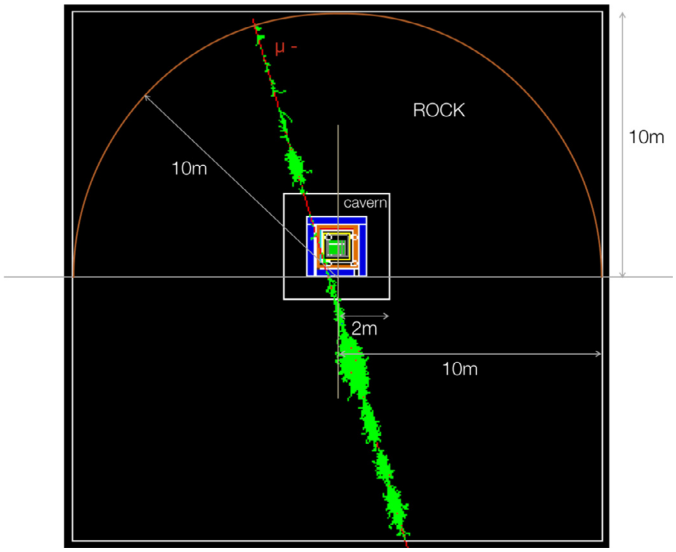

Fig. 2. Schematic layout of simulation geometry.

3.3. Neutron production at the boundary of rock and cavern

To validate the simulation for the neutron production we compared the neutron fluxes entering the cavern, which are produced in the rock. We also included neutrons scattered back from the rock wall as well as shielding materials surrounding the detector and reentering the cavern. Fig. 3 shows the neutron energy spectra at the boundary between the rock and cavern, obtained from the simulation of muon propagation and interaction with materials in the rock. There are four different shielding configurations inside the cavern, denoted as 1, 2, 3, and 4, defined in Section 3.4, therefore, we can see the effect of the neutrons reflected back from the wall and shielding materials inside the cavern. Most are dominant below ~1 MeV and it depends on the outmost shield layer whether it is polyethylene (PE) or not.

According to the simulation results neutron fluxes are 6.98×10^{-10} n/cm^2/s and 5.3×10^{-9} n/cm^2/s, for energies above 1 MeV, under shielding configuration 1 at Gran Sasso and under configuration 4 at Y2L, respectively. It is in good agreement with GEANT4 results of version 6.2 [26] and close to the FLUKA result [27], 8.7×10^{-10} n/cm^2/s, obtained from muon simulation in NaCl at Boulby.

3.4. Shielding configurations and shielding effects

We assumed the NaI detectors used by DAMA/LIBRA, and therefore there are 5 × 5 segmented NaI crystals with dimensions of (10.2 × 10.2 × 25.4) cm^3 for a single crystal. The target NaI crystals are inside a 10 cm copper shield and it is additionally surrounded by lead and polyethylene (PE) shields.