Cosmic ray muon telescope scintillator characterization tests

S. Barton and R. Armendariz, Aug 2023

Important note:
To make the coincidence rate mesurements the trigger outputs from the back of the oscilloscopes were sent to the Leader frequency counters; both oscilloscopes' trigger-outs have a known problem or limitation where in about 10-20% of measurements the trigger-out rate (at these low frequencies) can be as much as 30% lower than the actual coincidence rate

Three scintillators were tested in their measurement of muons. Scintillators' faces were laying flat (i.e. horizontal to ground) [scintillator surplus from HT]

20220701 (Red): 91x30.5x0.9, area = 2775.5 cm^2 (theory 46.3 muons/sec), with PMT58 AA720 (1.5 x 10^6 gain, DR 100 Hz, at 2000V)

20230321 (Blue) 91x30.5x.9, area = 2730 cm^2 (theroy 45.5 muons/sec), with PMT 9 AA2073 (1.6 x 10^6 gain, DR 26 Hz at 1800V) (DR 247 at 2200V)

20230320 (Yellow): 91x31x1, area = 2821 cm^2 (theory 47 muons/sec), with PMT24 AA1336 (10^6 gain, DR 269 Hz, at 2200V)
All three are double Tyvek wrapped, with silicone cookies on PMT lens

Quarknet Paddles used:
yellow paddle (counter 4): 30.4x25.3, area = 769 cm^2, at 0.785V
red paddle (counter 1): 31.4x26, area= 816 cm^2, at 0.725V

Test equipment and setup:
Coax from large scintillator pmt was chosen longer by tens of feet than paddles' coax, to synchronize arrival times of three pulses to oscilloscope, to compensate for its faster pmt pulse output

Oscilloscopes: 4CH Tektronix DPO4104 1GHz, s/n C011830, s/n C020623 (did not use CH2 - faulty)
100 mV/Div,-30 mV thresholds (30% of volts/div), Full bandwidths (1 GHz), 50 Ohm termination
Amplifier x 10, NIM PS776 s/n 1838
Digital Counters - LEADER LDC-822 80 MHz, s/n 4050083, s/n 3050024
Gate Time 10s (counts per sec averaged over 10 sec), Sensitivity 0.02 Vrms, 1 MOhm termination
HV supplies Ortec 456: s/n 4396

2-fold coincidence rate measurements for 20220701 on top of 20230320, seperated by a 8.5 cm (3.35") gap

expected muon rate for area of 2775.5 cm^2 is 46.3 Hz
Noise 2-fold theoretical rate = 2R1R2(GW), GW = 40ns (typical pmt pulse width)

					Measurements (data avg at 10s intervals)						
scintillator 20220701 (PMT58)	single rate Hz (max over 5 trials)	**scintilator 20230320 (PMT24)**	single rate Hz (max over 5 trials)	2R1R2(GW) Hz	Trial 1	Trial 2	Trial 3	Trial 4	Trial 5	Avg Hz	Avg - noise Hz
2000V		2200V		0.00						0.0	0.0
2100V		2300V		0.00						0.0	0.0
2200V	4631	2400V	2069	0.77	34.4	33.8	35.1	32.4	36.5	34.4	33.7
2300		2500		0.00						0.0	0.0

Scintillator: 20220701 (Red), 91cm long, area 2775.5 cm^2, PMT58 AA720 at 2200V (1.5 x 10^6 gain, DR 100 Hz, at 2000V)

compared the two fold coincidence rate of the paddles (4.5" seperation) to the 3 fold coincidence rate including large scintillator (4.5" seperation).
Conclusion: large scintillator detecting 83% of muons detected by paddles; to improve efficiency try increasing PMT HV on large scnitillator. The distance of paddles from large scintillator's PMT didn't significantly reduce results
Setup notes: The scintillators were arranged with the yellow paddle on top, the red paddle on the bottom, with the 20220701 sandwiched in the middle. The paddles were approximately 4.5" apart as measured from their centers.

	2 paddles, sandwiching the large scintillator												
	3 fold coincidence rate (data avg at 10s intervals)						paddles 2 fold coincidence rate (data avg at 10s intervals)						
position of paddles	trial 1	trial 2	trial 3	trial 4	trial 5	3 fold average	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	ratio of 3 fold to 2 fold
Far from pmt	5.1	7.0	7.0	6.9	7.2	6.6	6.6	7.7	9.0	8.0	8.7	8.0	**83%**
middle of big scintillator	8.1	6.5	6.9	6.9	6.4	7.0	9.2	8.0	8.3	8.1	7.7	8.3	**84%**
close to pmt	8.4	5.8	6.8	6.0	7.8	7.0	9.7	7.0	8.2	7.0	9.3	8.2	**84%**

compared the 2 fold coincidences of the yellow paddle with the large scintillator, to the red paddle with the yellow paddle
Conclusion: large scintillator detecting 92% of muons detected by paddles; to improve efficiency try increasing PMT HV on large scnitillator; and/or reduce the distance of paddle from large scintillator's PMT
setup change: placed the red paddle on the yellow paddle on the large scintillator, in the approximate center of the large scintillator

	yellow paddle/large scintillator (centers 1 - 2.25" seperation)						red paddle/yellow paddle (centers about 1.5" seperation)						
	2 fold coincidence rate (data avg at 10s intervals)						2 fold coincidence rate (data avg at 10s intervals)						
position of paddles	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	ratio: [2 fold with large scint] / [2 fold paddles]
middle of big scintillator	14.0	11.2	11.8	11.8	10.8	11.9	15.8	12.6	12.3	11.7	12.5	13.0	**92%**

scintillator: 20230321 (Blue) 91 cm long, area = 2730 cm^2, PMT 9 AA2073 at 2200V, (1.6 x 10^6 gain, DR 26 Hz at 1800V)

compared the two fold coincidence rate of the paddles (4.5" seperation) to the 3 fold coincidence rate including large scintillator (4.5" seperation).
Conclusion: large scintillator detecting 80-86% of muons detected by paddles; to improve efficiency try increasing PMT HV on large scnitillator. The distance of paddles from large scintillator's PMT didn't significantly reduce results

Setup notes: The scintillators were arranged with the large one sandwiched in the middle. The paddles were approximately 4.5" apart as measured from their centers.

	2 paddles, sandwiching the large scintillator						red paddle/yellow paddle (centers about 1.5" seperation)						
	3 fold coincidence rate (data avg at 10s intervals)						2 fold coincidence rate (data avg at 10s intervals)						
position of paddles	trial 1	trial 2	trial 3	trial 4	trial 5	3 fold average	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	ratio of 3 fold to 2 fold
Far from pmt	7.7	7.9	6.6	7.4	7.3	7.4	8.8	9.2	8.9	9.8	8.4	9.0	**82%**
middle of big scintillator	6.5	6.8	7.1	6.3	7.4	6.8	7.5	9.5	8.5	7.7	9.6	8.6	**80%**
close to pmt	7.2	8.1	7.3	7.9	7.0	7.5	8.3	9.6	8.6	9.5	7.8	8.8	**86%**

compared the 2 fold coincidences of the yellow paddle with the large scintillator, to the red paddle with the yellow paddle.
Conclusion: the large scintillator recorded 13% more counts than the red paddle

	yellow paddle/large scintillator (centers 1 - 2.25" seperation)						red paddle/yellow paddle (centers about 1.5" seperation)						
	2 fold coincidence rate (data avg at 10s intervals)						2 fold coincidence rate (data avg at 10s intervals)						
position of paddles	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	ratio: [2 fold with large scint] / [2 fold paddles]
middle of big scintillator	16.1	15.2	14.6	15.8	14.2	15.2	15.7	13.1	13.9	13.4	11.3	13.5	**113%**

scintillator: 20230320 (Yellow), 91 cm long, area = 2821 cm^2, with PMT24 AA1336 at 2200V (10^6 gain, DR 269 Hz, at 2200V)

compared the two fold coincidence rate of the paddles (4.5" seperation) to the 3 fold coincidence rate including large scintillator (4.5" seperation).
Conclusion: large scintillator detecting 80-86% of muons detected by paddles; to improve efficiency try increasing PMT HV on large scnitillator. The distance of paddles from large scintillator's PMT didn't significantly reduce results

Setup notes: The scintillators were arranged with the large one sandwiched in the middle. The paddles were approximately 4.5" apart as measured from their centers.

	2 paddles, sandwiching the large scintillator												
	3 fold coincidence rate (data avg at 10s intervals)						2 fold coincidence rate (data avg at 10s intervals)						
position of paddles	trial 1	trial 2	trial 3	trial 4	trial 5	3 fold average	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	ratio of 3 fold to 2 fold
Far from pmt	8.2	6.7	8.7	8.5	6.1	7.6	10.0	8.0	10.6	10.2	8.9	9.5	**80%**
middle of big scintillator	6.5	7.5	6.7	7.7	6.3	6.9	8.5	9.4	8.6	9.1	7.4	8.6	**81%**
close to pmt	6.7	8.1	9.3	6.7	7.3	7.6	8.7	8.8	10.2	8.1	8.5	8.9	**86%**

compared the 2 fold coincidences of the yellow paddle with the large scintillator, to the red paddle with the yellow paddle
Conclusion: large scintillator detecting 77% of muons detected by paddles; to improve efficiency try increasing PMT HV on large scnitillator; and/or reduce the distance of paddle from large scintillator's PMT

	yellow paddle/large scintillator (centers 1 - 2.25" seperation)						red paddle/yellow scintillator (centers about 1.5" seperation)						
	2 fold coincidence rate (data avg at 10s intervals)						2 fold coincidence rate (data avg at 10s intervals)						
position of paddles	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	trial 1	trial 2	trial 3	trial 4	trial 5	2 fold average	ratio: [2 fold with large scint] / [2 fold paddles]
middle of big scintillator	9.4	11.9	9.3	10.1	10.9	10.3	12.5	14.9	13.8	12.5	13.2	13.4	**77%**

Cosmic Ray muon telescope counters Testing - Oct 22, 2023

Scintillators:

20230320 (Yellow): 91x31x1, area = 2821 cm^2 (**theory 47 muons/sec**), with PMT24 AA1336 (10^6 gain, DR 269 Hz, at 2200V)

20230321 (Blue) 91x30.5x.9, area = 2730 cm^2 (**theroy 45.5 muons/sec**), with PMT 9 AA2073 (1.6 x 10^6 gain, DR 26 Hz at 1800V) (DR 247 at 2200V)

20220701 (Red): 91x30.5x0.9, area = 2775.5 cm^2 (**theory 46.3 muons/sec**), with PMT58 AA720 (1.5 x 10^6 gain, DR 100 Hz, at 2000V)

Scintillator seperation:
Yellow to Red 79 cm (31.1")
Yellow to Blue 16 cm
Blue to Red 63 cm

Signal cable attenuation test -- 50' cable measured 4% attenuation and is consistant with expectation:
a 1000 mV high square pulse was sent through a 50' 2" RG58 cable and measured 960 mV high.
pulse was 60 ns wide, 1.52 kHz frequency.
Theoretical expected attenuation per specs at 1 MHz is 0.4 dB per 100 feet; thuse expect 0.2 dB loss:
-0.2 dB = 10Log(Vlow/Vhigh) --> Vlow = Vhigh((10^-(0.2/10)), Vlow = 955 mV.
Note: per specs RG58 adds 29 pF per foot of capacitance

Determination of optimal high voltage to use on PMTs

	20230320 (Yellow)	**20230321 (Blue)**	**20220701 (Red)**
optimal HV setting	2500V: 2x10^6 gain, DR ~ 3.1kHz	2200V: 4.3x10^6 gain, DR ~4.5kHz	2400V: 3.6x10^6 gain, DR 2.5kHz
Area/theoretical rate	2821 cm^2, 47 Hz	2730 cm^2, 46 Hz	2775.5 cm^2, 46 Hz
PMT	**PMT 24**	**PMT 9**	**PMT 58**
	2150V: 10^6 g, ~200Hz	1800V: 1.6x10^6 g, 26Hz	2000V: 1.5x10^6 g, 100Hz 2200V:
		2200V: 4.3x10^6 g, 247Hz (2.2kHZ after restarted power); ~4.5 kHz (4 - 5 kHz) (2023)	2400V: 3.6x10^6 g, 1.24kHz; ~2.5kHz (2 - 3 kHz) (2023)
	2400V: 1.6x10^6 g, 3.34kHz	2108: 2500V ~10^7 g (extrapolated from fit), 622Hz	
	2500V: ~2x10^6 g (extrapolated from fit), 5.59kHz (2018) ~2.6 - 3.6 kHz (2023)	2023: first measured 200Hz then 3.5kHz after took scint out of frame and restarted pmt (may need time to settle)	~2600V: ~5.2x10^6 g (extrapolated from fit), ~7kHz (2023)
Expected noise coincidence rates (DR and muons)			
Light leak tests	No light leaks. Light tested both sides with 500W lamp at 2500V, 1-3kHz noise	No light leaks; light tested both sides with 500W lamp at 2500V, ~3.5kHz	No light leaks; light tested both sides with 500W lamp at 2600V, 6-9kHz

Coincidence rate measurements (these should be remeasured because later it was found out the oscilloscope channels may have had DC inaccuracies)

expected muon rate for each counter is 46-47 Hz (area of Red = 2775.5 cm^2 is 46.3 Hz)

Noise 2-fold theoretical coincidence rate = 0.32 Hz (=2R1R2(GW), GW = 40ns, use 2kHz each pmt)
Noise 3-fold theoreticalcoincidence rate = 4 x 10^-5 Hz (= 3R1R2R3(GW)^2, GW = 40ns, use 2kHz each pmt)

Setup: Measurements averaged over 10 seconds, -30 mV thresholds on all counters
scintillators seperated by a 6.5 - 9.5 cm gap which varied over length of scintillators, and differs for pair combinations

two fold: 20230320 yellow (2500V) on top of 20230321 blue (2200V)	Two fold coincidence Hz
trial1	30.1
trial2	34
trial3	39.2
trial4	36.8
trial5	32.8
avg	**34.58**

two fold: 20230321 blue on top of 20220701 red	Two fold coincidence Hz
trial1	34.2
trial2	33.7
trial3	38.7
trial4	37.2
trial5	36.6
avg	**36.08**

two fold: 20230320 yellow on top of 20220701 red	
trial1	32.7
trial2	31.1
trial3	36.5
trial4	33
trial5	34.2
avg	**33.5**

three fold: 20230320 yellow on top of 20230321 blue on top of 20220701 red	Three fold coincidence Hz	Noise rate Yellow kHz	Noise rate Blue kHz	Noise rate Red kHz
trial1	26.3	1.28	1.73	1.29
trial2	24	1.52	1.77	1.42
trial3	25.1	1.74	1.75	1.28
trial4	26.8	1.44	1.75	1.4
trial5	26.5	1.1	1.74	1.35
avg	**25.74**	**1.416**	**1.748**	**1.348**

two fold: 20230320 yellow on top of 20220701 red 29.75" gap seperated	
trial1	10
trial2	8.5
trial3	8.3
trial4	9.5
trial5	9
avg	**9.06**