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A neutron multiplicity meter for deep underground muon-induced high-energy neutron measurements

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Abstract

We present, for the first time, the design of an instrument capable of measuring the high energy (>60 MeV) muon-induced neutron flux deep underground. The instrument is based on applying the Gd-loaded liquid-scintillator technique to measure the rate of multiple low-energy neutron events produced in a Pb target and from this measurement to infer the rate of high energy neutron events. This unique signature allows both for efficient tagging of neutron multiplicity events as well as rejection of random gamma backgrounds so effectively that typical low-background techniques are not required. We present design studies based on Monte Carlo simulations that show that an apparatus consisting of a Pb target of 200 cm by 200 cm area by 60 cm thickness covered by a 60 cm thick Gd-loaded liquid scintillator (0.5% Gd content) detector could measure, at a depth of 2000 meters of water equivalent (m.w.e), a rate of 70 ± 8 (stat) events/year with a background of less than 10 events/year. We discuss the relevance of this technique to measuring the muon-induced neutron background in searches for dark matter in the form of Weakly Interacting Massive Particles (WIMP). Based on these studies, we also discuss the benefits of using a neutron multiplicity meter as a component of active shielding in such experiments.

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Keywords: Neutron background; Muon-induced neutrons; High energy neutrons; Dark matter; Underground physics; Neutron detectors

1. Introduction

The nature of dark matter is one of the most important outstanding issues in particle physics, cosmology and astrophysics. A leading hypothesis is that Weakly Interacting Massive Particles, or WIMPs, were produced in the early universe and make up the dark matter. So far this matter has only been observed through its gravitational effects. WIMPs cannot be Standard Model particles and so their discovery would hail a new form of matter. A detection would also help solve a long-standing riddle in cosmology that even questions our understanding of gravity. Dark matter is concentrated in the halos of galaxies, including the Milky Way. If WIMPs make up these halos they can be detected via scattering from atomic nuclei in a terrestrial detector. Experiments that search for WIMPs are one of the critical science drivers for a Deep Underground Science and Engineering Laboratory in the United States.

WIMP searches must be performed underground to shield from cosmic rays, which produce secondary particles that could fake a WIMP signal. Nuclear recoils from fast neutrons in underground laboratories are one of the most challenging backgrounds to WIMP detection. Experiments that search for WIMP dark matter rely on passive and active shielding to reduce gamma and neutron backgrounds. To reduce the neutron background, passive hydrogen-rich shielding and active charged-particle detectors are commonly used to moderate neutrons and veto muon-induced events, respectively. To reduce the gamma background, high-Z materials such as lead are used to attenuate gammas from ambient radioactive sources. While the high-Z shielding is effective against gammas, the shield itself becomes a source of increased neutron background due to secondary particles produced by unvetoed muon-

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induced neutrons that have energy above about 60 MeV. These neutrons have sufficient energy and low enough cross-section on hydrogen that they penetrate the moderator and reach the gamma-ray shield. They tend to interact there and cause spallation reactions, which produce multiple secondary neutrons with energy below 10 MeV. At these lower energies, the neutrons can reach the inner detector volume and cause WIMP-like nuclear recoils.

The high-energy neutrons and their parent reactions that originate with cosmic-ray muons are thus correlated with the unvetoed neutron events that mimic the WIMP signal. Neutron production by muons underground have been measured at a span of depths and muon energies, from about 20 meters of water equivalent (m.w.e.) depth and 10 GeV energy [1–3] to 5200 m.w.e. and 400 GeV [4]. An estimate of the neutron production as a function of muon energy for muons interacting in liquid scintillator has been obtained by Wang and co-workers [5] based on Monte Carlo simulations made with FLUKA [6] that is about a factor of two within the available data at that time for depths with a mean muon energy above 100 GeV. Since we are interested in neutrons with energy above ~60 MeV, we note this work is primarily sensitive to neutrons below this energy range as illustrated in Fig. 5 in their paper [5]. Galbiati and Beacom [7] have calculated, using FLUKA [8], the production rates for ^{12}B in muon–induced showers and have probed the neutron production in the energy range of ~10–100 MeV through the ^{12}C(n, p)^{12}B reaction and the calculation agrees well with measurements of ^{12}B at 2700 m.w.e. made by KamLAND [9].

At higher energies (>100 MeV) the shape of the neutron spectrum was compared to FLUKA [6] by Wang [5] and there is about a factor of two discrepancy with data taken with the liquid-scintillator LVD detector [10] at a depth of 3650 m.w.e and a mean muon energy of 270 GeV. Mei and Hime [11] claim that after making corrections for proton recoil quenching effects, the corrected LVD data agrees well with the shape of the spectrum predicted with FLUKA simulations. However, the individual who performed the analysis of the data, Kudryavtsev has pointed out that this correction is inappropriate [12]. At present, there is no other data at this energy to inform the production of high energy neutrons, leaving the discrepancy unresolved. The LVD collaboration recently presented results on measuring neutron production above 20 MeV by muons in liquid scintillator [13], and a Monte Carlo simulation is under development by the collaboration to convert this measurement to an absolute flux.

Neutron production by 200 GeV muons occurs through hadronic showers generated by the muons interacting in the rock, and to some extent by direct muon spallation [5]. The CERN NA55 experiment measured neutron production via direct muon spallation by looking at the production of fast neutrons (>10 MeV) by 190 GeV muons on graphite, copper and lead [14] at three different angles from the muon beam. Araujo and co-workers [15] show that this experimental data lies above the Monte Carlo simulations from between a factor 3–10 depending on the measured angle. These measurements could overestimate the rate because of contamination by neutrons produced by secondaries of the muon–nucleus interaction. The possible systematic uncertainties leave the matter inconclusive, informing neither muon spallation production nor the total fast-neutron yield above >10 MeV.

The measurements to date of neutrons at large depths involve either primary muon interactions in hydrocarbon liquid scintillator followed by cascade processes within the detector [10,16], or muon interactions in higher-Z material such as Pb and Cu [17] in which neutron production is dominated by relatively low-energy electromagnetic properties. Of particular interest for dark matter experiments, as noted above, is when high-energy neutrons produced in the rock through muon interactions and hadronic cascades, followed by spallation in high-Z shielding, lead to a flux of neutrons of mostly 10 MeV and below. In the work described here our simulations and calculations indicate that a modest size detector, by exploiting the multiplicity distribution of the spallation events, can provide a normalization of the neutron flux to a precision of about 12%. By measuring the high energy neutron flux at 2000 m.w.e. we will benchmark the neutron production by muon-induced hadronic showers and provide a normalization of the unvetoed neutron background. We have chosen this depth because the muon-induced neutron production is dominated by hadronic processes according to Wang and co-workers [5] based on Monte Carlo simulations made with the particle production and transport code FLUKA [6] and because the rate is good enough for a modest detector size (see Section 2) to be able to measure a rate of 70 ± 8 events/year for neutrons >60 MeV.

In addition to the interest for the shielding configurations for many dark matter experiments, improved knowledge and predictibility of the muon-induced high energy neutron flux (>60 MeV) at depth will aid in the understanding of neutron induced backgrounds in double beta decay experiments. For example, as noted by Mei and Hime [11], knowledge of the neutron background is needed to estimate the background due to elastic and inelastic events that generate gamma-rays near the 2 MeV endpoint, and to optimize shielding configurations that also typically involve massive lead and polyethylene shields to attenuate gammas and moderate neutrons. Thus for two major classes of low-background underground experiments, dark matter and double beta decay, a more precise measurement of the neutron background produced in the appropriate shield components will be of great utility, from the experiment planning stage through to data analysis.

2. Principle of the instrument

The instrument we have designed is based on applying the Gd-loaded liquid-scintillator technique to measure the rate of events with multiple low-energy neutrons produced in a Pb target. Our studies, which are presented in Section 3, indicate that at a depth of 2000 m.w.e., the dominant source of these events is due to muon-induced high energy neutrons interacting in the Pb. Gadolinium has a high thermal-neutron capture cross-section, and emits 8 MeV in gamma-rays after the capture. Since neutrons thermalize and capture with a mean of about 10 μs, measurements of the distinct capture times is a straightforward way to determine neutron multiplicity, and to tag and measure the underlying process of the fast-neutron production. This method, known as a Neutron Multiplicity Meter, has a long history of use, dating to searches for superheavy elements expected to decay to high-neutron-mulipltiplicity final states [18], and more recently in accelerator-based applications [19].

The basic design of the Neutron Multiplicity Meter applied to measure high energy neutrons (>60 MeV) underground employs the Gd-loaded liquid-scintillator detector ($\sim$0.5% Gd content) atop a 200-cm-square by 60-cm-thick Pb target in which high energy neutrons produced by muon interactions in the rock walls of the cavern will mainly enter from above, penetrate the scintillator, and cause neutron spallation in the Pb, as illustrated in Fig. 1. The secondary low-energy neutrons produced by the primary high energy neutron leave the Pb target and enter the Gd-loaded scintillator, where they are moderated and thermalized by the protons in the hydrocarbon which comprises the bulk of the scintillator. Within about 40 μs, most will have captured on the gadolinium, and thus the essential problem of detecting neutral particles with high efficiency has been turned to an advantage: the neutrons which are released simultaneously are dispersed in time, and individually captured and counted. As the simulations below illustrate, this unique signature allows both for efficient tagging of neutron multiplicity events as well as rejection of random gamma backgrounds so effectively that typical low-background techniques are not required.

3. Instrument design studies

In this section the design characteristics of the Neutron Multiplicity Meter adapted to measure high-energy neutron flux underground are developed. Extensive simulation studies of the muon-induced neutron background in the Soudan Mine at a depth of 2000 m.w.e. corresponding to 14 years of exposure have been performed using FLUKA simulation package [20,21]. These studies, carried out for background estimates in the CDMS II experiment, are based on an angular distribution of muons matched to this depth, and normalized to the measured flux in the CDMS II plastic-scintillator veto system [22]. In the study, the muons are propagated into a rock-wall cavern modeled as a six-sided 10-m-thick rock shell surrounding a 4 m by 8 m by 4 m cavity. The CDMS II experimental setup is inside the cavity and near one of the walls. High energy neutron production due to muons occurs through direct muon spallation and subsequent hadronic showers that develop in the rock. The angular distribution of neutrons above 60 MeV, as depicted by the distribution in Fig. 2, shows that the neutrons are mostly going downward at angles about 0.88π radians, where π radians corresponds to the direction vertically downward. Given the predominantly downward direction, the rate of incident high-energy neutrons is proportional to the area of the Pb target, which defines the first criterion for the setup.

The next criteria we consider for the Pb target are the optimal thickness and whether it is best placed above or below the scintillator tank. A simulation with FLUKA was performed by propagating a beam of 100-MeV neutrons at a 200 cm by 200 cm Pb target with thickness varying from 1 to 100 cm. We gauge the detectability of a subsequent multiplicity event by counting the number of secondary neutrons that emerge from the Pb with less than 10 MeV and are thus readily moderated and captured. We define the parameter P for both the top and bottom surfaces as the fraction of events for which a downward-direction

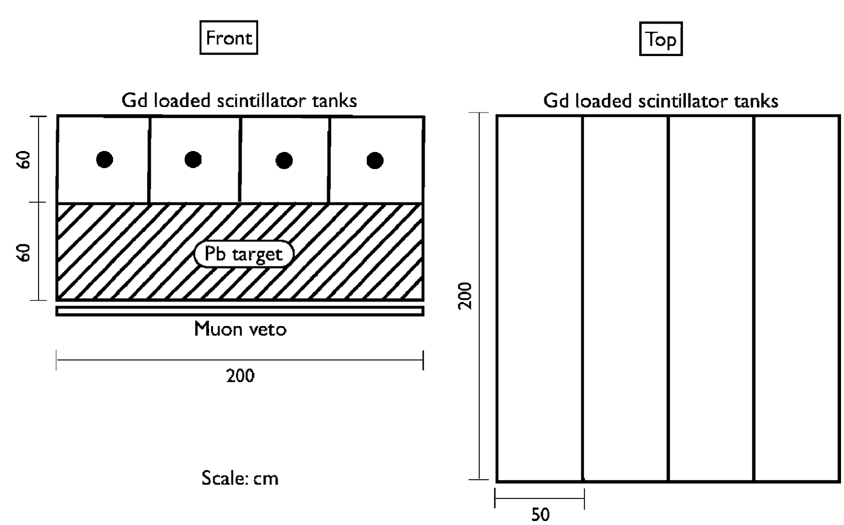

Fig. 1. Conceptual drawing of the Neutron Multiplicity Meter for deep underground muon-induced high energy neutron measurements.

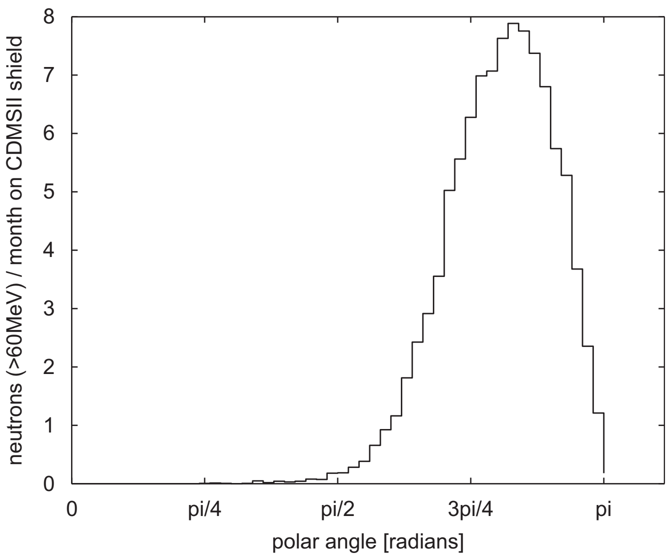

Fig. 2. Polar angular distribution of the neutrons with energy greater than 60 MeV incident on the CDMSII shield. Neutrons tend to have downward direction at an angle of about 0.88π radians with respect to the normal vector from the floor. Therefore, the area of the target is proportional to the rate of incident high energy neutrons.

100-MeV neutron results in at least 3 low-energy neutrons exiting either the side from which the neutron beam was incident (top) or the opposite side (bottom). The overall production point and neutron travel direction is illustrated in Fig. 3, which shows the neutron fluence (neutron track length per unit volume) in units of cm per cm^3 per primary neutron, based on a FLUKA simulation for a 60-cm-thick target. Quantitative results for P are shown in Fig. 4, where the "Pb target on bottom" means P is calculated for downward incident neutrons with upward-going secondaries to be detected in a top-side scintillator detector, and "Pb target on top" means P is calculated for downward secondaries to be detected bottom-side.

We observe that the emission of neutrons is roughly isotropic as expected, and that the spallation reaction occurs within the first 15 cm of Pb. Furthermore, as the thickness of the target increases beyond 20 cm, more of the secondaries are going upwards than downwards. This effect is due to backscattering from the Pb, which acts roughly like a "neutron mirror" for low energy neutrons, since the elastic collisions off the Pb nuclei do little to reduce the energy of the comparatively light neutrons. Most important for the overall configuration, we see that since the primary interaction rate is still increasing with thickness, the backscatter effect indicates that the multiplicity rate is higher on the top side, and higher for increasing thickness. To maximize the detected multiplicity rate, it is better to place the scintillator atop the Pb, which also has the advantage of tagging muons that strike the Pb directly.

So far, the detector configuration is to have the Gd-loaded scintillator on top of the Pb target. Since neutrons with an energy less than about 60 MeV will scatter off the

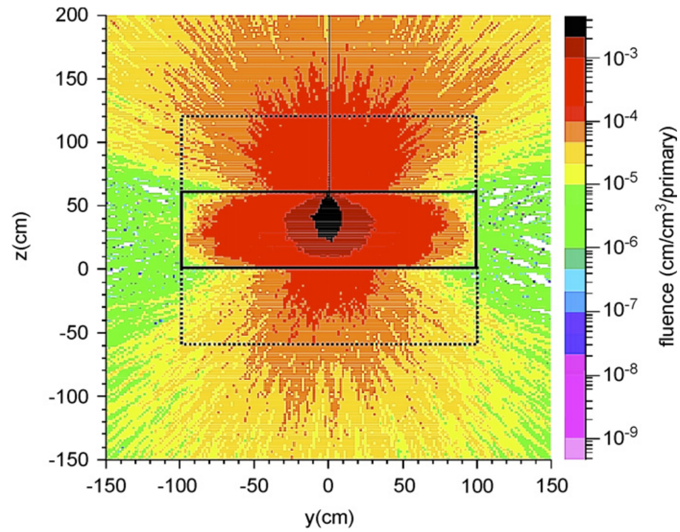

Fig. 3. Neutron fluence plot of a FLUKA simulation that propagates a beam of 100 MeV neutrons on a 60-cm-thick Pb target. The upper and lower rectangles are reference surfaces delimiting the counting boundary for the upper and lower neutrons, respectively. The central rectangle from $z = 0-60$ is the Pb target. The plot shows more evaporated neutrons going upwards than downwards (the forward direction relative to the beam) due to backscattering. This effect also causes very few neutrons to go forward as the thickness increases above about 20 cm.

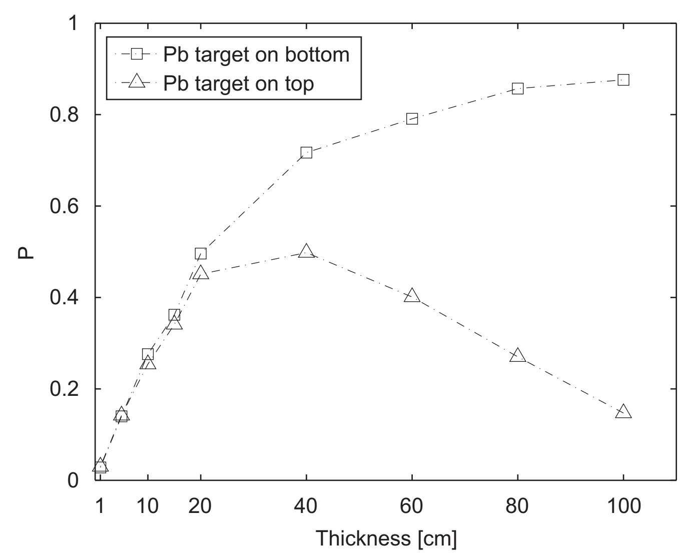

Fig. 4. Simulation with FLUKA to explore optimal target thickness and position of the Gd-loaded scintillator tank with respect to the Pb target. The parameter P is defined as the fraction of events (relative to the number of 100-MeV incident neutrons) that has 3 or more neutrons of 10 MeV or less going towards the top or the bottom of the Pb target. (See text for details.) Since a given event may have 3 or more neutrons going to the top and 3 or more going to the bottom, it is possible to have $P_{TOP} + P_{BOTTOM} > 1$, for example as observed for 40-, 60- and 80-cm thickness.

protons in the scintillator, they will tend to either fail to reach the Pb or reach it with insufficient energy to produce a multiplicity of 3 or more. In other words, the scintillator will filter low-energy neutrons and together with the requirement that the event has a multiplicity threshold of

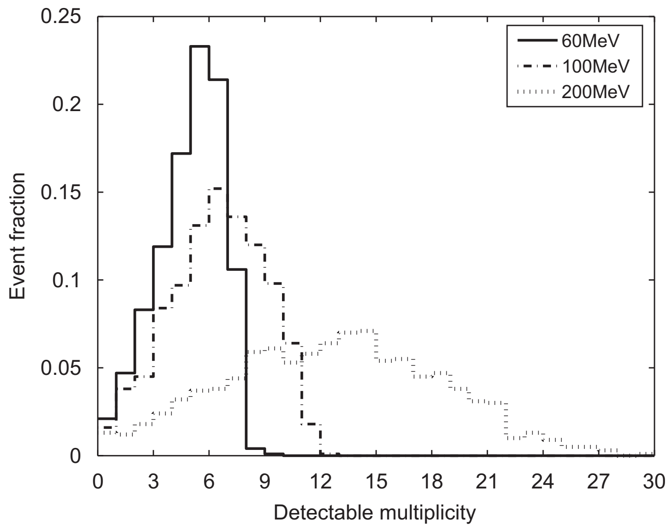

Fig. 5. A FLUKA simulation was done with a fixed target thickness of 100-cm and varying the incident neutron beam energy in order to explore the correlations between the energy of the incident high-energy neutron on the target and the detectable multiplicity. If we reference the beam direction a "downward," the detectable multiplicity is determined by counting the neutrons that reach a surface just above the Pb target.

3 or more secondary neutrons this will select only those primary neutrons with an incident energy of 60 MeV or more. To illustrate that high energy neutrons (>60 MeV) induce a multiplicity of 3 or more low-energy neutrons on a Pb target, Fig. 5 shows the induced detectable multiplicity, for a geometry of the Pb to have an area of 200 cm by 200 cm normal to the vertical, a thickness of 100 cm, and an incident downward-going neutron beam in FLUKA at energies of 60, 100, and 200 MeV. The detectable multiplicity was estimated by counting the number of neutrons below 10 MeV that enter a top-side detector with the same footprint as the Pb. The resulting multiplicity distributions for the three energies are shown in Fig. 5, where "Event Fraction" corresponds to the fraction of events with respect to the total number of incident neutrons. The plot shows that the majority of the events have a detectable multiplicity of 3 or more, and that there is an increase in multiplicity with primary neutron energy and although some information on the primary neutron energy is potentially available from the multiplicity distributions; at least an energy threshold on the primary neutron energy can be established using multiplicity, which has a fairly sharp turn on at 60 MeV for a multiplicity threshold of 3.

It is important to estimate the efficiency of the selection criteria for tagging high-energy neutron events as a function of multiplicity so that an optimization can be made to reject random coincidences and still achieve good efficiency for neutron-induced events. We identify a class of "clean" multiplicity events, that is, those that are clearly produced by high energy neutrons interacting in the target as opposed to other charged particles or gamma-rays that may also have been produced by the parent muon. To estimate the rate of these events as a function of multiplicity we use the events with neutron energy above 60 MeV from our 14-year Soudan simulation in which associated gamma-rays, muons, or hadrons deposit less than 2 MeV in the scintillator. The multiplicity is counted by considering only those secondaries with energy less than 10 MeV entering a top-side detector, and is plotted in Fig. 6. To see the effect of tightening the multiplicity cut to reduce the probability of random coincidences, the integral number of multiplicity-tagged events per year is plotted versus the minimum required multiplicity, and is displayed in Fig. 7. The total number of events changes only by about 10% between a minimum multiplicity of 3 and 10.

In determining the optimal thickness of the scintillator modules, we consider two requirements: the moderation of the secondary neutrons, and the absorption of the Gd capture gammas. The FLUKA simulation predicts that the spectrum of neutrons emerging from the Pb falls off almost completely by 5 MeV, as shown in Fig. 8. A scintillator region of 10 cm thickness would be sufficient to moderate them. However, we find that containing the capture gammas requires a thicker detector. In order to find the optimal thickness, we used the low-energy simulation code, MCNP-PoliMi [23], which includes the neutron-capture process. A beam of 0.5-MeV neutrons was propagated from the Pb up to a top-side scintillator tank, and the thickness of the tank was varied. In Fig. 9 the efficiency to detect the gamma cascade with a 3-MeV threshold is shown as a function of scintillator thickness. To allow for resolution effects, we choose 3 MeV as the nominal lower analysis threshold to gain immunity from gammas from natural radioactivity, the highest of which comes from ^{208}Tl with an energy of 2.6 MeV. We find that the detection efficiency increases with thickness because of improved

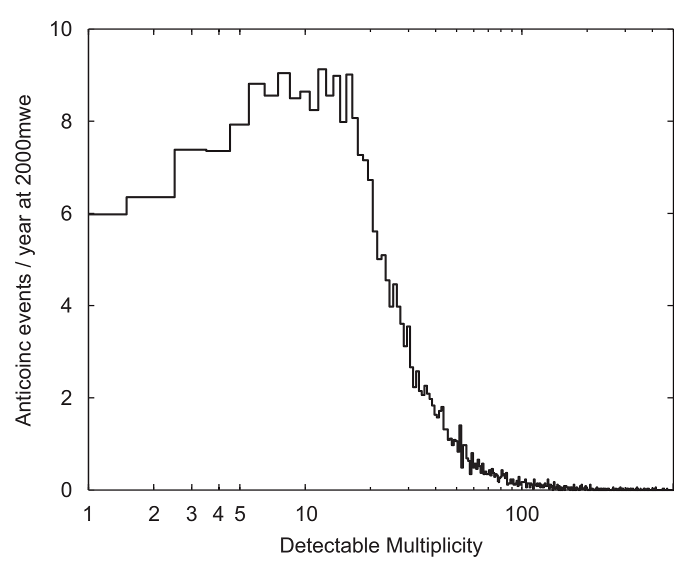

Fig. 6. The detectable multiplicity from a Pb slab of 200 cm by 200 cm area and 60 cm thickness for the events estimated to be anticoincident with an energy deposition of 2 MeV or more from charged particles, including muons and hadrons. The detectable multiplicity was counted only by looking at neutrons with energy less than 10 MeV going towards a surface on top of the Pb target.

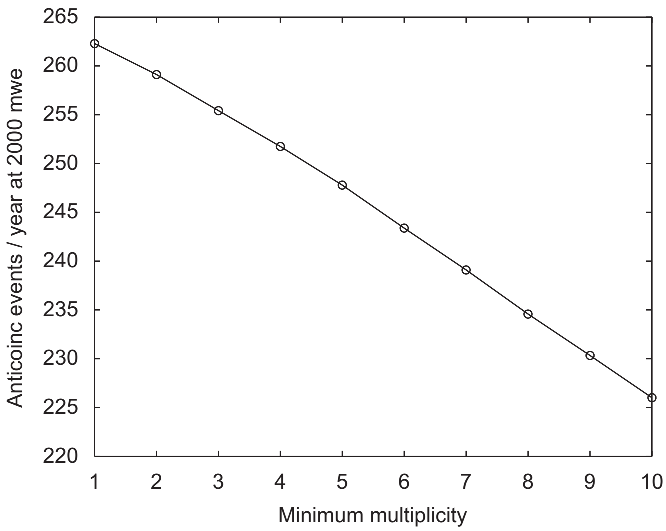

Fig. 7. The total number of events as a function of minimum multiplicity. The total number of events changes only by about 10% between a minimum multiplicity of 3 and 10.

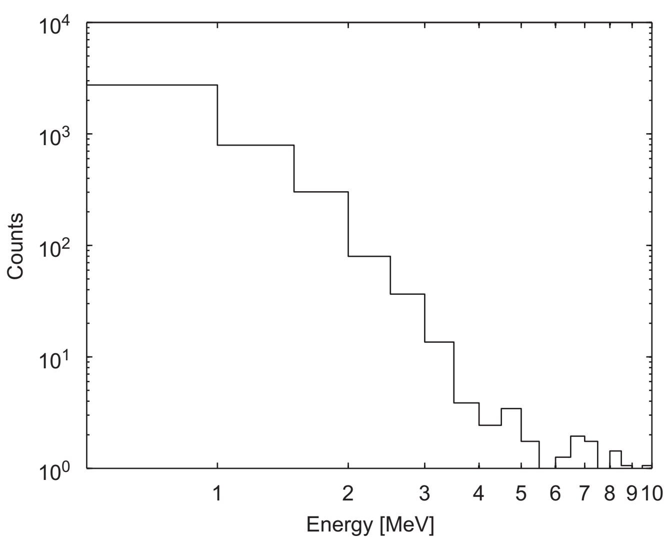

Fig. 8. Energy spectrum of secondary neutrons produced by high-energy neutrons (flux shown in Fig. 2) incident on the Pb target. Neutrons mostly have energy below 5 MeV energy, and indicates that the thickness of the scintillator is not driven by the moderation requirements. Rather, we find that the thickness is driven by the need to efficiently contain the gammas-emitted by the Gd.

containment of the gamma cascade. The efficiency to detect 3 MeV energy depositions from gamma-rays in the Gd-loaded scintillator tanks is considered to be 100%, as this can be easily achieved with a 5 inch PMT for the configuration shown in Fig. 1.

To assess the rate of background coincidences that can mimic the signal, we consider not just the energy criteria of nominally 3–8 MeV for individual captures, but also the time distribution of the captures. The time profile for the moderation, thermalization, diffusion and capture of multiple neutrons released simultaneously into the scintillator is broad, with a peak at about 10 μs after emission

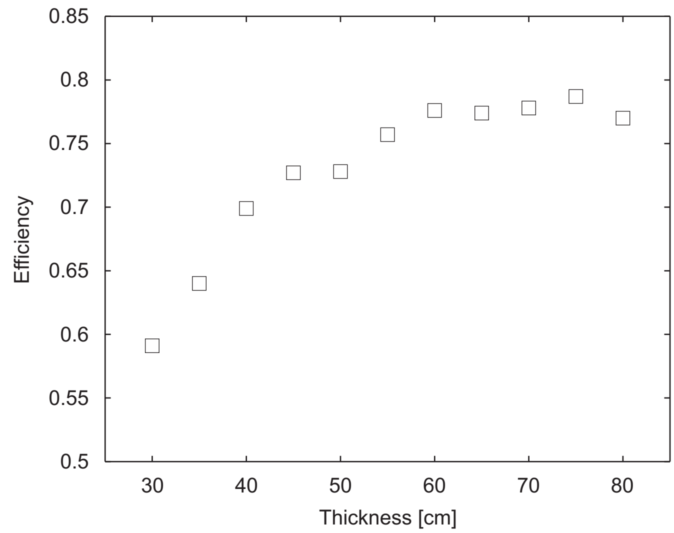

Fig. 9. Simulation with MCNP-PoliMi [23] of the Pb target with Gd-loaded scintillator contained in tanks placed on top of the target. A beam of neutrons with energy 0.5 MeV was propagated from the Pb to the scintillator tank. The thickness of the scintillator tank was varied. Efficiency corresponds to the fraction of incident neutrons for which the energy deposited in the Gd-loaded scintillator by gamma-rays is above 3 MeV.

and about 90% of captures occurring within the first 30 μs. It is the diffusion of the neutron what dominates the time between moderation and capture. A neutron burst results in a cleanly separated readily counted pulse train since the pulse widths of about 10 ns are narrow compared to the typical time between captures of order 1 μs.

Ambient gamma-rays, which dominate the rate of random events in the detector, can mimic a high energy neutron event due to accidental coincidences within the time and energy window defined for multiplicity events. The rate of gamma-induced background as a function of the multiplicity criterion is shown in Fig. 10 for a time window of 40 μs and three different gamma rates. The gamma rate at Soudan expected in the Gd liquid-scintillator volume is about 600 Hz, based on gamma rates measured with the CDMS II plastic scintillator panels for a 1 MeV threshold [24]. A reduction of an order of magnitude in rate can be achieved with a threshold of 3 MeV, which will render the rate of accidental 3-fold multiplicity events to 10^{-2} per day, or about one order of magnitude below the multiplicity rate predicted from high-energy neutrons interacting in the Pb. Further reduction of the gamma-ray rate can be achieved, if necessary, with a thin layer of Pb surrounding the scintillator. Alternatively, immunity from random coincidences can be gained by increasing the multiplicity criterion.

We also consider the background due to neutrons from radioactivity, which are dominated by alpha-n reactions in the rock originating from alpha decays in the uranium and thorium decay chains. The ambient rate of neutrons from radioactivity at Soudan is estimated from the measurements of the U/Th contamination in the Soudan rock [25]

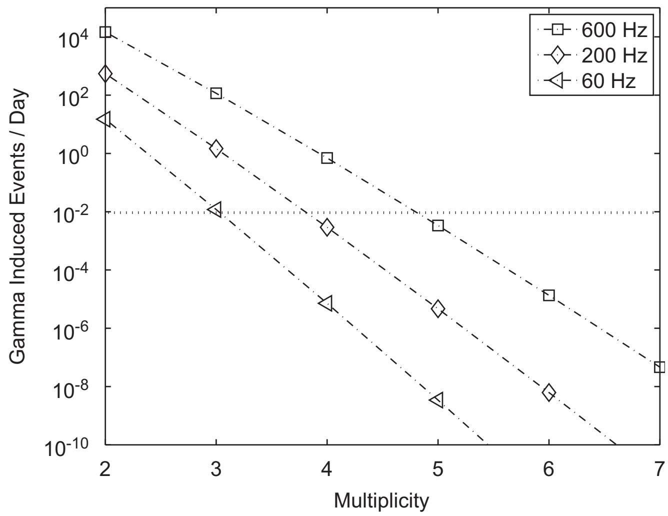

Fig. 10. Ambient gammas can mimic a high energy neutron event due to accidental coincidences. The rate of gamma-induced background events is plotted as a function of the multiplicity of the events for a time window of 40 μs and three different gamma rates [18].

and cross referenced with measurements of both the U/Th level and neutron flux at the Kamioka mine [26]. The resulting flux estimate of about 2×10^{-5} neutrons/cm^2/s produces a rate of about 3 neutrons/s in a detector with a scintillator volume of $200 \times 200 \times 60\,\mathrm{cm}^3$, and is a negligible source of multiplicity events.

Spontaneous fission from the ^{238}U in the rock could in principle produce events with multiplicity of 3 or more, although the most frequent multiplicity is 2. However, the relative rate of fissions to gammas from ^{238}U in secular equilibrium is down by six orders of magnitude. If the entire rate of ambient gammas is attributed to ^{238}U, the expected rate of multiplicity events from fission would still be negligible. However, if needed, a layer of 10–20 cm of polyethylene can easily shield them.

Events in which the muon itself passes through the scintillator are also considered. Most minimum ionizing muons will have sufficient pathlength of about 5 cm in the scintillator to be readily distinguished from Gd capture, allowing us to study muon-tagged events. For example, some of these muons will interact directly in the Pb, and produce a detectable population of neutron multiplicity events. While these events are of interest, they are dominated by low energy electromagnetic processes [16] and so are not as useful a cross check on the unvetoed population, which is dominated by higher-energy hadronic processes.

These tagged muon events will be identified by requiring more than 9 MeV in the scintillator, that is, above the maximum that can be caused by a neutron capture. However, this criterion will also include some events with no muon in the scintillator but which have instead a high-energy neutron that deposits more than 9 MeV by scattering in the scintillator. Based on a FLUKA simulation, the fraction of high-energy neutrons impinging on the apparatus that are in this category is about 35%, and will not be counted in the muon-free category of multiplicity events (which corresponds to the main population of interest, i.e., high energy neutrons produced by muons in the rock). The remaining 65% of incoming neutrons will deposit less than 9 MeV of prompt energy from the initial scatter followed by spallation of the Pb. When the prompt energy in these neutron-scatter-plus-multiplicity events is 3–8 MeV, it will be indistinguishable from events without a neutron scatter but one unit higher multiplicity. For example, a multiplicity-three event with 7 MeV of prompt energy will, to first approximation, appear the same as a multiplicity-four event with prompt energy below the 3-MeV threshold. Since both of these events are due to a high energy neutron, the inferred rate of high energy neutrons will not be biased.

Finally, muons that deposit less than 8–9 MeV in the scintillator (or none at all) but interact in the Pb and cause multiplicity events, represent a potential background to the multiplicity events due to high-energy neutrons. Of the estimated 350 muons/day that will pass through the Pb, there could be a few per day that cause such an event. However, these could be vetoed with a simple set of veto counters placed below the lead, and used in anticoincidence.

In summary, our design studies show that an apparatus consisting of a Pb target of 200 cm by 200 cm area by 60 cm thickness covered by a 60-cm-thick scintillation detector with Gd-capture detection efficiency of $\varepsilon_s(T)$, where T is the low-energy threshold for each distinct capture, and assuming an efficiency to detect 3 MeV gamma-rays in the Gd-scintillator tanks close to 100%, will yield a rate for M-fold multiplicity-tagged events of

$$R = N(1 - 0.35)(\varepsilon_s(T))^M \text{ events/year}$$

where N is the number of high-energy neutrons that induce an event with M or more detectable neutrons emerging from the Pb and entering the scintillator, and the factor of $(1 - 0.35)$ is due to neutron interactions in the scintillator that exceed the high energy threshold. Our FLUKA and MCNP-PoliMi simulations indicate that $M = 3$ gives $N = 255$ and $T = 3$ MeV gives $\varepsilon_s(T) = 0.75$, and therefore $R = 70 \pm 8$ events/year. Depending on the actual gamma rate and spectrum, some optimization is possible for increasing R but protecting against random multiplicity events, for example, by increasing the multiplicity requirement and lowering the energy threshold. Generally speaking, our method is capable of measuring the rate of high-energy neutrons to about 12% statistical error in the span of a year at a depth of 2000 m.w.e. The expected number of background events, which is dominated by the rate of random gamma-induced coincidences, is expected to be at most 10 events/year, and could be further suppressed by optimizing the multiplicity and energy thresholds. Note that we are not trying to deconvolve the primary neutron energy based on the detectable multiplicity shown in Fig. 6. Nevertheless, we can set a threshold on the primary neutron energy because unvetoed events with a multiplicity of 3 or more will be neutrons with a minimum energy of ~60 MeV given that lower energy "primary" neutrons will scatter with protons in the scintillator and reach the Pb target with much lower energy.

4. Discussion of other potential applications within shielding for underground dark matter experiments

In this section we present an application of a neutron multiplicity meter detector to a running dark matter experiment that serves as both an active shield and a monitor of the presence or rate of background events due to high energy neutrons. The idea exploits the same technique as a purpose-built instrument for background studies as described above. It's principal virtue in a WIMP search experiment is that it can closely monitor when a neutron background would appear in the data. A Gd-loaded liquid-scintillator detector integrated into the shield would detect, using the multiplicity technique, the same population of events that cause a flux of low-energy neutrons inside the shielded WIMP detector volume, namely, neutron multiplicity events produced in a Pb gamma-ray shield by an otherwise undetected high energy neutron. Since the underlying processes are the same, Monte Carlo simulations would give a very reliable measure of the ratio of the rate of multiplicity events in the external detector to the rate of WIMP-like events in the dark matter detectors due to the same neutron population.

Similar techniques to detect the presence of background sources have been successfully used, for example in the CDMS-I [27] and CDMS-II [28] experiments where multiple simultaneous nuclear-recoil events were used to determine the rate of single scatter nuclear-recoils due to the same neutron background flux. The ratio of multiple nuclear-recoil events to single nuclear recoils has the advantage of having a negligible source of systematic uncertainty since the neutron elastic cross-sections on Ge and Si are very well known. Nevertheless, the rate of multiple nuclear-recoil events is lower than the rate of single nuclear-recoil events, and the uncertainty in the singles rate is dominated by the fluctuations of the multiples when only a small number has been observed.

In other words, tagged events that are correlated with the production of a single nuclear recoil due to a neutron can be used to statistically predict the absolute number of these nuclear recoils. If we call these tagged events "background predictors" then the number of unvetoed singles can be estimated by determining the ratio of single nuclear recoils to the background predictor events with a Monte Carlo simulation, and then counting the number of background-predictor events in the experiment. Narrowing the statistical and systematic uncertainty of this ratio improves the ability to monitor and subtract the neutron background. Dark matter experiments that have a Pb layer or any high-Z material as their gamma-ray shield could use an external multiplicity meter to predict, in a statistical way, the number of unvetoed nuclear recoils due to neutrons. The background predictor events with high multiplicity are detected in the multiplicity meter outside the high-Z material. A virtue of this configuration is that the gamma background due to contaminants in the scintillator and Gd are shielded by the high-Z material.

As a further illustration based on Fig. 4 for 100 MeV incident neutrons and a typical 15–20 cm thick gamma-ray shield made of Pb, the fraction of high energy neutron events that produce multiple low energy neutrons going inside a Pb box will be roughly the same as outside. For example, the use of 60–80 cm of Gd-loaded liquid scintillator outside the gamma-ray shield layer allows the moderation of low energy neutrons originating from the radioactivity in the rock and at the same time functions as a neutron multiplicity counter that would allow the prediction of the number of neutron-induced events in the signal region. Note that the multiplicity threshold in this case should be set high enough so that gamma induced multiplicity events are kept at a negligible level, since the Pb layer would be about 20 cm thick.

The effect plotted in Fig. 4 shows that the low-energy neutrons produced from the neutron spallation reaction can be detected by clean low energy neutron detectors inside the gamma-ray shield (for example with plastic scintillator) but we have also found that outside of the gamma-ray shield, a 60–80 cm of Gd-loaded liquid scintillator with a threshold of a few MeV, would work as an active veto complementing the veto inside the gamma-ray shield (or as a standalone veto depending on rejection requirements) and as a monitor of the muon-induced neutron background. Note that the thickness of the scintillator outside the gamma-ray shield is driven by trying to contain the gamma-rays produced in the capture of a neutron by the Gd in order to have a high threshold to defeat ambient gammas from radioactivity, and also to keep moderating with high efficiency the neutrons produced from the radioactivity in the rock.

5. Conclusions

We have designed an instrument capable of measuring the high energy (>60 MeV) muon-induced neutron flux deep underground. The instrument is based on applying the Gd-loaded liquid-scintillator technique to measure the rate and multiplicity of low energy neutron events, and exploiting that the dominant source of events with multiplicity greater or equal to 3 are high energy neutron interactions. This unique signature allows both for efficient tagging of neutron multiplicity events as well as rejection of random gamma backgrounds so effectively that typical low-background techniques are not required. These design studies based on Monte Carlo simulations show that an apparatus consisting of a Pb target of 200 cm by 200 cm area by 60 cm thickness covered by a 60 cm thick Gd-loaded liquid scintillator (0.5% Gd content) detector could measure, at a depth of 2000 m.w.e., a rate of 70 ± 8 (stat) events/year. The number of background events is expected to be below 10 events/year and could be further suppressed by increasing the multiplicity threshold. We have discussed the relevance of this technique to monitor the muon-induced neutron background in searches for dark matter in the form of Weakly Interacting Massive Particles and, based on these studies, we also discuss the benefits of using a neutron multiplicity meter as a component of active neutron shielding.

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