An Inexpensive Cosmic Ray Detector for the Classroom

Jeffrey D. Goldader and Seulah Choi, The Baldwin School, Bryn Mawr, PA

Finding ways to demonstrate—in a high school classroom—that subatomic particles from space produce other particles capable of reaching the Earth's surface is not a trivial task. In this paper, we describe a Geiger-Muller tube-based cosmic ray coincidence detector we produced at a total cost of less than $200, using two tubes purchased used online; if the tubes were purchased new, the total cost would be about $325. Our detector is able to produce unambiguous CR detections in just 1000 total seconds of data collection. Furthermore, it is small and easily manipulated, allowing us to easily demonstrate the relationship between cosmic ray flux and the zenith angle.

Cosmic rays

Victor Hess was awarded a share of the 1936 Nobel Prize in physics for his 1912 discovery of cosmic rays (CRs)—particles from space. "Primary CRs" (largely protons, though including alpha particles and heavier atomic nuclei at greatly reduced abundances) are highly relativistic particles in space.[1] Lower energy primary CRs (GeV scales) were probably accelerated by supernova shock waves, though the highest energy cosmic rays (up to ~10^{20} eV) appear to have been produced by active galactic nuclei.[2] Arriving at Earth, primary CRs are destroyed by collisions with atoms in the Earth's atmosphere. These collisions result in cascades of "secondary" or "atmospheric CRs," similar to the way particles are produced in supercolliders. Large numbers of protons and neutrons, plus neutrinos, muons, pions, and electrons (and all their antiparticles) are created in the cascades. Muons are the most numerous charged particles that survive to reach the surface of the Earth, becoming "terrestrial CRs."

Most terrestrial CRs arrive at the ground from angles near the zenith, since a CR on a longer slant path through the atmosphere has a higher probability of being destroyed by decay or further interactions on its journey. For zenith angles $\theta < 70°$, the angular distribution of muons is $\propto \cos^2(\theta)$, though at higher angles that relation breaks down and there are detectable numbers of CRs on near-horizontal paths at sea level.[1]

But how can we prove to our students that cosmic rays exist? Some simple experiments—the loss of charge from electroscopes over time, random clicks from a Geiger counter, and tracks in cloud chambers—can be used to demonstrate the existence of free subatomic particles, but do not distinguish between CRs and particles of terrestrial origin.

Cosmic ray detection strategies

Several groups have designed experimental apparatus that can be used to directly detect CRs in a classroom setting. Among these are the QuarkNET[3] and Berkeley[4] CR detectors.
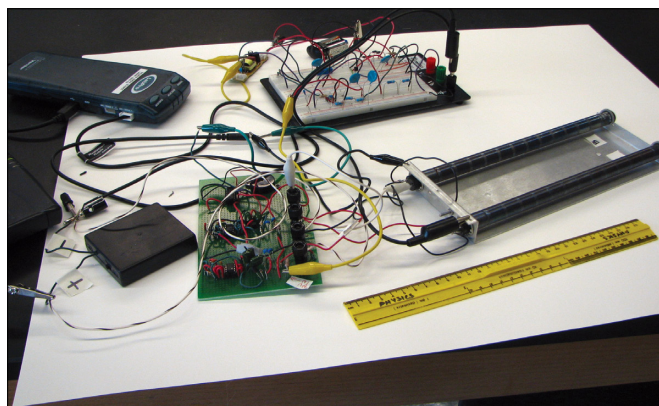

Fig. 1. We show the components of the cosmic ray detector, with a 30-cm ruler for scale. L-R: counting electronics (LabPro in the background); high-voltage power supply; Geiger-Muller tube assembly. The GM tube assembly is small and easy to orient at different angles.

These devices use photomultiplier tubes attached to pieces of scintillator plastic, and use complex readout electronics. They are *coincidence detectors*, requiring simultaneous detections in two or more aligned detectors. In a coincidence detector, the ability of cosmic rays to pass through matter allows them to pass through two (or more) aligned samples of scintillator, triggering the attached photomultipliers simultaneously. However, the high cost and relative complexity of photomultiplier tube-based CR detectors limit their use in a high school setting. (A complete QuarkNET system, including all electronics and detectors, costs more than $5000 as of this writing; the components of the Berkeley system, if purchased new, would run about half that sum.)

As noted earlier, Geiger counters are sensitive to CRs. A CR passing through the wall of a Geiger-Muller tube (GMT) will ionize gas atoms in the tube, and those electrons will be accelerated toward the high-voltage sense wire that runs down the length of the tube. Along the way, they ionize other atoms, creating a short-lived, measurable current pulse. Jackson and Welker[5] showed that a common digital data acquisition board or device (such as a PASCO ScienceWorkshop or Vernier LabPro) could be used to monitor several Geiger counters at once. Simultaneous detections are candidate CRs. This is still expensive—a good Geiger counter can run into the hundreds of dollars, and at least two are required. (Aware Electronics[6] produces a system for doing just this.) Researchers at the University of Pennsylvania have built their own GMTs and used them to create an inexpensive coincidence CR detector.[7] (A good resource for educational CR detectors is the website jlab.org/~cecire/toolkit/crdetectors.html.)

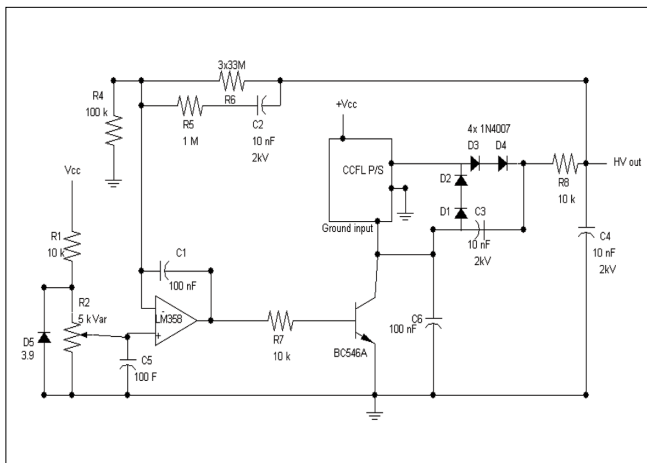Hobbyists, with lower budgets than most educational in-
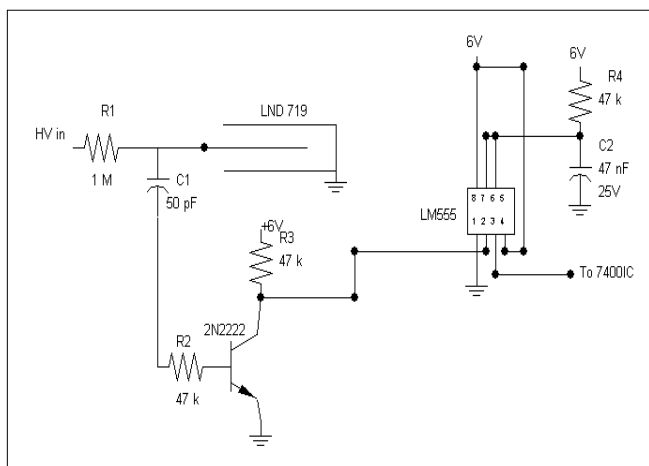
Fig. 2. CCFL-based high-voltage power supply.

Fig. 3. 555-based pulse detector.

stitutions, have also stepped into the gap. The website cosmicrays.org and the companion Yahoo! particle-detectors Internet forum (tech.groups.yahoo.com/group/particledetector/) are dedicated to this kind of experimentation. The inspiration for our detector came from these sources.

Construction

We based our detector (Fig. 1) on two LND-type 719 thin-walled GMTs[8] we purchased used for $90 on eBay. LND, Inc. has informed us that tubes may be purchased from them new at $140 each. The recommended voltage is 900 V, so it was necessary to construct a high-voltage power supply. A search of cosmicrays.org revealed a circuit for producing a low-current, high-voltage power supply using a CCFL (cold cathode fluorescent light) inverter commonly used in decorative PC case and automotive lighting. The inverter is inexpensive (< $10) and available from numerous electronics wholesalers. The circuit we used[9] is given in Fig. 2 and is powered with a common 9-V battery. Adjusting the variable resistor R2 varies the output voltage from 0 V up to a maximum that depends on the input voltage.
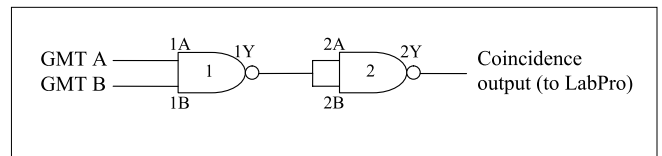

Fig. 4. Wiring the 7400 NAND as a coincidence detector.

Table I. Coincidence detection logic table. (0 = low, 1 = high)

Tube A	Tube B	NAND gate 1	NAND gate 2 (coincidence output)
0	0	1	0
1	0	1	0
0	1	1	0
1	1	0	1

The detector signal electronics[10] (Fig. 3) are simple. A transistor multiplies the signal pulse from an individual electron cascade in one of the GMTs. This is fed into a type-555 IC, which senses the increase over the reference voltage, and produces an output pulse whose duration is set by the choice of the resistor and capacitor (R4 and C2 in Fig. 3) attached to each 555 (we expect a pulse width of $t = 1.1 \times RC = 1.1 \times 47\ k\Omega \times 0.047\ \mu F = 2.4$ ms; the measured pulse width is about 2.8 ms, which is within the uncertainties of the components). The outputs from each tube's 555 are fed into a type-7400 IC, a quad-NAND gate, as shown in Fig. 4. This results in output pulses from the 7400 only for the time periods when the GMTs are both registering detections. The logic table is presented in Table I. The 555s and 7400 are powered by four AA batteries connected in series. All the grounds are tied together. The electronics can be wired and soldered by high school students (such as the second author of this paper!).

In addition to producing an audible tone using a small piezoelectric speaker, the output of the coincidence circuit is monitored by a Vernier LabPro,[11] connected to a notebook computer running Logger Pro software. We sent the coincidence signal into one of the two TTL digital inputs of a Lab-Pro configured to act as if a photogate was attached (pin 1 in a photogate cable, farthest from the clip, carries the signal; pin 5 is ground). The "photogate" state changes from "blocked" to "unblocked" when the 7400 output goes high. After the pulse, the signal returns to "blocked." The LabPro time stamps and measures the duration of each coincidence detection.

Testing the detector

In order to test the detector electronics, we measured the background count rates from each tube separately; they were indistinguishable at $(1 \pm 0.1)\ s^{-1}$. We also checked each GMT using a sample of uranium ore. The count rates increased when the source was brought near the tubes, as expected. Then, by placing the ore sample between the tubes, we achieved high enough count rates that large numbers of
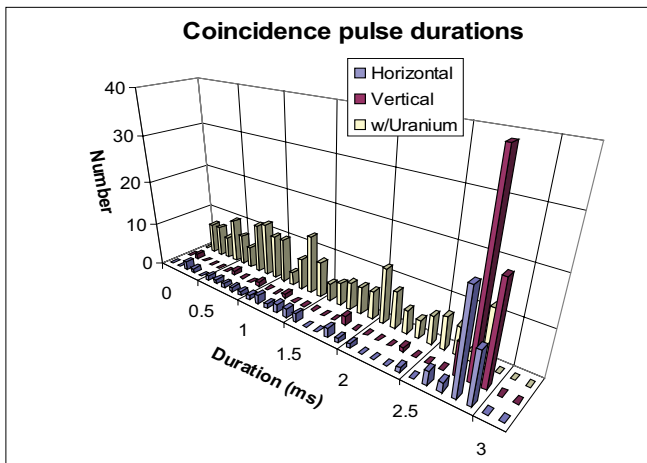
Fig. 5. We show histograms of pulse durations with the tubes aligned horizontally, vertically, and horizontally with a sample of uranium between them to generate spurious coincidences due to high count rates. The graph is clipped at 40 counts per 0.1-ms bin to emphasize the more sparsely populated bins, though the peak bin for vertical coincidences contains 97 counts. Simultaneous coincidences, expected for cosmic ray events, should last 2.8 ms, and spurious coincidences should have durations of 0 ms – 2.8 ms.

Fig. 6. Dependence of count rate on zenith angle θ. The count rate is clearly $\propto \cos^2(\theta)$, as expected for cosmic rays.

chance coincidence counts occurred, giving us confidence that our coincidence circuit was functioning. Furthermore, the coincidence pulse durations ranged from 0.03 ms to 2.8 ms, consistent with the chance overlapping of uncorrelated 2.8 ms pulses (Fig. 5).

We then tested whether CRs could be detected by comparing the count rate when the two tubes were oriented horizontally (next to each other) on a table with the rate when the tubes were aligned vertically, one directly above the other (Fig. 5). The vertically aligned tubes gave about four times the count rate of the horizontally aligned tubes. The difference was apparent within a few minutes. Furthermore, with longer runs and more detections, it was clear that the pulses came in two groups: one group strongly clustered near the 2.8-ms coincidence pulse length expected for CRs, and another spread roughly evenly 2.8 ms down to nearly 0 ms, as expected for chance coincidences due to background. Because our setup allows us to save the pulse lengths themselves, a fairly straightforward refinement of our methods should allow the exclusion of ~90% of the accidental coincidences (those with lengths of 2.5 ms or less, < 90% of the coincidence pulse width).

With individual tube background count rates of ~1 s^{-1}, the observed rate of accidental coincidence counts is approximately 0.004 s^{-1} (the expected accidental coincidence rate is $2tN^2 = 0.005$ s^{-1}, where $t = 2.8$ ms and $N = 1$ s^{-1}, the background count rate[5]). This is consistent with the fact that the total horizontal count rate is 10^{-2} s^{-1}, and 23 of the 60 total horizontal counts (38%) in Fig. 5 are less than 2.8 ms in duration. We conclude that accidental coincidences account for just less than half of the counts when the tubes are oriented
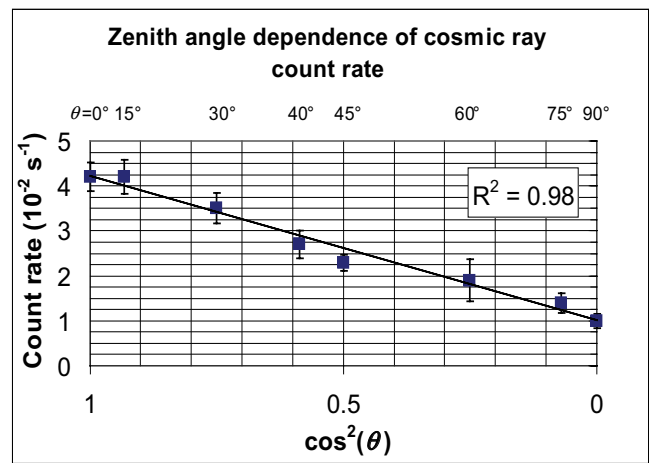
horizontally and about 1/10 of the counts when the tubes are aligned vertically.

Results

The cosmic ray signal, which is weak compared to the terrestrial background, is easily found using the coincidence circuit. With the tubes oriented vertically, we measured a typical coincidence count rate in 1000 s of data to be $(4.0\pm0.7)\times10^{-2}$ s^{-1}, whereas the count rate with the tubes oriented horizontally was $(1.0\pm0.3)\times10^{-2}$ s^{-1} in 1000 s of data. The $\pm1\sigma$ uncertainties are derived from Poisson statistics; for N counts in t seconds, the count rate is just N/t and the 1σ uncertainty is $\frac{\sqrt{N}}{t}$. A respectable 3σ detection of CRs can be obtained with 500 s of measurement at each configuration. In that time, we expect 20 ± 4.5 counts with the tubes oriented vertically, and 5 ± 2.2 counts with the tubes oriented horizontally, for a vertical/horizontal ratio of 4 ± 0.9, 3σ above the expected value of 1.0 for an isotropic signal.

We then rotated the tubes through several angles ranging from vertical to horizontal, taking data for longer periods of time. The results are given in Fig. 6, which was made from a total of ~8.5 hours of data. The count rate is clearly proportional to $\cos^2(\theta)$, as expected for cosmic rays.

We can estimate the overall efficiency of our detector by comparing our measured zenith count rate with the known muon flux. Following the method given by Ref. 14, the observed muon flux is

$$F_\mu = \frac{(\text{count rate})d^2}{(\text{area of upper detector})(\text{area of lower detector})}.$$

Using our observed zenith count rate of 4.2×10^{-2} s^{-1}, with the effective length and diameter of each tube as 0.229 m and 0.0155 m, with separation $d = 0.075$ m, we have a measured muon flux of 18 m$^{-2}\cdot$s$^{-1}\cdot$sr^{-1}. This is about 26% of the actual 70 m$^{-2}\cdot$s$^{-1}\cdot$sr^{-1} (data for $E > 1$ GeV muons compiled in Ref. 1), indicating a total system sensitivity of about 26%.

Other potential studies

The flux of CRs is known to be greater at higher altitudes due to less absorption, and our very portable device would be ideal for such measurements. In addition, others have shown that the CR flux varies[12] with the Earth's 24-hour day/night cycle due to changes in the local geomagnetic field[13] and also the strength of the interplanetary magnetic field, which varies on a 28-day cycle due to solar rotation and with the 11-year sunspot cycle as well.[1]

Conclusions

A low-cost classroom cosmic ray detector such as we have described in this paper not only directly demonstrates the existence of cosmic rays, but it also provides opportunities to give students hands-on work with electronics and multi-year research projects. Students can see for themselves the complex relationship between the Earth, the Sun, and events far off in interstellar space.

References

1. T. K. Geisser and T. Stanev in C. Amsler et al., "Cosmic rays," *Phys. Lett. B* **667,** 1 (2008).
2. Pierre Auger Collaboration, "Correlation of the highest-energy cosmic rays with nearby extragalactic objects," *Sci.* **318**, 938 (2007).
3. jlab.org/~cecire/toolkit/fnaldet.html.
4. lbl.gov/abc/cosmic/.
5. D. P. Jackson and M. T. Welker, "Measuring and modeling cosmic ray showers with an MBL system: An undergraduate project," *Am. J. Phys.* **69** (8), 896 (Aug. 2001).
6. aw-el.com/.
7. jlab.org/~cecire/toolkit/penndet.html.
8. lndinc.com/products/397/.
9. cosmicrays.org/muon-power-supply-ccfl.php, used with permission of Charlie Thompson.
10. galacticelectronics.com/GeigerCounter.html, used with permission of Jon Qualey.
11. www.vernier.com.
12. F. Blanco et al., "Educational cosmic ray experiments with Geiger counters," *Il Nuovo Cimento C* **29** (3), 381–390.
13. A. Cary, E. Mayfield, and J. Mottmann, "A toy 'magnetometer,'" *Phys. Teach.* **46,** 437–439 (Oct. 2008).
14. www2.slac.stanford.edu/vvc/cosmicrays/ts2derivation.html.

Jeff Goldader *received his PhD in astronomy from the University of Hawaii at Manoa. He spent three years as a post-doctoral fellow at the Space Telescope Science Institute in Baltimore, MD, and five years as a lecturer and researcher at the University of Pennsylvania, before making the jump to high school teaching. He is currently the Upper School physics teacher at The Baldwin School, an independent school for girls near Philadelphia.*

The Baldwin School, 701 Montgomery Ave., Bryn Mawr, PA 19010; jgoldader@baldwinschool.org

Seulah Choi *graduated from The Baldwin School in 2009, and will be attending The Johns Hopkins University in Baltimore, MD.*