Catching 'Rays'—Muon Science with Probeware

- Bernhard Beck-Winchatz and David Jabon

Take students out from their 'we are separate from the rest of the Universe' bubble and have them catch muons, particles spawned by cosmic rays from space. It's easy and not as expensive as it used to be, if you use readily available probeware!

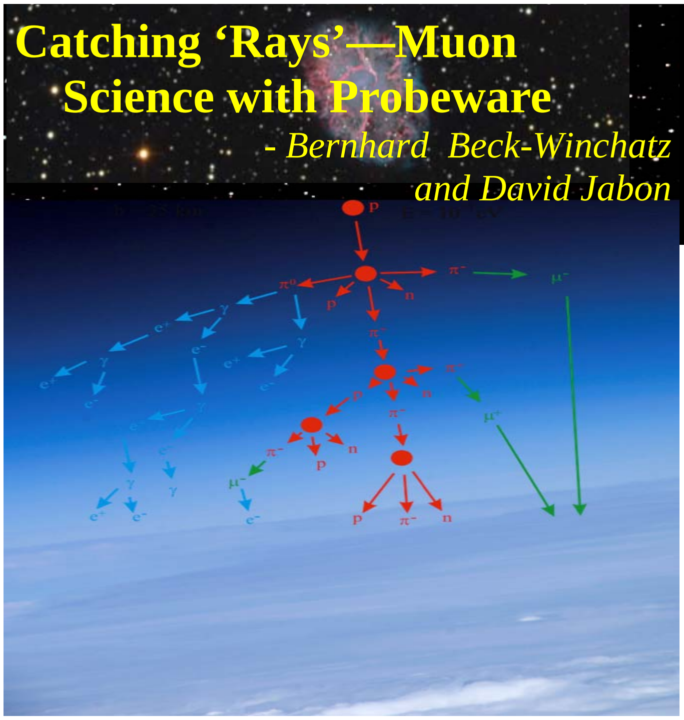


Figure 1. Galactic cosmic rays are probably created in supernova remnants such as the Crab Nebula. Muons are the products of cosmic rays hitting atoms in the atmosphere. Photo Credit: Chris Hetledge; diagram, Wikimedia Commons.

Charged particles—cosmic rays—enter our atmosphere at nearly the speed of light. The majority of these are protons, with a small percentage of helium and other heavier element nuclei. We cannot trace them back to their sources because their trajectories are bent by the magnetic fields of the Milky Way, Sun and Earth. But their high energies do tell us that most of them originate in powerful events such as supernova explosions (Figure 1). In addition to these *galactic* cosmic rays, a small percentage of *solar* and *anomalous* cosmic rays originate in energetic events on and near the Sun, such as solar flares and coronal mass ejections, and from the termination shock of the solar wind at the edge of the solar system.

Only a small fraction of cosmic rays that enter our atmosphere make it to the ground. Most of them collide with the nuclei of atmospheric molecules high up in the stratosphere, knocking out some of their protons and neutrons, and generating showers of secondary particles, such as pions, kaons and muons. The majority of these particles have extremely short lifetimes and decay into other particles before reaching the ground. The exception to this rule are muons, which survive for about 2.2 microseconds (0.0000022s) before they decay into electrons, positrons and neutrinos. If you do the math you will notice that even muons travelling at the speed of light should not be able to travel further than about half a mile before they decay. However, Einstein's relativistic time dilation (a story for another issue) lengthens their lifetime enough so that many of them to make it to the ground and into your classroom.

In this article we want to explain how you and your students can build a muon detector with standard equipment that is readily available from educational technology vendors, and that your school or college may already have

A Simple Muon Telescope

The idea of using muon telescopes in the classroom is not new. The Berkeley Lab Cosmic Ray Telescope Project (www.lbl.gov/abc/cosmic) and QuarkNet (quarknet.fnal.gov/toolkits/new/fnaldet.html) have designed educational cosmic ray telescopes that use scintillator plastic sheets and photomultiplier tubes connected to a circuit board. These excellent instruments have been used for fascinating research projects by many high school and college students. However, assembling them requires specialized tools that

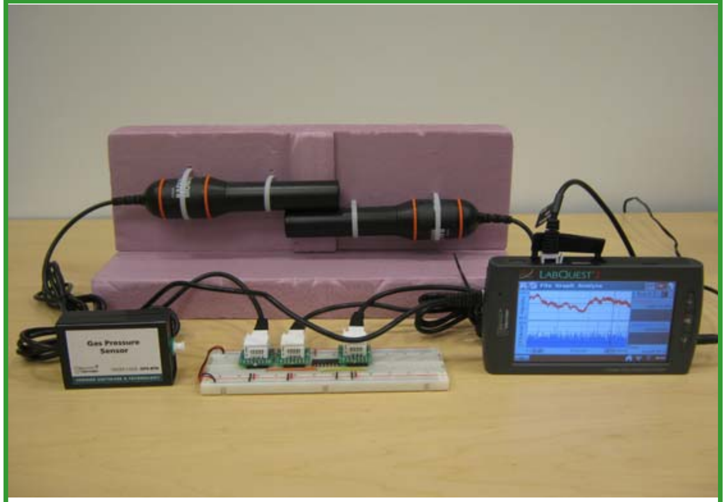


Figure 2. Our muon detector consists of two Vernier Radiation Monitors, a coincidence counter on a breadboard, and a LabQuest data logger. The gas pressure sensor is used to measure the barometric coefficient.

may not be available at many schools and colleges and will take most instructors and students at least several days to build. Here we would like to show you how to construct a much simpler muon detector based on standard probeware that can be assembled in about an hour, and can be used for many of the same experiments as the Berkeley and QuarkNet instruments.

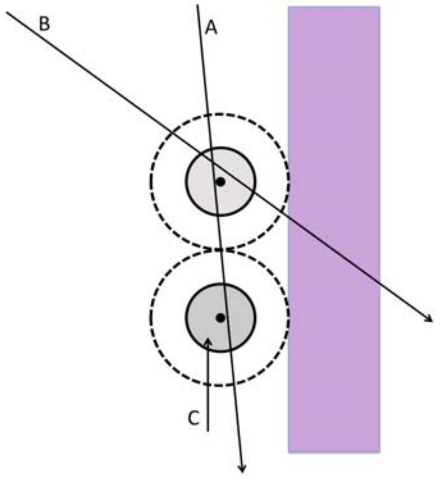


Figure 4. Particles (such as the one represented by the arrow labeled A) are only counted by the detector if their trajectories are aligned with the two Geiger-Müller tubes, and if they have enough energy to pass through both tubes. Particle B is not counted because its trajectory is not aligned with the detector. Particle C is not counted because it is stopped by the first Geiger counter due to its low energy.

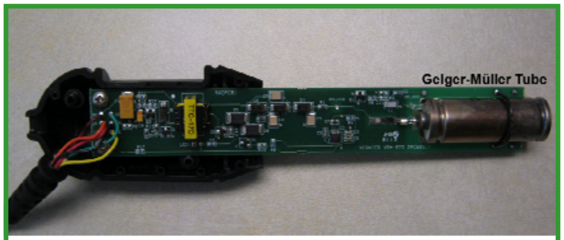


Figure 3. The radiation monitors in Figure 2 overlap so that the two Geiger-Müller tubes are vertically aligned.

Our design consists of two Vernier Radiation Monitors connected to a coincidence circuit on a breadboard and a Vernier LabQuest 2 data logger. (Similar equipment is available from Pasco and other probeware vendors.) To hold the radiation monitors in place, we use polystyrene, PVC pipes and cable ties, which are available at any hardware store. Our simplest design shown in Figure 2 consists of two pieces of polystyrene hot-glued together at a right angle. The tips of the two radiation monitors overlap so that their Geiger-Müller tubes are vertically aligned (see Figure 3). Both radiation monitors are connected to a coincidence counter on a breadboard, which only passes a signal to the data logger if both monitors detect a particle at (almost) the same time. This arrangement has two important advantages: First, it eliminates background radiation from airborne radon and thoron and from naturally occurring radioactive minerals in the ground, which does not have enough energy to pass through both detectors. This background radiation makes up about half the detections of an individual radiation monitor. Second, it only counts muons if their trajectory is in line with the two radiation monitors. This makes it possible to discriminate between muons arriving from different directions. In order to investigate the effect of barometric pressure on muon flux we

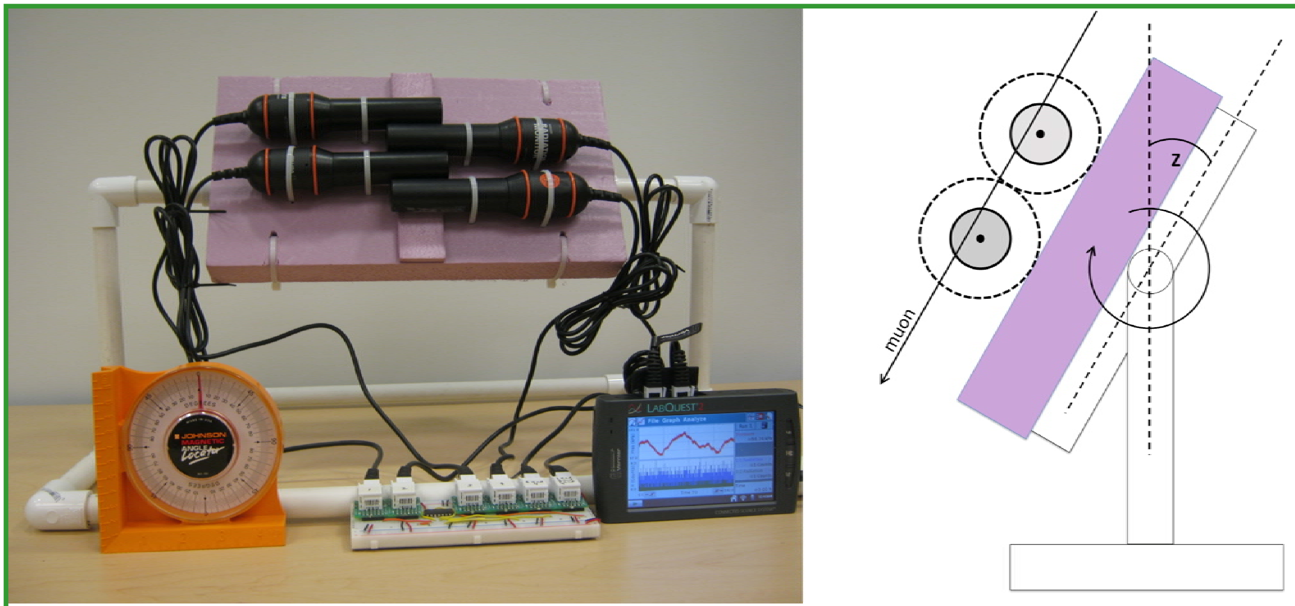


Figure 5. This design is built on a PVC pipe frame so that the detector can be pointed at different zenith angles Z. Using four instead of two radiation monitors allows us to vary the size of the solid angle seen by the detector and reduce the number of accidental coincidences. However, only two radiation monitors are needed to measure the zenith angle distribution of muons.

also connected a gas pressure sensor to the data logger.

Because of the vertical alignment of the two radiation monitors, the instrument shown in Figure 2 only detects muons that originate close to the zenith. To be able to compare muon fluxes at different zenith angles Z, we built a simple frame from ½-inch PVC pipe that allows us to rotate the radiation monitors. (Z is the angle measured from the zenith instead of the horizon to some point on the sky.) The design shown in Figure 5 uses four radiation monitors in coincidence. However, all investigations described in this article can be carried out with just two radiation monitors.

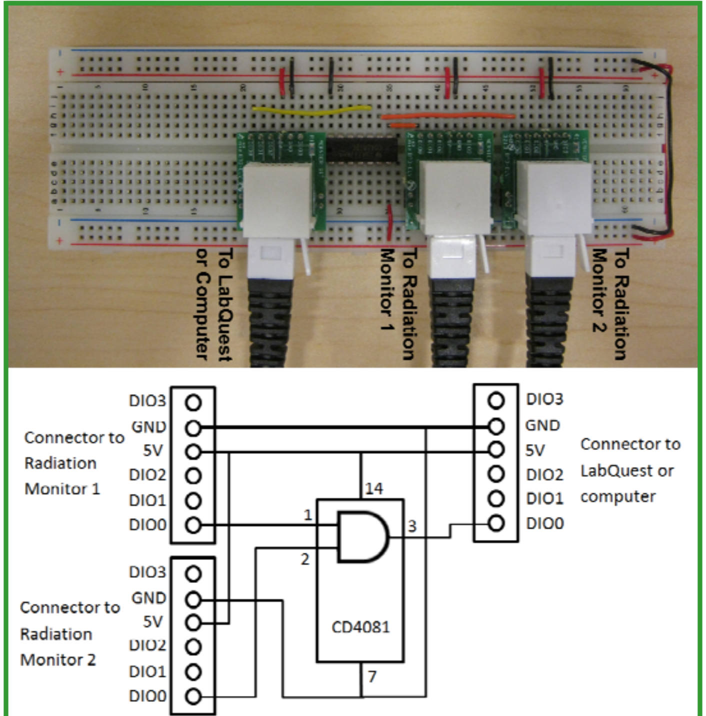


Figure 6. The coincidence counter consists of an AND gate and three Vernier Digital Proto Board Adapters. The red and black wires provide power from the LabQuest to the radiation monitors. When the monitors detect a particle they send a signal to the AND gate through the orange wires. The AND gate passes on this signal to the LabQuest only if both monitors detect a particle at (almost) the same time.

The Coincidence Circuit

The coincidence circuit (shown in Figure 6) is intended to be extremely simple to construct and can be built in less than an hour. It uses a single inexpensive integrated circuit, an AND gate and requires no soldering. The design uses custom connectors (Digital Proto Board Adapter from Vernier) so that one can simply plug the radiation monitors into the board. The connectors are the most expensive components; one could reduce the cost dramatically by not using them, but one would need to cut open cables and solder some components. Note one needs to use the larger standard breadboard (sized approximately 17.5 cm by 6.5 cm); we found it was not possible to fit the entire circuit on the smaller-sized standard breadboard. Building this simple circuit and using it as part of an experimental setup is particularly valuable for students, and it is very appealing from an instructional perspective: it has low complexity, presents minimal safety risks, and involves students in circuit building.

The Parts List for the Muon Probeware Detector

Part	Purchase information	Approximate cost	Quantity
Digital Proto Board Adapter	Vernier.com Part BTD-ELV	$10.00	3
Digital Sensor Cable	Vernier.com Part MDC-BTD	$5.00	1
Quad AND gate IC CD4081	Digikey.com Part 296-2066-5-ND	$0.52	1
Breadboard	Digikey.com Part 00-00078-ND	$6.24	1
22 gauge solid insulated wire for breadboard			

Student Investigations

Because muons carry an electric charge, they interact with the electrons of the molecules in their path and slow down as they travel through the atmosphere. The larger the mass of the atmospheric column the muons have to pass through, the more energy they lose, and the smaller the percentage of muons that make it to the ground. In addition, if your detector is set up inside your classroom, some of the muons that have made it through the atmosphere will be stopped by the concrete, cement, or other building materials in the floors above the classroom. Students can study the shielding effect of the building structure by comparing the muon count rates on different floors of the school building. For example, by setting up the detector on different floors of our office building on the DePaul University campus we found that the count rate drops by about 12% per floor.

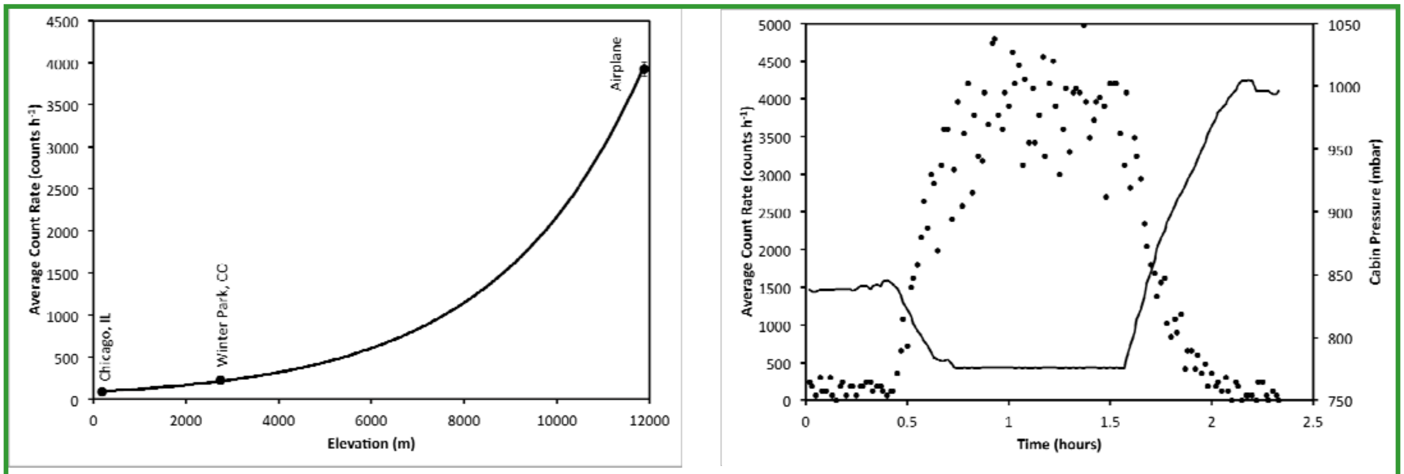


Figure 7 (left). Muon count rates measured in Chicago, IL, Winter Park, CO, and on a plane at an altitude of 11,900 m. The best fit exponential shows that the count rate increases by about 10% for every 300 m of elevation. Figure 8 (right). Muon count rates measured during a flight from Denver to Chicago with the detector shown in Figure 2. The solid line shows the cabin pressure.

How does elevation affect muon count rates?

Muon count rates increase with elevation because the mass of the air column they have to travel through to reach the detector decreases. At higher elevations, they lose less energy due to interactions with atmospheric molecules than at lower elevations, and more of them reach the ground. If your school is located in a mountainous region, students can investigate this effect by setting up their detector at different elevations. The effect is large enough that city students can investigate it by comparing count rates at the top of very tall buildings and at street level. Another possibility is to collaborate with students at schools that are located at different elevations.

We investigated the elevation effect during a recent trip to Winter Park, CO. In March and April 2014 the average muon count rate in our office located on the top floor of a four-story building on the DePaul University campus at an elevation of 200 m was about 91 cph (counts per hour). In our hotel room in Winter Park (elevation 2750 m), the average rate was 162.5. Unfortunately, the room was on the second floor of a five-story building, so the count rate was significantly reduced by the floors above the detector. To be able to compare the count rates measured in Winter Park and in Chicago, we corrected for this shielding effect by assuming the same absorption rate (12% per floor) that we measured on the DePaul campus. This gave us an estimated rate of 226 cph for the top floor of the hotel.

On the flight back home from Denver we were fortunate to have a pilot who was interested in cosmic rays and very supportive of science education. He gave us permission to set up the detector during the flight. Figure 7 shows the count rates (along with the cabin pressure) we measured during the flight. The average count rate of 3923 cph at the cruising altitude of 11,900 m is shown in Figure 8, along with the count rates measured in Chicago and Winter Park. By fitting an exponential to the three data points, we determined that the rate increases by about 10% for every 300 m of elevation.

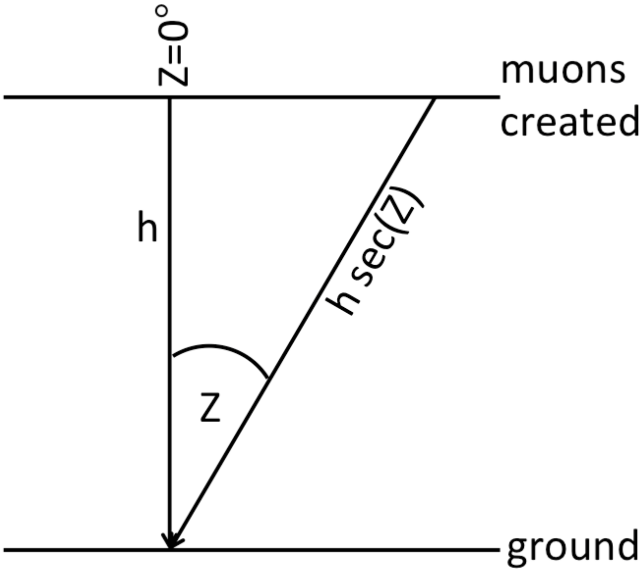
Because the count rate increases by a few percent between street level and the top of skyscrapers, using buildings to measure the elevation effect is a good opportunity to teach students about basic measurement statistics. In Chicago, we measured an average count rate of about 90 cph. We can use Poisson statistics to calculate the standard deviations of the measured count rates: After one hour, the standard deviation of the count rate is approximately $\sqrt{90} = 9.5$ counts, after two hours it is $\sqrt{180} = 13.4$ counts, and so on. How long do students have to collect data on top of a skyscraper where the count rate is expected to be

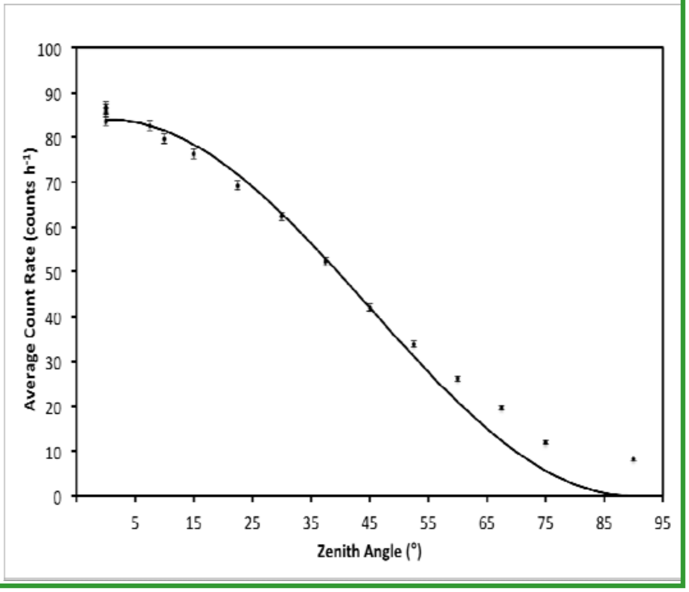
10% higher than at street level before they can be reasonably sure that the count rates are not the same? After 2.3 hours the expected number of counts is 207 ± 14.4 at street level and 228 ± 15.1 on top of the skyscraper (where 14.4 and 15.1 are the standard deviations). To determine whether there is a difference in count rates, students can compare their measurements with the “null hypothesis” that states the difference should be 0. The standard error for the difference is calculated by adding uncertainties in the following way:

$$SE(\text{skyscraper} - \text{street}) = \sqrt{14.4^2 + 15.1^2} = 20.8$$

If the difference in counts exceeds the standard error (SE), students can reject the null hypothesis that the count rates are equal, at the 68% confidence level. To achieve a 95% confidence level, students would need to collect data for over 9 hours. Thus, by planning their experiments and analyzing their data, students can directly experience how increasing the number of measurements decreases uncertainty and increases the statistical significance of a result. In our example, the difference of 21 is about the same as the SE, so the data is good.

Figure 9 (left). The distance muons have to travel from the top of the atmosphere to the detector increases proportionally to the secant of the zenith angle, resulting in the decrease in count rate shown in Figure 10. Figure 10 (right). Count rates for different zenith angles measured with the detector shown in Figure 5.





How does zenith angle affect muon count rates?

Muon count rates also decrease with increasing zenith angle (the angle between the zenith and the direction the detector is pointing) because the air column mass that muons have to travel through to reach the detector increases (Figure 9). To point the detector to different zenith angles, students can construct a PVC pipe frame such as the one in Figure 5. Figure 10 shows the count rates measured in our office. Each data point in this graph is based on three days of data, corresponding to about 6000 counts at Z = 0°, and about 600 counts at Z = 90°. Our measurements confirm the well-known empirical relationship

$$c(Z) = c(0^\circ) \times \cos^2(Z)$$

for zenith angles up to about 50°, with slightly larger count rates than predicted by this relationship near the horizon.

How does barometric pressure affect muon count rates?

Barometric pressure measures the weight of a column of air from the ground to the top of the atmosphere exerted on a unit area. Changes in barometric pressure are caused by changes in the mass of the atmospheric column above the detector and therefore also affect the muon count rates. The so-called *barometric coefficient* expresses this relationship as a percentage change of the count rate per 1 mbar pressure change. Measuring the barometric coefficient is another good opportunity to teach basic measurement statistics to your students because the variations in muon count rates due to barometric pressure changes are similar to daily random variations that are unrelated to pressure (Figure 11). After measuring count rates and pressure for a few days students will typically find almost no correlation between the two measures. The standard error of the slope in Figure 11 (calculated, for example, with the LINEST function in Excel) is larger that the slope itself. Does this mean barometric pressure does not affect count rates? No, because as students add more measurements for several weeks the uncertainty of the slope gets smaller and smaller, and eventually they will have collected enough data to show that count rates decrease with increasing pressure. Figure 11 includes 39 days of data, with each data point representing a period of 12 hours with approximately 1100 muon counts. The barometric coefficient calculated from this data is −0.13 ± 0.05 %/mbar, consistent with previous published measurements.

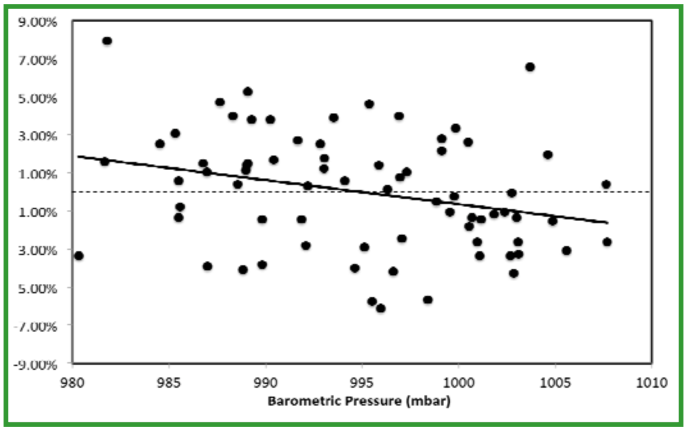


Figure 11. The 12-hour average muon count rates we measured in our office decreased at a rate of about 0.1% per mbar of atmospheric pressure.

Other investigations

In this article we provided four examples of independent variables that affect muon count rates and can be investigated with the probeware muon detector: building structure, elevation, zenith angle, and barometric pressure. There are many other possibilities. For example, does temperature and humidity affect count rates? How about weather, time of day or year, geographic latitude and longitude, azimuth, urban vs. rural areas, nearby power lines, sunspot cycle, solar flares, and Moon phases? How does moving the radiation monitors further apart or changing the geometry of the detector in some other way affect count rates? What happens if you place a lead block or other dense material in front of the two Geiger-Müller tubes, or between them? Can muons penetrate the ground and reach subway tunnels or caves?

Options

Our detector is probably not for you if you are excited about the idea of spending a few days on constructing a more powerful instrument, such as the Berkeley Lab Cosmic Ray Detector, including cutting and polishing scintillator paddles, soldering electronics components to a circuit board, and constructing a casing. One of the main advantages of the Berkeley detector and other similar instruments is that they have much larger collecting areas that allow you to get results more quickly. However, if you prefer not to spend a lot of time on constructing an instrument and instead want to start collecting data right away, then give our muon detector a try! TCA

Bernhard Beck-Winchatz is an astronomer who tans with muon rays in Chicago, IL; check his char level at bbeckwin@depaul.edu. David Jabon is a mathematician who calculates the damage. Both are associate professors in the STEM Studies Department at DePaul University and teach current and future teachers. All images from the authors, except Figure 1.