Background Rate Measurements in Plastic Scintillation Detectors

NuMI-L-639

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Background is an important consideration in the concept of outrigger detectors to supplement the MINOS far detector at Soudan. The background from cosmic ray muons is relatively easy to calculate. The correlated signals from atmospheric showers and the uncorrelated background due to environmental radioactivity are more difficult to address. We have made measurements to estimate these effects, using the cosmic ray stand erected by the MINOS collaboration as the basis of our apparatus. It consists of cosmic ray telescopes, a support structure, high voltage supplies, and electronics in NIM crates. Three additional counters were used in the study. These were 80 cm × 10 cm in area and 0.5 cm thick. Each counter was viewed on both ends by Phillips 2262B phototubes, which were attached by acrylic light guides 49 cm in length.

The Cosmic Ray Stand

The New Muon Lab cosmic ray stand consists of 15 pairs of scintillation counters, each of area 168 cm × 20 cm and separated horizontally by 31 cm gaps. The top and bottom counters of each pair are separated by 71 cm. A schematic representation may be seen in Figure 3.

Background Radioactivity

The counting rate due to radioactivity has been measured by plotting curves of detector response *versus* phototube voltage. One of the 15 pairs of cosmic ray stand counters was used for triggering. Coincidence of the upper and lower counters was the trigger. The counter to be tested was placed between the two trigger counters as shown in Figure 1. A coincidence of both ends of the test counter constituted a signal. We then measured the signal rate as a function of high voltage both with and without coincidence with the external trigger. The same voltage was applied to both ends of the test counter shown in

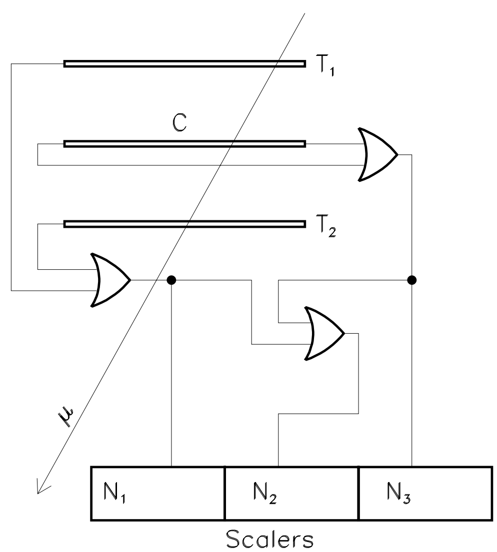

Figure 1. Schematic diagram of the test counter setup for radioactivity measurements.

The result for counter C_2 is shown in Figure 2. The efficiency of coincidence with the external trigger, $E = \frac{C_2}{T_1 \bullet T_2}$, saturates at about 1600V, indicating the effective detection of minimum-ionizing particles while the count rate continues to rise due to the lowering of the energy threshold. As shown in the figure, at a working voltage of 1600V the total rate is 35 Hz. About 14 Hz can be attributed to cosmic rays, using muon intensities as given in the Particle Data Book.[1]

$$180 \frac{\text{Hz}}{\text{m}^2} \times 0.08 \text{ m}^2 \approx 14 \text{ Hz} \qquad (1).$$

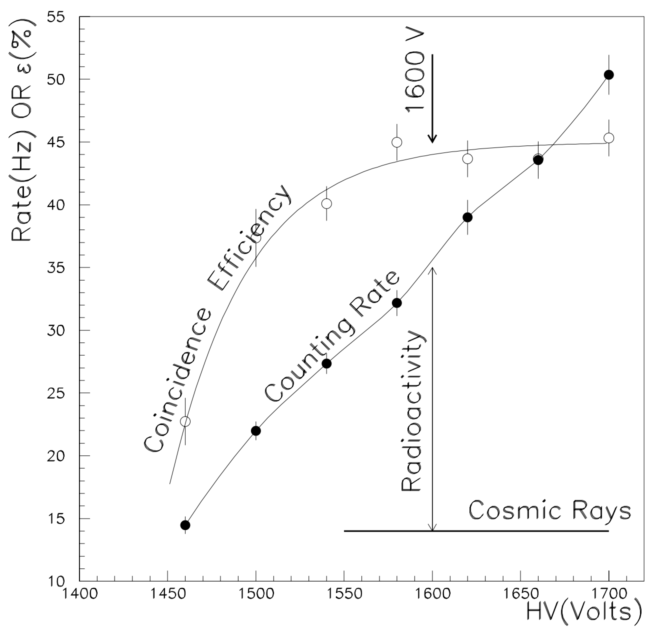

Figure 2. Estimated contribution of the ambient radioactivity to the counting rate. The open circles represent the efficiency (%) of the coincidence with the external trigger. It reaches a plateau near 1600 V, indicating a high efficiency for minimum-ionizing particles. Bullets show the counting rate in Hz (coincidence of both ends). Error bars are statistical only.

A rough crosscheck comes from the following test. At working voltage we orient the counter vertically and the rate drops from 35 to 28 Hz. From the $\cos^2\theta$ angular distribution of cosmic rays, one would expect a reduction of about 50% from this orientation, consistent with the 7 Hz observed. We attribute the excess rate to ambient radioactivity.

$$35 \text{ Hz} - 14 \text{ Hz} = 21 \text{ Hz} \qquad (2).$$

The results for the three tested counters are given in Table 1.

Counter	Measured Radioactivity (Hz)	Radioactivity Rate (Hz m^{-2})
1	44	550
2	21	260
3	16	200
Avg.	27	337

Table 1. Radioactivity rates in test counters as calculated from Equation 2.

All of the discriminator output pulses were adjusted to 7 – 10 ns FWHM. The out-of-time rate (between two ends of the same counter) was negligible.

To assess the potential impact of placing an outrigger detector for MINOS in a comparable background, we use the average rate and assume a detector plane area of 50 m^2.

$$337\ \frac{\text{Hz}}{\text{m}^2} \times 50\ \text{m}^2 = 16.9\ \frac{\text{kHz}}{\text{plane}} \qquad (3).$$

For a NuMI beam pulse duration of 20 ns, the coincidence rate in two such planes due to ambient radioactivity is given by

$$2 \cdot \left(1.69 \times 10^4\ \text{s}^{-1}\right)^2 \left(2 \times 10^{-8}\text{s}\right) = 11\ \text{Hz} \qquad (4).$$

For a live time of 100 s per year, this would result in 100 spurious coincidences, which is about the number of beam-related events expected. This rate is marginal, but possibly tolerable. However, it is a reasonable assumption that much of the background radioactivity at the New Muon Lab comes from the building materials, especially the concrete floor. With a judicious choice of building materials for the outrigger housing, the background radioactivity can be significantly decreased. Soudan2 estimates about 30% of their total rate coming from radioactivity in the concrete lining of the cavern.[2] If we reduce the rate due to radioactivity by 30% in each counter,

$$2 \cdot \left(1.18 \times 10^{4}\ \mathrm{s}^{-1}\right)^{2}\left(2 \times 10^{-8}\mathrm{s}\right) = 6\ \mathrm{Hz} \qquad (5).$$

In any case, if a third plane were affordable, then the triple coincidence due to background would be negligibly low.

Showers

We set up three test counters as shown in Figure 3 and measured the rate of double (C_1C_2) and triple ($C_1C_2C_3$) coincidences. The “veto” was highly inefficient due to the geometry of the test stand, however it was helpful in demonstrating the nature of the coincidence events. The C_2 and C_3 delays were adjusted by putting them close to C_1, as shown in Figure 4, and adding delay according to their final positions. A delay of 29 ns was added to C_2 and 15 ns to C_3. The total “veto” rate was about 170 Hz, which allowed the accidentals to be neglected. The “veto” pulse duration is not of concern and was set to 130 ns. The accidental coincidences were monitored by delaying C_2 by 150 ns. Table 2 summarizes approximately six days of running.

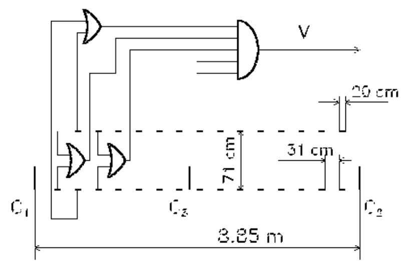

Figure 3. Schematic diagram of test setup for cosmic ray shower measurements.

Counters	Events	Rate (Hz)	Comments	Full Scale Rate (Hz)
C_1C_2	383	$7.7 \pm 0.4 \times 10^{-4}$		300 ± 16
$C_1C_2\overline{V}$	137	$2.8 \pm 0.2 \times 10^{-4}$		
$C_1C_{2\mathrm{del}}$	27	$5.5 \pm 1.0 \times 10^{-5}$		21 ± 4
$C_1C_2C_3$	52	$1.1 \pm 0.2 \times 10^{-4}$		41 ± 6
$C_1C_2C_3\overline{V}$	9	$1.8 \pm 0.6 \times 10^{-5}$		
$C_1C_{2\mathrm{del}}C_3$	0	$< 4.6 \times 10^{-6}$	90% CL	

Table 2 Coincidence rates with and without veto and with C_2 delayed. Errors are statistical only. The last column extrapolates rates to a counter of 50 m^2 area.

Indications of the Shower Data

First, we see that the double coincidence rate is 14 times higher than the accidental rate. There is a strong correlation between C_1 and C_2. The rate of triple coincidences reinforces this conclusion.

Secondly, we conclude that this time correlation comes from atmospheric showers rather than from single horizontal muons. The "veto" reduces the doubles rate by a factor of 3 and the triples rate by a factor of 6. This is all the more striking since the "veto" covers only 28% of the area between the counters, about 0.16 steradian of solid angle.

The conclusions above lead one to ask what doubles rate might be expected from the singles rates in Table 1 and the time resolution of the counters. Combining these rates with the 14 Hz from cosmic rays gives expected singles rates for C_1 and C_2 of 58 Hz and 35 Hz, respectively. The resolution time is about 15 ns (see Figure 4). The delayed rate would be

$$F_{del} = 58\ \text{Hz} \times 35\ \text{Hz} \times 2 \times 1.5 \times 10^{-10}\,\text{s} = 6.1 \times 10^{-5}\ \text{Hz} \qquad (6),$$

in good agreement with the measured value.

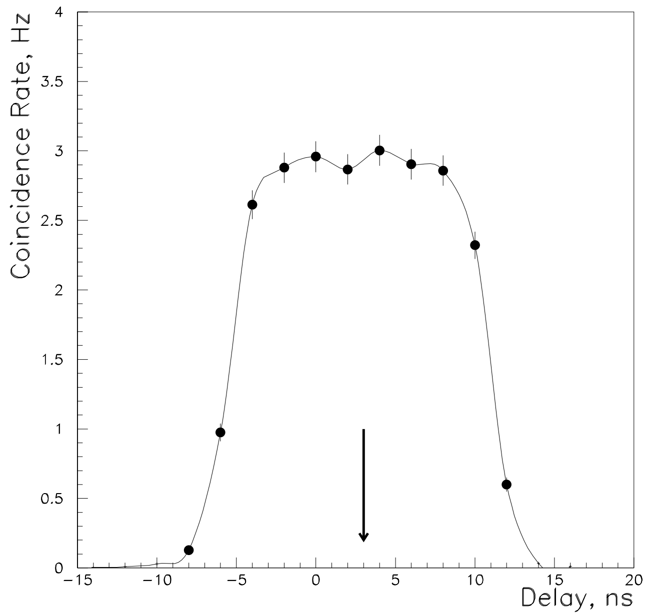

Figure 4. Delay curve between counters C_1 and C_2 when positioned close to one another. A delay of 29 ns is added by a separation of 8.85 m.

One can also use the non-vetoed triple coincidence to place an upper limit on the horizontal cosmic rays. The counter area is 0.08 m^2 with a lever arm of 8.85 m, so the solid angle as seen from the horizon is

$$\Omega = \frac{S}{L^2} = 10^{-3}\ \text{sr} \qquad (7).$$

Representing the angle to the horizon by θ_h, one can compare the triples rates with and without the veto.

$$F(\theta_h = 0) < \frac{1.8\times10^{-5}\ \text{Hz}}{0.08\ \text{m}^2\cdot10^{-3}\ \text{sr}} = 0.225\frac{\text{Hz}}{\text{m}^2\cdot\ \text{sr}} \approx \frac{1}{300}F(\theta_h = 90) \qquad (8).$$

Extrapolation of the Data to a Full-Scale Detector

Two issues are essential to consider.

First, for a given plane separation, the doubles rate should scale as the square of the area. One might naively expect the probability for a plane to register a hit to be proportional to its area and square it for two planes of equal area. In the Monte Carlo simulation of Figure 5 the atmospheric showers exhibit a slightly slower dependence of $S^{1.85}$, agreeing remarkably well with the measured point.

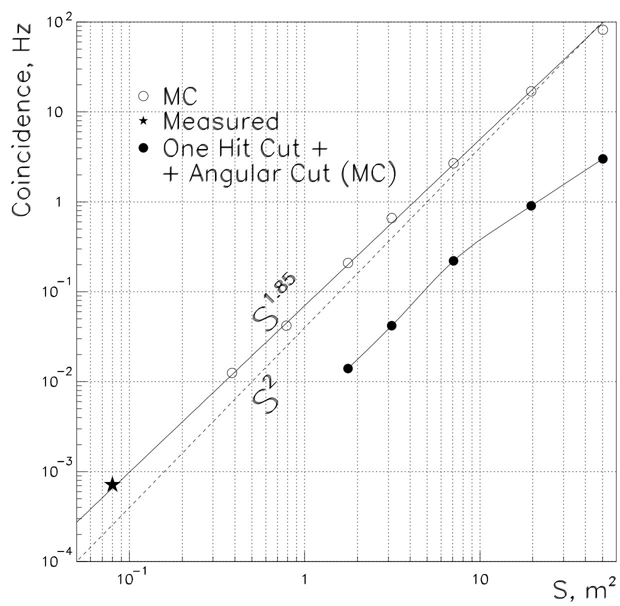

Figure 5. Coincidence rate between two vertically oriented counters separated by 8 m as a function of counter area. The open circles are Monte Carlo; the star is the measured value; the bullets are a “one-hit” cut.

A full size detector would provide a tool to suppress showers, which is not available with small counters. That is a “single hit” cut: a requirement that there be exactly one hit in each plane. The data in Table 2 demonstrate this qualitatively. If there is a signal in two planes, the very often there is at least one other particle coming from above. Chances are this particle will make an extra hit, thus killing the whole event. The MC simulation predicts a suppression factor of about 15 due to this cut (see Figure 5). For a two-plane detector of area 50 m^2 the suppressed rate is about 3 Hz, which is less than the rate due to radioactivity.

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[1] T. K. Gaisser and T. Stanov, European Physical Journal C, Volume 3, Number 1-4, p 133 (1998)

[2] K. Ruddick, *Counting Rates in the MINOS Plastic Scintillator Detector Due to Rock and Steel Radioactivity*, NuMI-L-313 (1997)