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Scintillator Optimization Study for Nuclear Nonproliferation, Safeguards, and Security Based Applications

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EXECUTIVE SUMMARY

The following report summarizes my overall research and experience in the Department of Homeland Security HS-STEM Summer Internship Program at the Idaho National Laboratory. First, I give an introduction to scintillators principles. This includes the basic physics and methodology for radiation detection. Secondly, an introduction to my work is presented which includes the problem and approach. Next, I summarize the skills I learned in the internship as well as interesting knowledge that I was exposed to. I finish with my future career plans as well as acknowledgements.

CONTENTS

FIGURES

ACRONYMS

AMEDD - Army Medical Department

AN/PRD - Army Navy/ Human Portable Radiac Passive Detector (Army Navy Nomenclature)

ATLAS - A Toroidal LHC Apparatus

ATR -Advanced Test Reactor

CT -Computer Tomography

DHS -Department of Homeland Security

EBR I -Experimental Breeder Reactor I

EXO Enriched Xenon Observatory

GEANT -Geometry and Tracking

IAEA -International Atomic Agency

INL -Idaho National Laboratory

LHC -Large Hadron Collider

MFC -Material and Fuel Complex

NGSI -Next Generation Safeguards Initiative

NNSA -National Nuclear Security Administration

PET -Positron Emission Tomography

PMT -Photomultiplier Tube

PNNL -Pacific Northwest National Laboratory

PVT -Polyvinyl Toluene

RPM -Radiation Portal Monitors

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1. INTRODUCTION

Scintillator technologies have a wide range of applications ranging from scientific to national and homeland security applications. Even though the Cold War has ended with the fall of the Soviet Union some 25 years ago, a nuclear threat still exists. [1] There are a growing number of nuclear technologies that pose a threat that include radiological dispersion devices and thermonuclear bombs. In response, there have been several systems that employ scintillator technology set in place to monitor such threats. One example of a system is the Department of Homeland Security's (DHS) Radiation Portal Monitors (RPMs) which contain tubes filled with helium-3 or polyvinyl toluene (PVT). An example of a RPM is shown in Figure 1. Handheld Survey meters also make use of scintillator technology that make sampling radioactive contaminated areas more convenient.

In addition to homeland security applications, there exist a great many other uses for scintillators. Medical imaging uses scintillators in tomograms such as PETs and CT scans. Astrophysics research uses them for X-Ray and Gamma Telescopes. Scintillators are also used as detectors in high energy physics in experiments such as ATLAS in the LHC.

Figure 1. A truck passing through a RPM. The two yellow panels contain ^{3}He proportional counters and/or plastic scintillation detectors. [2]

2. SCINTILLATION DETECTION PRICIPLES

Materials that produce luminescent light are called Scintillators. They do so when ionizing radiation, such as high-energy photons or subatomic particles, strike the material and Compton scatter. Next, the material "scintillates" where it re-emits the energy. Next, the light is collected by a photocathode that converts the optical light into electrons through the photoelectric effect (figure 2). Finally, the electrons are multiplied in the Photomultiplier Tube (PMT) where a voltage bias is applied and can be read in by a data acquisition system as current. The entire process can be seen in figure 3.

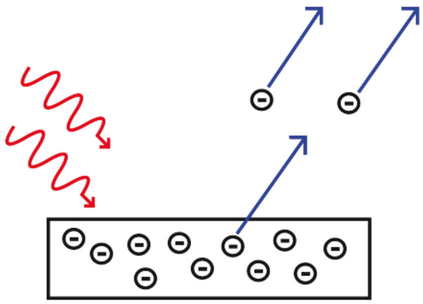

Figure 2. A drawing of the Photoelectric Effect. Photons are shown in red and electrons are represented in blue. [3]

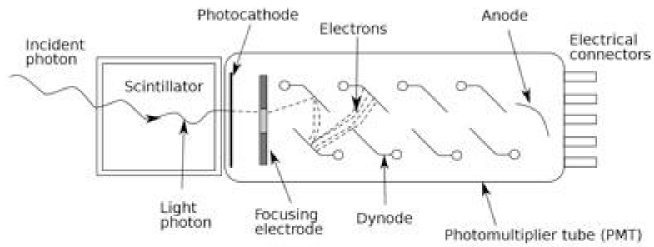

Figure 3. A diagram of how a standard scintillator works from incident radiation to PMT response.

According to Knoll, the ideal scintillation material should have the following properties:

1. High efficiency for converting radiation energy into detectable light.
2. Conversion between deposited energy and light yield should be linear.
3. The Material should be transparent as to not absorb the scintillation light it produced.
4. The decay time of the light should be short to create fast signal pulses.
5. Should contain high purity of optical material and be able to manufacture in large quantities.
6. Have a refraction index that is near that of the PMT for efficient optical coupling. [4]

These characteristics pertain to the material and chemical composition of the scintillator. There is a lot of research into creating new a better scintillation material. However, we predict that the geometric form factor of the scintillator can have a significant effect on scintillator response. Today, there is a substantial amount of research and development focused on organic and other scintillating compounds. However, it has gradually slowed down.

3. PROBLEM AND APPROACH

We believe that the physical shape of the scintillator affects the resolution and sensitivity of current available scintillating materials. The study will be done by using GEANT4, a platform that simulates the passage of particles through matter. [5] A model of a detector that we have in inventory, a BC408 scintillator, was modeled. The model was based the program on an example provided by the program called “OpNovice”. Below is an image of the programmed detector next to the picture of the actual detector.

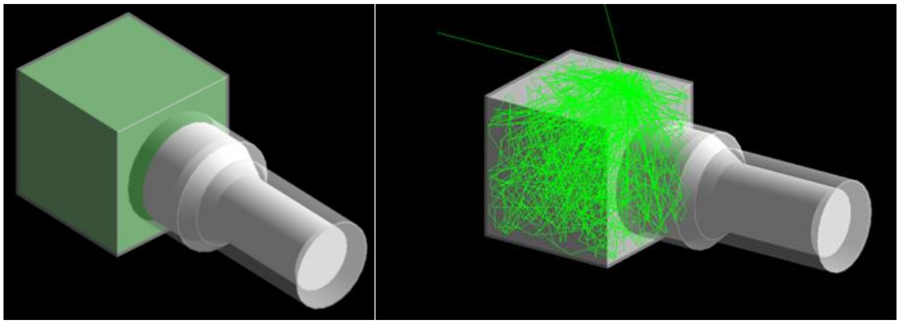

Figure 4. The modeled plastic scintillator. On the left the scintillating volume is shown in green, while on the right the volume is made grey to better show the paths of optical light created by an incident photon.

Once the programing of the detector geometries was complete, I added the scintillator physics and the material definitions found in the BC408 manual. Finally, I defined the PMT photocathode (see Figure 3) as the SensitiveDetector with an Optical Photon filter. The SensitiveDetector records the energy and time the photon hits the photocathode. The program then prints this information to a file for further analysis. Figure 5 shows a histogram of the energy distribution compared to the energy distribution provided by the plastic scintillator manufacturer. The two graphs are expected to be similar in shape as they represent the same characteristics of the scintillator. The simulations agree well with the provided data, with both distributions peaking at ~430 nm.

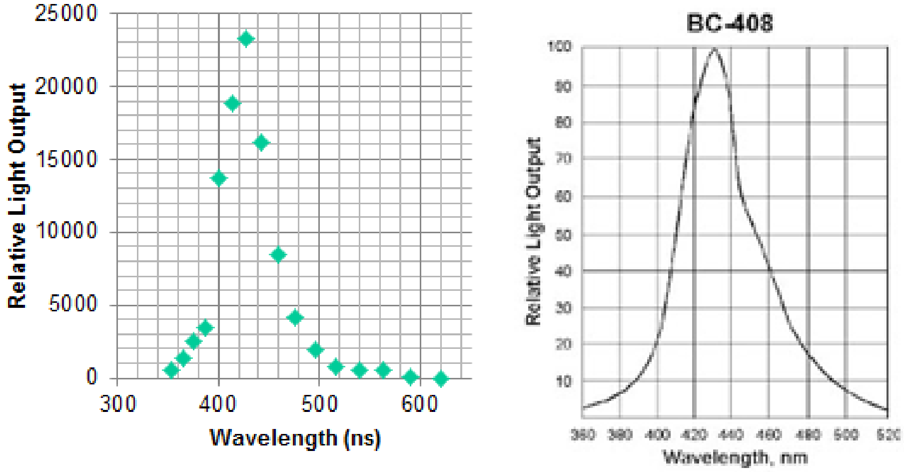

Figure 5. GEANT4 simulated light response of BC-408 (Left) alongside the values reported by the detector manufacturer.

A time distribution of the photons hitting PMT sensitive detector was compared to a tabletop measurement in the laboratory. This is shown in the experimental scope trace was captured by placing a ^{137}Cs source, which emits a 661.7 keV gamma ray, on top of the scintillator. The simulated response was done by placing an isotropic source on top of the scintillator that shoots 10,000 662 keV photons in the detectors axial direction.

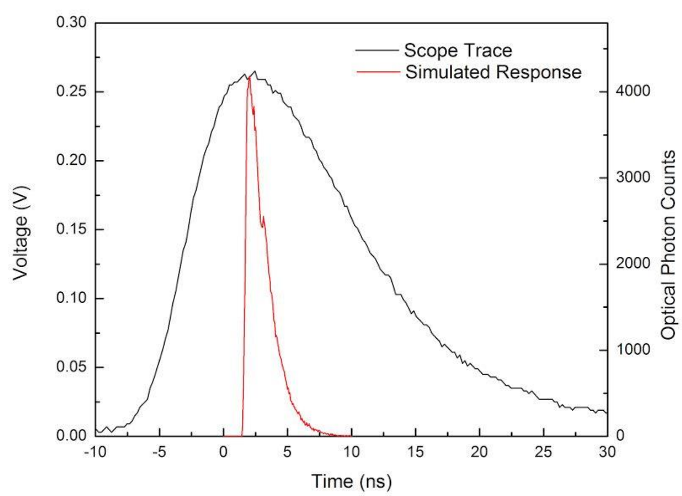

Figure 6. GEANT4 simulated pulse prior to PMT conversion (red) compared to a pulse trace from an oscilloscope.

The next step, which has not been completed, is to verify that the simulations model real life experimentation. This can be done mathematically by convolving the simulated scintillator response with the PMT response function (see below). In equation, S_{ideal} is the overall detector response which is correlated to the scope trace. In addition, the resolution of the detector would correlate with the variance of these pulses for multiple runs. In other words, a more uniform pulse shape distribution for different incoming photon angles and positions will result in a higher level of achievable energy resolution.

$$S_{ideal} = (G \otimes P)(t) = \int_{-\infty}^{\infty} G(t-\tau)P(\tau)\,d\tau$$

G(t) = Simulated Scintillator Response
P(t) = Gaussian PMT Response

Finally, different geometries were modeled which can be viewed in Figure 7. In these tests, beams of 10,000 662 keV photons were incident at various angles. The results can be seen in Figure 8.

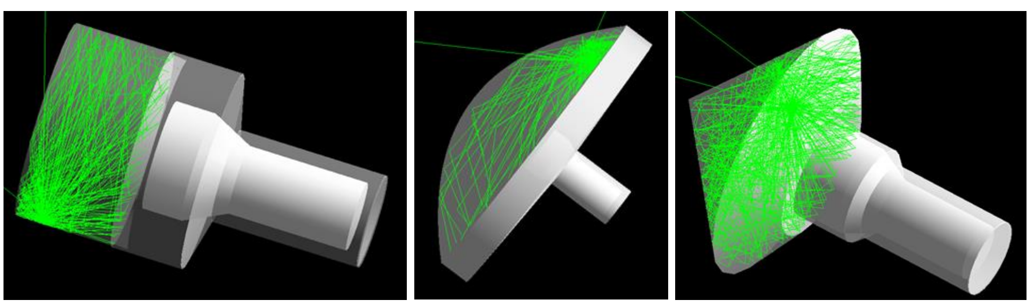

Figure 7. Examples of studied geometric form factors included a cylinder (left), a paraboloid (center), and a diamond (right).

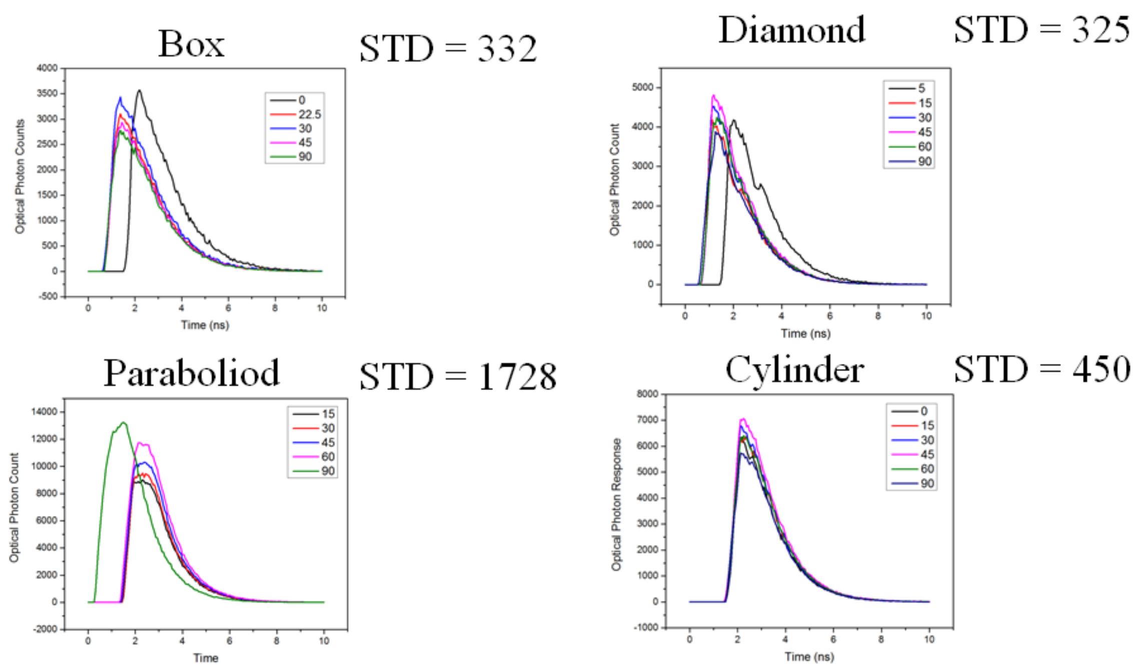

Figure 8. Simulated scintillator responses for various incident 662 keV gamma angles. STD values are the standard deviation in pulse height for each form factor.

4. SKILLS AND KNOWLEDGE GAINED

The greatest skill I have learned is programming in GEANT4. This software allows simulation of particles and matter. It is currently used in the high energy physics community in experiments such as the LHC and EXO-200. This valuable ability will greatly help me in my future career and make me a valuable member in research groups.

At INL, I was able to visit the site, which includes the Experimental Breeder Reactor I (EBR-I), the Advanced Test Reactor (ATR), as well as the hot cells at the Materials and Fuel Complex (MFC). EBR-1 is the world's first electricity-generating nuclear power plant. ATR was a delight to tour as it was my first visit to a nuclear reactor. There, I was able to observe the distinctive bright blue Cherenkov radiation from the spent fuel in the pool canal.

In addition, I was sent to a 5 day summer course in Nuclear Safeguards at the Pacific Northwest National Laboratory (PNNL) in Washington State. There, I was able to visit the *Areva* fuel fabrication plant, which is a once in a lifetime opportunity. We saw all the steps of the reactor fuel manufacturing. Next, we had classroom courses in safeguards instructed by current researchers as well as former International Atomic Energy Agency (IAEA) employees. We learned about current safeguards initiatives as well as being able to exercise those is skills in different activities. In addition, on the last day, I was able to present my work in a 15 minute oral presentation.

I also was able to audit an Army AMEDD course. This course is designed for military personnel whose military occupation specialty deals with radiation (e.g. 72A, Nuclear Medicine Scientist). There, I learned procedures that include securing a radioactive contaminated area and surveying those areas. I was also able to practice with their equipment such as the AN/PRD-77. Finally, I learned OpOrder procedures, in which an executable plan is created that direct a unit in a military operation.

Finally, I learned life skills such as cooking for myself, as well as driving a manual transmission.

5. ACADEMIC CAREER AND PLANNING

This experience has giving me a great exposure to Nuclear Engineering, especially in the nonproliferation field. This internship has made me consider applying to graduate school for nuclear engineering.

This internship has also giving me a great introduction to the scientific research community. First, I learned research methods and steps needed start and complete a project. This includes the planning and conceptual stage. Next would be experimentation and verification. Finally, the analysis and results stage.

6. ACKNOWLEDGEMENTS

I would like to thank the DHS HS-STEM Summer Internship Program for the funding as well as the opportunity to participate. I am grateful for my mentor Dr. Scott Thompson for his guidance and support through this internship. In addition, NNSA's Next Generation Safeguards Initiative (NGSI) and the nonproliferation group at PNNL for allowing me to attend the Safeguards Course.

8. WORKS CITED

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