Optimizing Scintillation and Light Transmission for use in a High Energy Particle Detector

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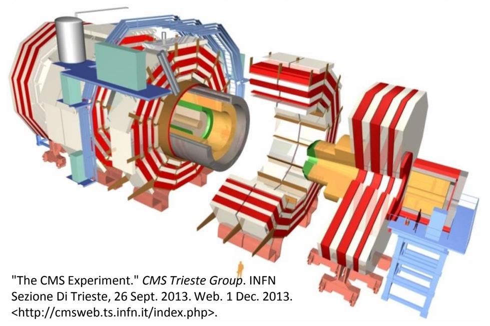
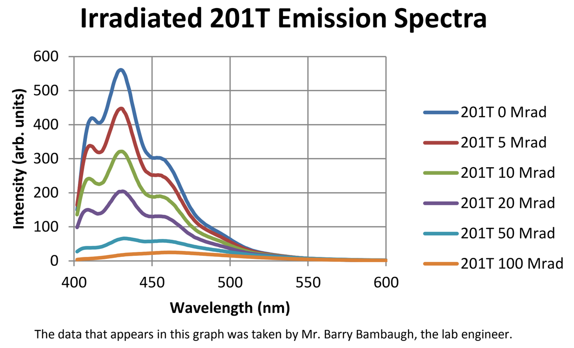
INTRODUCTION

Nearly 100 meters below Cressy, France, lies a huge solenoid magnet whose magnetic field is nearly 100,000 times that of the Earth (CMS). This magnet is the main component of CMS (the Compact Muon Solenoid), a calorimeter detector built on the LHC (Large Hadron Collider) at CERN in Switzerland and France (CMS Collaboration). Its goals are "to explore physics at the TeV scale . . . and to look for evidence of physics beyond the standard model, such as supersymmetry, or extra dimensions" (Compact Muon Solenoid (CMS)), and it attempts to achieve these goals by colliding proton beams and measuring the energy of subatomic decay products that pass through it. When subatomic particles pass through one of multiple layers of scintillating plastic tiles in the detector, photons released by the tile travel to waveshifting optical fibers and are transmitted to photo-sensors. There, intensity and other characteristics of the photons can be analyzed to discern information about the particles.



"The CMS Experiment." *CMS Trieste Group*. INFN Sezione Di Trieste, 26 Sept. 2013. Web. 1 Dec. 2013. <http://cmsweb.ts.infn.it/index.php>.

As high levels of precision are needed for analyzing high energy particle collisions, it is essential that the CMS collaboration incorporate new technological advances into its detector. CMS is currently shut down for maintenance and upgrades, and two areas for potential improvement include the light generation by the scintillating tiles and the light propagation through the optic fibers. CMS currently uses Eljen Technology scintillating plastic tiles to generate blue light, which then enters an embedded optical fiber and is waveshifted to green. However, when exposed to high levels of radiation inside the detector, the scintillating and wavelength shifting plastics turn dark and lose their ability to generate and waveshift light. The degradation of the scintillating and wavelength shifting plastics is a major problem because as light output decreases, the amount of information that can be discerned about the collisions decreases as well.



The data that appears in this graph was taken by Mr. Barry Bambaugh, the lab engineer.

One solution to the degradation problem is to use scintillator/wavelength shifter combinations that result in greater light output. Eljen Technologies includes general descriptions (ex. "good general properties, high attenuation length") and major dopants for each of its plastic products, but it does not list detailed characteristics such as the exact chemical makeup for every product. Thus, the only way to determine what combination yields the greatest light output is through experimentation, and it is possible that other combinations could produce more light than the previous 201 scintillator/204 wavelength shifter combination. The first goal of this project was to determine which combination of Eljen Technologies' 201, 205, 206, and 208 plastic scintillators and 204, 209, 210, 224, 225 plastic wavelength shifters results in the greatest light output (or to verify that the 201/204 combination was indeed the combination with the greatest light output). The liquid scintillator EJ-309 was tested as well because unlike the plastic scintillators, the replacement of which requires disassembly of the detector exterior, a liquid scintillator could easily be pumped in and out of the detector when it needs to be replaced.

Another solution to the degradation problem is to use red-shifting wavelength shifters, because lower-frequency red light attenuates over a longer length than higher-frequency green light. The second goal of this project was to characterize the performance of red wavelength shifters as a viable alternative to green wavelength shifters.

A final solution to the degradation problem is to use an optical fiber arrangement that minimizes light attenuation as the light is propagated to the detector. The second goal of this project was to construct a new optical fiber arrangement that maximizes light transmission throughout the detector once light is generated by the scintillating tiles.

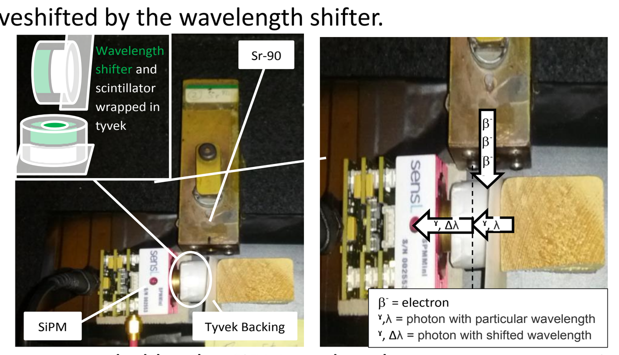
HYPOTHESIS

That 1) an optimal combination of scintillating and wavelength shifting materials that results in greater light emission than the previous combination (201T-2 scint, 204T-1 wls) can be found, 2) red-shifting wavelength shifting plastics are a viable alternative to green-shifting wavelength shifting plastics, and 3) an optical fiber arrangement that minimizes light attenuation as the light is propagated through the detector can be constructed.

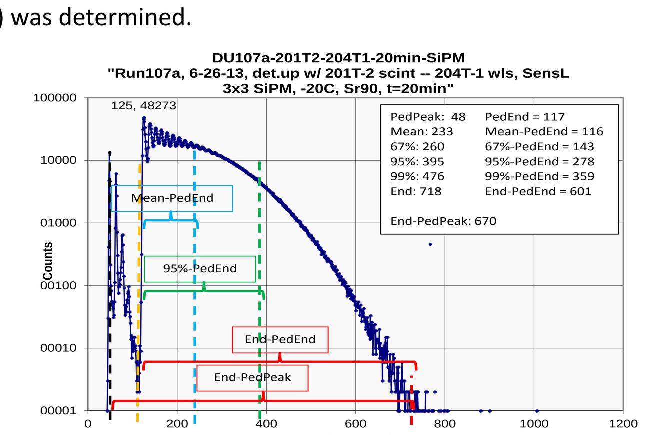
PROCEDURE/MATERIALS

Part 1: Plastic Scintillator/Wavelength Shifter Combination Testing with Pedestal

- Various scintillators and wavelength shifters were placed in a light-tight box with a beta emitter (Sr-90 source) and a silicon photomultiplier (SiPM). The scintillators and wavelength shifters were wrapped in tyvek (a reflective covering) to maximize the amount of light transferred to the SiPM.
- Beta particles from the Sr-90 passed through the scintillator, causing the scintillator to emit light, and the light was waveshifted by the wavelength shifter.



- The output light was recorded by the SiPM, and each event was categorized by its energy (in this case, intensity). With the aid of a QVT (a device that records charge, voltage, and time), an oscilloscope, and a computer, each event was binned according to its energy (the *i*th bin represented (¼)*i* pC of charge on the SiPM), and a histogram was created.
- The scintillator-wavelength shifter combinations were compared by analyzing the characteristics of their histograms using an original computer program.
- With the aid of the lab engineer Barry Bambaugh, the pedestal (the leftmost multi-peaked spike) was created by setting the qVt to record only some events whose energy was below a threshold. This was necessary because many lower energy events were background noise, and recording all the background noise would skew results and cause a single bin to fill to its 65535 event capacity within seconds. The pedestal also provided a reference point so that distribution measurements would be accurate even if some charge was left on the SiPM when a new trial was begun.
- Each scintillator's emission spectrum was determined using a spectrophotometer
- In attempt to simulate the pairing of plastic scintillators and wavelength shifters, each wavelength shifter's emission spectrum (using each scintillator's peak emission wavelength as the excitation wavelength) was determined.



DATA

RESULTS

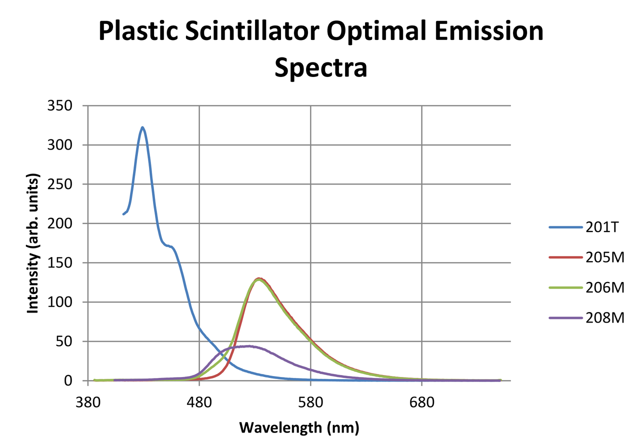
PART 1: PLASTIC SCINTILLATOR/WAVELENGTH SHIFTER COMBINATION TESTING WITH PEDESTAL

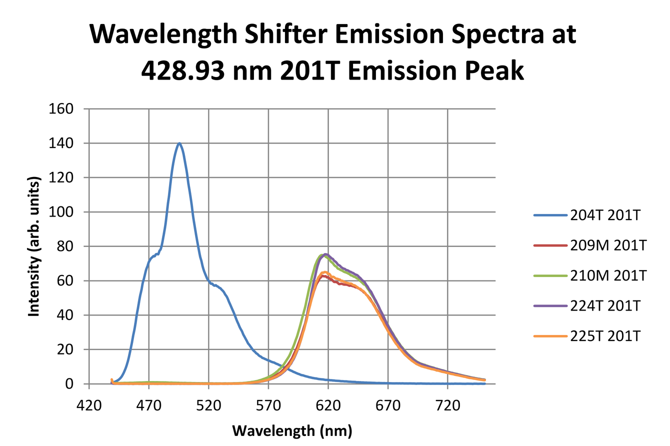
Plastic Scintillator/Wavelength Shifter Combination Distributions (Pedestal)

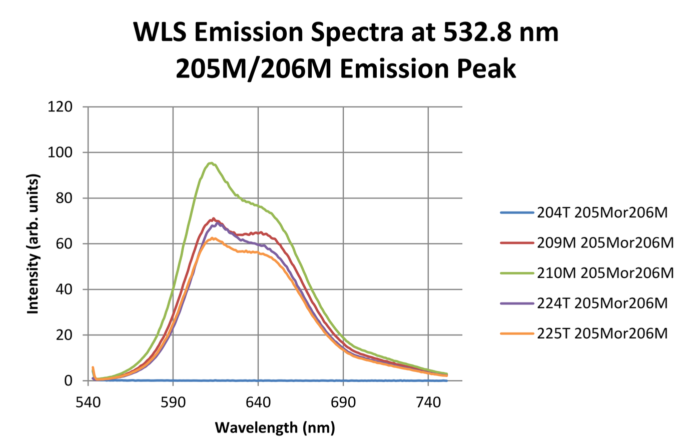
	Mean				67%				95%				99%				Endpoint			
	201	205	206	208	201	205	206	208	201	205	206	208	201	205	206	208	201	205	206	208
204	117	255	111	85	142	288	134	101	270	432	258	205	348	518	335	272	582	778	575	486
209	52	162	41	34	60	169	48	39	114	217	92	78	154	254	126	112	308	397	266	242
210	49	164	41	34	57	164	48	39	111	224	94	79	151	265	130	113	301	419	269	241
224	59	167	48	36	68	175	57	42	129	226	106	79	172	262	143	108	327	394	269	204
225	58	169	50	38	68	178	59	45	131	230	109	84	176	269	146	113	330	403	272	217

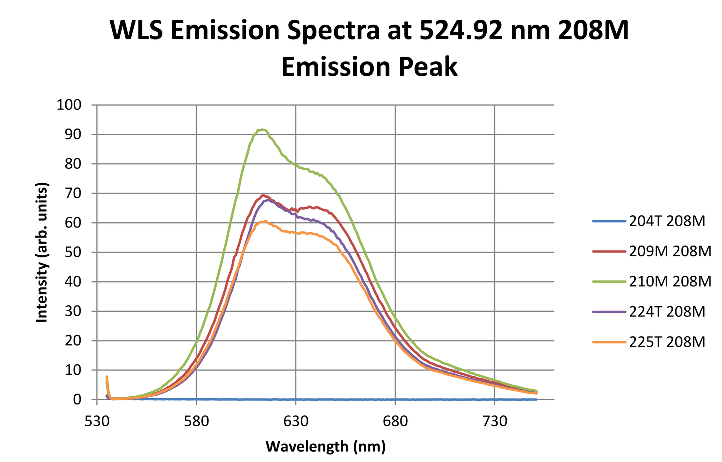
Table 1: Distribution lengths for each scintillator-wavelength shifter pair. The color of a cell associated with a combination indicates its distribution length relative to the other combinations for a given measurement. Green represents a broad distribution, while red represents a narrow distribution. Scintillators are on the horizontal axis, and wavelength shifters are on the vertical axis.

- As seen in Table 1 at the left, the 201 scintillator and the 204 wavelength shifter had the largest distributions in each of the trials. Moreover, the 201 scintillator yielded a greater light output than every other scintillator for any given wavelength shifter partner, and the 204 wavelength shifter yielded a greater light output than every other wavelength shifter for any given scintillator partner.
- [Insert results for graph 1, 2, 3, 4]

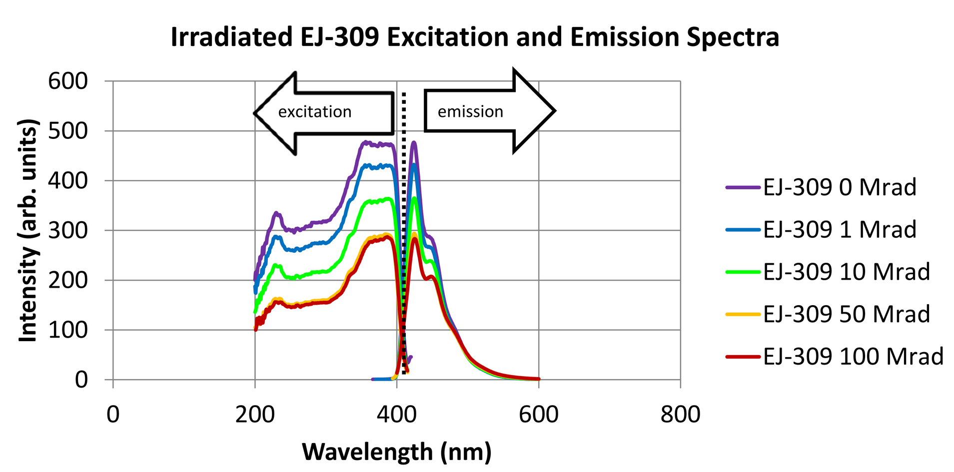




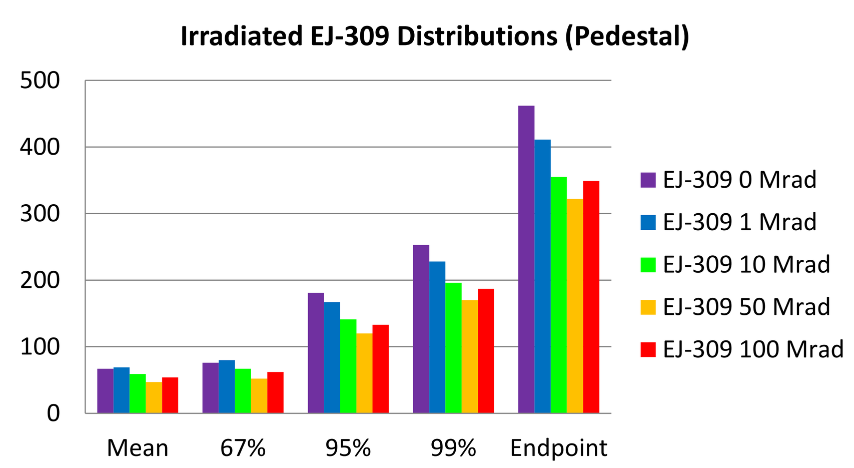




PART 2: EJ-309 LIQUID SCINTILLATOR RADIATION TESTING WITH PEDESTAL



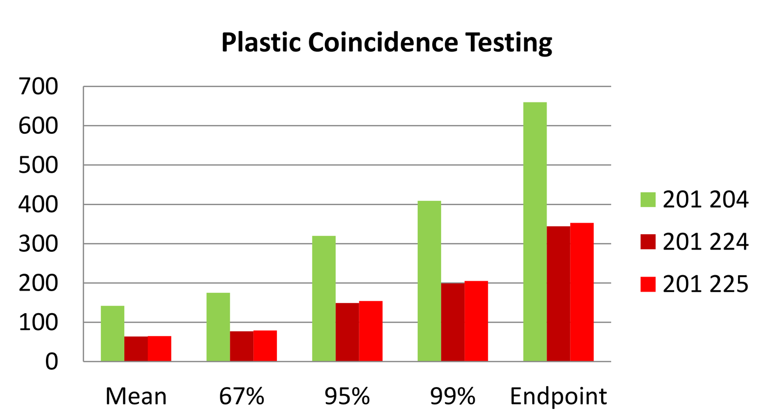
Graph 5: The absorption and emission spectra of EJ-309 liquid scintillator at different levels of irradiation. The excitation curve (the leftmost section) indicates how much light the sample absorbed at a given light wavelength, and the emission curve (the rightmost region) indicates how much light the sample emitted at a given light wavelength.



Graph 6: The distribution lengths of the irradiated EJ-309 samples, measured at the mean, 67 percentile, 95 percentile, 99 percentile, and estimated endpoint.

- Both the energy distribution of light scintillated by EJ-309 liquid scintillator and the intensity of the EJ-309 liquid scintillator excitation and emission spectra rapidly decreased when the liquid scintillator was exposed to lower doses of radiation (1 Mrad, 10Mrad, 50 Mrad) (see graphs 5 and 6).
- However, in the spectrophotometer test, the higher dose (100Mrad) did not produce much further degradation, and in the light-tight box test, the 100Mrad EJ-309 had a broader distribution that the 50 Mrad EJ-309 at each point of measurement.

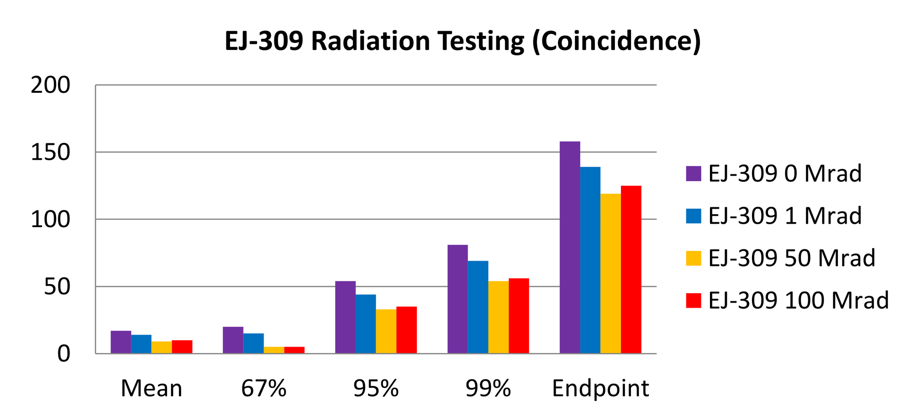
PART 3: PLASTIC SCINTILLATOR/WAVELENGTH SHIFTER COMBINATION TESTING WITH COINCIDENCE



Graph 7: The distribution lengths of the 204, 224, and 225 plastic wavelength shifters paired with the 201 scintillator.

- Consistent with previous results, the best-performing combination that waveshifted to green (201/204) yielded a broader distribution than both combinations that waveshifted to red, (201/224 and 201/225), and the 201/224 combination had a slightly broader distribution than the 201/225 combination (see graph 7 to the left).

PART 4: EJ-309 LIQUID SCINTILLATOR RADIATION TESTING WITH PEDESTAL



Graph 8: The distribution lengths of the irradiated EJ-309 samples using the coincidence setup.

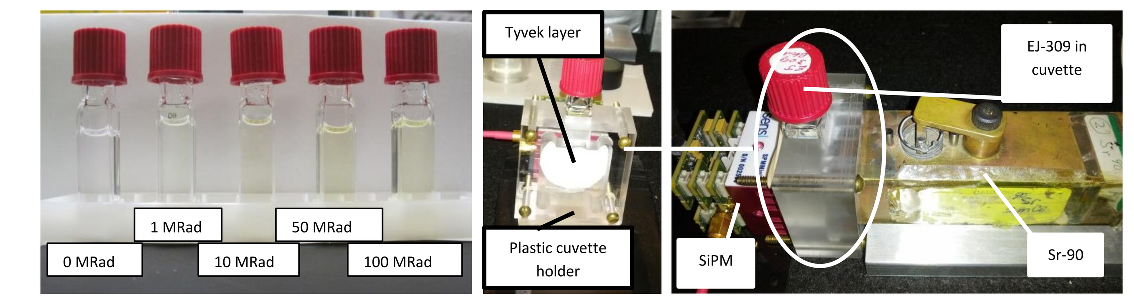
- The pattern of EJ-309 radiation degradation first noticed in part 2 was again noticed in part 4 – the 100 Mrad EJ-309 had a greater or equal distribution length to that of the 50 Mrad EJ-309 (see graph 8 on the left).

ALL GRAPHS AND PICTURES WERE CREATED BY JUSTIN SKYCAK

NOTE: PROCEDURES WERE IMPLEMENTED AND DATA WAS OBTAINED WITH THE ASSISTANCE OF COLLABORATOR ANDREW HENDERSON

Part 2: EJ-309 Liquid Scintillator Radiation Testing with Pedestal

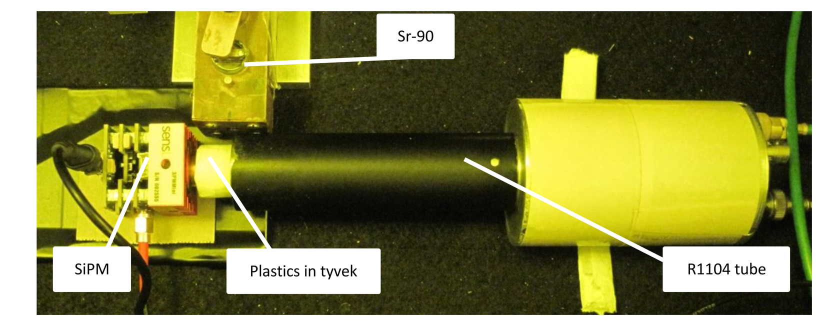
- The EJ-309 liquid scintillator was tested in a similar manner as the scintillating and wavelength shifting plastics. Because the radiation susceptibility of the liquid scintillator was unknown and there was no simple method to use the exact setup as was used for the plastics, the focus of the liquid scintillator testing was to determine the effect of radiation on the scintillating ability of the liquid scintillator rather than to compare the liquid scintillator to the plastic scintillators.
- Scintillator was poured into quartz jars, which were taken to a radiation lab for irradiation.
- Once each sample received its intended dose of radiation, it was poured into a quartz cuvette so it could be tested in the light-tight box and in the spectrophotometer.
- The light-tight box testing procedure was done in the same manner as for the scintillating and wavelength shifting plastics, except for a few minor differences: the plastics encased in tyvek were replaced by EJ-309 liquid scintillator-filled quartz cuvettes partially encased in tyvek, a plastic apparatus was used to hold the cuvettes, and the source was placed in the line of the SiPM and cuvette rather than on the side.



- The data were analyzed using the same program that was used to categorize the length of the scintillating and wavelength shifting plastic distributions.

Part 3: Plastic Scintillator/Wavelength Shifter Combination Testing with Coincidence

- Because replication of results is vital to the scientific inquiry, the best-performing (broadest distribution) combinations that waveshifted to green (201/204) and that waveshifted to red (201/225 and 201/224 – both were retested because their distributions were very close in length) were retested using a coincidence circuit utilizing both a SiPM and an R1104 photomultiplier tube (PMT).
- Because the qVt recorded only events which were detected by both the SiPM and the PMT, this setup greatly reduced the amount of lower energy noise and eliminated the need for a pedestal.



Part 4: EJ-309 Liquid Scintillator Radiation Testing with Pedestal

- In attempt to replicate a surprising finding from part 2, the irradiated EJ-309 liquid scintillator samples were retested using a coincidence setup similar to the coincidence setup that was used to test the best-performing plastic scintillator/wavelength shifter combinations.
- The only difference was that the plastics were replaced by a cuvette filled with irradiated EJ-309. No plastic holder was used, but parts of the cuvette that were not exposed to the SiPM, PMT, or Sr-90 beta source were covered with tyvek.

DISCUSSION

The superiority of the standard 201 scintillator/204 wavelength shifter was supported by the data – none of the other plastic scintillator/wavelength shifter pairs generated nearly as much light as did the standard 201/204 combination. This was not surprising, since the 201 scintillator and the 204 wavelength shifter were the standard plastics employed in the CMS detector in previous years.

However, the EJ-309 liquid scintillator may generate more light than the standard 201/204 pair at high levels of radiation. Plastic scintillators and wavelength shifters are not radiation-hard – their ability to scintillate and wavelength shift diminishes as they are exposed to increasing levels of radiation – but there appears to be a threshold at which the EJ-309 liquid scintillator loses its susceptibility to radiation. The data suggest that EJ-309 liquid scintillator is susceptible to radiation damages from 1 Mrad to some dosage between 10 and 50 Mrad, but not to radiation doses greater than 50 Mrad. A surprising result from the light-tight box testing was the slightly broader distribution of the 100 Mrad sample as compared to the 50 Mrad sample. Although the liquid scintillator's scintillation ability could not be compared to that of the plastics due to slightly different experimental setups, it is plausible that the liquid scintillator may have a greater scintillation ability than the standard 201/204 pair at high radiation levels.

Another surprising characteristic of the EJ-309 liquid scintillator is its wavelength shifting ability. As seen in graph 5, the liquid scintillator's emission spectra were consistently shifted right from its excitation spectra, and the magnitude of wavelength shifting appeared to be unaffected by radiation. Although the wavelength most of the light waveshifted by the liquid scintillator was short of green (~520-570 nm), this finding suggests that other liquid scintillators may also possess the desired wavelength shifting characteristics.

Interestingly, the red wavelength shifters resulted in narrower (by a factor of approximately 1/2) energy distributions than did the standard green wavelength shifter. Had the energy distributions been affected significantly by photon frequency of green vs red light, the photon peaks on the graphs of green wavelength shifters would have been noticeably more spaced than those on the graphs of red wavelength shifters. Thus, the broader distributions of the graphs of the green wavelength shifter suggest that the green wavelength shifters block less incoming photons than do the red wavelength shifters tested in this experiment. Although this result cannot be generalized to all green and red wavelength shifters, there may be some quality of the Eljen Technologies green wavelength shifters that allows them to block fewer incoming photons than the Eljen Technologies red wavelength shifters.

Although the red wavelength shifters resulted in energy distributions with lengths roughly half those of the green wavelength shifter, red wavelength shifters may be a viable alternative to green wavelength shifters for long fiber optic arrangements because their longer attenuation lengths would pay back the initial energy loss.

One may question whether a source of error stems from the fact that there was no way to ensure that each trial had the same number of scintillation events. Some trials had fewer than 2 million events, while other trials had over 4 million events. However, because the number of events was extremely large for each trial, it was assumed (and justified by the law of large numbers) that the distributions would not change significantly with additional events. This assumption holds as long as the intensity of an event is time-independent, which has been supported by extremely similar results of repeated trials.

CONCLUSIONS

- Of all the possible combinations of Eljen Technologies' 201, 205, 206, and 208 plastic scintillators and 204, 209, 210, 224, 225 plastic wavelength shifters, the standard 201/204 pair resulted in the greatest light output of all the pairs and the 201/225 pair resulted in the greatest output of all the pairs that waveshifted to red. Due to their higher attenuation lengths, red wavelength shifters may be a viable alternative to green wavelength shifters for long optical fiber arrangements. Like that of the plastics, the scintillation ability of the EJ-309 liquid scintillator decreases with increasing radiation. However, unlike the plastics, the EJ-309 appears to be unaffected by further radiation past a threshold (somewhere between 10 Mrad and 50 Mrad). It was also found that the EJ-309 liquid scintillator has wavelength shifting properties, although very little of the emitted light waveshifts as far as green. It may be worthwhile to investigate other liquid scintillators since they may have a radiation damage threshold and wavelength shifting abilities and can easily be replaced inside the detector.
- The next part of the project will investigate optical fiber arrangements that minimize light attenuation as the light is propagated through the detector. Quartz capillary tubes will be filled with various scintillating liquids and paints, and their light output will be measured by shining an LED on the tube and recording output light with photo-diodes. By moving the LED along the length of the tube, the relative magnitudes of light output and absolute attenuation lengths of each setup can be measured.