Investigating cosmic ray coincidences

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Investigating cosmic ray coincidences

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Abstract

Every laboratory has its own supply of high energy particles. Secondary cosmic rays provide a sea level flux of muons at a rate of about 1 cm^{-2} min^{-1}. This article describes an extracurricular A-level investigation that indicates muon–electron collisions in the roof of the laboratory.

Introduction

Physics students at Preston College are fortunate in having a laboratory equipped for cosmic ray measurements. The laboratory has been developed over a number of years through the generous recycling of surplus equipment from the UK universities of Leeds, Lancaster and Nottingham. The development of powerful personal computers and advances in electronics in the last 20 years have meant that keen A-level students can undertake real investigative projects in fields that were only recently the province of university laboratories. Such activity significantly enhances the study of physics at A-level and appeals to students keen to work eventually at the frontiers of their subject.

In recent years, work at the college has involved a direct measurement of the mean lifetime of the muon [1] and a demonstration of cosmic-ray-induced electromagnetic cascades [2]. The college is currently working, with two neighbouring schools, towards the development of an extended array of cosmic ray detectors. The array will be capable of registering the occurrence of large muon showers produced by the highest energy cosmic rays ever seen. The early stages of this development involved investigating coincidences between cosmic ray detectors placed some metres apart.

Extensive air showers

Cosmic ray air showers were discovered in the 1930s. The newly developed Geiger–Müller counter and cloud chamber were used as tools in the analysis of the properties of cosmic ray particles. The penetrating properties of the particles were investigated using GM tubes placed in a line vertically. Coincident counts indicated the passage of particles through absorbers placed between the counters. Alternatively, the coincidences were used to trigger a cloud chamber placed between the detectors.

The early research workers were surprised to find that the Geiger counters also recorded a high rate of coincidences when placed apart in a horizontal plane. In the second half of the 1930s, Pierre Auger carried out a detailed study of these horizontal counter coincidences and found that the detectors were regularly triggered together even when separated by hundreds of metres. It eventually became clear that extensive showers of charged and uncharged particles were being produced when primary cosmic ray particles from deep space collided with nuclei in the Earth's atmosphere. Measurements in the latter half of the twentieth century showed that the largest of the extensive showers are associated with cosmic rays with energies of the order 10^{20} eV. The source of such energetic particles is unknown and research teams across the world are actively working to identify it [3].

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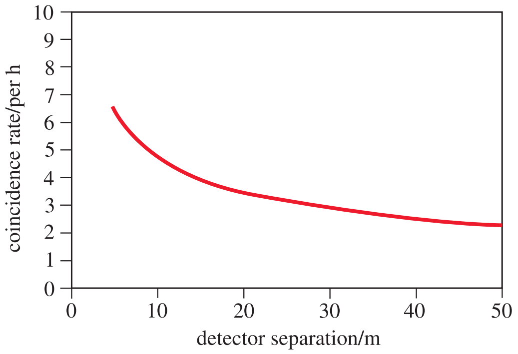

Figure 1. Typical variation of coincidence rate between two cosmic ray detectors for large separations.

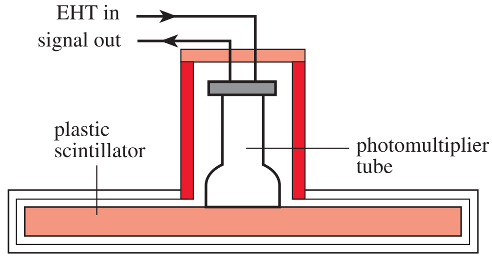

Figure 2. Scintillator and photomultiplier arrangement in the cosmic ray detectors.

Narrow showers

When two cosmic ray detectors are operated in coincidence, in a horizontal plane, the coincidence rate decreases steadily as the distance between the detectors increases (figure 1). The decrease is understandable because the footprint of cosmic ray air showers is limited in size and there are more small showers than large ones. The shower size is related to the energy of the initiating cosmic ray particle and lower energy particles are more frequent than the higher energy ones. The graph of the variation of counter coincidence rate versus separation is called a decoherence curve.

It is found that if the counters are brought closer than a few metres then the coincidence rate rises dramatically as the detector separation decreases. The rise is much greater than would be expected from the known variation of cosmic ray air shower sizes and the variation of particle density with shower radius. It is this rise in the coincidence rate at small detector separations that was the subject of our investigation.

The detectors and counting arrangements

The detectors consisted of simple photomultiplier and scintillator combinations in lightproof boxes made from wood. Each detector consisted of a 12 cm photomultiplier tube placed in direct contact with a piece of plastic scintillator (figure 2). The scintillator size was 30 cm × 60 cm × 2 cm. The detectors were set to give count rates of about 17 s^{-1}. This is consistent with a sea-level background cosmic ray flux of 1 particle cm^{-2} min^{-1} and the collection efficiency of our detectors. Particles passing through the middle of the detector, close to the photomultiplier tube, produced the main pulses. Those particles passing through the outer regions of the scintillator produced smaller pulses due to the scattering of the light within the detector so that the effective collecting area turned out to be less than the geometric area of the scintillator.

The counts were monitored using a computer. The detector pulses were fed to a discriminator that filtered out the lower level photomultiplier noise pulses and produced a logic pulse at its output. The discriminator outputs were shaped by monostable circuits set to produce 0.1 μs TTL pulses. These pulses were captured by the computer through the control lines of the printer port. A simple Visual Basic program displayed the frequencies of coincident counts in a given time interval. The coincidence count rates were low and the computer measurement system meant that we could automate the process to count over long time intervals. The program allowed a Poisson distribution of counts to be built up over time, hence satisfying us that the counts were randomly distributed and not due to spurious electronic events in the laboratory. It also gave us a running calculation of the mean count per time interval at a given detector spacing. A typical screen display is given in figure 3.

Experimental arrangements and findings

The two detectors, labelled A and B, were first placed with A directly above B (figure 4) at a fixed separation of 20 cm. The variation of coincidence rate was recorded for different thicknesses of lead placed between the two counters. The outputs of the two counters were fed to an AND gate in order to record coincidences. The investigations were carried out in the laboratory underneath a flat roof of wood, standard roof weatherproofing and a low-

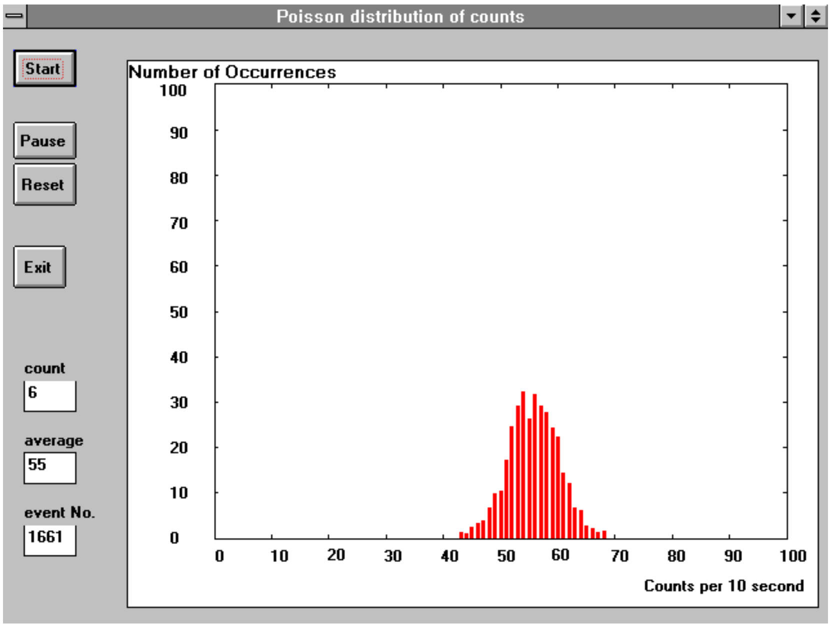

Figure 3. Typical screen display of the Visual Basic count monitor.

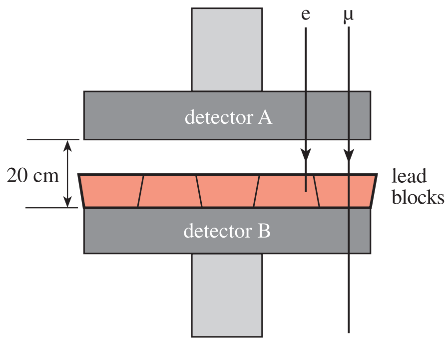

Figure 4. The detector and lead block arrangement for monitoring single-particle coincidences.

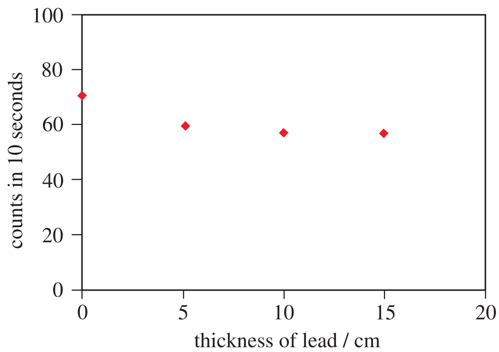

Figure 5. Variation of coincidence count rate as the thickness of lead is increased.

density suspended ceiling. The distance between the roof and the upper detector was about 2.2 m.

With each counter giving an independent count of 170 per 10 second interval, the coincidence rate without the lead was found to be around 70 per 10 second interval. The difference between the count rates can be accounted for by the geometry of the arrangement, with particles arriving at an angle to the vertical capable of passing through one detector but not the other.

When a 5 cm layer of lead was placed between the counters the coincidence rate dropped to 60 per 10 second interval. Further layers of lead reduced the count rate a little further to about 55 counts per interval (figure 5). The ability of the particles to pass though more than 10–15 cm of lead suggests that the particles were mainly muons. The ratio of background muons to electrons at sea level is known to be about 75: 25.

The two counters were then placed side by side in a horizontal plane with a separation of 60 cm between their centres and with no lead covering. This arrangement would respond to coincident pairs or groups of particles. The computer was set to count for 10 minute intervals and continually display the developing Poisson curve. The coincidence rate with the counters placed side by side was measured to be 78

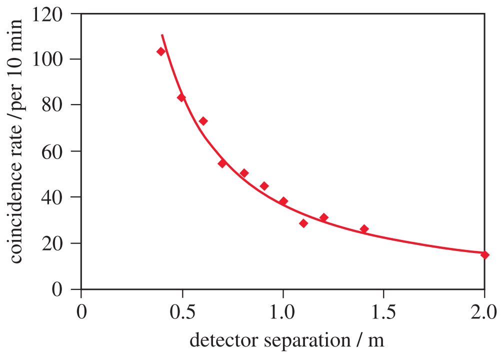

Figure 6. Typical variation of coincidence rate for detectors A and B placed side by side in a horizontal plane.

coincidences per 10 minute interval. This was a count of the order of 1 coincidence per 10 second interval in comparison with the 70 coincidences obtained with the counters vertically in line with each other.

The expected coincidence rate due to chance overlap of counts, rather than due to real coincident pairs of particles, was calculated using chance rate $= 2n_A n_B \, dt$ where n_A and n_B are the count rates for counters A and B respectively and dt is the monostable output pulse width at the input to the AND gate. With counters A and B each giving a count rate of about 17 s^{-1}, and with a counter pulse width of 0.1 μs, the expected chance coincidence rate would be 6×10^{-4} per 10 second interval. The chance coincidence rate was regarded as insignificant.

With each counter recording about 170 counts per 10 second interval, and with the pair of counters recording about 1 coincidence per 10 second interval at a separation of 60 cm, we concluded that about 1 in 170 of the particles was accompanied by a second one.

The variation of coincidence count rate with detector separation was measured. It was found that the coincidence rate dropped significantly over a separation of 1.5 m (figure 6). The relationship between the coincidence rate and the counter separation was found to be of the form

$$\text{coincidence rate} = \text{constant} \times \text{separation}^{-n}$$

with $n = 1.2 \pm 0.1$.

We repeated the measurements using a third detector placed about 1 metre away and connected in anticoincidence with the two counters. This would eliminate coincident counts due to extended showers of particles. The rates did not change significantly so we concluded that our coincidences were associated with particle pairs or close groups rather than larger showers.

We then placed 5 cm of lead on the surface of each detector. The count rate of each counter dropped only slightly but the coincidence rate at each separation dropped by about 75%. The significant reduction in the coincidence rate with the addition of the lead suggested that at least three quarters of the unshielded counter coincidences had involved electrons going through at least one counter. One quarter of the coincidences involved either electrons with sufficient energy to pass through 5 cm of lead, pairs of muons or similar penetrating particles.

We assumed, at this stage, that a number of electrons were being knocked forward in muon collisions with atomic electrons in the roof material, and coincident muon–electron pairs were being detected by the unshielded detectors. In the shielded counters the electrons were being stopped by the lead.

We investigated the variation of coincidence rate at a fixed separation with 5 cm, 10 cm and 15 cm of lead on both counters. The addition of 15 cm of lead reduced the coincidence rate to 1/6th of that obtained with no shielding. We thought that the probability of electrons getting through 15 cm of lead was small and concluded that about one sixth of the coincidences might be due to close pairs of muons.

We then repeated the two counter coincidence measurements, with unshielded detectors, above the roof material. Experimentation on the roof was limited by a number of factors. The EHT supplies, the processing electronics and the computer had to be moved to roof level. The detectors would have to be left on the roof for a lengthy time interval. They were not waterproof and there were very few days without rain. We also had to ensure that the detectors and our feet did not damage the weatherproofing. We had to work well away from the roof edge for safety reasons. We managed to make measurements over four counter separations in the time that we had available. The lower set of four points in figure 7 shows the number of coincidences per 10 minute interval for the four separations. The upper set of points shows the variation of count rate against separation with the counters back in the laboratory below the roof.

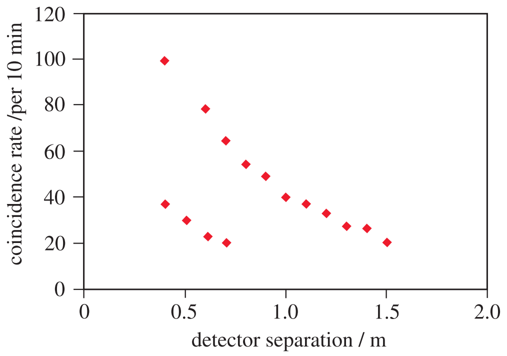

Figure 7. Comparison of the variation of coincidence rates for the two detectors separated in a horizontal plane in the lab (upper points) and on the roof (lower points).

The individual counter rates of about 170 per 10 second interval were similar above and below the roof material but the coincidence rates from the measurements above the roof were roughly one third of those found in the lab. This rate was higher than we had expected. We were working with the assumption that our coincident particles were produced in the roof material and that we should not see many coincidences above it. It seemed that about one third of the counts were due to pairs produced in the atmosphere. On reflection we recognized that the ratio of densities of the roof material to air was of the order 1000:1. If the materials in the roof were about 3 cm thick then a depth of air of about 30 m would have the same scattering properties and hence we could expect to see a reasonable coincidence rate outside the building.

Summary of observations

The findings illustrate that the majority of the cosmic ray secondary particles detected at ground level are penetrating particles, assumed to be muons, and that about 1% of the particles are closely accompanied by electrons. The variation of coincidence rate with counter separation suggests that the majority of the muon–electron pairs have an angular separation of no more than a few tens of degrees. It is suggested that the electrons are probably knocked forward by muons colliding with atoms. The high rate of two-particle coincidences measured in the laboratory suggests that a significant number of muon–electron collisions occur in the roof material. We tried to find a physical justification of the observed power law in terms of particle scattering but were not successful. This aspect of the work will be continued.

Investigations with GM tubes

We decided to see whether similar effects could be seen using Geiger–Müller tubes in coincidence rather than the scintillation counters. We used MX168 counters which had a length of 4 cm and a diameter of about 2 cm. This gave an effective counting area of 8 cm^2 per tube. The much reduced counting area, in comparison with the scintillation counter area, meant a similarly reduced counting rate but it would allow the counters to be placed closer together. Some evidence of a decoherence curve was seen for small counter separations but the overall count and coincidence rates were much too small to produce reliable results.

Conclusion

The investigation has shown that interactions of cosmic ray secondaries with air and with denser material can be demonstrated in a college laboratory if suitably sized detectors are available. The coincident count rate between two suitable detectors at separations of less than 2 m shows a significant rise as the detector separation decreases. We interpreted the rise in terms of collisions between muons and atomic electrons, with the latter being knocked forward and accompanying the muons within a small angle.

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[2] Dunne P 1999 Demonstrating cosmic ray induced electromagnetic cascades in the A-level laboratory *Phys. Educ.* **34** 19–27

[3] The Auger Project http://www.auger.org/

Related reading and links

Preston College Cosmic Ray Group Website http://www.preston.ac.uk/cosmic

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Friedlander M W 1989 *Cosmic Rays* (Cambridge, MA: Harvard University Press)