The Physics Teacher

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Eleanor Anne Winkler, Paul Graham, Nathan A. Unterman, et al.

Beyond the Classroom: Profiling Muon Flux in Relation to Overburden in Fermilab's MINOS Tunnel

Eleanor Anne Winkler, Paul Graham, and Nathan A. Unterman, New Trier Township High School, Winnetka, IL
Benjamin Grey, Jacob M. Miller, Max J. Miller, and Allen J. Sears, Ida Crown Jewish Academy, Skokie, IL
Alex Bernat, Shoshana Frank, Joshua Simon, and Shira K. Eliaser, Rochelle Zell Jewish High School, Deerfield, IL
Tom Blackmore, Emmanuelle Copeland, and Marybeth Senser, Downers Grove South High School, Downers Grove, IL
Henry Seiden and Anthony Valsamis, Glenbrook North High School, Northbrook, IL
Mark Adams, QuarkNet, Batavia, IL

With support from QuarkNet,[1] high school students investigated the effect of overburden on muon flux by collecting data from Fermilab's Main Injector Neutrino Oscillation Search (MINOS) tunnel. Muon flux varied due to a change in overburden created by a 103-meter deep access shaft. A profile of muon flux as a function of distance from the access shaft was measured by observing muon flux from different locations within the tunnel.

The team hypothesized muon flux would decrease as the detectors were moved away from the shaft. They also hypothesized the muon flux would decrease while descending in the elevator shaft. The results provided insight into the capacity of overburden of soil and rock to shield muons. There were some surprises in the implementation of the experiment. The tunnel part of the experiment needed corrections due to muon flux from Fermilab's neutrino beam. Students identified and solved this problem. There was also an anomalous spike in muon flux during the elevator experiment as the elevator descended through the neutrino beam. This experiment may be beneficial in understanding how the differences of overburden formed by the access shaft may affect the underground particle detectors.

The collaboration, the Muon Underground Shielding Experiment (MUSE), which included five Chicago area high schools,[2] was formed under the umbrella of the University of Illinois at Chicago QuarkNet Center. These students, like any researchers, were able to perform an experiment at Fermilab, adhering to Fermilab's processes and protocols, and including submission of a proposal in the form of a Technical Scope of Work,[3] equipment qualification,[4] and safety training.[5]

Throughout the experiment, students learned that as cosmic rays hit Earth, the rays interact with atoms in the atmosphere and create showers of different particles, including muons, pions, and positrons. Most of these secondary particles are absorbed through interactions within the atmosphere. Muons reach Earth's surface due to their long lifetime. Higher-energy muons can penetrate overburden greater than the depth of the MINOS tunnel at Fermilab[6] (Fig. 1). There have been studies conducted to measure the effect of overburden on cosmic ray flux in both slanted (mountain) and flat configurations. One such study reports exponential decreases in flux as depth increased.[7] Since the overburden material varies, there is no absolute relationship with depth. The Bogdanova study reported how muon flux changed as a function of zenith angle directly under an access shaft.[8] Vertical muon flux was significantly greater in the shaft when compared with measurements under similar overburden without a shaft. The distribution of muon flux in the shaft off the vertical only began matching solid overburden for angles greater than 60º. The Bogdanova experiment measured muon flux rates at different zenith angles from directly underneath an access shaft. The students' experiment measured the differences in muon flux at locations at varying distances from the access shaft. It seems reasonable that a sizable access shaft can affect background ionizing radiation deep underground at some distance away from the bottom of the shaft.

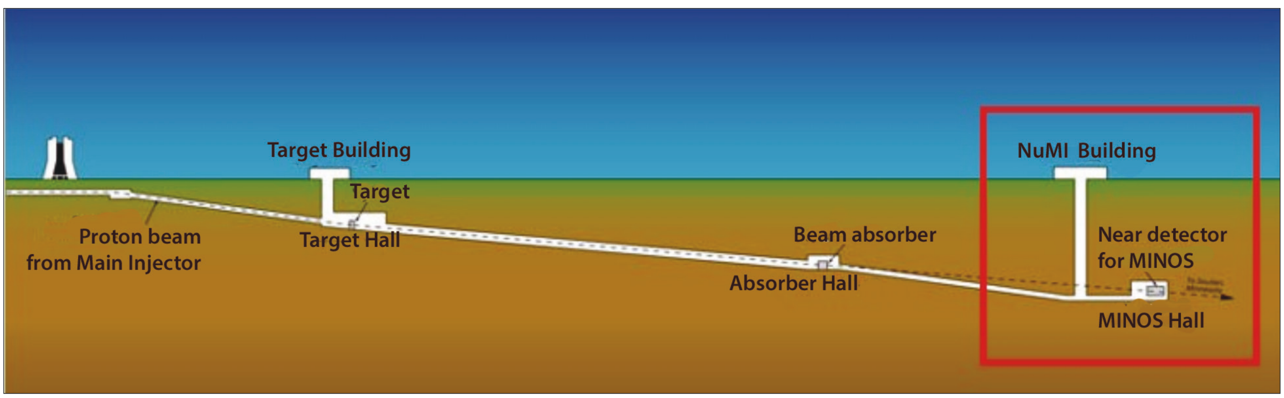

Fig. 1. This is an elevation profile of the MINOS tunnel. The rightmost elevator shaft, closest to the MINOS detector, was used in this experiment. This shaft is 103 meters deep. The distance from the shaft to the MINOS detector is 86 meters. The dotted line shows the approximate path of the neutrino beam.[9]

The team conducted feasibility studies using QuarkNet cosmic ray muon detectors[10] at New Trier and Downers Grove South High Schools. Each detector consists of four scintillation counters, photomultiplier tubes, and a data acquisition (DAQ) readout board. Experiments found a measurable reduction of flux as the detectors were moved from upper to lower floors, simulating changes in overburden found

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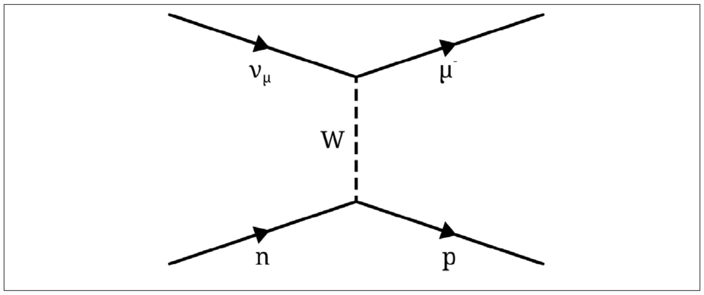

Fig. 2. Feynman diagram of a muon neutrino interacting with a neutron.

above the MINOS tunnel. There was no GPS signal in the tunnel, however, absolute timing proved unnecessary due to the accuracy of the processor clock on the DAQ board. Power was maintained by an uninterruptible power supply when moving the detectors from the surface where GPS was available to the tunnel.

A Fermilab neutrino beam was in operation during this experiment. When this beamline was on, extraneous muons produced by muon neutrino interactions in the rock were registered by the MUSE detectors (Fig. 2). As a remedy, the team studied the differences in data at each location when the beam was on, causing significant increased counts, and off and created a normalization to correct the data, so that muons from

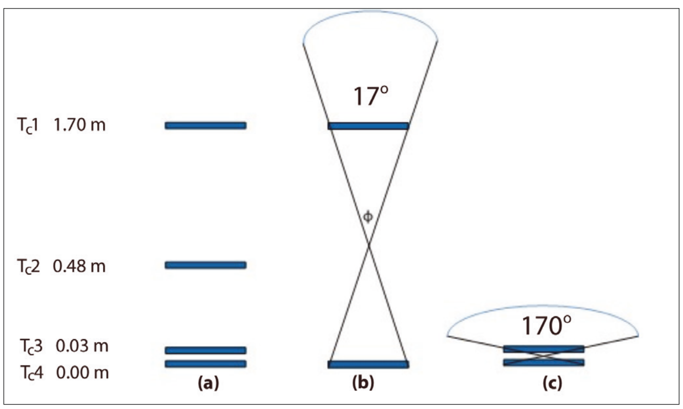

Fig. 3. (a) The vertical detector profile view of the T_C detector. Each scintillator was 25 cm x 30 cm. (b) The angle of acceptance, Φ, measured between counters T_C1 and T_C4. (c) Angle of acceptance for counters T_C3 and T_C4.

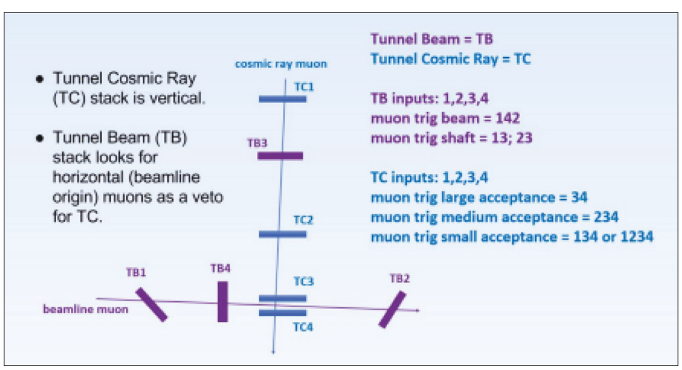

Fig. 4. Final design of tunnel detectors on the cart. Aligned with the tunnel (horizontal) is detector T_B and detector T_C is pointed vertically. T_C1 to T_C4 is 1.70 m, T_B1 to T_B2 is 1.22 m. Muon trigger large acceptance = T_C3 and T_C4. Muon trigger medium acceptance = T_C2, T_C3, and T_C4. Muon trigger small acceptance = T_C1, T_C3, and T_C4 or T_C1, T_C2, T_C3, and T_C4.

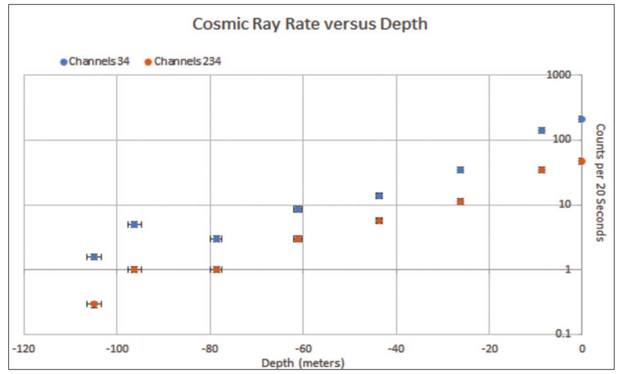

Fig. 5. Cosmic ray rate vs. depth. Note anomaly at -96 m.

Fermilab's beam activity did not contaminate the cosmic ray muon results.

The design process began with two detectors: one at the surface used as a control, T_S, and the other in the 103-meter deep tunnel, T_C. Both detectors had the same vertical orientation, with two counters stacked atop each other and two additional counters spaced out above. This spacing was important in order to analyze a range of angles of acceptance (Fig. 3), providing different slices of the sky and shaft for the data.

Counters T_C3 and T_C4 measured an acceptance angle of 170° (full sky), counters T_C2 and T_C4 measured an angle of 55°, and counters T_C1 and T_C4 measured an angle of 17°. This difference enabled the team to compare flux data at different acceptance angles to characterize the cosmic ray flux due to the access shaft.

A horizontally oriented detector, T_B, was added to detect the potential effects of a neutrino beam passing through the tunnel. For consistency, this new detector was integrated on the same cart as the T_C detector. In the analysis phase, the T_B detector data was used to correct the T_C data for effects from the neutrino beam. Figure 4 shows the final design of the tunnel and beam detectors. All three detectors used in the experiment are the same as those used in the feasibility studies.

Once the design for the detectors was finalized, the detectors were moved into place. All three detectors (surface T_C and tunnel T_C and T_B) were initially placed next to the access shaft to establish a common control value. Later, the surface detector remained on a cart next to the access shaft, and the cart carrying the tunnel and beam detectors was positioned in the tunnel and moved farther downstream in weekly intervals, up to 86 meters away from the access shaft.

As a separate run, the team recorded data as the two tunnel detectors descended into the shaft through the elevator. There were three two-minute data runs: one for each trip. As anticipated, there was an exponential decrease in count rates as the overburden increased (Fig. 5). An enhancement in count rates 96 meters deep was unanticipated. Furthermore, this anomaly was seen on both detectors for all three runs, with no change in count rates on the surface detector. The MINOS neutrino beam passes through the access shaft at a depth of 96 meters and, according to Fermilab's logs, was active during this period. The neutrino beam passes through rock before reaching the shaft, generating muons. The researchers concluded that these interactions created the spike in muon counts, but the

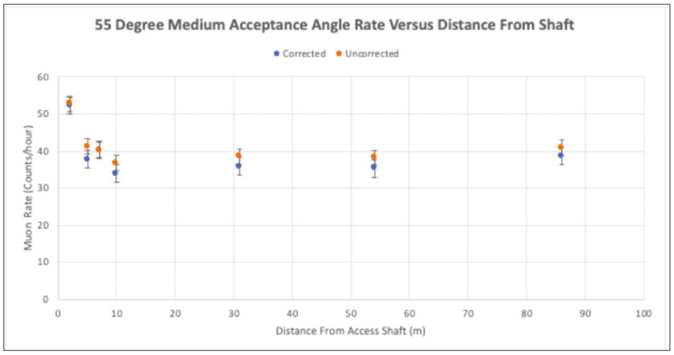

Fig. 6. Muon flux at acceptance angle of 55° vs. distance from shaft. Note the steep decline near the shaft.

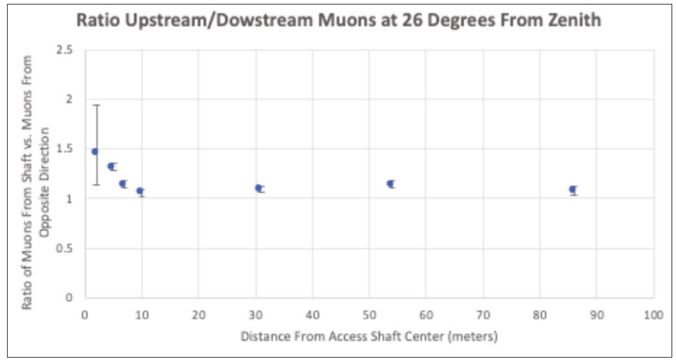

Fig. 7. The ratio of upstream (coming from access shaft) to downstream muons vs. the distance from the access shaft for the T_B detector.

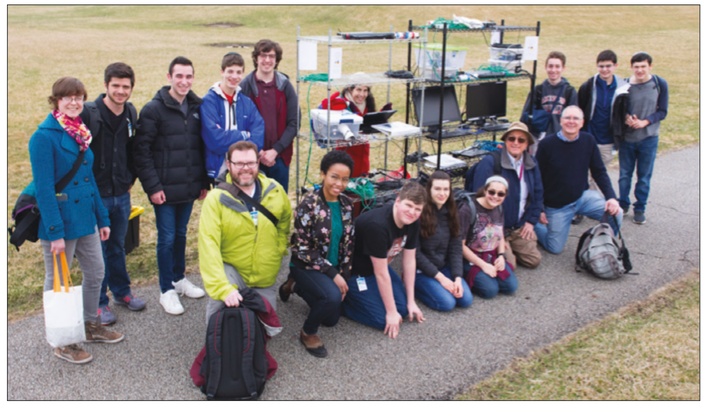

Fig. 8. The MUSE team when moving the experiment to the MINOS facility.

presence of muons from the neutrinos demanded further investigation.

Due to extra counts from the neutrino beam, corrections to the data were necessary. To achieve this, Eq. (1) was implemented with the daily counts (A), the percent of the day the beam was active (B), and a correction factor (C):

$$A_0 = A(1 - B * C) \quad . \tag{1}$$

The same correction factor was used for all distances from the shaft, but was unique to each selection of counters. To determine the correction factor, the experimenters calculated the slope of the number of counts vs. the percent of the time the beam was on. For counters T_C2 and T_C3, C was 0.15. For counters T_C2, T_C3, and T_C4, C was 0.091. For counters T_C1, T_C2, T_C3, and T_C4, the correction was not necessary, so the factor was zero. The rate of muons at each location was calculated by dividing the sum of the daily corrected counts by the duration of each run. Cosmic ray muon rates vary due to changes in atmospheric pressure. To account for this potential variation, the data were also normalized to the rates of the surface detector.

The main goal of the experiment was to determine whether cosmic ray muon flux in the MINOS tunnel would increase as the muon detectors neared the access shaft to the tunnel. The findings were consistent with the hypothesis. Muon flux as a function of distance was graphed (Fig. 6), and confirmed that muon flux does indeed decrease as the muon detectors are moved away from the shaft. The error bars represent statistical errors. As both sets of data from the 55° acceptance angle rate vs. distance from the shaft indicate, the muon flux decreases precipitously near the shaft, but as the distance from the shaft increases, the muon flux becomes asymptotic. This change was anticipated by the experimenters because the access shaft should not affect the amount of overburden unless the detectors are nearby. The raised data point at 86 meters from the shaft was due to a greater cavern height. Based on the elevator runs, the reduced burden produced a 16% increase in rate, although that was not applied in Fig. 6.

The experimenters compared the number of muons detected from upstream, in the direction of the access shaft, to those from downstream (Fig. 7). To profile the shaft with non-vertical muons, detectors were set up at 26° from the zenith, one aiming upstream, T_B2 and T_B3, and one pointing toward downstream, T_B1 and T_B3. This angle was chosen to optimize the experiment, given the physical constraints of the equipment dimensions. Counts per hour from upstream, including the empty shaft, were consistently higher than the counts per hour from downstream (no voids) at every location. The greatest difference was directly next to the access shaft. Ratios of upstream/downstream are shown in Fig. 7.

By taking the ratio of the upstream/downstream counts, errors due to the neutrino beam were minimized while still profiling the tunnel and shaft. This provided an independent confirmation of the hypothesis. In both cases, the effect of the missing overburden was observed throughout the first 10 meters from the shaft.

The experimenters determined that underground depth has a notable impact on muon flux. As horizontal distance from the opening shaft increased, detected muon counts sharply decreased for the first 10 meters. The results inform future experiments about a small possible interference from cosmic rays. Additionally, the elevator data provided evidence that the neutrino beamline was creating local muons. Muons in the beamline had been anticipated, but during the experiment, the collaborators discovered that most muons were generated from neutrino interactions with the rock. Some neutrino experiments at MINOS use these "rock muons" to monitor their detector operations.

Pedagogical perspective

Science curricula are increasingly focused on developing science and engineering practices. This experiment gave students a wider variety of science and engineering experiences than the typical classroom laboratory exercises can provide. Students needed to develop a method to manage and share the extraordinary amount of data generated during the experiment. Google Sheets was used to allow for multiple experimenters to input and analyze data asynchronously. Communication skills were developed beyond a typical classroom discussion. Students developed presentations and posters for the 2020 AAPT Winter Meeting. Communicating with scientists as peers was at first awkward, but became normal over time. One of the most important lessons learned is that experts do not always have the answer. There is no "teacher" with the answers in the real-life laboratory. Students came to realize that building a strong collaboration is how science is pushed forward.

The experience was astounding for those involved, and it developed the students' skills in conducting formal experiments. "We learned to be scientists. We executed every step of the process, including getting permission from Fermilab to conduct the experiment, setting up the experiment, analyzing the data, and presenting our findings at AAPT," said Benjamin Grey. Working with Fermilab scientists was enlightening and helped the experimenters understand more about the scientific process. Additionally, they chose their own roles and responsibilities in the collaboration, which gave them the opportunity to thrive in a professional environment.

Acknowledgments

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New Trier Township High School, Winnetka, IL; ellieaw13@gmail.com