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Estimating the Neutron Background from Natural Radioactivity in the Soudan Mine

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Abstract

Based on the description of the rock surrounding the Soudan mine we estimate the neutron background from natural radioactivity for the fully implemented CDMS detectors. Nuclear recoil spectra are presented for both the BLIP & FLIP detectors. The computed integrated rates are 0.02 and 0.07 recoils/kg/day for recoil energy $E_R > 5$ keV for BLIP and FLIP respectively.

The Soudan Mine The Soudan mine was the first iron mine in Minnesota, and produced high-grade hematite (Fe_2O_3) until 1962, when surface mining of low-grade ore became economically preferable to underground mining. The mine was turned into a Minnesota state park, and has since been used as a laboratory for particle physics experiments.

The underground chamber measures approximately $240 \times 45 \times 45$ feet^3 ($73 \times 14 \times 14$ m^3), and is located at a depth of 2340 feet (713 m, or about 2000 meters of water equivalent, mw.e.) below the ground surrounded by a thick layer of volcanic rock known as "Ely greenstone". Table 1 shows the composition of Ely greenstone from several published measurements of the rock in the Soudan region [1]. The density is $\rho \sim 2.75 - 2.95$ g/cm^3. The cavern is lined with a thin(~ 5 cm) layer of concrete, which is known to be more radioactive than the rock. The concrete liner has been ignored in this study.

Composition of Ely Greenstone	
Compound	%
SiO_2	50.6
Al_2O_3	15.0
CaO	9.0
FeO	8.6
MgO	6.5
H_2O	2.7
Fe_2O_3	2.6
Na_2O	2.5
TiO_2	1.1
K_2O	0.4
CO_2	0.3
MnO	0.2
P_2O_5	0.1

Concentration of Radioactive Isotopes	
^{238}U	(0.17±0.06) ppm
^{232}Th	(0.89±0.2) ppm
^{40}K	(0.79±0.04) %

Interaction Lengths of 1 MeV Neutrons	
Material	λ_i(cm)
Air	8460.0
Rock	1.8
Iron	2.3
Copper	3.5
Silicon	4.5
Polyethylene	5.0
Scintillator	6.0
Germanium	15.0

Table 1: Left. *Table of compounds found in Ely greenstone.* Center. *Concentrations of the radioactive isotopes present in the Ely greenstone.* Right: *The distance between interactions, λ_i for 1 MeV neutrons in some relevant materials. These interaction lengths come from MICAP, and are for the appropriate atomic densities of these materials in the simulation. The interaction lengths for the compound materials are weighted averages over the nuclei in the compound.*

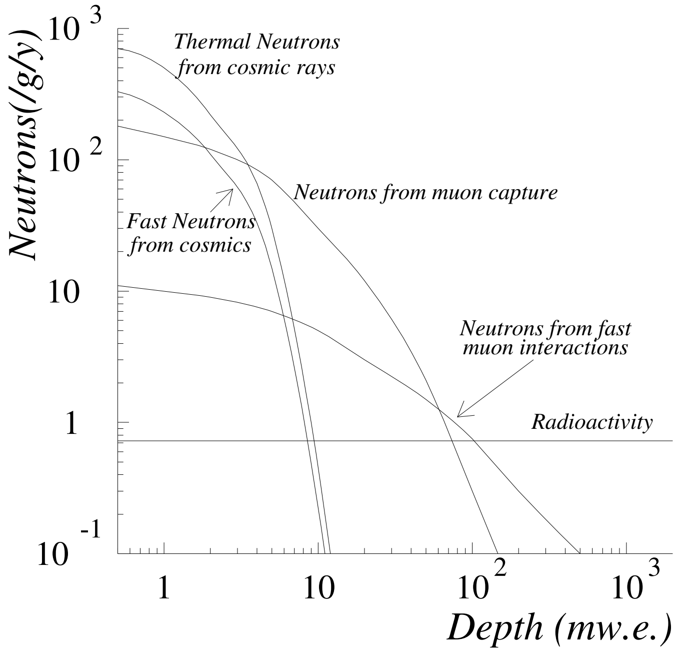

Figure 1: *Rate of neutron production as a function of depth underground in meters of water equivalent.*

Sources of Neutron Background Figure 1 [2] illustrates rates of neutron production as a function of depth. The two principal sources of neutrons in the Soudan mine are cosmic ray muons and natural radioactivity of the rock. At the Soudan depth, neutrons in cosmic rays can be neglected. Neutrons from cosmic muons are predicted to be at least an order of magnitude less than the natural radioactivity of the rock. Radioactivity in the surrounding rock is virtually independent of the depth below the surface, and so it leads to a limit on the neutron background.

Natural Radioactivity in the Soudan Mine The concentrations of radioactive isotopes in the Ely greenstone are presented in table 1. The principal source of neutrons is (α,n) reactions in the rock, where the α's are emitted by the Uranium and Thorium, and Al, Na, Mg, and ^{18}O produce neutrons in response to the α's.

Based on measurements of neutron production in these isotopes and the composition of the rock, the neutron flux is estimated at $(2.0 \pm 0.2) \times 10^{-8}$ n/g/s from (α,n) and 2.7×10^{-9} n/g/s from spontaneous fission [1].

The energy spectrum of these neutrons can be estimated to a Poisson distribution [3]:

$$dN(E) = \sqrt{E} e^{-E/1.29} dE, \tag{1}$$

where E is the neutron energy in MeV.

The Monte Carlo Starting with the rate and spectrum of the neutrons in the rock, we wrote a Monte Carlo simulation to estimate the flux of neutrons inside our detector placed inside the cave.

Propagation of neutrons in the rock and the cave We used the GEANT Monte Carlo package for the event generation and geometry definition. We used the MICAP package to simulate the propagation of low energy (≤ 20 MeV) neutrons through the materials.

The average distance between collisions at 1 MeV was 1.8 cm. The average displacement of our neutrons was 17 cm, and the average neutron energy loss per collision about $.11E$. None of the neutrons traveled further than 1 meter in the rock.

The initial neutrons were generated at random locations in a cylindrical volume of length 76 m, radius 10 m in the rock walls around the cavern. This generation volume was a layer of rock at least 1.5 meters thick around the cavern. The neutrons were generated with spherically symmetric directions with energy according to eq. 1. Neutrons below 10 keV were not tracked, since they will not be detected in our apparatus. The mass of rock in the generation volume was 3.9×10^7 kg, giving a neutron rate of 815 n/s from this volume.

Of the neutrons generated in this volume, about 5% enter the cavern. The average length traveled by a 1 MeV neutron in the air before collision is about 85 m. This length does not reduce much with reducing energy, which means that most neutrons travel straight through the cavern. Many bounce off the walls and make a handful of passes through the cave before their energy falls below 10 keV.

By counting the number of neutrons passing through various-sized volumes inside the cavern we determined that they behaved roughly as an ideal gas. Namely, the flux into a given volume was independent of the position of the volume inside the cavern, and proportional to its surface area.

Neutrons in the shield Owing to the large size of the cavern, a neutron that enters the cave is not likely to pass through any given (small) detector volume. An enormous sample of events would be required to simulate a modest flux through a detector if the events were generated randomly in the rock as described above.

The spectrum of neutrons passing through a large volume inside the cavern. The integrated flux is 2.0×10^{-6} neutrons/(cm^{2}s). This spectrum is typical of neutrons passing through any surface in the cavern, and was used to generate neutrons on the detector.

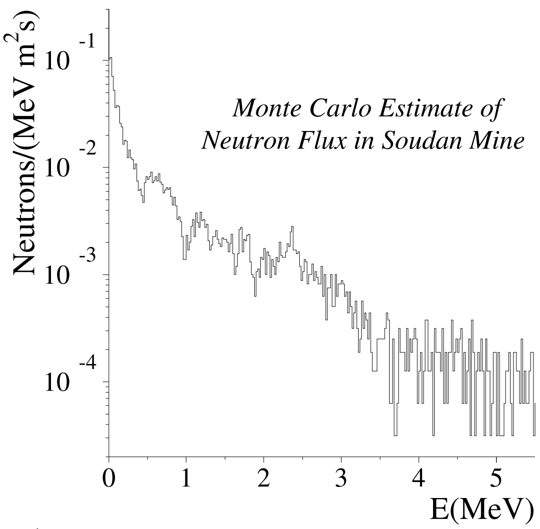

Figure 2:

Figure 2 shows the spectrum of neutrons entering a large volume inside the cave. According to the ideal gas approximation for neutrons in the cavern, this will be proportional to the spectrum of events impinging upon any surface in the cavern, in particular, a volume enclosing the detector. The flux entering the volume was $\phi_n^{cave} = 2.0 \times 10^{-6}$ neutrons/cm^{2}s.

We thus defined a small volume inside of which was a description of the shielding, cryogenics and 7 towers of 6 detectors, each detector being a silicon disk of radius 3.75 cm, thickness $\sim$1 cm. We injected neutrons into this volume according to the spectrum in figure 2. This box was $163 \times 163 \times 173$ cm^3, having a surface area of $A_{box} = 1.65 \times 10^5$ cm^2. The position of the neuron's entry was randomly chosen on the surface of the volume, and its direction spherically symmetric (but inward). Figure 3a shows the geometrical setup with a neutron track.

In order to obtain an appreciable number of events in the detector in a reasonable time, neutrons were "multiplied" as they traveled inward. This was achieved by dividing the setup into concentric spheres and storing the tracks as they passed from one to another. At each boundary the neutrons were sent inward many times. The event shown in figure 3 was generated in the innermost sphere and is propagated through the lead shield to the detector.

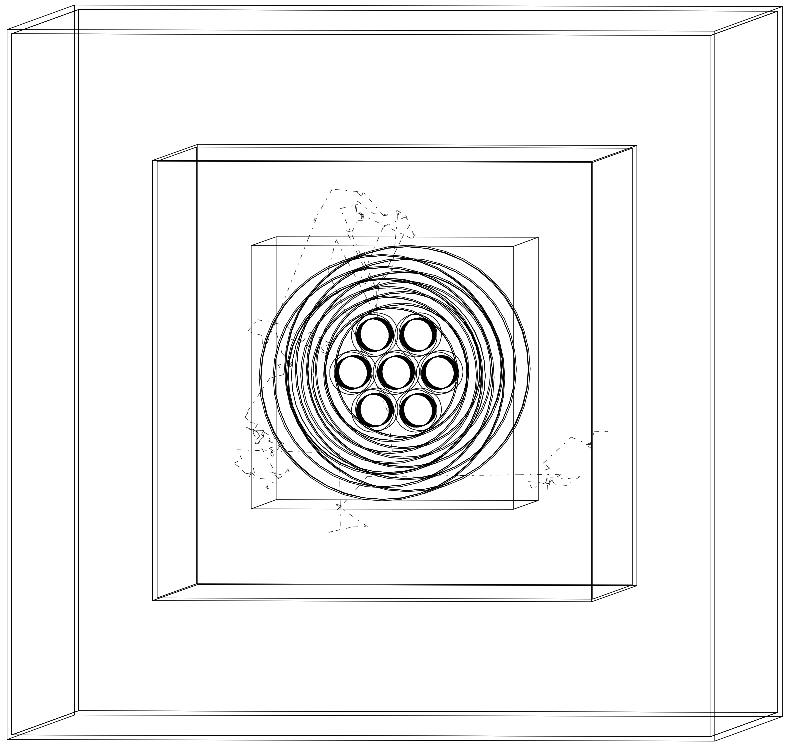

Figure 3: *A 3-D perspective of the detector geometry with a neutron track generated on the outer surface. The layers represent the polyethylene moderator (outermost), lead shielding, copper cans, and inner lead shield. There is no inner moderator. The inner volume is filled with 7 towers of 6 detectors. This event was generated in the inner lead shield.*

Neutrons in the detectors Figure 4 shows the spectrum nuclear recoil energy in the BLIP (Ge) and FLIP (Si) detectors in units of recoils/kg/keV/day. The data shown in figure 4 comprises 22,645 recoils for BLIP and 30,381 for FLIP.

About 2/3 of the neutrons passing through the detectors n_{det} scatter off a nucleus giving a recoil. The absolute flux of neutrons through the detectors, ϕ_n^{det} is is determined using the overall neutron "gain",g arising from the multiplication described above, and the rate in the cave, ϕ_n^{cave}.

$$\begin{aligned} \phi_n^{det} &= \frac{n_{det}}{g n_{box}} \cdot A_{box} \phi_n^{cave} \\ &\approx \frac{40,000 \text{ events}}{(8.5 \times 10^4)(2 \times 10^4)} \cdot 1.65 \times 10^5 \text{cm}^2 \cdot 2.0 \times 10^{-6} \text{cm}^2 \text{s}^{-1} \\ &= 7.8 \times 10^{-6} \text{neutrons/s} = 0.67 \text{ neutrons/day}, \end{aligned} \tag{2}$$

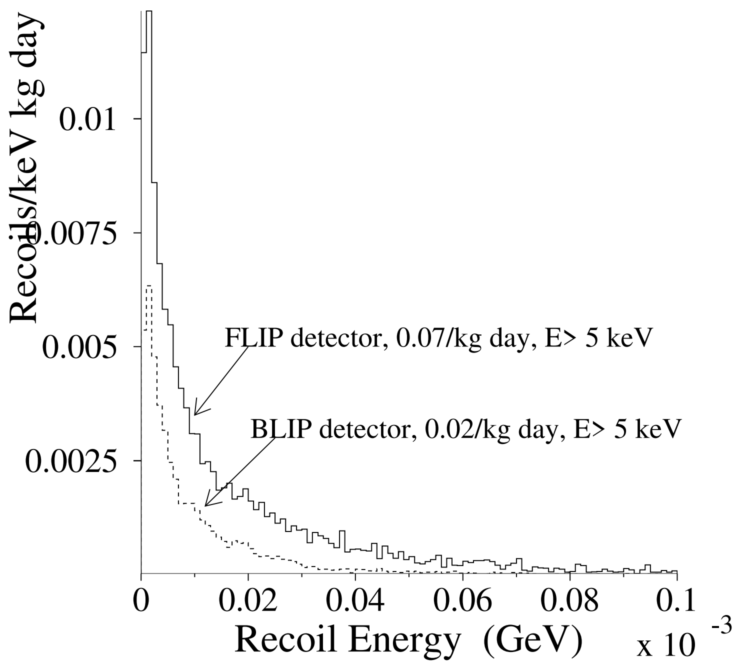

Figure 4: *The energy of the recoiling nucleus in the Germanium BLIP and Silicon FLIP detector after collision with neutron background. The shape of the spectra is different due to the lighter nuclear mass of Silicon. The integrated rate above 5 keV is 0.03 Recoils/kg/day for Germanium and 0.07 Recoils/kg/day for Silicon.*

Conclusions In addition to the study presented here, an estimate of the backgrounds from gamma rays and cosmic muon induced neutrons can be made with the same tools. This would be a test the assumption that the neutrons from natural radioactivity of the rock is the largest source of background. Calculation of errors for this study are also foreseen.

Figure 4 is the status of this study, but it is not the end of the story. It is important to know how effectively these neutron-induced nuclear recoils can be distinguished from the WIMP signal. Preliminary studies indicate that about 20% of the recoils from neutrons scatter in more than one detector, which clearly distinguishes them from WIMPS. The shape of the neutron spectrum is different to the spectrum from a more massive particle, providing another handle on the WIMP signal. In all, a WIMP recoil rate of 0.001 recoils/kg/day will sit on top of a neutron background $\sim$ 20 times larger. How well we can deal with that background will determine our sensitivity to WIMPS.

References

[1] K. Ruddick. *Underground Particle Fluxes in the Soudan Mine.* Internal Note NuMI-L-210. 1996.

[2] A. Dasilva. *Development of a Low Background Environment for the Cryogenic Dark Matter Search.* Ph.D. Thesis, University of British Columbia. April, 1996.

[3] E. Segrè. *Nuclei and Particles*, Second Edition. W. A. Benjamin, Inc. 1977.