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Efficiency measurements of used Nuclear Enterprises-114 PVT plastic scintillator made with a muon telescope - “sandwich test”

Work performed in BNL EDG Lab 2-233

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Introduction

A muon telescope setup was used to measure the efficiency of sheets of NE-114 PVT plastic scintillator. 100 scintillators of dimensions ~ 107 cm x 30 cm x 2 cm, donated from Fermilab CDF surplus, will be tested following the procedures outlined here. The scintillators are binge cut to 95 cm long for a cosmic ray detector array. The NE-114 manufacturer specification wavelength of maximum emission is 434 nm. The measurements include different mating techniques between the photomultiplier tube (pmt) and scintillator: an optical-interface pad "silicone cookie" was compression mated, a solid acrylic cookie was mated with optical grease BC-630, versus bonded with optical cement EJ-500. Light reflection measurements were made of the aluminum foil and Tyvek wrapping materials by themselves before wrapping the counters; light transmission measurements through the different cookies were also made. The reflection and transmission tests were conducted for us by Sean Stoll using a Hitachi model 3210 double-beam spectrophotometer, following the procedures outlined in PHENIX Note #245 and #245 Addendum.

Summary of results

The light output from these scintillators from cosmic ray muons produces pulses on an oscilloscope about an order of magnitude lower than other newer and higher quality scintillator counters we have used. However better sanding, polishing, and wrapping methods are now used by the students. The most significant finding is that the discriminator setting is, by far, the most important variable to set properly. Increasing the discriminator threshold from 3 mV to 10 mV lowered the efficiency by 10% to as high as an 80% reduction in efficiency, depending on how far the cosmic ray track was from the pmt. The type of wrapping materials, cookies used, mating whether by compression, grease, or glue, or absence of a cookie all together, only changed the results by about 10-15%; however

Cookies and wrapping paper

At 430 nm light reflection off one layer all white Tyvek was 90%, two layers 96%, and two layers aluminum foil 86%. The red and blue colored printed letters on the Tyvek reduced reflected light by between 2% to 8% depending on single or double wrapped (Figure A). At 430 nm the light transmission through the newly purchased 6 mm thick silicone cookie, and older used 2mm cookie, were both 92%; the solid acrylic cookie transmitted 89% of the light (Figure B) (test method described in PHENIX Note #245).

Scintillator counter discriminator thresholds

For the two small telescoping paddle counters it was determined that a 10 mV discriminator threshold produced the best results; setting the discriminators lower resulted in what appeared to be noise in their 2-fold coincidence rate. The reason we believe this to be noise is the 2-fold rate began to exceed 13 Hz, the expected muon rate, for our paddle sizes, at 1 per cm^2 per minute (Figure 10). However, it is noted here that the dark rate measured from these paddles at operating voltage was only about 300 Hz each, thus the noise coincidence was not expected to be significant (see the Appendix).

For the NE-114 scintillator counter under test a choice of 3 mV discriminator threshold was determined to work best; Setting the discriminator a few mV higher resulted in a significant reduction in detection rate. This is because the large majority of cosmic ray muons detected with the counter's pmt set at 10^6 gain were are about 7 mV in amplitude through 50 Ohms on the oscilloscope. Various charge distributions made from the NE-114 counter, each for 200,000 events, confirmed that the majority of cosmics produce pulses between 5 and 10 mV in amplitude depending on how far from the pmt the muon penetrates the counter (Figures 10 – 19).

Mating the PMT to NE-114 scintillator

Compression mating the pmt to the scintillator with a new silicone cookie produced the best results. Optically bonding (i.e. gluing) the UVT acrylic cookie to the scintillator was mechanically very sturdy however the light output was significantly less (Figures 16 – 17).

Efficiency as a function of distance the cosmic ray track is from the PMT

The NE-114 counter s/n 20170710 is 90% efficient across its length of up to 25" which was measured, when its discriminator threshold is set to 3 mV, this drops to only 15% efficient when set to 10mV (Figures 10 – 17).

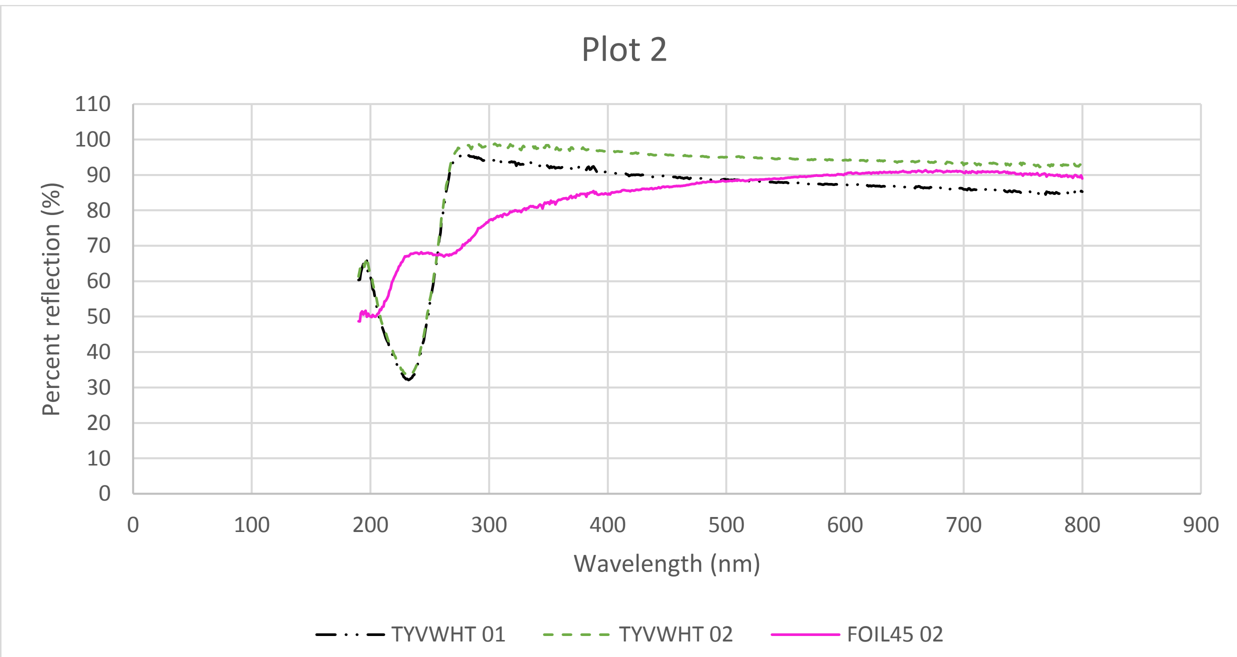


Figure A: Comparison of light reflection off one and two layers of white Tyvek wrapping paper, and two layers of aluminum foil (the foil is backed with white paper on the backside to reinforce it). Test method described in PHENIX Tech note 245.

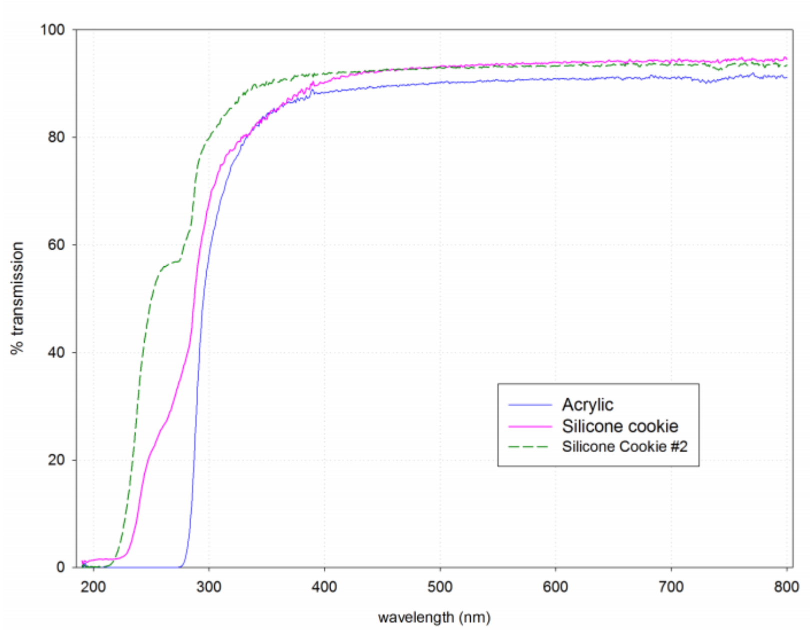


Figure B: Light transmission tests through the different cookies: "Acrylic" is the 1 cm thick slotted plastic cookie; "Silicone cookie" is the 2 mm thick, much older and used cookie; "Silicone Cookie #2" is the newly purchased 6mm thick cookie. Test method described in PHENIX Tech note 245.

Procedure

Two telescoping scintillator paddles were used, one paddle placed above and the other below the NE114 scintillator under test - a "sandwich-test." Each paddle was compression mated to a pmt. The 2-fold coincidence cosmic ray rate for the paddles was measured simultaneous with the 3-fold coincidence rate. Efficiency was measured at different distances from the pmt-side of the NE-114 scintillator under test:

Efficiency (%) = [3-fold coincidence rate/2-fold coincidence rate] x 100% Eq. 1

Each of these variables affected the efficiency results:

1. Reflectivity of wrapping material.
2. Optical mating between pmt and scintillator.
3. Gain of telescoping counters, determined by the HV applied.
4. Gain of pmt attached to scintillator under test, determined by the HV applied.
5. Discriminator thresholds set for each of the three counters.

The widths of the discriminator outputs were each set to 85 ns; the square wave outputs of the 2-fold coincidence unit, and the 3-fold coincidence unit measured to be 40 ns wide. The coincidence rate was not measured as a function of varying discriminator output widths.

Equipment

NE-114 scintillator under test

Two different scintillator plates were tested:

> Counter 5 s/n 20170710; dimensions: 90.5cm x 30.3cm x 2cm; wrapped in aluminum foil and later rewrapped with two layers of Tyvek.
>
> Counter 2 s/n 20170713; dimensions: 108cm x 30cm x 2cm; wrapped in one layer of Tyvek.
>
> The same pmt was used, a 2” Hamamatsu H2431-50, s/n AA1071 (“PMT 26”).

Measurements made with different mating techniques between PMT & scintillator:

> 1/16” thick optical interface pad (silicone cookie) compression mated
>
> 1 cm thick acrylic cookie (not known if it is UVT), bonded with optical grease BC-630
>
> 1 cm thick acrylic cookie (not known if it is UVT), bonded with optical cement EJ-500

Two telescoping paddle counters used to sandwich the scintillator under test:

Fermilab Quarknet paddle “counter 1” (marked with red tape); HV set at 720V via a low-to-high voltage converter set at 0.720 V (ratio 1:1000).

Fermilab Quarknet paddle “counter 4” (marked with yellow tape); HV set at 777 V via a low-to-high voltage converter set at 0.777 V (ratio 1:1000)

Both scintillator paddles are 819 cm^2, 1 cm thick, EJ-200 PVT plastic wrapped in aluminum foil and black paper; each was compression mated to a SensTech P30CW5 photomultiplier module with Dow Corning optical couplant Q2-3067.

Electronics:

> HV power supply (NIM module, BNL 106900)
>
> Dual Channel Visual Scaler (NIM module, Joerger).
>
> Sixteen channel amplifier model 776 – (NIM module, BNL 13175) - *x10 amplifier used.*
>
> Six channel discriminator model 711 – (NIM module, BNL 5052).
>
> Quad gate/delay generator model 794 – (NIM module, BNL 20992) – *Set to 8.3 s delay*.
>
> Multimeter: V&A (VA19).
>
> 500 MHz oscilloscope Tektronix DPO 4054 (s/n C022247)

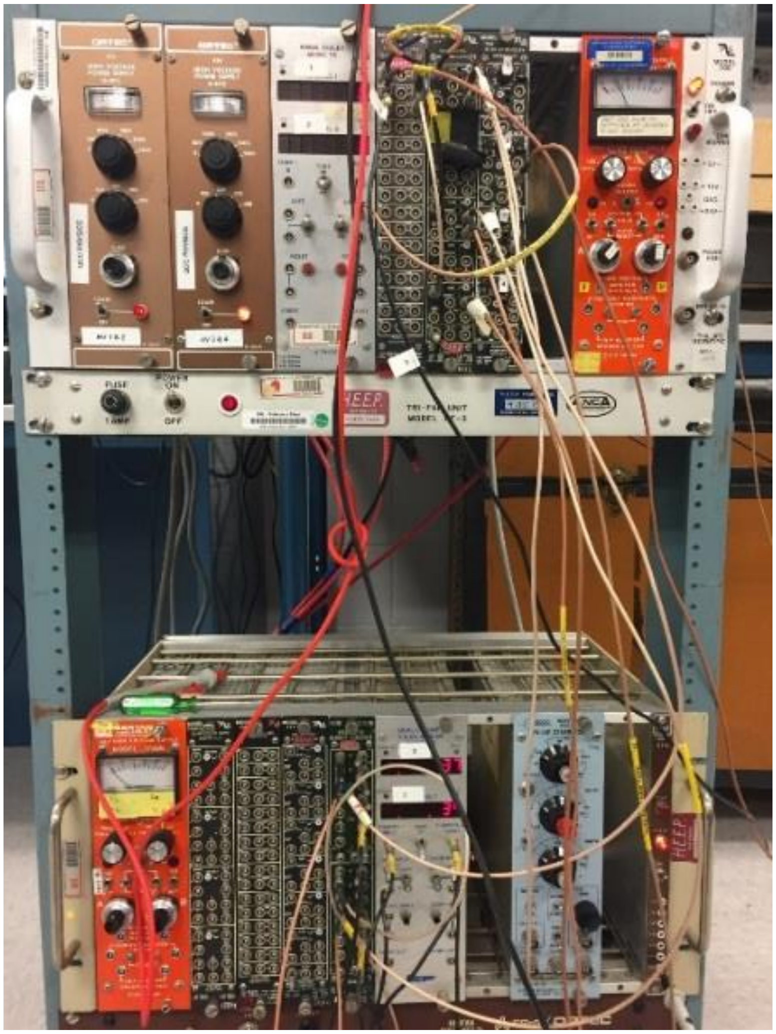


Figure. 1. NIM bin electronic modules used for the experiment.

Fig. 2. Sandwich test setup

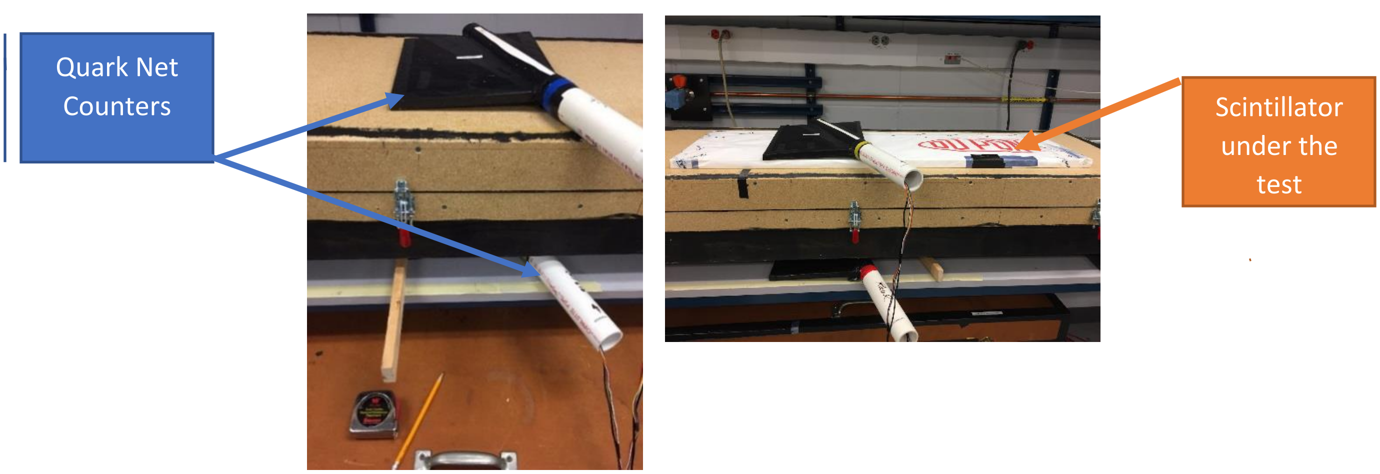


Figure. 3. Sandwich test schematic

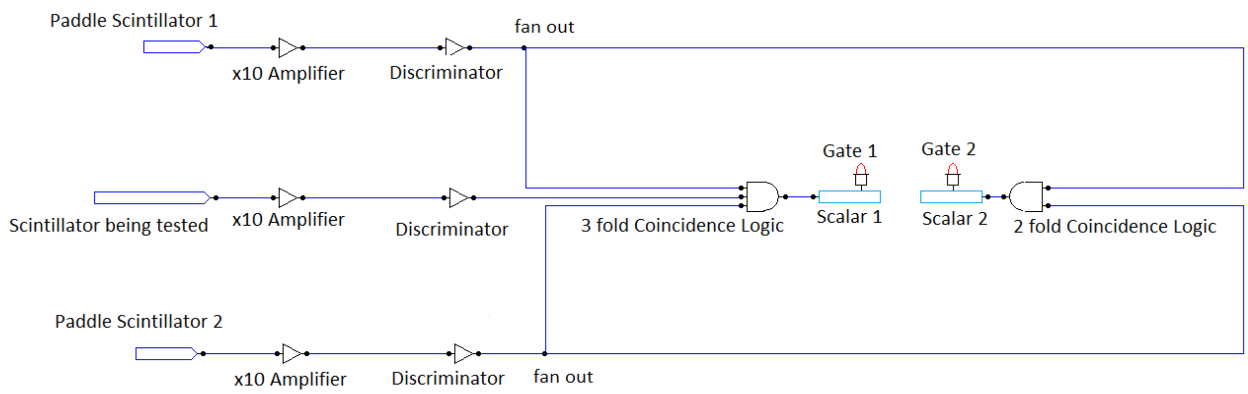
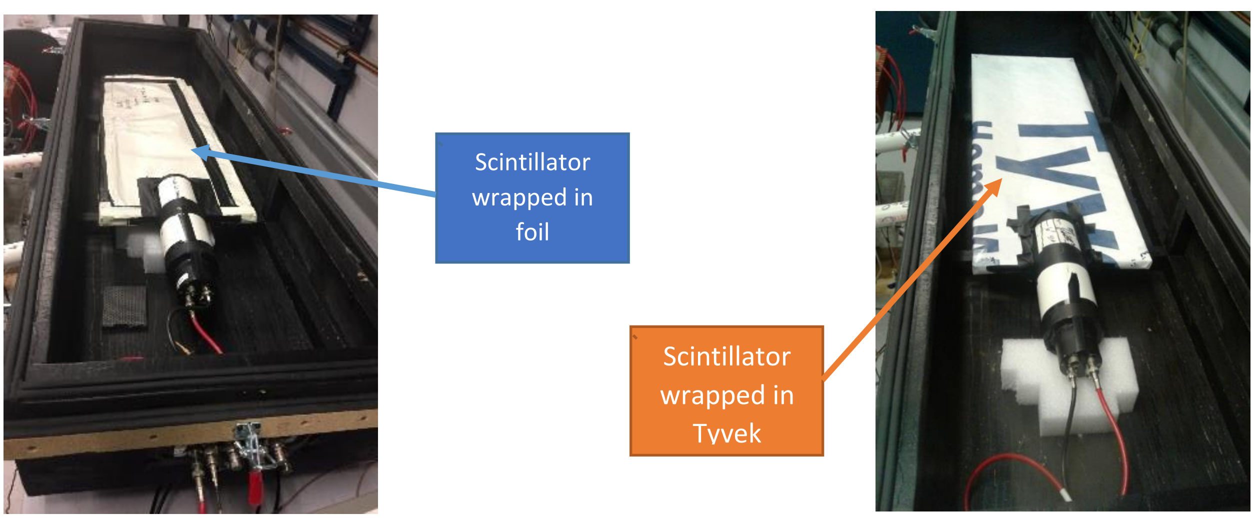


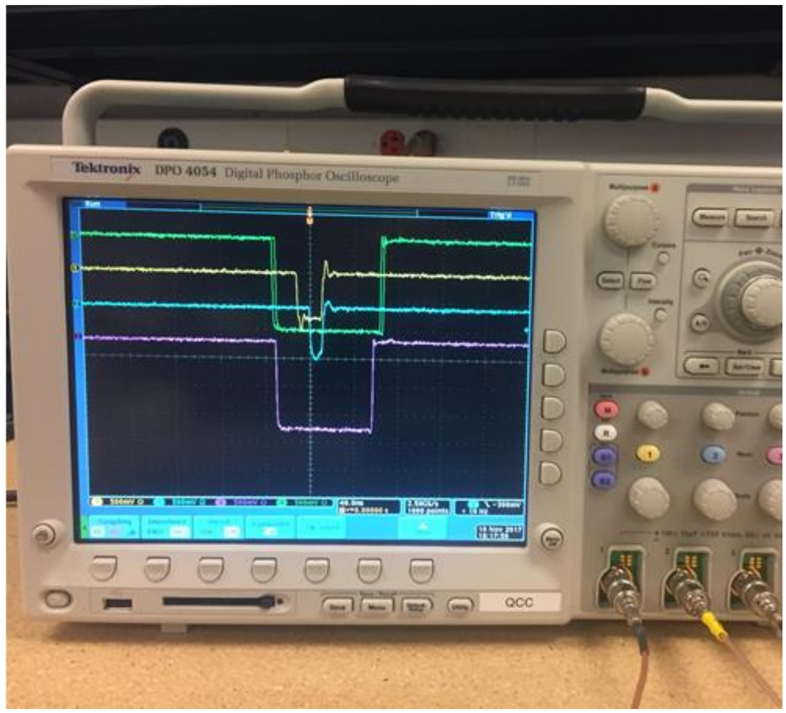
Figure. 4. Two wrapping techniques for scintillator counter 2 – 20170710



The outputs of our signals from the various NIM module used in the tests are shown in Figure 5.

Figure. 5. NIM electronics signals used

- Green and Purple graphs represent discriminator unit signals for two small muon detectors the width of the gate approximately 85(ns) and an amplitude is 1.5 (V)
- Yellow and blue graphs represent the width of 2 fold and 3 fold coincidence signals after coincidence unit.



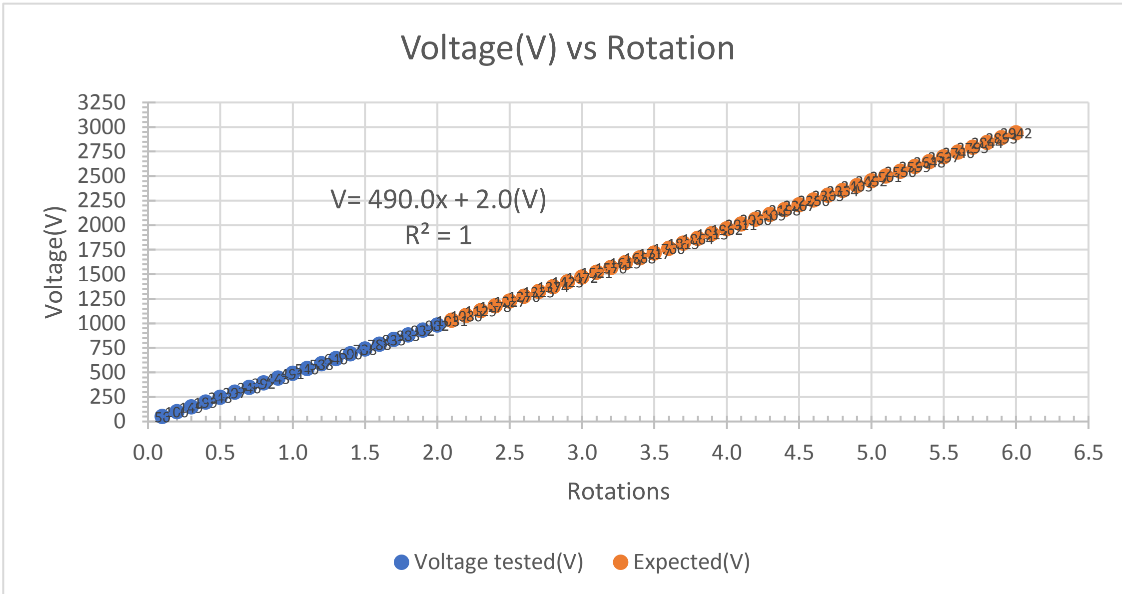
Equipment Adjustments:

For the measurements an attempt was made to equalize the gain at $g = 10^6$ on all three counters' pmts. This is discussed immediately below.

Power supply setting for PMT Hamamatsu AA1071 mated to NE114 scintillator under test

The pmt used for many tests (s/n AA1071) mated to the scintillator under test was measured to have a gain of 10^6 at 2150 V, and it was desired to use an HV set for $g = 10^6$. The output of the power supply was measured and the extrapolated results shown in Figure 6 illustrate that at 4.4 knob rotations it is expected to output 2150 V; thus for all the tests with this tube the power supply knob was set to 4.4 rotations for AA1071.

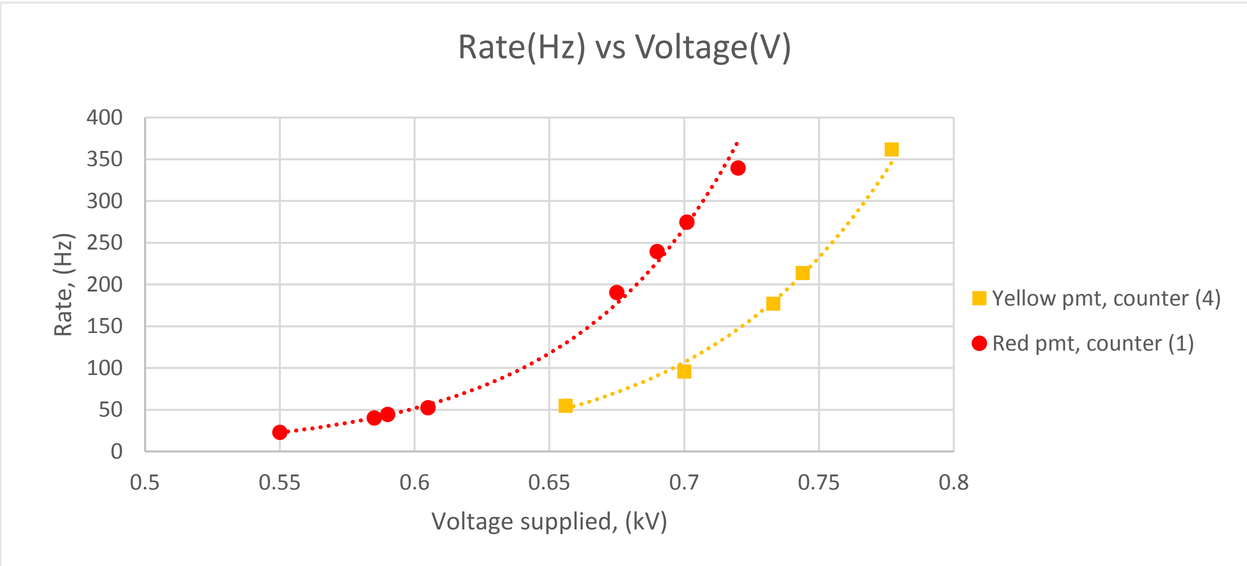
Figure. 6. Power Supply characteristics (BNL 106900)



Power supply settings for two telescoping paddle counters (AKA "QuarkNet counters")

The two pmts contain an internal LV DC to HV DC converter. The dark rate for each tube was measured as a function of LV shown in Figure 6; the output of each pmt was amplified x10 and then sent into a discriminator set at -30 mV; thus 3 mV is the equivalent lower-threshold for the dark rate plots shown.

Figure. 6. Quark Net counters characteristics. Data table 1



The gain functions for these two pmts mated to the paddle counters were not measured beforehand; in an attempt to set their gain to about 10^6 their LV was adjusted such that their lowest amplitude dark pulses measured ~ 1 mV through a 50 **Ω** load on an oscilloscope. 1 mV was chosen for the following reason: the pmt pulses are near triangular with area *A*, thus when a single photoelectron is emitted from the cathode, if gain is set at 10^6, then for a pmt pulse of width $\Delta T \sim 20$ ns, the expected peak voltage is estimated to be about 0.8 mV. We adjusted the supplied power by looking at the signals on the oscilloscope shown in Fig. 7:

$$\text{PMT pulse area } A = \frac{1}{2}\Delta T \cdot V_{\text{peak}} = \Sigma\, V_i \Delta t = \Sigma\, (I_i R)\Delta t = \Sigma \left(\frac{Q_i}{\Delta t_i} R\right)\Delta t = R Q_{\text{pulse}}$$

$$V_{\text{peak}} = \frac{2R}{\Delta T} Q_{\text{pulse}} = \frac{2R}{\Delta T} ge = \frac{2(50\Omega)}{20x10^{-9}\text{s}}\,(1.6x10^{-19}\text{C})g = 0.8\,mV$$

Fig. 7. Oscilloscope (Tektronix DPO 4054) showing typical 1 mV dark pulse noise from telescoping counter for HV set to 10E6 gain

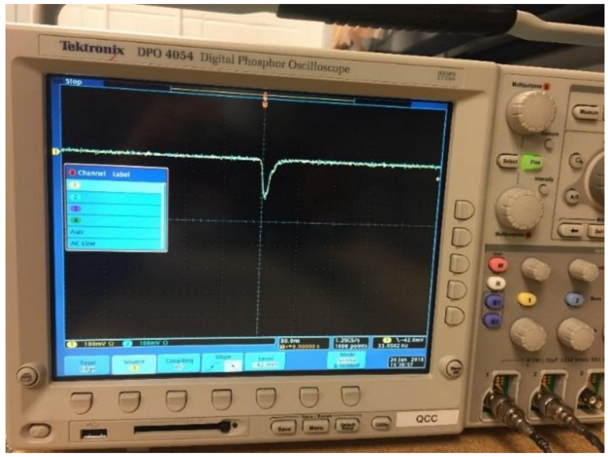
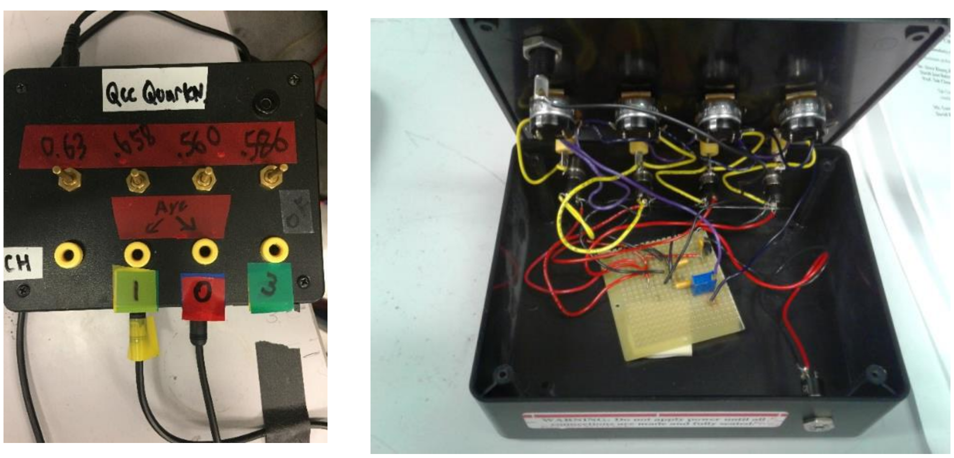


Figure 8 shows a low voltage divider circuit which was used to adjust the voltage as needed to the two paddle counters.

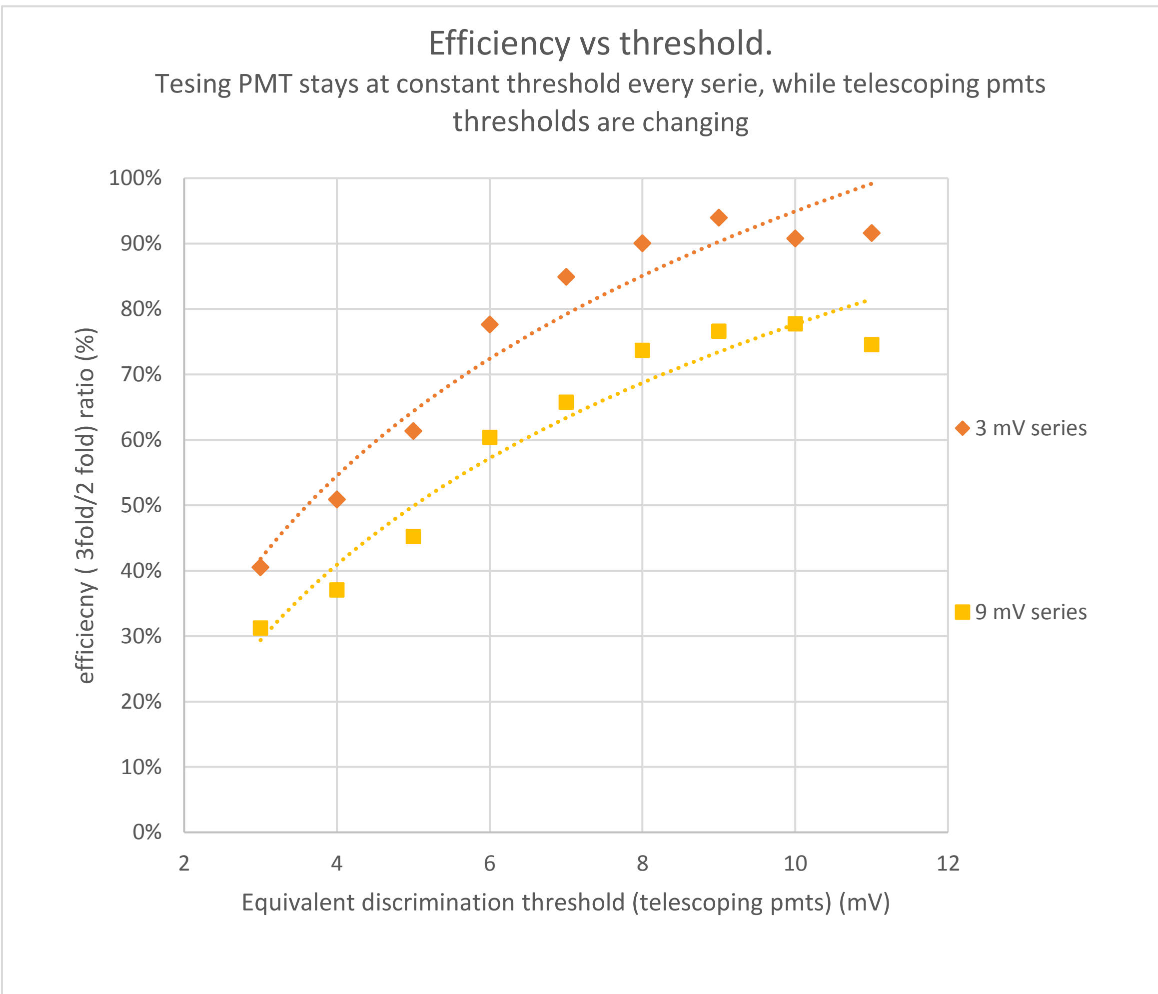
Fig. 8. Power Distribution Unit (PDU).



Results

The cosmic ray muon detection efficiency of our scintillator under test is defined here as (3-fold coincidence rate) / (2-fold coincidence rate). Thus, efficiency here is relative to the two paddle counters. Efficiency was measured over different variables. Figures 10 and 11 show efficiency as a function of discriminator thresholds for all three counters in the muon telescope. When the paddle counters are set at a discriminator setting of about 10 mV the efficiency plateaus.

Figure. 10. Efficiency as a function of discriminator threshold settings for the three counters in the telescope. The 3 mV and 9 mV "series" refers to the discriminator settings for the NE-114 scintillator under test. The x-axis is the discriminator threshold for the two paddle counters. (Foil and black paper wrapping, Scintillator plate used was NE-114, 20170710, Data table 3).



Comparing wrapping techniques

The goal is to determine the most efficient way of wrapping scintillator plates. Some photons are traveling along the scintillator plate, with an angle, which makes it possible for them to escape the plate and never be detected by the photomultiplier tube. Our objective is to reflect these photons back. We will compare two wrapping techniques for the same scintillator plate. First when wrapped in foil and paper, second when wrapped in two Tyvek layers. There are different types of reflecting materials and we ought to determine the efficiency of every one of them

We conducted experiments with two different sets of discrimination thresholds.
First test with (10, 10, 3) mV for telescoping counters and testing counter accordingly.
Second test with (10, 10, 10) mV for telescoping counters and testing counter accordingly.

The same scintillator, but different wrapping did not change the efficiency.

Figure. 11. Efficiency along the distance of Scintillator plate NE-114, 20170710 wrapped with foil and black paper. Data Table 4

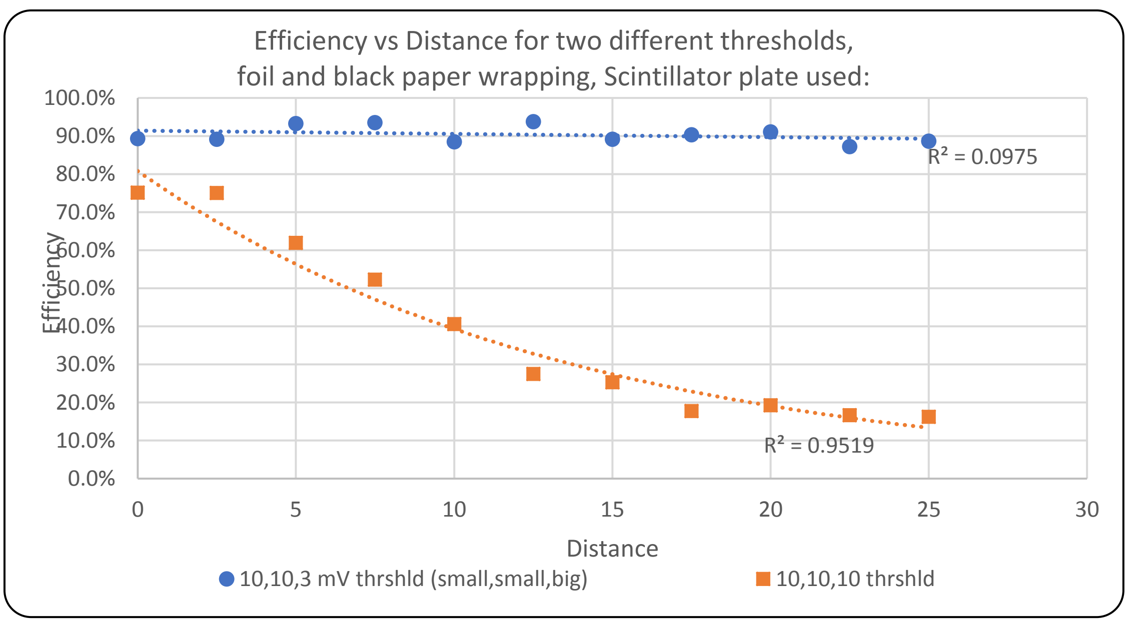


Figure. 12. Efficiency along the distance of Scintillator plate NE-114, 20170710 wrapped with two layers of Tyvek. Data Table 6

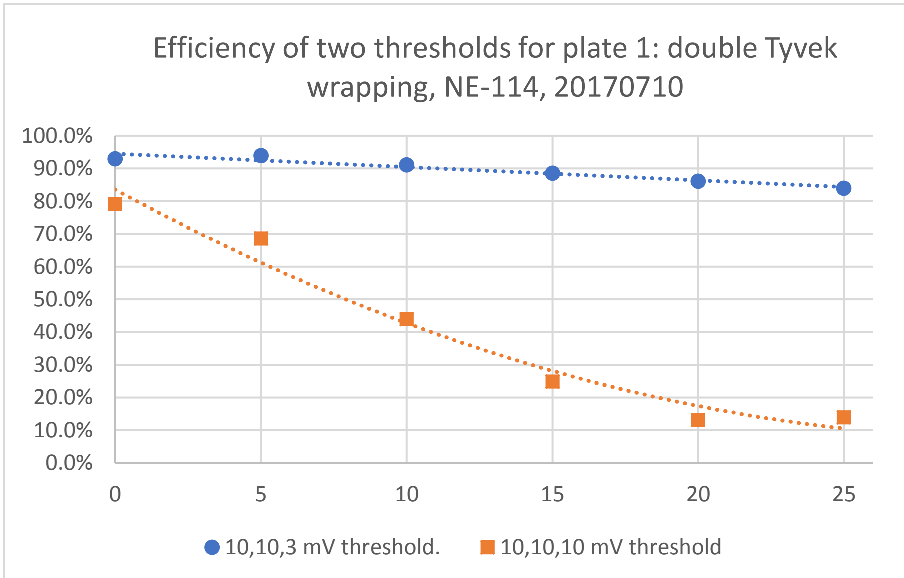
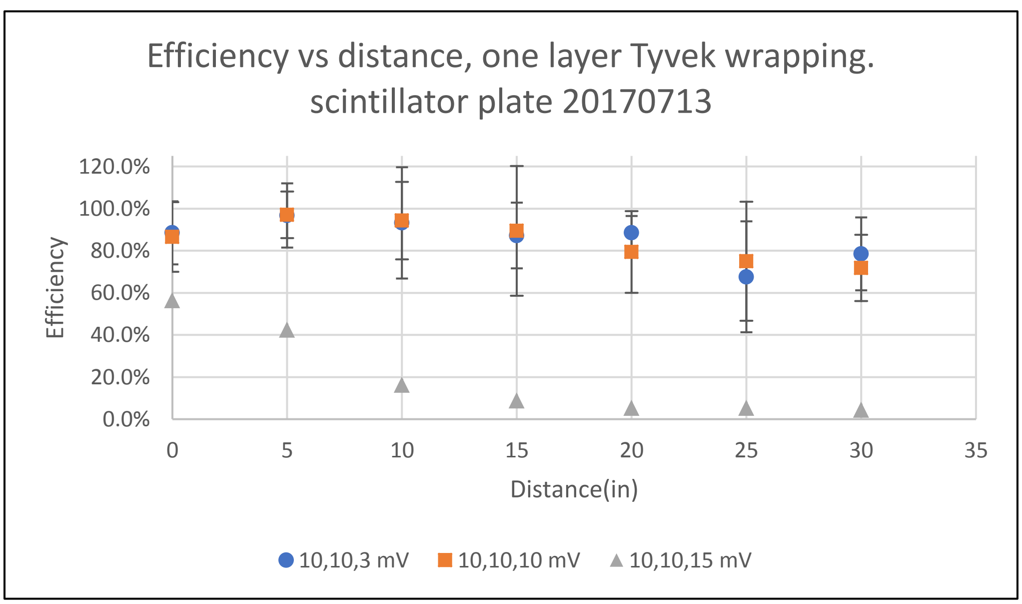
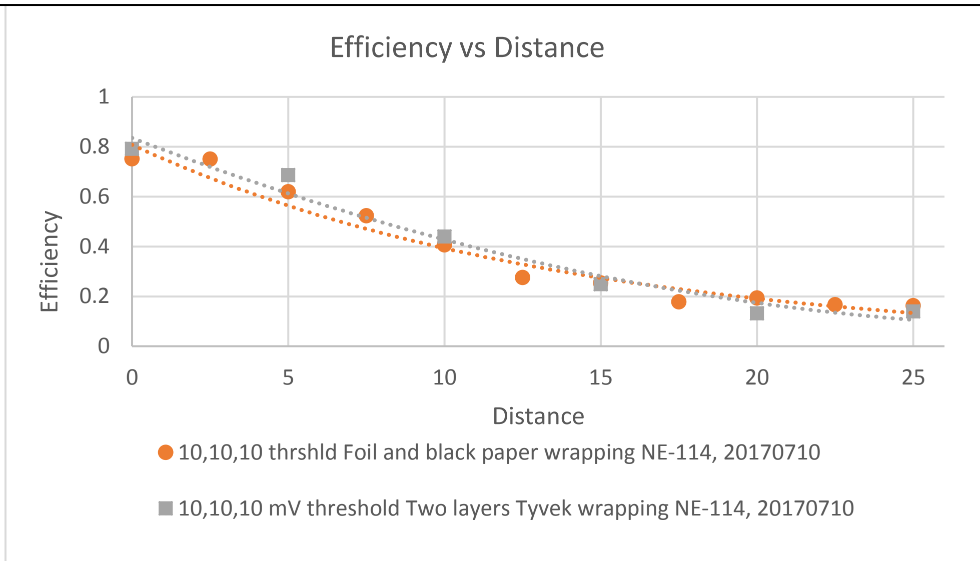


Figure. 13. Efficiency along the distance of Scintillator plate NE-114, 20170713 wrapped one layer Tyvek wrapping. Data Table 5



Figures 14 a and b: Comparing results for two wrapping techniques applied to one scintillator plate, NE-114, 20170710.



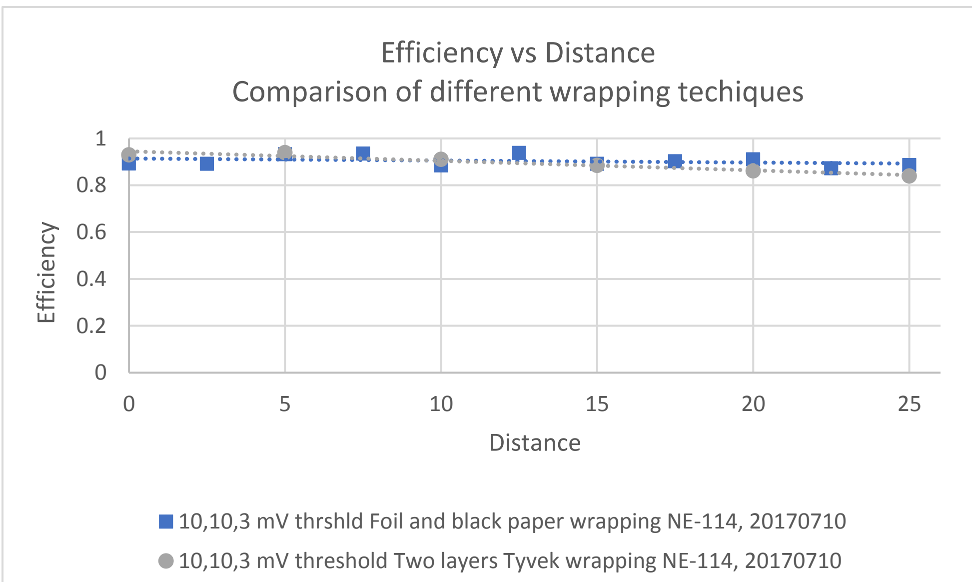
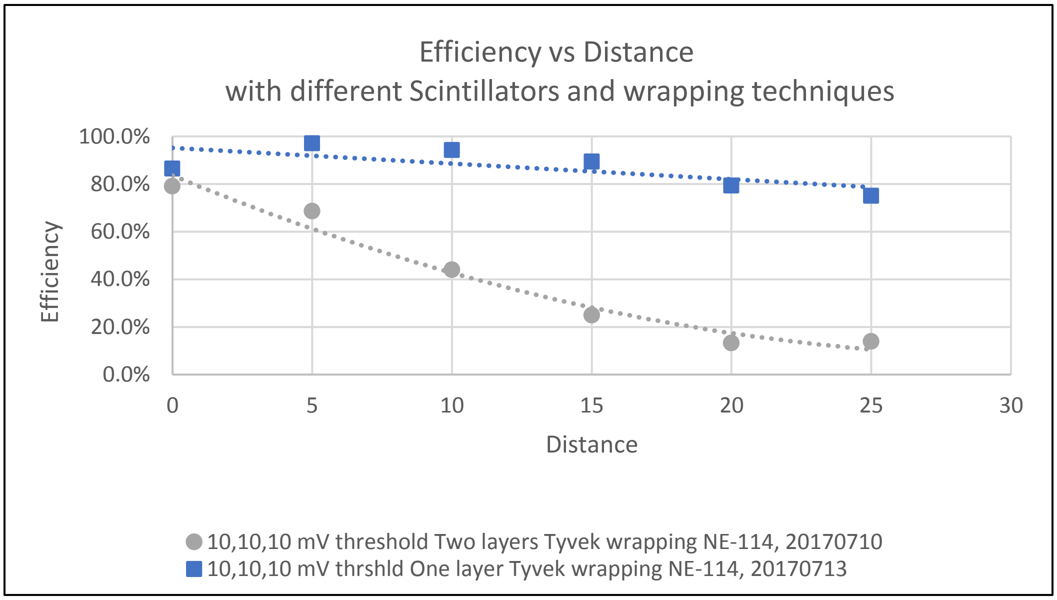


Figure. 15. Comparing results for two wrapping techniques applied to one scintillator plate, NE-114, 20170710 and 20170713.

This graph is for deeper research purpose, there are two variables different in the setup: scintillator and wrapping but Comparing two scintillators with a similar wrapping technique we have notice that the second scintillator is more efficient.



Measuring efficiency for different pmt mating techniques

In this experiment, we tested four mating techniques with scintillator plate s/n 20170713:

1) Silicone cookie (1/16") placed in between photomultiplier tube and scintillator
2) Acrylic cookie and optical grease applied on both sides of the cookie
3) Acrylic cookie and optical grease applied between cookie and photomultiplier tube and optical cement applied between cookie and scintillator
4) Acrylic cookie and optical cement applied on both sides of the cookie

Figure. 16. Mating Techniques Graph. Scintillator plate NE-114, 20170713, wrapped with one layer Tyvek. 10, 10, 10 mV thresholds.

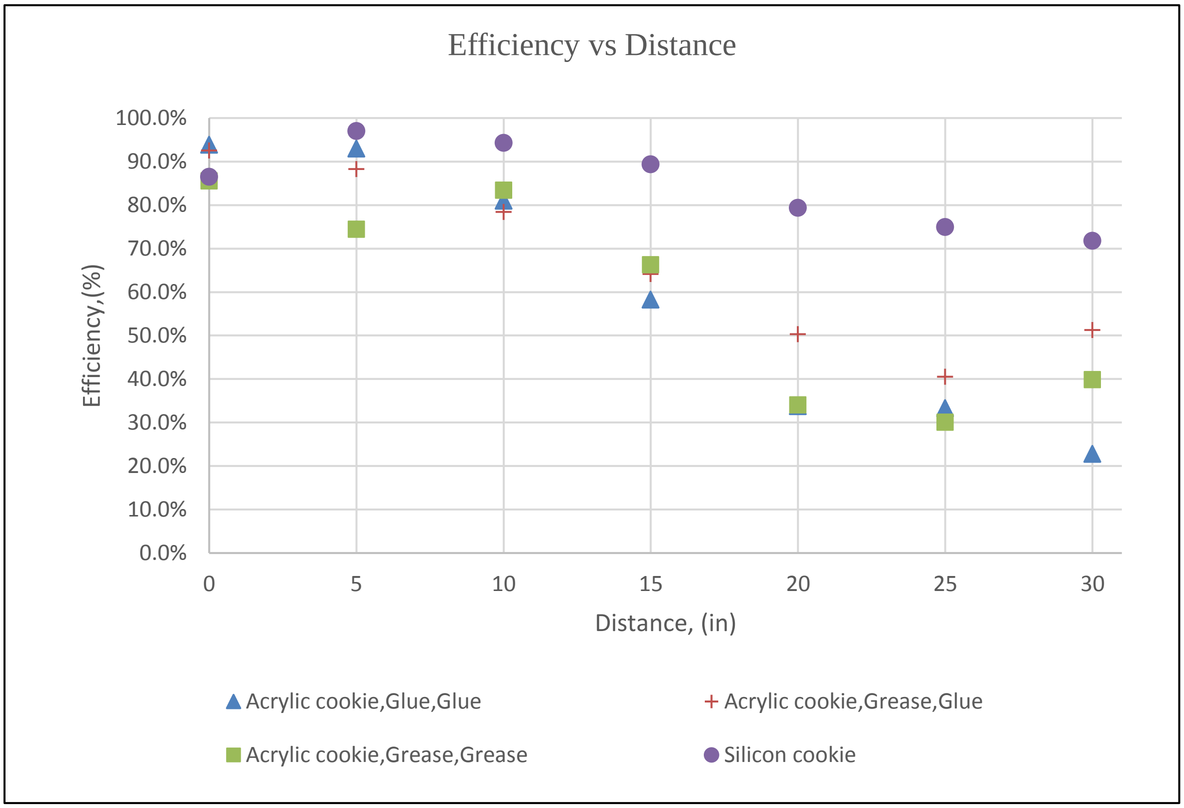
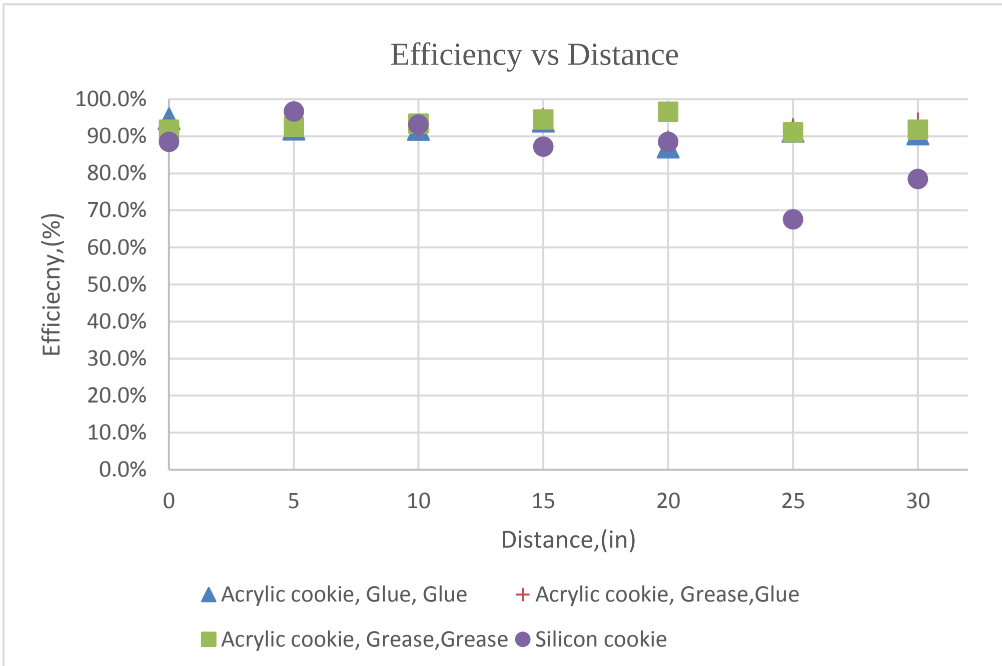


Figure. 17. Mating Techniques Graph. Scintillator plate NE-114, 20170713, wrapped with one layer Tyvek. 10, 10, 3 mV thresholds.



Additional tests:

1) It was determined after some of our measurements that a strip of Tyvek reflecting material was missing in a ~ 1 inch border around where the pmt mates to the scintillator; the gap was later closed with Tyvek and tests repeated resulting in a 10% higher efficiency.
2) Measurements were made with and without white Teflon reflective plumbing tape wrapped around the perimeter of the acrylic cookie, no difference in efficiency was measured.

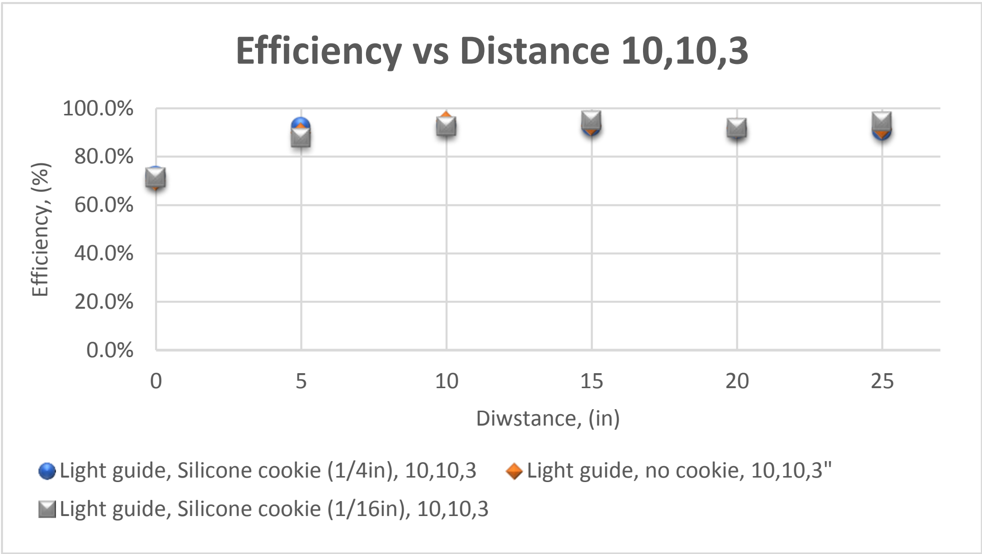
Tests of different mating of the pmt to the scintillator

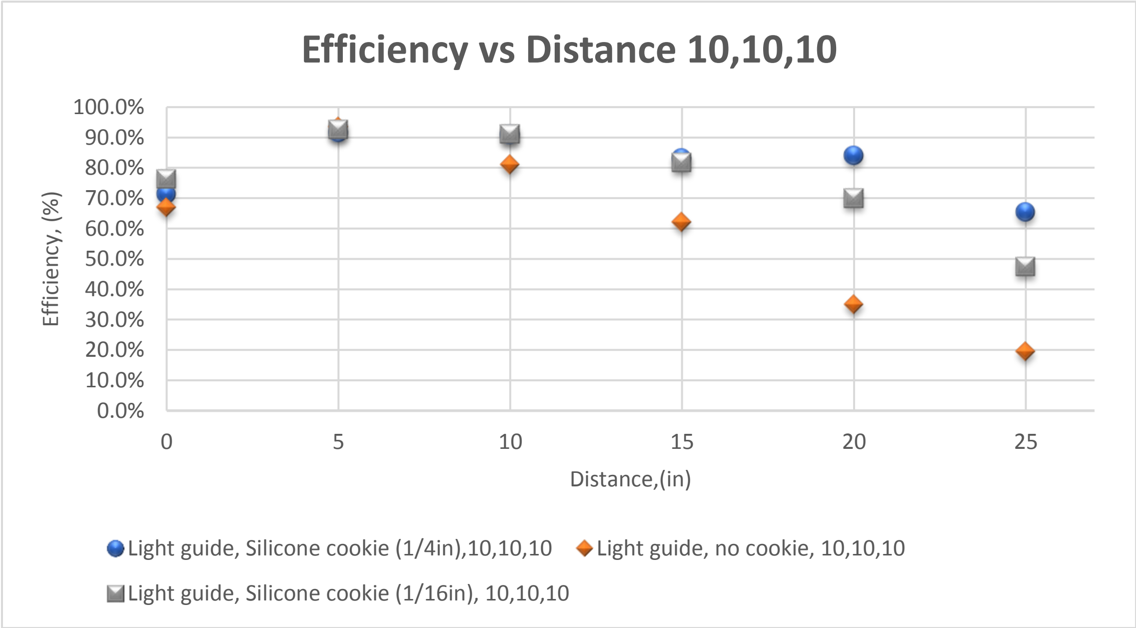
In the following part of the experiment, we tested five mating techniques with scintillator plate s/n 20170710:

1) Light guide, Silicone cookie (1/4in)
2) Light guide, Silicone cookie (1/16in)
3) Light guide, no cookie
4) Silicone cookie (1/4in)

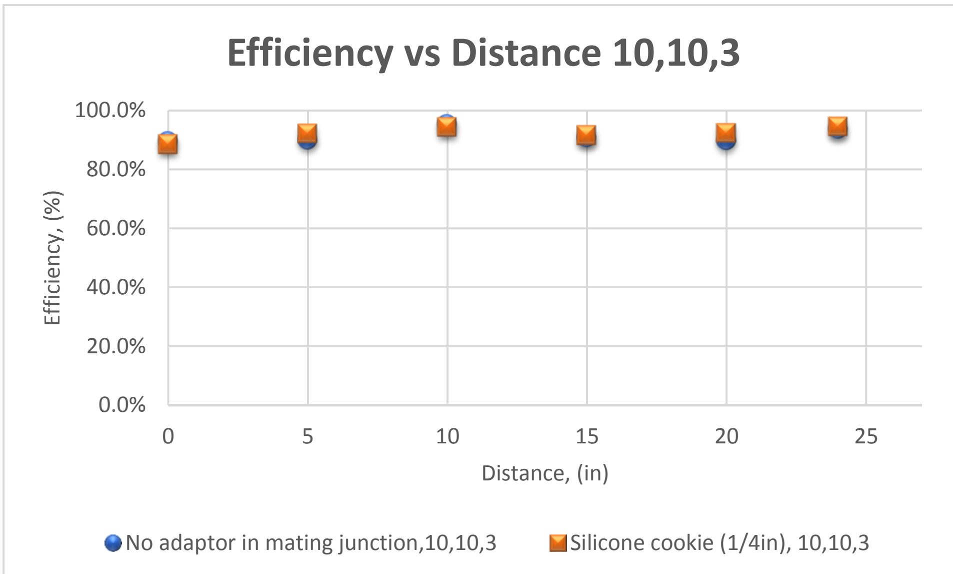
5) No adaptor in mating junction

Figures 18 a and b: Mating Techniques Graph. Scintillator plate NE-114, 20170710, wrapped with two layer Tyvek. 10, 10, 3 mV thresholds. Data table 7





Figures 19 a and b: Mating Techniques Graph. Scintillator plate NE-114, 20170710, wrapped with two layer Tyvek. 10, 10, 10 mV thresholds. Data table 7



Appendix

Calculating false coincidence rate probability:

The probability of 2-fold and 3-fold coincidences occurring from the dark noise rate was estimated using the formulas below, and not expected to be significant. The two paddle counters' pmts noise single rates were measured at about 300 Hz each while at operating voltage with a 3 mV discriminator threshold; the NE-114 counter pmt noise rate was measured at 4500 Hz at operating voltage and a 3 mV discriminator threshold.

Gate Width

Voltage

Random "noise" pulses

The rate of noise depends on the voltage applied to the photomultiplier tubes – Higher voltage produces more random pulses.

– Rate on channel 1 is R_1

– Rate on channel 2 is R_2

– Accidental rate when channel 1 fires first: R_1R_2*w

– Accidental rate when channel 2 fires first: R_2 R_1*w

– Total accidental rate: 2 R_1R_2*w= 2*300*300*85*(10^-9)= 0.0153

– Three-fold accidental rate: $R_1R_2R_3$*w^2 =4500*300*300*85*85*(10^-9)^2= 3*(10^-6).

– Gate width was set to 85 ns for all three discriminators.

– Accounts for different lengths of cables, different "transit times" in photomultiplier tubes.

Data tables:

Data table 1

Red counter						
voltage (V)	counts					rate
0.605	471	436	438	420	419	53
0.55	203	173	186	192	195	23
0.585	330	352	335	331	324	40
0.59	371	340	393	354	381	44
0.701	2219	2170	2353	2301	2370	275
0.675	1561	1621	1559	1613	1556	191
0.69	1939	2018	1982	2087	1916	240
0.72	2726	2813	2860	2843	2848	340

Yellow counter	
voltage (V)	rate (Hz)
0.656	55
0.7	96
0.733	177
0.744	214
0.777	362

Data Table 2

I want to measure effi. function of threshold of the big PMT
I will be changing a threshold for big PMT
Threshold for small pmts is fixed at 8 (mV) equivailance voltage

blue=0.593V	Yellow=0.777V										rate (Hz)		
eqv thrshld (mV)	2 fold counts					3fold counts					2 fold	3 fold	effi.
2	36	25	30	36	30	33	22	26	32	27	3.783133	3.37349	89%
3	34	28	30	38	39	31	21	23	31	44	4.072289	3.61446	89%
4	27	25	39	37	31	24	20	35	30	27	3.831325	3.27711	86%
5	30	37	31	33	24	25	29	19	27	19	3.734940	2.86747	77%
6	32	37	39	36	37	18	24	24	21	23	4.361446	2.65060	61%
7	22	37	33	34	26	13	23	13	20	8	3.662651	1.85542	51%
8	33	29	37	44	22	14	13	11	21	7	3.975904	1.59036	40%

Data Table 3

I want to measure effi. As a function of threshold of the small scintillators													
set large scintilator equivalence threshold 3 mV													
Threshold for small scintillators is changing													
red=0.720V		Yellow=0.777V									rate (Hz)		
equivalen	2 fold counts					3fold counts					2 fold	3 fold	effi.
3	70	76	79	105	82	30	25	35	41	36	10	4	41%
4	86	56	69	70	65	43	29	32	36	36	8	4	51%
5	58	47	59	53	47	38	33	33	33	25	6	4	61%
6	34	50	48	38	40	25	43	32	31	32	5	4	78%
7	41	35	29	42	52	34	27	26	35	47	5	4	85%
8	38	33	39	32	29	35	28	34	31	26	4	4	90%
9	37	41	39	28	37	34	40	36	27	34	4	4	94%
10	22	36	35	34	36	19	33	33	30	33	4	4	91%
11	33	36	38	18	30	32	31	35	17	27	4	3	92%

I want to measure effi. As a function of threshold of the small scintillators													
set large scintilator equivalence threshold 4 mV													
Threshold for small scintillators is changing													
red=0.720V		Yellow=0.777V									rate (Hz)		
equivalen	2 fold counts					3fold counts					2 fold	3 fold	effi.
3	63	64	85	79	70	25	30	38	27	28	9	4	41%
4	69	76	70	70	59	35	40	35	29	26	8	4	48%
5	38	49	41	58	46	26	33	27	37	31	6	4	66%
6	52	28	42	48	39	41	23	27	37	31	5	4	76%
7	29	33	40	41	30	28	27	30	33	24	4	3	82%
8	40	29	21	30	35	32	23	19	29	28	4	3	85%
9	31	32	30	36	36	29	31	28	29	32	4	4	90%
10	37	37	27	28	42	32	34	22	27	39	4	4	90%
11	30	38	38	32	31	28	35	36	29	29	4	4	93%

I want to measure effi. As a function of threshold of the small scintillators													
set large scintilator equivalence threshold 9 mV													
Threshold for small scintillators is changing													
red=0.720V		Yellow=0.777V									rate (Hz)		
equivalen	2 fold counts					3fold counts					2 fold	3 fold	effi.
3	93	71	60	65	105	30	27	20	15	31	9	3	31%
4	66	64	58	60	84	26	24	18	26	29	8	3	37%
5	61	59	49	52	60	29	28	20	27	23	7	3	45%
6	40	36	48	44	49	24	18	35	26	28	5	3	60%
7	36	35	42	35	36	27	20	30	19	25	4	3	66%
8	32	34	37	33	31	22	27	31	20	23	4	3	74%
9	45	40	38	26	39	32	34	32	18	28	5	3	77%
10	34	39	37	36	29	26	33	28	27	22	4	3	78%
11	38	35	30	27	31	28	29	21	20	22	4	3	75%

I want to measure effi. As a function of threshold of the small scintillators													
set large scintilator equivalence threshold 15 mV													
Threshold for small scintillators is changing													
red=0.720V		Yellow=0.777V									rate (Hz)		
equivalen	2 fold counts					3fold counts					2 fold	3 fold	effi.
3	81	79	116	78	94	13	17	25	13	18	11	2	19%
4	61	61	91	75	52	20	15	19	14	12	8	2	24%
5	28	58	61	59	70	8	13	17	20	18	7	2	28%
6	56	47	35	37	47	17	13	11	12	16	5	2	31%
7	38	56	32	43	37	15	20	11	5	18	5	2	33%
8	32	30	45	41	41	12	16	18	17	22	5	2	45%
9	33	22	33	41	31	16	11	17	15	9	4	2	43%
10	29	28	33	29	34	8	12	14	13	14	4	1	40%
11	39	28	28	37	29	15	16	10	11	6	4	1	36%

Data Table 4

I want to measure effi. As a function of distance along a big scintillator													
set large scintilator equivalence threshold 3 mV													
Threshold for small scintillator: = 10mV													
Red=0.720V		Yellow=0.777V				rate (Hz)							
Distance	2 fold counts					3fold counts					Average 2	Average 3	effi.
0	35	26	44	36	37	32	22	40	31	34	35.6	31.8	89.3%
2.5	33	36	39	42	34	29	29	37	38	31	36.8	32.8	89.1%
5	36	45	32	28	37	33	44	28	27	34	35.6	33.2	93.3%
7.5	35	38	37	29	46	33	37	33	26	44	37	34.6	93.5%
10	35	38	37	39	33	31	35	32	34	29	36.4	32.2	88.5%
12.5	41	24	39	42	31	39	21	38	39	29	35.4	33.2	93.8%
15	36	33	39	48	28	35	30	34	39	26	36.8	32.8	89.1%
17.5	28	36	44	30	37	24	31	39	28	36	35	31.6	90.3%
20	34	27	32	35	29	32	24	28	33	26	31.4	28.6	91.1%
22.5	32	30	23	45	34	28	24	20	40	31	32.8	28.6	87.2%
25	30	48	38	37	32	29	43	34	32	26	37	32.8	88.6%

I want to measure effi. As a function of distance along a big scintillator													
set large scintilator equivalence threshold 10 mV													
Threshold for small scintillator: = 10mV													
Red=0.720V		Yellow=0.777V				rate (Hz)							
Distance	2 fold counts					3fold counts					Average 2	Average 3	effi.
0	27	37	24	42	31	21	26	17	32	25	32.2	24.2	75.2%
2.5	40	39	25	19	41	29	27	19	15	33	32.8	24.6	75.0%
5	33	37	22	42	29	11	26	15	28	21	32.6	20.2	62.0%
7.5	38	38	35	36	29	23	24	15	18	12	35.2	18.4	52.3%
10	34	41	31	33	36	13	19	16	10	13	35	14.2	40.6%
12.5	38	40	29	27	37	11	10	10	8	8	34.2	9.4	27.5%
15	42	29	31	43	37	14	5	8	8	11	36.4	9.2	25.3%
17.5	29	36	27	39	38	7	7	4	7	5	33.8	6	17.8%
20	33	41	28	27	37	8	9	4	3	8	33.2	6.4	19.3%
22.5	30	29	34	23	34	5	5	5	3	7	30	5	16.7%
25	32	45	40	36	32	4	8	6	9	3	37	6	16.2%

Data Table 5

I want to measure effi. As a function of distance along a big scintillator																
set large scintilator equivalence threshold 3 mV																
Threshold for small scintillators			= 10mV													
Red=0.720V		Yellow=0.777V				rate (Hz)							Standard Deviation	Standard Deviation		
Distance	2 fold counts					3fold counts					Average 2	Average 3	2 fold	3 fold	Error propagation	effi.
0	41	35	34	43	38	38	28	30	38	35	38.2	33.8	3.834058	4.604346	15.0%	88.5%
5	29	37	29	29	29	27	35	28	29	29	30.6	29.6	3.577709	3.130495	15.3%	96.7%
10	41	36	24	27	34	36	34	22	27	32	32.4	30.2	6.8775	5.674504	26.4%	93.2%
15	38	39	39	32	32	36	33	35	27	26	36	31.4	3.674235	4.615192	15.6%	87.2%
20	33	35	33	37	36	28	30	30	34	32	34.8	30.8	1.788854	2.280351	8.0%	88.5%
25	43	21	34	33	45	27	14	22	24	32	35.2	23.8	9.549869	6.648308	26.3%	67.6%
30	42	33	41	32	38	29	28	34	21	34	37.2	29.2	4.549725	5.357238	17.3%	78.5%

I want to measure effi. As a function of distance along a big scintillator																
set large scintilator equivalence threshold 10 mV																
Threshold for small scintillators			= 10mV													
Red=0.720V		Yellow=0.777V				rate (Hz)							Standard Deviation	Standard Deviation		
Distance	2 fold counts					3fold counts					Average 2	Average 3	2 fold	3 fold	Error propagation	effi.
0	35	32	37	32	42	31	30	30	25	38	35.6	30.8	4.159327	4.658326	16.5%	86.5%
5	31	35	31	35	37	30	34	30	34	36	33.8	32.8	2.683282	2.683282	11.1%	97.0%
10	32	33	31	41	38	29	32	28	40	36	35	33	4.301163	5	18.4%	94.3%
15	36	47	26	30	31	35	41	22	26	28	34	30.4	8.093207	7.569676	30.8%	89.4%
20	27	40	26	35	37	25	31	20	27	28	33	26.2	6.204837	4.086563	19.4%	79.4%
25	38	31	45	28	26	27	24	37	18	20	33.6	25.2	7.829432	7.463243	28.3%	75.0%
30	29	38	36	42	36	19	29	25	31	26	36.2	26	4.711688	4.582576	15.7%	71.8%

I want to measure effi. As a function of distance along a big scintillator																
set large scintilator equivalence threshold 15 mV																
Threshold for small scintillators			= 10mV													
Red=0.720V		Yellow=0.777V				rate (Hz)							Standard Deviation	Standard Deviation		
Distance	2 fold counts					3fold counts					Average 2	Average 3	2 fold	3 fold	Error propagation	effi.
0	44	35	27	30	41	28	21	14	15	22	35.4	20	7.162402	5.700877	19.7%	56.5%
5	27	38	37	30	21	10	21	22	7	5	30.6	13	7.092249	7.968689	27.8%	42.5%
10	34	30	31	29	30	3	5	4	4	9	30.8	5	1.923538	2.345208	7.7%	16.2%
15	44	34	41	30	43	3	3	6	1	4	38.4	3.4	6.107373	1.81659	4.9%	8.9%
20	23	33	40	34	38	1	2	2	2	2	33.6	1.8	6.580274	0.447214	1.7%	5.4%
25	34	36	30	30	40	1	1	1	1	5	34	1.8	4.242641	1.788854	5.3%	5.3%
30	37	35	42	31	33	3	2	1	1	1	35.6	1.6	4.219005	0.894427	2.6%	4.5%

Data Table 6

I want to measure effi. As a function of distance along a big scintillator																
set large scintilator equivalence threshold 3 mV																
Threshold for small scintillator:			= 10mV													
Red=0.720V		Yellow=0.777V				rate (Hz)							Standard Deviation	Standard Deviation		
Distance	2 fold counts					3fold counts					Average 2	Average 3	2 fold	3 fold	Error propagation	effi.
0	34	38	43	42	28	33	33	39	41	26	37	34.4	6.164414	5.899152	22.2%	93.0%
5	37	23	36	24	27	36	21	34	22	25	29.4	27.6	6.655825	6.94982	31.8%	93.9%
10	40	26	23	27	41	36	25	23	22	37	31.4	28.6	8.443933	7.300685	33.8%	91.1%
15	29	35	25	34	34	27	33	21	29	29	31.4	27.8	4.27785	4.38178	18.4%	88.5%
20	39	39	29	39	27	37	33	23	34	22	34.6	29.8	6.0663	6.83374	24.9%	86.1%
25	37	43	37	44	38	31	34	32	39	31	39.8	33.4	3.420526	3.361547	11.1%	83.9%

I want to measure effi. As a function of distance along a big scintillator																
set large scintilator equivalence threshold 3 mV																
Threshold for small scintillator:			= 10mV													
Red=0.720V		Yellow=0.777V				rate (Hz)							Standard Deviation	Standard Deviation		
Distance	2 fold counts					3fold counts					Average 2	Average 3	2 fold	3 fold	Error propagation	effi.
0	25	51	31	28	28	22	38	24	22	23	32.6	25.8	10.50238	6.870226	33.1%	79.1%
5	23	34	32	31	39	16	23	21	22	27	31.8	21.8	5.80517	3.962323	17.7%	68.6%
10	43	35	42	38	33	22	13	15	16	18	38.2	16.8	4.32435	3.420526	10.2%	44.0%
15	40	41	34	43	35	10	14	8	8	8	38.6	9.6	3.911521	2.607681	7.2%	24.9%
20	40	38	26	34	29	5	4	1	5	7	33.4	4.4	5.899152	2.19089	7.0%	13.2%
25	37	28	31	26	43	6	5	2	4	6	33	4.6	6.964194	1.67332	5.9%	13.9%

Data Table 7

Light guide, Silicone cookie 1/4"

I want to measure effi. As a function of distance along a big scintillator
set large scintilator equivalence threshold 3 mV
Threshold for small scintillator: = 10mV
Red=0.720V Yellow=0.777V rate (Hz)

Distance	2 fold counts					3fold counts					Average 2	Average 3	Standard Deviation 2 fold	Standard Deviation 3 fold	Error propagation	effi.
0	27	29	23	25	22	21	21	16	19	14	25.2	18.2	2.863564	3.114482	14.8%	72.2%
5	33	25	51	41	37	30	25	44	38	36	37.4	34.6	9.633276	7.334848	30.9%	92.5%
10	27	31	30	32	36	27	31	27	30	30	31.2	29	3.271085	1.870829	11.4%	92.9%
15	43	26	37	30	28	42	25	32	29	24	32.8	30.4	7.049823	7.231874	29.7%	92.7%
20	35	42	41	30	42	32	39	37	27	39	38	34.8	5.338539	5.215362	18.8%	91.6%
25	35	40	32	28	41	33	36	28	25	38	35.2	32	5.449771	5.43139	20.9%	90.9%

I want to measure effi. As a function of distance along a big scintillator
set large scintilator equivalence threshold 10 mV
Threshold for small scintillator: = 10mV
Red=0.720V Yellow=0.777V rate (Hz)

Distance	2 fold counts					3fold counts					Average 2	Average 3	Standard Deviation 2 fold	Standard Deviation 3 fold	Error propagation	effi.
0	35	39	38	37	40	23	27	28	28	29	37.8	27	1.923538	2.345208	7.2%	71.4%
5	34	33	44	39	41	32	30	41	33	39	38.2	35	4.658326	4.743416	16.7%	91.6%
10	38	29	33	39	29	38	26	28	35	26	33.6	30.6	4.774935	5.549775	21.0%	91.1%
15	30	35	30	42	30	25	32	25	34	23	33.4	27.8	5.272571	4.868265	19.6%	83.2%
20	27	37	35	33	32	23	32	28	25	30	32.8	27.6	3.768289	3.646917	14.7%	84.1%
25	26	23	50	36	33	16	15	31	24	24	33.6	22	10.54988	6.595453	28.4%	65.5%

Light guide, No cookie

I want to measure effi. As a function of distance along a big scintillator
set large scintilator equivalence threshold 3 mV
Threshold for small scintillator: = 10mV
Red=0.720V Yellow=0.777V rate (Hz)

Distance	2 fold counts					3fold counts					Average 2	Average 3	Standard Deviation 2 fold	Standard Deviation 3 fold	Error propagation	effi.
0	34	41	38	21	23	25	30	24	15	16	31.4	22	8.961027	6.363961	28.5%	70.1%
5	32	38	36	38	35	31	34	32	34	30	35.8	32.2	2.48998	1.788854	8.0%	89.9%
10	39	40	26	29	41	37	37	24	28	40	35	33.2	6.964194	6.83374	27.2%	94.9%
15	35	49	40	43	41	33	47	38	37	38	41.6	38.6	5.07937	5.128353	16.7%	92.8%
20	33	33	27	26	41	31	30	24	23	39	32	29.4	6	6.426508	26.5%	91.9%
25	39	32	31	42	32	37	27	29	39	29	35.2	32.2	4.969909	5.403702	20.1%	91.5%

I want to measure effi. As a function of distance along a big scintillator
set large scintilator equivalence threshold 10 mV
Threshold for small scintillator: = 10mV
Red=0.720V Yellow=0.777V rate (Hz)

Distance	2 fold counts					3fold counts					Average 2	Average 3	Standard Deviation 2 fold	Standard Deviation 3 fold	Error propagation	effi.
0	24	34	47	37	34	15	25	32	25	21	35.2	23.6	8.228001	6.228965	23.6%	67.0%
5	28	24	32	36	36	26	23	32	32	33	31.2	29.2	5.215362	4.438468	21.1%	93.6%
10	33	41	31	28	47	29	34	26	19	38	36	29.2	7.81025	7.328028	26.9%	81.1%
15	38	23	27	32	44	18	15	17	22	30	32.8	20.4	8.408329	5.94138	24.1%	62.2%
20	27	36	28	20	37	8	15	7	7	15	29.6	10.4	7.021396	4.219005	16.5%	35.1%
25	36	26	35	30	36	10	5	3	6	8	32.6	6.4	4.449719	2.701851	8.7%	19.6%

Light guide, (1/16in) silicone cookie.

I want to measure effi. As a function of distance along a big scintillator
set large scintilator equivalence threshold 3 mV
Threshold for small scintillator: = 10mV
Red=0.720V Yellow=0.777V rate (Hz)

Distance	2 fold counts					3fold counts					Average 2	Average 3	Standard Deviation 2 fold	Standard Deviation 3 fold	Error propagation	effi.
0	39	39	38	38	35	27	30	21	28	29	37.8	27	1.643168	3.535534	9.9%	71.4%
5	36	29	40	28	24	31	27	35	26	19	31.4	27.6	6.465292	5.98331	26.3%	87.9%
10	23	35	34	24	34	21	33	30	22	33	30	27.8	5.958188	5.890671	26.9%	92.7%
15	34	30	30	35	33	32	29	29	31	33	32.4	30.8	2.302173	1.788854	8.7%	95.1%
20	29	24	28	37	34	27	22	25	34	32	30.4	28	5.128353	4.949747	22.5%	92.1%
25	30	33	27	32	27	28	30	27	30	26	29.8	28.2	2.774887	1.788854	10.7%	94.6%

I want to measure effi. As a function of distance along a big scintillator
set large scintilator equivalence threshold 10 mV
Threshold for small scintillator: = 10mV
Red=0.720V Yellow=0.777V rate (Hz)

Distance	2 fold counts					3fold counts					Average 2	Average 3	Standard Deviation 2 fold	Standard Deviation 3 fold	Error propagation	effi.
0	36	20	27	36	25	24	14	21	31	20	28.8	22	7.049823	6.204837	28.5%	76.4%
5	36	38	31	44	29	34	35	29	42	25	35.6	33	5.94138	6.442049	23.8%	92.7%
10	36	31	34	32	27	32	30	31	29	24	32	29.2	3.391165	3.114482	13.7%	91.3%
15	27	31	40	35	43	21	27	33	29	34	35.2	28.8	6.496153	5.215362	21.2%	81.8%
20	28	24	40	43	35	22	18	24	28	27	34	23.8	7.968689	4.024922	20.2%	70.0%
25	33	35	35	32	23	15	17	16	18	9	31.6	15	4.97996	3.535534	13.5%	47.5%

Conclusions:

- We have developed a working procedure with a muon telescope (aka Sandwich Prototype Testing) of measuring plastic scintillators' efficiency.
- We concluded that black paper and foil wrapping have the similar reflection percent as Tyvek.
- We compared results for different scintillator plates. We have to look into this further to determine why one scintillator plate is more efficient then another. It could be several reasons: crazing, sanding and polishing methods, or light absorption characteristics.
- The new silicone cookie is the most efficient method in mating a photomultiplier tube to a plastic scintillator. However the acrylic cookie optically glued from both sides provides the best mechanical stability.

Future plans:

- With a developed method we will measure attenuation length and light yield of scintillators. We are going to apply this method to select the best scintillators for the cosmic ray shower detector array.