Underground Muon Flux Experiment beside the LUX-ZEPLIN Dark Matter Detector

Andy Freeman[1], Ashley Marines[2]

Department of Physics, Black Hills State University, Spearfish, SD, USA

afreema6@u.rochester.edu[1], amarines@islander.tamucc.edu[2]

Introduction

The LUX-ZEPLIN (LZ) dark matter detector at the Sanford Underground Research Facility (SURF) in Lead, SD is one of the world's most sensitive dark matter detection experiments. The experiment is run within the Davis Cavern which is nearly a mile underground to help shield the detector from cosmic rays which constantly penetrate Earth's surface.

Muons are a part of this shower of particles. They are negatively charged and carry 200 times the mass of an electron, and travel very close to the speed of light. A very small fraction of muons are expected to traverse the near mile of Earth's crust and produce a signal in the LZ detector. Information of the muon flux at the LZ detector is important for the classification of signals produced.

With this motivation, a muon flux experiment was proposed, planned, and started in the Davis Cavern, right beside the LZ detector. The muon detector needed to be modified to conduct an underground low-flux experiment that requires data collection on the time scale of months.

The detector allows for publicly available data upload and analysis online. The Cosmic Ray E-Lab website where data is uploaded, *i2u2.org/elab/cosmic/*, is used by high school teachers and students around the world that do similar experiments. Uploading the underground muon flux data will not only provide researchers at SURF with valuable information but will also allow for teachers and students across the globe to perform unique analyses of data not typically available on the website.

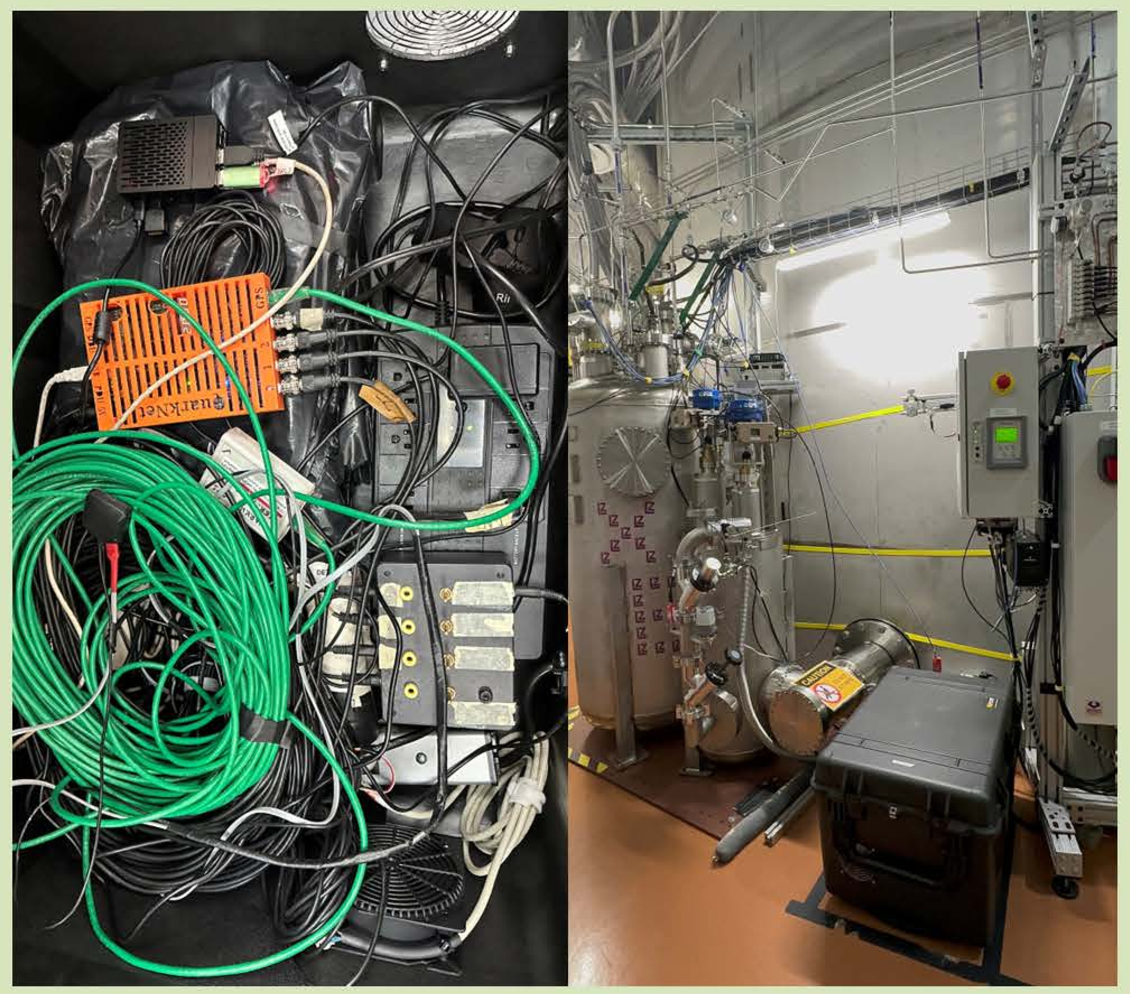

Figure 1a (left): Top view of the QuarkNet Cosmic Ray Detector inside of the crate. The scintillators and photomultiplier tubes are layered underneath the black plastic bag, the DAQ is inside the orange casing, and the Raspberry Pi is seen in the black casing in the top left of the crate. Also seen is a fan and vents for ventilation purposes.

Figure 1b (right): Shown is the black case holding the QNCRD sitting on the floor beside the LZ detector.

Detector Information

The QuarkNet Cosmic Ray Detector operates with four scintillators stacked directly on top of each other, each connected to its own photomultiplier tube (PMT). A muon travelling through the detector produces light within the scintillator, which is then converted to an electrical signal by the PMT and sent to the data acquisition (DAQ) board. Also connected to the system is a GPS module which can't provide location information underground—it does, however, provide relative time information which is crucial to identifying separate muon events. The detector was integrated with its computer software using a Raspberry Pi. An image of the setup is shown in Figure 1a.

The detector was set to four-fold coincidence, meaning that a signal must be seen from all four panels in time coincidence for an event to be recognized.

Data Collection

Prior to the start of data collection, the detector spent a lot of time in the surface lab at SURF. Data collection, upload, and analysis were practiced. The voltages on the detector PMTs were also configured. Before heading underground, the detector calibration was validated. For a two-day long period of data collection, a muon flux that was within the expected range on the surface was observed.

The relevant GPS information needed for a successful and accurate data upload was researched extensively. The information that was necessary for a proper upload to the E-Lab website was determined; a python script was then developed to satisfy these requirements while also preserving raw muon detection data.

During data collection, muon detection information writes directly into a raw text file. Each line in the text file contains 16 words of information, including a high-resolution hexadecimal number containing GPS-tick information, the time-and-date information of the event, the status of the GPS signal, and much more time-over-threshold information. An example of a group of these lines are shown in Figure 2.

The detector was condensed into a plastic crate. The inside of the crate is shown in Figure 1a. Finally, the detector was brought underground and placed next to the outer water tank of the LZ dark matter detector, as shown in Figure 1b. The prior work with the detector on the surface allowed for the immediate commencement of data collection.

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E1010BA9 B3 00 35 00 34 00 35 00 DFAB115F 163717.001 240624 A 00 0 +0034
E1010BA9 00 3F 00 00 00 00 00 00 DFAB115F 163717.001 240624 A 00 0 +0034
E1010BAA 00 00 00 00 00 00 00 27 DFAB115F 163717.001 240624 A 00 0 +0034
E1010BAA 00 00 00 2B 00 00 00 00 DFAB115F 163717.001 240624 A 00 0 +0034
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E1024C70 AE 00 00 00 00 00 00 00 DFAB115F 163717.001 240624 A 00 0 +0034
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E1024C71 00 00 00 22 00 00 00 00 DFAB115F 163717.001 240624 A 00 0 +0034
E1024C71 00 00 00 00 00 2B 00 00 DFAB115F 163717.001 240624 A 00 0 +0034
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Figure 2: An example of the data stream coming from the QuarkNet Cosmic Ray Detector. Two consecutive events are shown in the text file. The data contains 16 words per line. The raw time-over-threshold data is contained within words 2 through 9 as hexadecimal numbers with 3/4 nanosecond resolution. The relevant GPS, time, and date data is contained within columns 10 through 13, which are the columns that need to be modified when taking data from places where a GPS connection isn't possible (underground). Columns 1 and 10 both describe event tick information with 24 nanosecond resolution.

Expected Results

The most recent muon flux experiment performed in the Davis Campus was using the Majorana Demonstrator veto system. This study concluded a total muon flux of $(5.31 \pm 0.17) \times 10^{-9}\ \mu/cm^2/s$ in the Davis Cavern [1]. The plates on the QNCRD are roughly 770 cm^2. Using the results from this previous research in the Davis Cavern, we expect to detect one muon every 2.83 days. This gives motivation for a period of data collection on the scale of months before establishing a muon flux value.

There are other experimental results to base of expectations upon. In an even earlier experiment at SURF, the water equivalent depth of the 4850 ft level at SURF was determined to be 4.4 km [2]. Lots of research has been performed determining muon flux as a function of water equivalent (w.e.) depth. A plot combining the measurements from various muon flux experiments is shown in Figure 3.

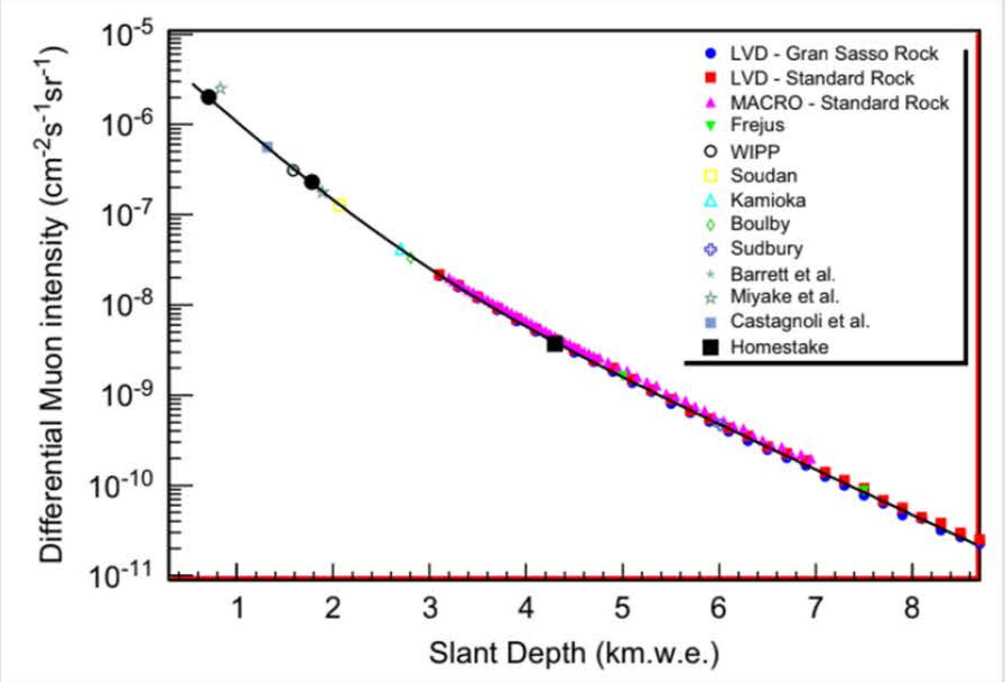

Figure 3: From Ref. 2, a plot of differential muon intensity vs water equivalent depth. The 4850ft level at SURF is 4.4 km water equivalent.

The differential muon intensity is defined as muon flux per unit solid angle, known as a steradian (sr). A different study involving the QNCRD evaluated the four stacked plate configuration to have a solid angle of 1.93 sr [3]. This approximation achieves a similar estimate for the total muon flux the QNCRD will experience at a 4.4 km w.e. depth. A model for total muon flux as a function of depth is shown in Figure 4.

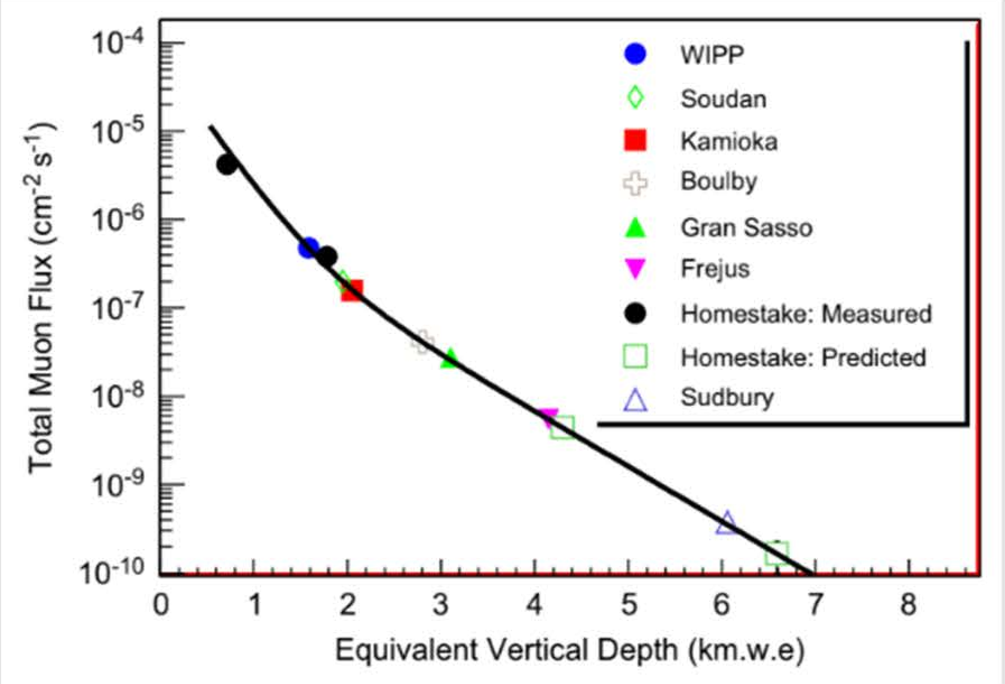

Figure 4: From ref. 2, a plot of total muon flux vs water equivalent depth. The 4850ft level at SURF is 4.4 km water equivalent. The predicted total muon flux (green square on the graph) at the 4850 ft level (4.4 km w.e.) from this model is $4.4 \times 10^{-9}\ \mu/cm^2/s$.

Conclusion

An underground muon flux experiment was started in the Davis Cavern using the QuarkNet Cosmic Ray Detector. A python script was written to reconstruct the time-and-date information of each event with 1 second resolution and provide accurate GPS information which allowed for data upload and analysis online. This script allowed for long periods of data collection without need for a steady GPS signal. This allowed for the detector to be taken into a location with lower muon flux, where data needs to be taken on the timescale of months. Data is currently being taken and is too early to conclude upon. The early results agree with previous literature from the cavern. This experiment will also serve as a test of the ability and validity of the QNCRD in very low flux environments.

Future Applications

The detector was placed close by the Environmental Monitoring System (EMS) of the LZ detector. The EMS consists of a BF3 and NaI crystals that detector neutrons and gamma rays. The EMS serves as a check on the activity of the cave separate from the LZ detector. The muon detector runs on its own as it stands, but the detector could potentially be integrated into the EMS. Doing so would likely require data analyses to be held offline, as opposed to the online data upload.

Other applications of this experiment could happen at different levels within the facility. Doing so would allow for an analysis of how muon flux changes with respect to depth below Earth's surface. This information could be valuable in determining depth requirements for future ultra-sensitive detectors like LZ.

References

[1] N. Abgrall et al., "Muon flux measurements at the davis campus of the sanford underground research facility with the majorana demonstrator veto system," Astroparticle Physics, vol. 93, pp. 70–75, Jul. 2017, doi: 10.1016/j.astropartphys.2017.01.013.

[2] Gray, F. E., et al. "Cosmic Ray Muon Flux at the Sanford Underground Laboratory at Homestake." arXiv [Nucl-Ex], 2010, http://arxiv.org/abs/1007.1921.

[3] Venterea, Ricco, and Urbas Ekka. "An Analysis of Muon Flux from Angle Variation of the QuarkNet Cosmic Ray Detector." arXiv [Astro-Ph.HE], 2023, http://arxiv.org/abs/2306.13689.

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E.Bishop@ed.ac.uk

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cronish@sanfordlab.org

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jdelgaudio@sanfordlab.org

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