SCINTILLATORS AND WAVELENGTH SHIFTERS FOR THE DETECTION OF IONIZING RADIATION


Department of Physics and QuarkNet Center, University of Notre Dame
Notre Dame, Indiana 46556, USA

V. CLENDENEN AND C. HURLBUT
Ludlum Measurements Inc, 501 Oak Street
Sweetwater, Texas 79556, USA

New scintillators and waveshifter materials are under development for use in detecting charged particles in tracking applications and for detecting showering particles in calorimetric applications. Goals have been to identify and produce fast and efficient dye materials that fluoresce in the middle of the visible spectrum where polystyrene and polyvinyl toluene have good optical transparency, to replace existing materials currently in use in the field of particle physics. As a result of this study, several fluorescent dyes have been identified with fast and efficient emission, that fluorescence in the green ($\lambda \sim 490-520$ nm). These are candidate materials for new scintillators and waveshifters.

1. Introduction

Over the last decade several techniques have emerged for the readout of particle physics detectors for scintillation tracking and sampling calorimetry.¹² For tracking detectors, of which the most ambitious example is the DØ Central Fiber Tracker,³ each fiber in the tracking detector has its own photosensor. The active detector material is multi-clad polystyrene scintillating fiber of 830µm diameter and in lengths of up to 2.7 m. The scintillator is based on a primary dye p-terphenyl and a secondary dye 3-hydroxyflavone. The scintillating fibers are optically coupled to fiber-optic waveguides of the same diameter and in lengths of over 8 meters which convey the scintillation light to cryogenically cooled photosensors called visible light photon counters (VLPC).

¹ This work is supported by the U. S. Department of Energy, SBIR and STTR Programs.
² Work is partially supported by the U. S. National Science Foundation QuarkNet and RET Programs and the University of Notre Dame.
For calorimetric detectors, examples are the “megatile” and “tile” sampling calorimeters of CDF, CMS and ATLAS. Plates or “tiles” of conventional blue-violet emitting scintillator are read out with embedded multi-clad waveshifter fiber containing the dye Y11. The base materials of the scintillating tiles are formed of either polystyrene or polyvinyl toluene (PVT) depending upon cost or placement in the experiments. Of the two, PVT-based materials are the most efficient, but PVT also tends to be more expensive and less radiation resistant than polystyrene.

The major research and development effort considered in this paper focuses on advances in calorimetric technique – improvement in the wavelength shifting of blue-violet scintillation materials and in the development of new green-emitting scintillators. Since tile/plate materials can be produced in either polystyrene or PVT, but fiber can only be produced effectively in polystyrene, the research effort has focused on both compositions.

2. Scintillators and Wavelength Shifters

Plastic samples of PVT and polystyrene were polymerized in 1-inch diameter test tubes and then sliced and polished into disks of 1 cm thickness for further study. Standard samples were fabricated to form a reference base to which other materials could be compared. The chosen scintillation standard was EJ200. This modeled the brightest conventional blue-violet emitting scintillator with \( \lambda \approx 425 \text{nm} \). To waveshift the light from this standard scintillator, we chose the classic material used by the scientific community, the highly efficient dye Y11 in PVT and or polystyrene.

Several hundred new samples of various types were prepared (polymerized) similarly in 1-inch test tubes with a variety of new fluorescent dyes or dye combinations. Some of these materials were scintillators – containing primary and secondary dyes. Others were waveshifters only – containing no primaries.

2.1. Optical Characteristics of Scintillators and Waveshifters

Initially the materials were characterized as to their optical properties. Emission and excitation spectra for each of the samples were measured with a Hitachi F2000 Spectrophotometer attached to a custom data acquisition system. Figure 1 displays such spectra for the standard scintillator, standard waveshifter (Y11), and two new shifter dyes (DSB1 and DSB2) produced in this program. Once the emission properties were known, fluorescence decay times of the samples were measured with a nitrogen laser spectrometer. Samples were excited at \( \lambda = 337 \text{nm} \), and the fluorescence decay at emission maximum observed. The comparative measurements for the Standards and DSB1 and DSB2 are displayed in Figure 2.
The spectral measurements of Figures 1 and 2 reveal that the new dyes are spectrally comparable to the standard waveshifter and as such are an excellent spectral match for the standard scintillator. Additionally they are considerably faster by a factor of 3-4 in fluorescence decay than the standard Y11 waveshifter when excited optically.

Figure 1. Emission and absorption spectra. Standard blue-violet emitting scintillator (upper left). Standard Y11 waveshifter (upper right). New DSB1 waveshifter (lower left). New DSB2 waveshifter (lower right). The spectral excitation and emission properties of DSB1 and DSB2 are seen to be similar to Y11.

Figure 2. Fluorescence decay times excited by a nitrogen laser at 337 nm. Light is detected at the emission maximum for samples shown in Figure 1, and fit to a single exponential decay in time after the peak of each pulse. Standard blue-violet emitting scintillator, 1.67ns (upper left). Standard Y11 waveshifter 8.3ns (upper right). New DSB1 waveshifter, 1.8ns (lower left). New DSB2 waveshifter, 2.2ns (lower right).
2.2. Scintillator Studies

Efficiencies of the scintillator samples were characterized by exposing them to a $^{90}$Sr beta source. Signals were detected with a Hamamatsu R1104 photo multiplier connected to a LeCroy QVT pulse height analyzer and read into a custom computer data acquisition system. Figure 3 displays the measured scintillation efficiencies as a function of wavelength for a variety of scintillation materials prepared in this program. The efficiencies are normalized to the standard scintillator that emits at $\lambda \approx 425$nm, and measurements are corrected (scaled) for the wavelength dependent quantum efficiency of the R1104 PMT. There are a number of interesting features revealed in the figure. For a given type of sample, there is a range of possible efficiencies separated by about 20% in overall value. Those at the high end are PVT based; those at the low end are polystyrene based. Intermediate values correspond to the choice of primary dyes used in the compositions. The figure reveals a significant number of potentially useful and efficient candidate scintillation materials in the wavelength range $470 \text{nm} \leq \lambda \leq 530 \text{nm}$.

Figure 3. Scintillation efficiency of a variety of scintillation compositions as a function of peak emission wavelength for each sample. Efficiency is normalized to the scintillation standard at $\lambda = 425$ nm. Efficiency is measured by response to a $^{90}$Sr beta source. Light is detected with a Hamamatsu R1104 PMT and is corrected (scaled) for wavelength dependent photocathode response.

Figure 4 reveals the corresponding fluorescence decay time of the scintillation samples as a function of wavelength measured with the nitrogen
laser spectrometer. The fastest of these, with fluorescence near 500nm, are DSF1, DSF2, DSB1, and DSB2.

2.3. Waveshifter Studies

Shifter efficiency was determined by exposing the standard scintillator sample to a \(^{90}\)Sr beta source. A waveshifter sample was placed between the scintillator sample and the R1104 PMT. To assure that light from the scintillator did not leak directly through the waveshifter sample into the PMT, a filter foil was inserted between the waveshifter and the PMT to eliminate the scintillator signal from reaching the PMT directly. Figure 5 displays the results of this study as a function of the maximum emission wavelength of the waveshifter. This study provided relatively little definitive information between materials – rather it indicated at the level of the measurements that nearly all the waveshifter samples were fairly comparable in performance in shifting capability in the form of bulk (centimeter thick) samples. Greater discrimination between materials was then provided by fluorescence decay time of the materials as the critical discriminator. These measurements are shown in Figure 6. Measurements were made utilizing the nitrogen laser spectrometer and again reveal the relative speed of DSF1, DSB1, and DSB2 and similarly indicate that K27 (Y11) is slow.
Figure 5. Wavelength shifter efficiency as a function of peak emission wavelength of the shifter. Samples are shifting the scintillation light of the standard scintillator excited by a $^{90}\text{Sr}$ beta source. Light is detected with a Hamamatsu R1104 PMT and corrected for wavelength dependent photocathode response.

Figure 6. Fluorescence decay time for a variety of wavelength shifters as a function of peak emission wavelength. Samples are excited by a nitrogen laser pulse at 337nm.
3. Tile-Fiber Measurements

Those materials that revealed promising scintillation performance and rapid fluorescence decay were then incorporated into multi-clad fiber for waveshifter studies. The dye materials so chosen included DSB1, DSB2, BDOC and were compared to the standard dye Y11. These were used to read out scintillation tiles of 10cm x 10cm dimension and 6mm thickness of standard scintillation material with emission maximum in the blue-violet. Figure 7 shows the detection system which included a three fold coincidence of trigger counters, including a PMT which viewed the scintillation tile itself and two other thin independent counters one above and one below the tile. The coincidence of these counters was used as a gate for the signal from the waveshifter fiber, which was located in a groove in the tile and read out by means of a Hamamatsu R943 GaAs PMT. The signals from the R943 PMT were averaged for up to 2048 pulses and displayed on an HP54502A digitizing oscilloscope and read into a computer. Such signals could be recorded for cosmic ray triggers and for triggers from a $^{106}$Ru beta source. Either generated essentially the same results at our present level of measurement.

Figure 7. The detection system for tile-fiber measurements in which fluorescence efficiency of fiber waveshifters is studied. The scintillating tile with embedded wavelength shifter fiber is visible in the center of the figure. The black cylinder at the very right center is the R943 PMT that detects the light from the shifter fiber.
Figure 8 displays the averaged pulses for DSB1, DSB2, BDOC and Y11 waveshifters of the standard scintillation tile when excited with the $^{106}$Ru source. As can be clearly seen, the DSB1 and DSB2 signals are significantly faster than that of the conventional Y11. The width at half maximum of the DSB1/DSB2 signals is 12.5 ns; for the Y11 signal it is 25 ns. Fitting a single exponential to the fast decay of the DSB1 (DSB2) signal yields a decay time of 8 ns (9 ns) that includes the response of the tile, the fluorescent dyes, as well as the R943 PMT. A similar fit to the Y11 signal yields a decay time of 25 ns. However, if one integrates over a full 100 ns, the fluorescence yield of Y11 and DSB1 are comparable, whereas DSB2 is slightly less efficient (~5%). Over short time intervals DSB1 and DSB2 are clearly superior to Y11 in performance.

Figure 8. Averaged pulses recorded for various waveshifter fibers detecting light from a scintillating tile excited by a $^{106}$Ru source. The fast pulses are due to DSB1 and DSB2, two new dyes developed in this program. Y11 is the intermediate sized and slowest pulse. The smaller pulse is due to the new dye BDOC which, although fast, is less efficient at shifting blue-violet light. The main
divisions of the horizontal axis in the figure are 20 ns intervals and the full time on the horizontal axis is 100 ns.

4. Radiation Resistance Studies

To date, our radiation resistance measurements have been limited to exposure of the small 1-inch diameter x 1-cm thick bulk samples to doses of 1Mrad of $^{60}$Co. Measurements of the relative efficiency of samples before and after radiation exposure are presented as a function of sample emission wavelength in Figure 9. When irradiated, samples were maintained in an inert (nitrogen) atmosphere. The figure reveals that typically samples lost approximately 10% of efficiency after 1Mrad of exposure.

Clearly a great deal more work needs to be done here. Actual detector elements, for example tile–fiber materials, now need to be exposed to radiation in doses of varying amounts and under various exposure rates, to have a clear understanding of the radiation resistance behavior of these new materials. This is an important topic of future study in the program.

Figure 9. Measurement of the scintillation efficiency of small 1-inch by 1-cm thick samples of scintillator materials exposed to 1Mrad of $^{60}$Co irradiation. What is plotted is the ratio of light yield after irradiation to before irradiation for samples as a function of their maximum emission wavelength. The results indicate that for these very small samples, recovery to 90% of original efficiency occurs for essentially all materials. As such these measurements are not particularly informative. More definitive studies are required of actual detector materials (tiles and fibers in needed lengths) in order to draw meaningful conclusions.
5. Conclusions

From the studies carried out in this program, a wide variety of new scintillation and waveshifter materials has been produced and studied with fluorescence emission wavelengths in the middle of the visible spectrum and with rapid fluorescence decay times and reasonable efficiency. Of these, several promising materials have been produced, and a number of these have been incorporated into multi-clad fiber and tested as waveshifters in tile-fiber geometry. Initial measurements indicate that at least two of these, DSB1 and DSB2, offer superior performance in fluorescence decay time to conventional Y11 waveshifter while maintaining high fluorescence efficiency. These materials are therefore potential replacements for Y11 in any application where fast timing is required, or where improved signal to noise would be an advantage by utilizing short integration times.

Acknowledgments

We would like to thank the staff of the Notre Dame Radiation Laboratory for the use of the nitrogen laser spectrometer, A. Pla-Dalmau of Fermilab for assistance with the sample irradiation studies, E. Skup of Fermilab for tile grooving, and K. Kephart of Fermilab for tile polishing and preparation, and to the University of Notre Dame for support for facilities and resources for high school students and teachers at the Notre Dame QuarkNet Center.

References

4. The CDF II Technical Design Report, Fermilab-Pub-96/390-E.
7. The dye Y11 is variously called K27.