Dusel R&D: A Multiplicity Meter for Benchmarking Cosmogenic Neutron Backgrounds for Underground Experiments

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Project Summary — Dusel R&D: A Multiplicity Meter for Benchmarking Cosmogenic Neutron Backgrounds for Underground Experiments

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. The rate of this background is at present poorly quantified, and here we propose a straightforward, portable experiment that will pin down their rate to about 10% at a depth of 2000 meters of water equivalent (mwe). These fast neutrons, with energies above about $60\,\mathrm{MeV}$, result from penetrating cosmic ray muons that interact with the rock overburden and produce neutrons through direct muon spallation, and in subsequent electromagnetic and hadronic showers. Neutrons from these processes penetrate and interact with shielding material in dark matter experiments to produce slower neutrons that cause nuclear recoils. Dark matter experiments, among others, rely on numerical Monte Carlo simulations to predict the background rate due to neutrons. At depths of 2000 mwe and below, the rate of neutron-induced backgrounds is correlated with the production of fast neutrons by muons and subsequent hadronic showers. The simulation of these processes is uncertain because of the lack of appropriate data for direct comparison.

In the work we propose here we will measure in a purpose-built detector the rate of fast neutrons in an underground laboratory through the rate of events they induce that have multiple lower-energy neutrons. We will use the long-used technique of gadolinium-loaded liquid scintillator to implement a neutron multiplicity meter adjacent to a lead "radiator" similar to the shielding in an actual dark matter experiment.

High-energy neutrons will strike a lead nucleus and initiate a spallation event. In a majority of cases, 3 or more neutrons will enter the adjacent scintillator volume. After moderation and thermalization off the hydrogen-rich scintillator, more than 90% of the neutrons will capture on gadolinium nuclei, and cause the release of 8 MeV in gamma ray energy. Since each neutron will thermalize and capture at different times over a roughly $30\text{-}\mu s$ time span, each capture will result in detectable gamma signals that are on average distinct in time from one another. By measuring the time history of the gamma signals, and requiring 3 or more, random backgrounds are suppressed and a clear signature of neutron multiplicity events is obtained.

We propose to build a modest detector with a scintillator volume of 2 cubic meters and operate it in the Soudan Mine for a period of at least one year. At a depth of 2000 mwe, we estimate that on the order of one hundred events with multiplicity of 3 or greater would be detected, providing a 10% measurement of the rate. The dominant source of background is due to chance multiplicity events from ambient uncorrelated gamma rays but we estimate that these will occur at a negligible rate. The data on neutron multiplicity would allow the underlying neutron production processes to be measured, also providing information about the parent high-energy neutron spectrum. Together, the rate, multiplicity and energy measurements, will help to normalize the simulation codes and provide insight into deficiencies in modeling the underlying processes. Following a successful outcome in this performance period, further operation at different depths, with different radiator material and/or test beams could be carried out.

The Soudan Underground Laboratory at 2000 mwe depth is the site of the Cryogenic Dark Matter Search, CDMS-II, of which both PI's are members. Locating the multiplicity detector at this site would minimize operating costs since we are already present there. The broader impacts of this work extend well beyond the goals of the CDMS experiment. All dark matter experiments, as well as many other underground experiments, rely on a knowledge of the neutron background environment. Being able to predict this background with greater reliability will serve well this community, and provide improved extrapolations for experiments aiming to operate in deeper sites at a future Dusel. By applying this technique at Soudan depth and obtaining a significant sample of events in a modest detector, we will demonstrate the feasibility of larger detectors that could be built and operated for benchmarking studies at greater depth.

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1   Introduction

The identification of dark matter is of fundamental importance to cosmology, astrophysics and high-energy particle physics [1]. Over the last decade, a variety of cosmological observations, from the primordial abundance of light elements to the study of large scale structure, in combination with high-redshift supernovae findings and detailed mapping of the anisotropy of the cosmic microwave background, have led to the construction of a concordance model of cosmology. In this very successful model, the universe is made of $\sim 4\%$ baryons which constitute the ordinary matter, $\sim 23\%$ non-baryonic dark matter and $\sim 73\%$ dark energy [2]. The findings from cosmology bolster the long history of astronomical observations indicating dark matter. Indeed, weak-lensing observations show strong evidence for dark- and light-matter distributions in galaxy clusters that are offset from one another, indicating a matter-based component is involved in accounting for earlier dynamical observations for dark matter [3]. Of particular importance to the detection of dark matter is the evidence from rotation curves for the apparent missing mass in galactic halos [4], including the Milky Way. Identifying dark matter and dark energy as understood in this model are the most important challenges to cosmology.

Weakly Interactive Massive Particles (WIMPs) represent a generic class of candidates for this dark matter [5], in which supersymmetric particle represent a well-studied candidate [6]. These Big Bang relic particles are particularly interesting because of the convergence of independent arguments from cosmology and particle physics. WIMPs would have been in thermal equilibrium with quarks and leptons in the hot early universe and decoupled when they were non-relativistic. Purely cosmological considerations lead to the conclusion that WIMPs should interact with a cross section similar to that of the weak interactions. Separate indications are that new physics appears to be needed at the W and Z scale in order to solve the famous "hierarchy problem." Precision electroweak data constrain the Higgs mass to be in the 120-170 GeV/c^2 range in spite of the radiative corrections that tend to drive it to higher values. These corrections tend to be cancelled in supersymmetry, which naturally predicts that the lightest supersymmetric partner (LSP) is stable and interacts at roughly the Weak-Interaction rate, allowing it to decouple from ordinary matter in the early universe with a relic density comparable to the dark matter density.

If WIMPs are indeed the dark matter in the galactic halo then they can be detected via elastic scattering from atomic nuclei in a suitable terrestrial target, but the event rates are low. Unfortunately, the early Universe constraints on the production of WIMPs do not tightly constrain the elastic cross section on nuclei, and so experiments as large as one ton capable of probing cross sections down to $10^{-46}\,\mathrm{cm}^2$ per nucleon will be required to search the next region of promising parameter space. Or if, as we hope, the cross section is higher, detectors at this scale will be able to make more precise measurements of the cross section and mass. Already at the present limit of $10^{-43}\,\mathrm{cm}^2$ at mass of $60\,\mathrm{GeV}/c^2$, the Cryogenic Dark Matter Search (CDMS) experiment has the best constraint on the cross section with an exposure of $50\,\mathrm{kg}$-days. This experiment, on which we are both collaborators, operates at the Soudan Mine at a depth of 2300 feet, or 2000 meters of water equivalent (mwe), and is discussed further in Section 2. Here, we note that the depth is required to reduce the backgrounds related to penetrating cosmic ray muons.

Many collaborations, including CDMS, plan to carry out larger experiments at Dusel or other underground sites. Their success depends not simply on suppressing the backgrounds, but having a well-characterized measure of the expected residual rate — otherwise, it is difficult [impossible?] to determine that a WIMP signal is bona fide. The primary backgrounds in dark matter experiments are due to two primary sources. Neutrons, which arise from natural radioactivity and cosmic ray interactions, cause nuclear recoils just like WIMPs and cannot be distinguished on an event by event basis. Gammas and betas, which arise from residual radioactivity internal to the detector apparatus, produce electron recoils. Suppression of the electromagnetic backgrounds is handled to varying degrees using different detector techniques that discriminate between their electron recoils versus the nuclear recoils produced by WIMPs and neutrons. These are experiment-specific considerations, which are beyond the scope of this discussion, except to note that progress to reject electron recoils is being made on many fronts from cryogenic detectors to liquified noble gases, as well as improvements to conventional inorganic scintillators and novel bubble chambers.

In the work proposed here, we focus on the cos-

mogenic neutron background, which is common to all dark matter searches, as well as other classes of underground experiments like double beta decay. These entire classes of experiments, which are among the prominent physics drivers for establishing Dusel, all need to address the background from neutrons, and cosmogenic neutrons in particular, which is what dictates the need for greater depth in order to improve experiment sensitivity.

Neutrons from natural radioactivity have energies on the order of 10 MeV and below, and can be suppressed to a sufficiently high degree by careful choice of low-radioactivity materials inside the apparatus and appropriate shielding for external sources on this energy scale. External sources of 10 MeV neutrons are effectively moderated by hydrogen rich material to energies below about 100 keV, at which point the have insufficient energy to produce nuclear recoils above typical detector thresholds of 10 keV recoil energy. The more troublesome neutron background, which we address in the work proposed here, are neutrons produced by cosmic ray interactions through interactions in the rock caverns. Neutrons with energy in the approximate range of 50–500 MeV are produced by interactions in the rock and can emerge into the cavern from the first few meters of rock. About ??% of the time, no accompanying charged particles enter the cavern so conventional vetoes are not effective. Also, at these neutron energies, the cross section on nuclei falls rapidly and so hydrogenic moderators become far less effective, as well as making direct vetoing of the neutrons challenging.

While various solutions to this high-energy neutron background are being considered, including deeper sites, and surrounding experiments with large scintillator vetoes or water shields, in virtually all cases experiments rely on numerical Monte Carlo production and transport codes to simulate and predict the level of background. These codes, such as Fluka and Geant4, attempt to include the most up to date knowledge of the physics processes that lead to the production of high energy neutrons from muon interactions and the secondary processes that lead dark-matter-like nuclear recoils. However, these codes differ substantially, in some cases by a factor of 3 [ref/check this statement] with the best available data. Improving upon this paucity of data to cross check the codes is essential to building confidence in these widely used tools.

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WIMP searches must be performed underground in order to be shielded from cosmic rays, which produce secondary particles that could fake a WIMP signal. Experiments that search for WIMPs are thus one of the critical science drivers for a Deep Underground Science and Engineering Laboratory in the United States.

However, the energy deposition and the rates are low, and two broad classes of background must be reduced, rejected, or measured and subtracted in order to reveal a dark matter signal. Generally speaking, the two classes are neutrons and electromagnetic processes. Neutron present a background because, like WIMPs, they produce nuclear recoil events. Neutrons... which are the emphasis of this work... located deep underground to protect from cosmic rays.

In comparison, electromagnetic processes...

———- Although the earthen overburden in the lab reduces the flux of cosmic ray muons that produce neutrons, a residual flux remains because of the presence of energetic penetrating muons from high-energy cosmic rays the multi-step process is poorly modeled though often simulated. Data from the detector we propose, would provide of muon-nucleusprocess is poorly— through a poorly-modeled series of interactions — a flux of low-energy neutrons. Since both WIMPs and neutrons scatter from atomic nuclei, they are expected to leave the same characteristic signal in a dark matter detector.

Sophisticated detectors have been used to great advantage to reduce backgrounds that scatter from electrons, such as those in the Cryogenic Dark Matter Search, of which we are part. The sensitivity gains are in large part due to a reduction of the predominant electromagnetic backgrounds which are due to ambient radioactivity. However, even these detectors, which are excellent at distinguishing nuclear recoils from electron recoils, cannot reject false-positive single-scatter neutron-induced recoils.

In addition to siting experiments deep underground, neutron backgrounds are suppressed by several methods, which include the use of materials with low natural radioactivity, shielding with hydrogen-rich moderator to slow the neutrons so they don't produce energetic recoils, and surrounding detectors with active detectors to detect muons or related particles produced in the same interactions leading to the offending neutrons. These methods are quite effective, with the exception of shielding neutrons with a kinetic energy in excess of about 50 MeV. Above these energies, the probability of scattering in the shield makes the moderation process fail and instead it is more likely for the neutron to interact in the experimental apparatus, produce low-energy "daughter" neutrons, and the these daughters scatter in the dark matter detectors.

importance of prediction... use of MCs... difficulty to benchmark... proposed work... multiplicity me-

ter... proven method... yields rate and multiplicity...

2   Results from Prior Support

The Cryogenic Dark Matter Search (CDMS) collaboration is operating the CDMS II experiment [7] to search for WIMPs in the Soudan Underground Laboratory. The collaboration consists of thirteen institutions. In the sections that follow, the accomplishments of the collaboration are described, with a focus on the science output — the world's most sensitive experiment to WIMP dark matter — and the technical accomplishments required to achieve them. Highlights of the Case and UCSB groups' contributions, which are supported by the NSF and DOE, respectively, are noted.

2.1   Science Results

The CDMS II project includes the fabrication, testing and operation of five towers of detectors, each with six ZIP detectors. Towers 1 & 2 were installed at Soudan in March 2003, and data were taken with Tower 1 alone from October 2003 to January, 2004. During the second data run at Soudan, both towers were operated between March 25 and August 8, 2006 at a base temperature below 50 mK. A total of 74.5 live days were accumulated with the six Ge and six Si ZIP detectors.

Energy calibrations were performed repeatedly during the run using a ^{133}Ba gamma source with distinctive lines at 356 keV and 384 keV. The agreement between data and Monte Carlo simulations and the observation of the 10.4 keV Ga line from neutron activation of Ge indicated that the energy calibration was accurate and stable to within a few percent. To guarantee stability of operation and effective neutralization of the crystals during the WIMP search runs, the region outside the nuclear-recoil band of the WIMP-search data was continuously monitored, and the crystals were neutralized with infrared radiation every four hours. In addition to ^{133}Ba calibration data, ^{252}Cf calibration data were taken seven times throughout the runs to characterize nuclear recoils in the detectors.

We performed blind analyses, in which the nuclear-recoil region for the WIMP-search data was not inspected until all cuts and analysis thresholds were defined using *in situ* gamma and neutron calibrations. A combination of ionization-yield and phonon-timing cuts rejected virtually all calibration electron recoils while accepting most of the nuclear recoils (see Figure 1). The analysis of the first Soudan CDMS II WIMP-search data set revealed one nuclear-recoil candidate

in 52.6 kg-d raw exposure in our Ge detectors, consistent with the background of 0.7 ± 0.4 electron-recoil events expected to be misidentified as nuclear-recoils. No candidates were found in the 5.3 kg-d raw exposure of the single Si detector considered.

Figure 1: Variables used to reject surface electron recoils (7-100 keV), for data from a Si (left) and a Ge (right) detector. The top is the timing parameter, and the bottom the $\Delta\chi^2$. Light (red) lines show distributions of low-yield electron recoils from the ^{133}Ba source, while dark (blue) lines show distributions of nuclear recoils from the ^{252}Cf source. Dashed lines indicate the minimum values for acceptable WIMP candidates.

For the two-tower data, five different methods were used to calculate phonon-timing cuts: one simple method similar to that used in the previous run and four advanced techniques. Each used the ^{133}Ba gamma calibrations, which produce mostly bulk events, but also a distribution of low-yield surface events primarily from electrons ejected from neighboring material onto the ZIP detectors. These surface events allow us to determine the effectiveness of phonon-timing cuts for surface events such as those due to surface beta contamination. Based on the simple phonon-timing cut and the ^{133}Ba calibration sets and including systematic errors, we expected 0.4 ± 0.4 electron-recoil events in Ge to be misidentified as nuclear-recoils. The advanced techniques result in predicted background leakage up to nearly three times lower.

This blind analysis of the second Soudan CDMS II WIMP-search data set, using the simple phonon-timing cut revealed one nuclear-recoil candidate in 96.8 kg-d raw exposure in our Ge detectors and no nuclear-recoil events in 31.0 kg-d in Si. Figure 2 displays the ionization yield of WIMP-search events in the Ge and Si ZIP detectors that passed the same cuts applied to calibration data in Fig. 1

Figure 2: Ionization yield versus recoil energy for events in all Ge detectors (upper) and Si detectors (lower) passing initial selection prior to (small open circles) and after (larger filled symbols) phonon-timing cuts. The single event passing all cuts in the signal region is denoted with a star.

Figure 3: Fig place holder. WIMP-nucleon cross section upper limits (90% C.L.) versus WIMP mass. The upper CDMS Ge curve also uses data from the current run, while the lower Ge curve includes the previous run [7]. Supersymmetruc models allow the largest shaded (light-blue) region [10], and the smaller shaded (green) region [11]. The shaded region in the upper left is from DAMA [12].

The event passing all cuts in Ge was found to occur during an extended time when the detector suffered inefficient ionization collection; more care will be taken to exclude such data from future analyses. These results are consistent with those obtained using all phonon-timing analysis techniques. As shown in Fig. 3, these data set an upper limit on the WIMP-nucleon cross-section of 1.6×10^{-43} cm^2 (3×10^{-42} cm^2) in Ge(Si) at the 90% C.L. at a WIMP mass of 60 GeV for spin-independent, coherent scalar interactions and a standard WIMP halo. At 60 GeV, this limit is nearly an order of magnitude lower than that of any other experiment.

Reports on the two-tower results have been published in *Physical Review Letters* [8] and *Physical Review D* [9], and a detailed *Physical Review* paper combining the data from both runs at Soudan is in preparation.

2.2 CDMS II Completion

On August 8, 2004, after nearly a year at 50 mK, we began warming up the experiment to install several necessary upgrades. Chief among these were the three new detector towers, the flex circuits to read them out, and a cryocooler to mitigate their additional heat loads and reduce helium consumption. Figure 4 shows the five-tower arrangement for this installation. All 30 detectors are now operating. The final commissioning activities for the five tower science run are

underway. The science run itself is imminent, and should begin during the week of Oct 8, 2006. The operational details remain to be determined, but the five tower run will last upwards of two years.

Figure 4: Towers 1 & 2 have been operated in Soudan; Towers 3, 4 & 5 have been installed and all five Towers are now operating in Soudan.

Based on our projected raw exposure of about 1300 kg-d for the CDMS II experiment through the end of 2007, we expect to extend our sensitivity for a WIMP-nucleon cross section down to a 90%-C.L. upper limit of $\sim 2 \times 10^{-44}$ cm^2 for our projected background of 1.0 events (without background subtraction). A cross section of 4×10^{-44} cm^2 would result in 8 expected events, enough to provide a 99%-C.L.

detection even if the expected background has significant uncertainties. In practice, we may find placing stricter cuts will extend our reach by reducing the expected background.

[case group...]

[ucsb group...]

2.3 Technical Contributions

2.3.1 Detector Testing & Characterization in CDMS II

[trim down case part; add ucsb part]

We have used the Case Test Facility (TF) for cryogenic testing of CDMS II ZIP detectors and superconducting thin-film samples since 1998. The facility consists of an Oxford Kelvinox 400 dilution refrigerator, 12-channel electronic readout, DAQ and 14-node computing cluster for ZIP data processing and analysis. Further facilities include a $100 \, \mathrm{ft}^2$ class-100 cleanroom with LN-boiloff gas-purge to reduce ZIP detector exposure to radon and polyethylene-shielded storage to reduce activation from neutron capture in the germanium detectors and copper holders.

The test facility has served as an effective vehicle for educating students and postdoctoral scientists. Five Ph.D. students have made significant contributions to ZIP detector testing, four of whom have already completed their dissertations. Eight undergraduate students made important contributions to the infrastructure and operations of the test facility while completing their baccalaureate degrees. Four postdoctoral researchers with varied prior experience have been introduced to particle astrophysics with low-temperature, low-noise readout ZIP detectors by means of the test facility. Learning to operate the cryogenic systems and detectors at Case has been excellent training and allowed group members to be effective contributors to operations of the main experiment at Soudan.

Activities at the test facility have been to support CDMS II detector development and production. Cold hardware necessary for instrumenting the ZIP detectors has been evaluated, providing very valuable experience troubleshooting low-noise electronics. Other studies have been initiated to characterize the detector response to specific particle interactions. One such study involved surface events generated via Compton scattering followed by the ejection of electrons from one detector into its nearest neighbor. Finally, standard particle detector instrumentation such as NaI scintillation counters have been used to count the rate from ^{60}Co nuclear orientation thermometer. The instrumentation associated with the

proposed project is well within the experience of the Case PI and group.

2.3.2 Backgrounds

Most events misidentified as nuclear recoils because of low ionization yield are expected to come from beta particles emitted on or near the detectors. The beta particles are poorly penetrating, and therefore deposit energy in the ionization dead layer at the detector surface. In order to try to reach lower-level assays for such contamination, we developed at Case a new approach to this problem by using surface probes to identify specific problematic elements that have beta-emitting isotopes. This method has been pursued further with collaborators at the University of Minnesota.

Assays of ZIP-detector witness samples were made via Secondary-Ion Mass Spectroscopy, Auger analysis, and Rutherford Back-Scattering combined with Particle-Induced X-ray Emission. These analyses suggest the presence of about a few hundred parts per million natural potassium, which results in about 5% of the observed beta rate. These assays also indicate that a few monolayers of carbon are present on the ZIP surfaces, consistent with exposure to air, but there is no evidence of buried carbon. This amount yields 0.3 betas/day per ZIP, with a 156 keV endpoint, or less than 10% of the total observed beta rate, assuming ^{14}C occurs in its natural abundance. Work is ongoing to further calibrate and refine these results in our effort to identify specific isotopes and to use these identifications to target specific steps in the detector processing or handling where they might be introduced.

2.4 Broader Impacts

[adapted from last Case proposal; needs to be expanded/modified to include UCSB]

The broader impacts of our work fall into two general categories: education and public outreach, and technology transfer. Our groups have been active participants in the public programs at the Soudan Mine, which included daily science tours in the mine, as well as special student-group visits throughout the year. Through these programs, we have enjoyed unprecedented access to the public by serving as science tour guides and answering questions about dark matter, cosmology and particle physics. We have constructed exhibit materials and posters to help us tap into the public's fascination with cosmology.

The broader impact of the technical work we do is preparing undergraduates for graduate school and

other endeavors, by encouraging students to undertake senior projects in our lab. [need to adjust rest of this for Case+UCSB] Between the PI and Co-PI, we have supervised eight (and counting!) senior projects on CDMS II. The majority of these students have gone on to graduate school in physics. Also, a former senior research associate, upon leaving our group, took up a position with a firm that develops and produces radiation detectors. Thus, individuals that have received training or developed new expertise in our group, have gone on to apply these skills in the private sector.

add something on neutron bkg work? eg, kamat and perera theses cited in recent work... other items?

3 Program of Work: The Neutron Multiplicity Meter

3.1 Motivation

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-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 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 m.w.e. depth and 10 GeV energy [13, 14] to 5200 m.w.e. and 400 GeV [15]. 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 [16] based on Monte Carlo simulations made with the particle production and transport code

FLUKA [17, 18]. In particular, at a neutron energy of 100 MeV and above, their results show a discrepancy as large as a factor of two with data taken with the liquid-scintillator LVD detector [19] at a depth of 3650 m.w.e and a mean muon energy of 270 GeV.

Mei and Hime [20] 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 LVD collaboration says this correction is inappropriate. An extensive search of the literature did not reveal any other data at these energies to inform the production of high-energy neutrons, which leaves the discrepancy unresolved.

High-energy neutron production by muons occurs through hadronic showers generated by the muons interacting in the rock, and to some extent by direct muon spallation. 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 [21] at three different angles from the muon beam. Araujo and co-workers [22] show that this experimental data lies above the Monte Carlo simulations from between a factor 3 to 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, or underestimate the rate due to high-energy neutron detection inefficiency in the small target. The possible systematic errors leave the matter inconclusive, informing neither the production by muon spallation nor the total fast neutron yield above 10 MeV.

Furthermore, the measurements of neutrons at large depths reported in the literature involve either primary muon interactions in hydrocarbon liquid scintillator followed by cascade processes within the detector (see [19] and discussion therein; [23]), or muon interactions in higher-Z material such as Pb and Cu [24] in which neutron production is dominated by relatively low-energy electromagnetic properties. In contrast, of particular interest for dark matter experiments, as we described above, is the distinct circumstance in which unvetoed 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 at 10 MeV and below. In the work proposed 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 unvetoed neutron flux to an accuracy of about 10%. By measuring the high-energy neutron flux at 2000 m.w.e. we will benchmark the neutron produc-

tion by muon induced hadronic showers and provide a normalization of the unvetoed neutron background.

In addition to the interest for the shielding configurations for many dark matter experiments, improved knowledge and predictibility of the neutron flux at depth will aid in the understanding of neutron induced backgrounds in double beta decay experiments. For example, as noted by Mei and Hime [20], 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 Dusel 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.

3.2 Principle of the Instrument

The proposed instrument is based on applying the Gd-loaded liquid-scintillator technique to measure the rate of high-energy neutrons underground based on the neutron multiplicity induced in a lead target [26]. Gadolinium has a high thermal-neutron capture cross section, and emits 8 MeV in gamma rays after the capture. Since each of the multiple neutrons thermalizes at a different time, a measurement of the capture times is a straightforward way to determine neutron multiplicy 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 searched for superheavy elements expected to decay to high-neutron-muliplicity final states [27], and more recently in accelerator-based applications [28].

The basic design of the Neutron Multiplicity Meter applied to measure high-energy neutrons (>60 MeV) underground employs the Gd-loaded liquid-scintillator detector atop a wide 200-cm-square by 60-cm-thick Pb target [26] 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. The disintegration of the Pb nucleus will produce several neutrons with typical energy below 10 MeV emitted isotropically — the interaction of say, a 100 MeV, neutron tends to raise the average energy per nucleon by at most only about a tenth of its approximately 5 MeV binding energy. This results in an excited nuclear state that de-excites through the roughly-isotropic emission of neutrons in a so-called evaporative process. These neutrons 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 $40\,\mu sec$, most will have captured on the gadolinium, and thus the essential problem of detecting neutral particles with high efficiency has been turned to advantage: the neutrons which are released in simultaneously burst of three or more are spread out in time, and individually captured and counted. As the simulations below illustrate, this unique signature allows both for efficient tagging of neutron muliplicity events as well as rejection of random gamma backgrounds so effective that typical low-background techniques are not required [26].

3.3 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 [26] using the FLUKA simulation package [17, 18]. These studies, carried out for background estimates in the CDMS II experiment, are based on throwing an angular distribution of muons appropriate for this depth, and normalized to the measured flux in the CDMS II plastic-scintillator veto system. In the study, the muons are thrown into a rock-wall cavern modeled as a 6-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 Figure 5, shows that the neutrons are mostly going downward at angles greater than about $0.88\,\pi$ radians, where π radians corresponds to vertically downward direction. 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 considered for the target were the optimal thickness and whether it is best placed above or below the scintillator tank. A simulation with FLUKA was performed by throwing a beam of 100-MeV neutrons at a 2 m by 2 m Pb target with thickness varying from 1 to 100 cm. The detectability of a subsequent multiplicity event is gauged by counting the number of secondary neutrons that emerge from

Figure 5: 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 $0.88\,\pi$ radians with respect to the normal vector from the floor. Therefore, the rate of incident high-energy neutrons is proportional to the area of the target [26].

Figure 6: Neutron fluence plot of a FLUKA simulation that throws 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 $z=0$ to 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 [26].

the Pb with less than 10 MeV and are thus readily moderated and captured. A parameter P is defined for both the top and bottom surfaces as the fraction of events for which a downward-thrown 100-MeV neutron results in at least 3 low-energy neutrons exiting either the side from which the neutrons was thrown (top) or the side opposite (bottom). The overall production point and neutron travel direction is illustrated in Figure 6, which shows the neutron fluence (neutron track length per unit volume) in units of cm per cm^3 per primary neutron thrown, based on a FLUKA simulation for a 60-cm-thick target.

Quantitative results for P are shown in Figure 7, 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. 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 due to an effective backscattering effect 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 is that since the primary interaction

Figure 7: 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 neutrons thrown) 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 $P_{\mathrm{TOP}} + P_{\mathrm{BOTTOM}} > 1$, for example as observed for 40-, 60- and 80-cm thickness. [26]

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 mulitplicity rate, the scintillator is placed atop the Pb, which also has the advantage of tagging muons that strike the Pb directly (see below).

In addition to optimizing the detector layout, we also wish to estimate how the detected event rate and multiplcity varies with the energy of the incident fast neutrons. For this study, the geometry of the Pb covers an area of 200 cm by 200 cm normal to the vertical with a thickness of 100 cm, and downward-going neutron beam at energies of 60, 100, and 200 MeV are throws in FLUKA. 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 Figure 8, where "Event Fraction" corresponds to the fraction of events that had at least one neutron emerging on the top side. The plot shows that the majority of the

can be made to reject random coincidences and still achieve good efficiency for neutron-induced events. In order to estimate the rate per year of high-energy neutron events with a minimum detectable multiplicity, the fraction of high-energy neutrons (> 60 MeV) that are anticoincident with a signal of 2 MeV in the CDMS II veto, was thrown at a Pb slab of 200 cm by 200 cm in area and 60-cm thick. The rate for detectable "clean" multiplicity events, that is, events that are in anticoincidence with energy depositions of 2 MeV or more from gammas or charged particles, including muons and hadrons, is shown in Figure 9 as a function of multiplicity. This multiplicity was

Figure 9: 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 any prompt energy deposition of 2 MeV or more from charged particles, including muons and hadrons. The detectable multiplicity was determined only by counting neutrons with energy less than 10 MeV going towards a surface on top of the Pb target [26], that is, entering the scintillator region.

Figure 8: 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. Taking the beam direction as "downward," the detectable multiplicity is determined by counting the neutrons that reach a surface just above the Pb target [26].

events have a detectable multiplicity of 3 or more, and that there is an increase in multiplicity with primary neutron energy indicating some information on that quantity my be extracted from the data.

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

counted by considering only those secondaries with energy less than 10 MeV entering a top-side detector. 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 mulitplicity, and is displayed in Figure 10. The total number of events changes only by about 10% between a minimum multiplicity of 3 and 10, allowing flexibility on setting the multiplicity threshold.

In determining the optimal thickness of the scintillator modules, the two requirements considered are the moderation of the secondary neutrons, and the absorbtion of the Gd capture gammas. The FLUKA simulation predicts that the spectrum of neutrons emerging from the Pb falls off almost completely by

Figure 10: The total number of events as a function of minimum multiplicity. Note the suppressed zero on the ordinate — the total number of events changes only by about 10% between a minimum multiplicity of 3 and 10 [26].

5 MeV, as shown in Figure 11. A scintillator region

Figure 11: Energy spectrum of secondary neutrons produced by high-energy neutrons (flux shown in Fig. 5) 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, the thickness is driven by the need to efficiently contain the gammas emitted by the Gd. [26].

of 10 cm thickness would be sufficient to moderate them. However, containing the capture gammas requires a thicker detector. In order to find the optimal thickness, the low-energy simulation code, MCNP-PoliMi [25], which includes the neutron-capture process, was used. A beam of 0.5-MeV neutrons was

thrown from the Pb up to a top-side scintillator tank, and the thickness of the tank was varied. In Figure 12 the efficiency to detect events with a 3-MeV threshold is shown as a function of scintillator thickness. To allow for resolution effects, 3 MeV is taken as the

Figure 12: Simulation with MCNP-PoliMi [25] 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 thrown from the Pb to the scintillator tank. The thickness of the scintillator tank was varied. Efficiency corresponds to the number of incident neutrons that deposit energy in the Gd-loaded scintillator above 3 MeV [26].

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. The energy deposited in the scintillator consists of mainly two components, one from neutron-proton scattering, the other from the 8-MeV of gamma cascade released from the Gd, typically shared between 3 or 4 gammas. The detection efficiency increases with thickness not because of better moderation but rather because the better containment of the gamma cascade. In particular, detection of neutrons below a few MeV relies mostly on containing the capture gammas to deposit energy above the 3-MeV threshold. Based on these studies, and the goal of ∼100 events per year, we choose a scintillator thickness of 50 cm.

To assess the rate of background coincidences that can mimic the signal, we need to 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 and capture of multiple neutrons released simultaneously into the scintillator is broad, with a peak at about 10 μsec after emission and about 90% of

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captures ocurring within the first $30\,\mu$sec. A neutron burst results in a cleanly-separated readily-counted pulse train since the pulse widths of about 10 nsec are narrow compared to the typical time between captures of order $1\,\mu$sec. The triggering and DAQ to record these data is straightforward, and discussed below.

Ambient gammas, which will 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. 13 for a time window of $40\,\mu$sec and three different gamma rates. The gamma rate at

Figure 13: 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 microseconds and three different gamma rates [27].

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 [29]. 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 mulitplicity 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. If needed, further reduction is possible by increasing the multiplicity, slightly raising the threshold, or adding a thin amount of Pb shielding.

We also consider the background due to neutrons from radioactivity, which are dominated by alpha-n reactions in the rock oringinating from alpha decays in the uranium and thorium chains. The ambient rate of neutrons from radioactivity at Soudan is estimated

from the measurements of the U/Th contamination in the Soudan rock [30] and cross tabulated with measurements of both the U/Th level and neutron flux at the Kamioka mine [31]. The resulting flux estimate of about 2×10^{-5} neutrons/cm^2/sec produces a rate of about 3 neutrons/sec in our proposed detector, and is therefore 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 6 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. [would welcome a cross check of this – my notes show U has 13 Bq/kg of gammas and about 16 fissions/sec/kg -dsa.]

While the backgrounds from these other processes under control, it is also interesting to consider event classes related directly to the muon and neutron events we wish to study. One broad class are events in which the muon itself passes through the scintillator. Most minimum ionizing muons will have sufficient pathlength of about 5 cm in the scintillator to be readily distinguished from at 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 [23] and so are not as useful a cross check on the unveoted population, which is dominated by higher-energy hadronic processes.

A crossfeed into this muon-tagged sample comes from high-energy neutrons that interact in the scintillator, if those interactions also deposit above the 8–9 MeV associated with Gd captures. Based on a FLUKA simulation, the fraction of high-energy neutrons impinging on the apparatus that are in this category is about 32%, with the remainder interacting in the Pb. Of the remaining 68% that deposit less than 8–9 MeV and produce spallation of the Pb, the multiplicity distribution will occasionally be skewed slightly upward by one unit. But this class of events will not affect the inferred rate of high-energy neutrons, since they are of that same origin.

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 count of multiplicity events due to high-energy neutrons. There could be a few per day of the estimated 350 muons/day that will pass through

the Pb, and 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, these design studies show that an apparatus consisting of a Pb target of 200 cm by 200 cm area by 60 cm thick covered by a 50-cm-thick scintillation detector with Gd-capture detection efficiency of $\varepsilon_s(T)$, where T is the low energy threshold for each distinct capture, will yield a rate for M-fold multiplicity-tagged events of

$$R = N\,(1 - 0.32)\,(\varepsilon_s(T))^M \text{ events/year}$$

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 $(1 - 0.32)$ is due to neutron interactions in the scintillator that exceed the high-energy threshold. The FLUKA and MCNP-PoliMi simulations [26] indicate that M=3 gives N=255 and T=3 MeV gives $\varepsilon_s(T)$=0.78, and therefore $R = 82 \pm 12$ 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. For comparison, M=5 gives N=248, but combined with T=1 MeV giving $\varepsilon_s(T)$=0.89, we get $R = 94 \pm 11$ events/year. Generally speaking, this method is capable of measuring the rate of high-energy neutrons to about 10% statistical error in the span of one year.

3.4 Anticipated Results

The proposed apparatus will allow the determination of the primary neutron rate to the level of 10% after one year of operation. As an illustration of an immediate outcome of this measurement use the example of the current run of the CDMS II experiment at Soudan. The new neutron measurement will significantly reduce the normalization uncertainty on the estimated cosmogenic neutron background for the CDMS II five-tower exposure, thus improving the statistical significance of even one candidate WIMP event. The neutron background estimate, for an exposure of 1300 kg-d, is about 0.1 events, but with a poorly determined systematic error that could be larger by a factor of two. To be sure, there are other tools at the collaboration's disposal, such as the differential rate of WIMPs and neutrons in germanium versus silicon targets. The neutron contribution to single scatter nuclear recoil events (the signature of WIMP events) can also be estimated by observing some number of multiple-scatter nuclear recoils, which are necessarily due to neutrons.

More importantly, we are motivated by the longer term proposal for dark matter matter research to be carried out at Dusel, and elsewhere. These measurements will provide a benchmark of the basic tools that are used to predict the sensitivity of a given apparatus and site, and aid in the interpretation of results.

In addition to the overall rate normalization, we may will learn about the primary neutron energy through its correlation with the secondary neutron multiplicity. From this correlation, the primary neutron event sample can then be statistically associated with the detailed neutron production processes. A course of calibration runs using a test beam (*e.g.* FNAL or LANL) of neutrons at energies above 60 MeV would be very valuable in benchmarking the production Monte Carlo for the multiplicity. Even in the absence of benchmarking with a test beam, a correlation between observed multiplicity and primary neutron energy will allow some spectroscopic information to be obtained from the multiplicity instrument, itself, through exposure underground. Pending further studies and intial use of the instrument, we will consider proposing at a later date test-beam studies.

3.5 Detector Layout and Design

Our design for the detector is shown in Figure 14. Large boxes containing Gadolinium loaded scintillator, read out by phototubes at either end, sit atop a base of lead that constitutes a target for neutrons. The device sits on the ground, and is surrounded by charged particle veto.

One scintillator box is shown in Figure 14, but there would be three more boxes deployed in the dimension perpendicular to the plane of the page, for a total of four boxes. The horizontal area of the array would be 200 cm by 200 cm, and the height of lead and scintillator resulted from a cost optimization.

The boxes themselves are 50 cm by 50 cm by 200 cm. The height of 50 cm is dictated by the efficiency for detecting the gammas from neutron capture on Gadolinium. The 50 cm width results from a compromise between wanting a light-guide geometry benefitting from total internal reflection, and wanting to minimize the number of channels for cost. The crude segmentation also allows rudimentary studies of the spatial distribution of candidate events.

We plan to build the boxes out of 1/4" UVT Acrylic. Some structural tests will tell us whether ribbing or a thicker wall are necessary. The UCSB group has a fair amount of experience in forming acrylic structures, having made a scintillator calorimeter in

Figure 14: Layout of the proposed Neutron Multiplicity Meter. The main detector element consists large boxes of Gadolinium loaded liquid scintillator, which sit atop a base of lead. A high energy neutron would leave no signal in the veto counters, a small prompt signal in the liquid scintillator, and then induce a high energy shower in the lead base. Liberated neutrons are then emitted uniformly, and are moderated and captured on the Gadolinium nuclei in the liquid scintillator over a time interval of about $40\,\mu$s. Each capture releases about $8\,$MeV in γ rays.

the 1970's, the veto systems for CDMS-I and CDMS-II. We will machine the acrylic pieces in the UCSB machine shop and assemble them in the High Energy Physics labs at UCSB. The design work will be done by our two engineers, Susanne Kyre and Dean White, and the assembly will be performed by another engineer, Dan Callahan. Callahan traditionally is paid out of project funds, while the engineers are on our DOE base grant.

Our design also calls for pyramidal light-guide boxes on the ends of the central scintillator box. These boxes would be filled with a white oil such as Marcol-7. Placement of a light guide in the liquid scintillator itself would create dead areas of scintillator, and the cost of the dead scintillator exceeds the cost of the pyramidal light guides. In practice, we will do some optimization of the light collection design with a small scale prototype.

The lead base will consist of bricks formed from virgin lead from a low-activity mine such as Doe Run. This lead is nearly the same price as generic lead. We prefer not to use recycled lead because its radiation exposure might leave behind radioactive impurities that would cause a significant background rate in the liquid scintillator. We believe that with suitable shimming, the detector boxes can sit more or less atop the lead.

Our plan for the veto detector is to use counters left over from other experiments at SLAC, Fermilab, or Soudan.

3.6 Data Acquisition

The necessary data acquisition system needed can be appreciated by studying the time sequence of expected pulses for the device shown in Figure 15. A prompt pulse is followed some number of microseconds later by a sequence of pulses, each of which originates as a neutron capture. The large prompt energy deposition would make muon events distinguishable from neutron events.

The data acquisition system is straightforward, and consists of a digital trigger, a waveform digitizer, a history buffer, and a data acquisition computer. A diagram of the system is shown in Figure 16.

The data acquisition system is rather similar to that used for the CDMS-II experiment, and we have used the actual costs from the construction of that system to cost out the system described in Figure 16. We assume that some elements of the system, including the high voltage power supply and the discriminators, will be obtained from surplus at SLAC, Fermilab, or Soudan.

Figure 15: Traces of Events from the Neutron Multiplicity Meter. Time is plotted along the horizontal and the phototube signal (negative) along the vertical. The first pulse is prompt, within a few nanoseconds of the passage of the initating particle. For a neutron, the prompt signal could be caused by showering in the scintillator, backsplash from the hadronic shower in the lead, or even a prompt proton recoil from a fast neutron from the hadronic shower. Signals from subsequent neutron captures follow, separated by a few microseconds. When a muon initiates an event, the prompt pulse is far larger.

Figure 16: Proposed Data Acquisition System. Pulses from the phototube bases are split, with one output routed to the waveform digitizer, and the other to the trigger. After discriminators, a fast scaler would generate a trigger when more than n pulses occur within a certain time window, of approximately 30 or $40\,\mu$s. The trigger would cause the computer to read out the waveform digitizer and the veto history buffer.

4 Broader Impacts of this Proposal

The specific technical impacts of this work will inform the nuclear recoil rate due to cosmogenic muon interactions at the Soudan mine depth. This will be of great benefit to CDMS by improving the signal to background while in the WIMP search discovery phase. The impact on the broader community will come from feedback of this rate of high energy neutrons to normalize the particle generation and transport Monte Carlo simulations. Two factors make this data unique. First, this will be the only such measure for neutrons with energy greater than 60 MeV at this depth. The integral measurement obtained will give some leverage on the muon-induced neutron production processes that are relevant at this depth. Secondly, the multiplicity spectrum for secondary neutrons arising from spallation of Pb has not been studied at this depth. While there will be uncertainties that arise from needing to use Monte Carlo to associate the observed multiplicity with the primary neutron energy, some benchmarking on the primary neutron energy spectrum may be possible. The results from this modest apparatus could inform designs for larger-scale studies.

[If we push the test beam idea to calibrate our multiplicity yield against neutron energy at even two points, how much of an improvement would that give us in estimating the primary neutron energy?]

[adapted from previous Case proposal... need to update On a broader scale, as discussed in Section 2.4, the broader impacts of our work fall into the general areas of education and public outreach, and training individuals and developing advanced radiation detector technology. The work we propose here, which will be carried out in conjunction with our work on Super-CDMS, will continue to impact both of these areas.

In the area of technology development, it is of course impossible to predict the specific professional path of any of the students and research associates in our group. However, the broad range of training they will receive while carrying out this R&D program will serve them well in their future careers, whether they continue to work in particle astrophysics, or apply their expertise in other areas of national need, such as radiation detectors for use in nuclear energy or national security, medical physics, medical imaging, sensors for use in manufacturing, etc. Indeed, past members of our group as well as the broader collaboration are pursuing careers in these areas. For example, A. Bolozdynya, a former Senior Research Associate in our Case group, works at Constellation Technology Corp., a company that "develops and

implements innovative technologies for nuclear, biological and chemical detection and provides analytical services to enhance public safety and welfare." A. Da Silva, a former Ph.D. student on CDMS, worked in radiology and medical imaging as a post-doctoral researcher at UC San Francisco, and is now employed at ADAC Laboratories, a maker of nuclear-medicine systems. These are but two examples of former CDMS members using their expertise and training beyond the confines of our field.

In the area of education and public outreach, we will continue our involvement in the public programs at the Soudan Mine by giving tours and leading Question & Answer sessions for Soudan Mine visitors. In the area of education and public outreach, we will continue our involvement in the public programs at the Soudan Mine by giving tours and leading Question & Answer sessions for Soudan Mine visitors. The neutron multiplicity apparatus would be a highly valuable addition to the science tour, as it would be an apparatus on a scale more accessible than MINOS, and involve physics that is more readily accessible to the underground experience of the visitors on the tours.

5   Summary

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