Measurement of Ultimate Speed: A High School Experience

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QuarkNet (2007) is a nationwide High Energy Physics (HEP) outreach program that has provided laboratory experiences to high school students. Originally conceived as a program to provide high school teachers with knowledge about HEP research, QuarkNet at the University of Illinois at Chicago (UIC) has also provided students with mentoring on performing cosmic ray experiments at their schools. The program has been supported by funds from the National Science Foundation. UIC has provided apparatus resources and has trained students in physics and astronomy experiments. High school teachers and students have attended summer workshops at UIC in order to gain experience with cosmic ray detectors. They have brought that experience as well as the detectors that they helped build, back to their classrooms in order to carry out further experiments, and in order to encourage participation by other students. These students are part of a nationwide network where they share their cosmic ray data and discuss their findings. In this way, they strengthen science education at their schools, working like scientists to collect, analyze, share, and discuss data and interpretations.

QuarkNet's Evolution at Glenbrook South High School

Since 2001, Mark Adams has been building partnerships with various high schools. In this article, we share how one such partnership, with teacher Steve Grosland at Glenbrook South High School (GBS), has evolved from students attending introductory lectures at UIC to independent research performed by students at their school. Leading students to study cosmic rays at their school has been a gradual process. The project was based on a cosmic ray muon study, where observing muons formed an investigative tool that brought both HEP and astronomy facilities directly into high schools. Local detectors served two agendas. In their default configuration, they made students part of an astronomy collaboration, recording astronomical data from large cosmic ray air showers. Schools were also encouraged to use their detectors to pursue an assortment of individual astronomy research projects, observations of environmental conditions that modify cosmic ray rates, and measurements of the fundamental properties of the muon itself. The goal has been to guide students through a process that follows actual scientific practice in HEP: physics topic selection, experimental design, data taking, analysis and interpretation of results, all leading to new research ideas.

Steve Grosland first explored technical and physics-driven aspects of cosmic rays at the 2006 UIC summer workshop, where he gained familiarity with the detectors and worked with students from other schools. He eventually recruited GBS students to attend additional UIC workshops, where they worked with students from other schools following a problem-based learning approach, learned how to operate the detectors, and carried out basic measurements of the cosmic ray rate and muon lifetime. A week of immersion in this practice allowed students to extend cosmic ray studies into new directions of their choosing. All students were required to give oral reports on their experimental results at the workshop's closing session. Just as in any science venture, progress uncovered more layers of complexity that needed to be explored. To help students see the bigger picture, they took working field trips to Fermilab and to Adler Planetarium.

Student-Designed Research

During the 2007 summer workshop, after learning the basics of detector calibration, GBS students developed a completely new research project. They arranged their detectors in the corners of a square and then enlarged the sides of the square from 0.5m to 20m, measuring the rate of cosmic ray showers containing multiple muons as a function of detector separation. This was "doing science" in its purest form. They designed a measurement that no one else had done, and postulated that it could provide information on the structure of cosmic ray showers. There was no known answer. The students were explorers. They unexpectedly discovered that the muon rate distribution exhibited different behavior below and above a detector separation of 3 meters, from which the structure of the shower was extracted. It was a beautiful example of students developing their own research questions as part of a scaffolded experience.

The QuarkNet students at GBS have formed a year-round science club and they refer to themselves as "Cozzies." With detectors that are part of a running experiment in place, students (and co-authors) Hannah Nelson and Albert Kim, who performed the experiment that is presented below, were recruited for the summer 2008 workshop. During that workshop, they attended lectures on astronomy, learned about scintillation detectors, and performed several experiments with cosmic rays. They enjoyed that week of research enough to extend their participation into another week in order to explore an idea they had developed. During their extended summer project at UIC, Hannah and Albert measured the rate of cosmic rays over time and correlated it with the local air pressure and temperature. They hypothesized that the muon rate would change with temperature. However after correcting for some change seen due to pressure, no additional temperature effect was observed.

Later in the summer of 2008, Hannah and Albert returned to UIC several times to assist in planning for future projects at GBS during the school year. They tested a new data acquisition (DAQ) card design under cosmic ray conditions, and for the first time across the nation, they proved that two cards could attain relative timing to an accuracy of several nanoseconds rather than the 50ns (50 billionths of a second) of a previous design. This was essential for being able to operate multiple detector systems at one physical site. A second set of detectors from another school was also moved to GBS. Thus, GBS established the first long-term effort at any school to operate multiple detectors, significantly enhancing their cosmic ray capabilities.

Detectors at high schools have served two roles: as detector sites for the nation-wide collaboration, and as a resource for individual student projects. These two roles have been complementary and important for involving students in accessible research projects. Much of the rest of this article will describe details of one of the most sophisticated experiments carried out at QuarkNet high schools. Hannah and Albert used cosmic ray muons to measure the maximum speed allowed in the Universe. The speed of muons was found to be very close to the ultimate speed that is allowed by Einstein's theory of special relativity (Einstein, 1905), as nothing can travel faster than the speed of light in vacuum. The measurement offered an opportunity to consider the shocking fundamental concept of physical reality, that time is not the same for all observers, which is rarely accessible to students. Hannah and Albert advanced from being trained and directly mentored by Mark and Steve to doing independent research supervised by Steve.

As they were setting up the experiment, Hannah and Albert shared that their "motivation for running this experiment was to see how close we could get with our experience to the accepted speed of a muon. We also wanted to run this experiment because the speed of a muon is a fundamental idea in the science of cosmic rays. Therefore, we felt that this experiment would serve as a proper foundation for our future research. This experiment would provide us with experience and a better understanding of how to use our equipment." Below we present the experiment performed by describing the detector components, detailing the experimental technique used, and sharing results and conclusions.

Cosmic ray muons passed through the GBS building and were observed by up to four scintillation counters, each made of a sheet of scintillator, and attached to a photomultiplier tube (PMT). The outputs from the PMTs were sent to a DAQ card that provided the interface to a computer for data collection. When a charged particle traversed the scintillator, light was emitted and reflected internally until it reached the PMT, which converted the light into a small electrical current, as displayed on the oscilloscope in figure 1. The programmable data acquisition card digitized the signals from four PMTs, decided which pattern of counter hits would be saved, and wrote a file containing the times of hit counters for further analysis.

A side view of the detector geometry for two configurations used in this experiment is shown in figure 2. Muons traversed the counters vertically, intersecting both counter A and counter B. The time difference between signals from counters depended not only on the distance between the counters, but also on the response of the counters, and on the various lengths of the signal cables. Students learned that the best way to control all of these extra effects was to explicitly design the experiment to minimize them, by collecting data in two counter configurations (normal and swapped). The position of counter A was changed, including its cables, so that by comparing the time difference between A and B in both configurations, the results were equivalent to measuring the time difference between counter A alone in two positions (AA').

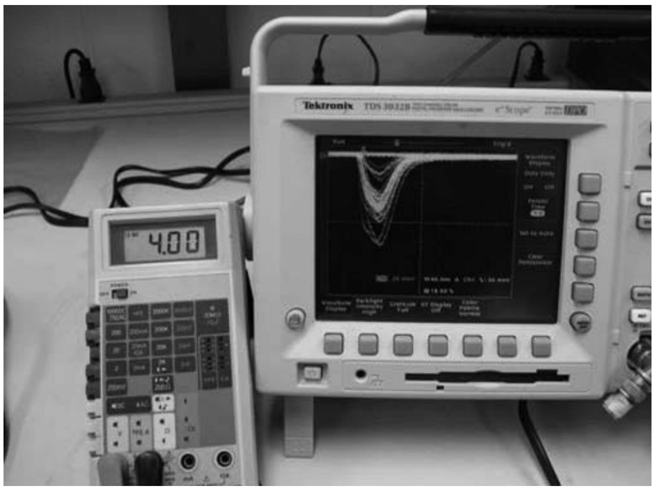

Figure 1. PMT signal versus time on the oscilloscope, with PMT high voltage readout on the digital voltmeter to the left.

The distributions of the time difference between counters AB and A'B are shown for both configurations in figure 3. The speed of the muon was calculated by dividing the distance (d) between positions of A and A' by the time difference (ΔT) between the two distributions: Speed of muon = d/ΔT = 2.40m/8.11ns = 2.96 x10^8 m/s = 0.987c.

Understanding the meaning of errors is an essential part of science education, and it is often overlooked. Being able to estimate errors would serve students well, and is clearly applicable to concepts in the world outside of science, such as risk assessment and investment strategy. In order to judge the quality of their measurement of the muon speed, students identified sources of two types of errors. First, they learned the critical lesson that error was not calculated from how well the result agreed with the accepted value; it had to be measured independently. The error on the mean of the timing distributions (statistical error) depended on the observed width of the distribution divided by the square root of the number of events in the peak. This resulted in an error of 0.006c on the muon's speed. However, another type of error (systematic error) was not addressed by the swap technique. A method to estimate the bias caused by two muons in the cosmic ray air shower, neither of which hit both counters, was developed. Requiring a muon to miss a third counter that was added between A and B enhanced the two-muon sample, and allowed students to estimate that systematic error contributed a 2% error to the speed. Thus, the final result for the speed of muons was: v = 0.987c +-0.006c (stat) +-0.02c (sys).

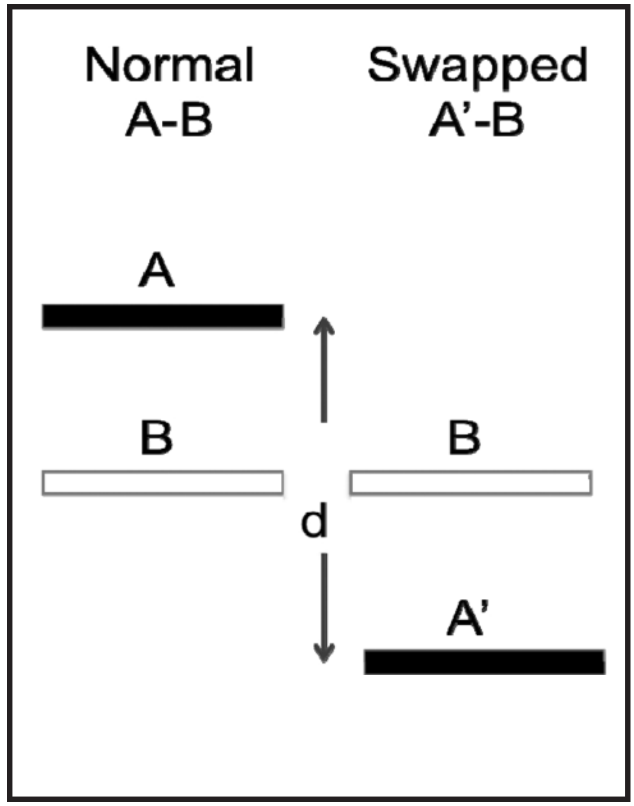

Figure 2. Schematic diagram of two-counter apparatus.

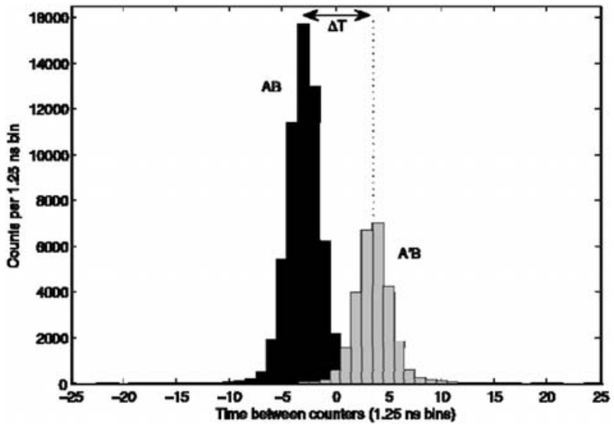

Figure 3. Time difference between AB and A'B counters.

Once the measurement was completed, the research group engaged in a discussion around how to improve the precision of the measurement—a fundamental step in scientific research. Three additional techniques were designed and subsequently implemented: 1) three counters were used to reject events contributing to the two-muon background; 2) the separation distance between counters was increased to reduce the error on the speed; and 3) since larger signals fired the electronics sooner than smaller signals, an improved time was calculated for each event by correcting for the size of the PMT signals. After applying the three techniques above, the data showed the timing distributions in **figure 4,** and the speed of the muon was found to be: v = 2d/ΔT = 2*2.40m/16.08ns = 2.985+-0.01 x10^8 m/s = 0.997c+-0.004c.

The systematic error was significantly reduced compared to the original two-counter data, but no attempt was made to measure it directly. The GBS students have plans to continue to improve their experiment. In a future version, the detector will be moved to an atrium at GBS where the separation can be increased to more than six meters, reducing the error on the speed by another factor of three. The systematic error will also be addressed by measuring muon trajectories that are tilted from vertical. One of the fundamental goals of QuarkNet is to enable students to develop methods to improve results of their experiments.

This experiment offered students an opportunity to experience for themselves the value of keeping detailed logbooks, recording each step of the experiment, and organizing equipment and data. This is how Hannah and Albert articulated their learning regarding this dimension of their experience as they reflected on challenges they encountered. "A major obstacle faced at the beginning of our experiment was disorganization. The numerous wires eventually became entangled as we constantly rearranged our counters. As a result, after the first two weeks of collecting data, we realized that the wires were incorrectly connected and all our data was skewed. After this costly mistake, we spent hours reorganizing and labeling the counters and the cables until finally the counters and cables corresponded with each other. The next obstacle we faced was analyzing our raw data in a manner that was meaningful to us. The data we collect are provided to us in a format that would seem foreign to any uneducated reader. As a result, we had our teacher, Mr. Grosland, and our UIC correspondent, Professor Adams, explain how the data was displayed and how it was to be interpreted. Every obstacle after that point seemed trivial to us."

Furthermore, by performing this complex measurement, students engaged in the same steps physicists use in HEP practice. In this way, they came to realize that, in their words, "the scientific process is not simple. While we faced many difficulties, ultimately, we were able to overcome them and successfully complete our experiment." Students had to become proficient using many tools and conducting multiple tasks: a digital oscilloscope, a readout card developed at Fermilab and at the University of Washington (Hansen, et al., 2004), programming an on-board processor, high voltage

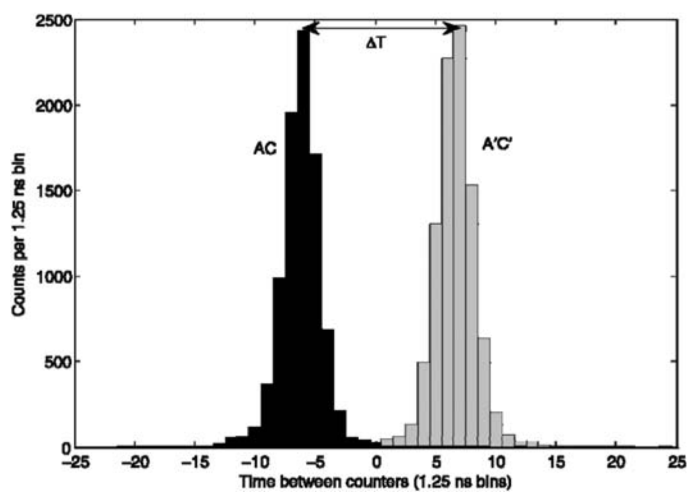

Figure 4. Time difference between outside counters A and C in the three-counter geometry.

supplies, a filter program on a UIC Linux machine, and further analysis using an Excel program. A global positioning satellite receiver was mounted on the roof of the school (figure 5) to provide an accurate time stamp for each recorded muon. Students debugged the electronic readout system, calibrated the counters, collected data over weeks, and analyzed and presented research results. Though shorter in duration than standard HEP experiments, the students' experience closely paralleled experiments performed by HEP scientists.

Concluding Thoughts

Cosmic ray experiments carried out by Glenbrook South High School students at GBS and UIC have extensively increased the sophistication of scientific study available not only to members of the Cozzies science club, but also to the general physics student population at GBS. Students trained at UIC not only developed their own research directions as they explored more complex scientific measurements, but they recruited other students to join them to perform additional experiments using the same apparatus. In the process of performing these experiments, students have been prepared to do more scientific work on their own.

Students used particle physics counters to measure the speed of high energy cosmic ray muons, finding it consistent with the speed of light within errors (muon speed = 0.997c +- 004c). This result is also consistent with the expected speed of relativistic muons detected at the surface of the Earth. As students engaged with, and understood, the critical role of errors in the scientific process they significantly enhanced their ability to skeptically assess general scientific statements from other venues.

This project required a high level of commitment from the two lead students who have become the school's experts. It also provided a range of activities in which additional students can participate. Students have learned how to develop and study their own research questions, and they are presently designing a lab to investigate whether the muon rate changes as a function of the passage of the Sun. Further cosmic ray efforts at GBS will include the integration of experiments into the physics and astronomy curriculum as well as the development of a broader set of experiments for the science club. We are currently searching for multiple muons in air showers along with a dozen other Chicago area schools, and have become part of a collaboration that correlates similar measurements from other high schools across the nation.

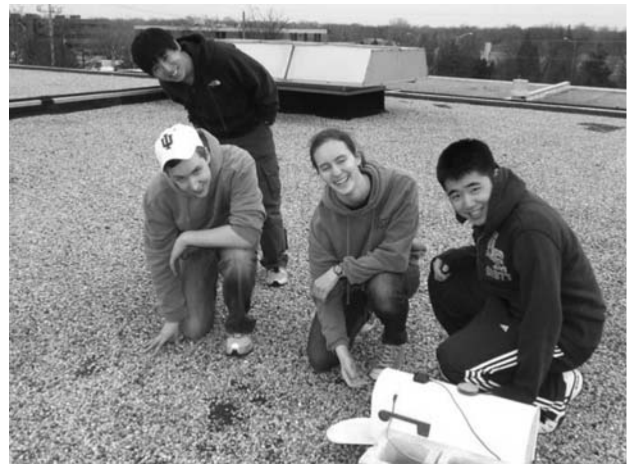

Figure 5. GBS students install GPS receiver on the school's roof.

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