Prepared for: Dept of Energy

Prepared by: Andrew Stroud
(MS Student)

Dr. Lee Sawyer
(Professor of Physics)
Louisiana Tech University

Introduction

The crucial difference between electromagnetic and hadronic shower development comes from the fact that a considerable fraction of the energy is carried by non-ionizing particles, *i.e.* the soft (few MeV) neutrons from the nuclear evaporation process[5]. The neutron components of hadron-initiated showers are one of the hardest processes to deal with from both a hardware and software point of view, since neutrons are long-lived and interact exclusively through the strong interactions. This leads to neutrons traveling long distances in the calorimeter before interacting, producing pulses much later than the initial shower development in calorimeters sensitive to neutron interactions, and may lead to neutron signal contamination in other elements of multi-component detectors. For experiments relying on particle-flow calorimetry (such as the detectors being proposed for the International Linear Collider) neutron production is viewed as an irreducible energy loss mechanism, contributing to the so-called “confusion term” in the particle flow resolution.

Project Goals

The goals of the project as outlined in the original proposal[6]:

During the first year, we would

- 1) Perform detailed simulation studies of the proposed prototype calorimeter in order to optimize the sampling of the neutron component of the hadronic shower without compromising the resolution from the ionizing component. Particular care will be taken into understanding the amount of scintillator needed to both moderate the neutrons produced during the shower, and to sample a significant fraction during the readout of the rest of the shower's energy deposition.
- 2) Perfect the casting of the scintillator tiles with embedded nanoparticles, and produce enough scintillator for the prototype modules.
- 3) Cut grooves in test tiles and embed WLS fibers in the tiles.
- 4) Test the readout of the scintillator tiles using MA-PMTs to be purchased in year one.

By the end of year one we will have an optimized NECH module design, tiles ready for incorporation into a prototype module, and the first readout elements (MA-PMTs, ADC card) for the prototype module.

During year two we would

- 1) Purchase and machine iron for the prototype module.
- 2) Construct the first prototype NECH module.
- 3) Test the module with cosmic rays.
- 4) Test the module with the Louisiana Tech neutron gun.
- 5) Begin procurement of materials and construction of the larger test beam module, subject to minor changes to the design based on our experience with the first prototype module.

By the end of year two we will have our first results of the sensitivity of the NECH module to charged particles and neutrons, and comparisons of neutron detection efficiency to simulation studies.

During year three, we will

- 1) Complete construction of the NECH test beam module.
- 2) Test the NECH module at the Meson Test Beam Facility at Fermilab (subject to approval of a Memorandum of Understanding with the lab).
- 3) Analyze the test beam results.
- 4) Publish the results.

By the end of year three we will be able to say whether, and under what circumstances, neutron-enhanced calorimetry for hadrons can be used in experiments in high energy and nuclear physics

Project History

2006-2007

- Initial experiments conducted to create scintillator tiles using both commercial and in house means.
- Creation of the first light tight box.
- Prototype housing created for tile stack.
- Comparison study of photonic sensors.
- Creation of coupling devices between sensors and WLS fibers using in house 3D printers.

2007-2008

- Acquired 10 scintillator samples created at the Fermilab Extrusion facility, each with a different doping level of Gd_2O_3 .
- Initial light yield tests carried out on samples using SiPMs and prototype amplifier circuits.

2008-2009 (Last year of Dept of Energy funding)

- MIP (minimum ionizing particle) test constructed consisting of triple coincidence and test PMTs within larger light tight box.
- Creation of data acquisition process.
- Tests using the MIP setup conducted on Fermilab samples.
- A new means of doping scintillator with gadolinium was developed using a four step method.

2009-2010

- Groove cutting tests using existing tiles.
- Steel plates acquired for module.
- New housing for calorimeter tiles constructed.
- New Amplifier circuits created, tested, and manufactured for SiPMs.
- Aluminum mold created for scintillator tile casting.
- Large sonication bath acquired.
- Trip to Fermilab's Extrusion and Meson beam facility to schedule time for beam usage.
- Creation of the first scintillator tiles using Aluminum mold.

Budget

The original budget for the project was placed at \$119,140 from the Department of Energy, with additional funding allocated from Louisiana Tech for student support and extension of the project after the end of Dept. of Energy funding.

This project served as the thesis project for one Applied Physics Masters student, Matthew Abbott, and as a senior design projects for four Electrical Engineering students (Benjamin Toler, Ali Nasir, and Charles Olsen, and Jason Rollins) and two Physics majors (Chris Galyean and Andrew Stroud). Several of these students received partial or full support from the project and/or matching university funds.

Technical Accomplishments

Simulation Studies

A simulation study of the effect of Gd₂O-doped of scintillator was developed using the SLIC interface to the GEANT detector simulation package. SLIC was developed at Stanford for Linear Collider-related detector studies, and provides an easily configurable XML interface for detector specification. A 42-layer scintillator/iron module was studied, with the aim of eventually building such a module for test beam studies. A smaller 4-layer prototype module was built for local testing. These studies were primarily aimed at optimizing shower containment vs cost, with future studies of sampling weights planned after initial test beam results were obtained.

Figure 1 Top: (left) 42-layer module structure for test beam studies. (right) 4-layer prototype structure Bottom: A simulated proton-induced shower in the full module design.

Figure 2 Simulation results of protons fired at the 42-layer module at various beam energies.

Scintillator Testing Light-Tight Box

In order to examine the capabilities of the scintillator samples and response devices a testing platform was needed. For this reason a light tight box large enough to house both tiles and detectors was constructed [2]. The box, once shut, allowed for the removal of ambient light, which could potentially have damaged the PMTs or amplifier circuits. A BNC and lemo connector panel built into the box allowed for external equipment such as voltage sources and oscilloscopes to be connected to the setup within.

Figure 3. The interior of the light tight box constructed for testing with a scintillator paddle and PMT setup.

Silicon Photomultiplier (SiPM)

A comparison study of photomultiplier tubes (PMTs), avalanche photodiodes (APDs), and solid state silicon photomultipliers (SiPMs) was undertaken to see which of the light capturing device

would work best with the scintillator tiles [3]. While the SiPMs were less efficient as the avalanche diodes, they did contain a larger area of exposure and higher gain than the photodiodes. They were also cheaper, faster, more rugged, and smaller than the PMTs used in previous experiments at Louisiana Tech [8]. SiPMs were purchased from the Photonique that could work within the light bands emitted by the scintillator and the WLS fibers. In addition, amplifiers circuits were fabricated to improve readout from the sensors. Since the fiber optics would be imbedded into the scintillator tiles, couplers between the fiber and sensors were created using the 3D printers at Louisiana Tech.

Figure 4. left) photomultiplier tube (PMT). top center) avalanche photodiode (APD). bottom center) silicon photomultiplier (SiPM). right) Couplers for all three devices to WLS fibers.

Scintillator Testing

To evaluate the performance of Gd_2O_3 doped scintillator, a new testing platform was constructed. The MIP (minimum ionizing particle) data acquisition setup used cosmic rays as the interaction source [7]. In order to make sure that a cosmic ray went through the scintillator being tested, the testing platform had three vertically aligned scintillator paddles (two above and one below the test scintillator). Each paddle was coupled to a PMT that made sure the cosmic ray was on a path to travel through the test scintillator. The new platform was placed within a larger light tight box to reduce the effects of ambient light.

Figure 5 a) Raw PMT signal for a single paddle. b) The signal then passed through a discriminator. c) Finally, all three discriminated and "anded" coincidence signals along with the test scintillator signal.

Before finally pursuing an in-house solution to casting the doped scintillator (as described in the next section), several alternative methods (as originally proposed for the project) were pursued. First, we entered into an agreement with Eljen Inc to have test scintillator sheets cast. WE had hoped that an industrial manufacturer would have the necessary capability to produce sufficient scintillator on a reasonably short time scale. However, the test sheets showed distinct settling of the Gd₂O₃ nanoparticle dopant on one side of the sheets, which after further discussion with Eljen proved to be unavoidable due to their casting process.

After our initial experience with Eljen, we began discussion of the the project with Dr. Ann Plaudal of Fermilab, who had a similar interest in developing nanoparticle-doped scintillators.. The Fermilab Scintillator Extrusion facility was gracious enough to produce scintillator samples containing various dopant levels of Gd₂O₃ to the project. These were in the form of scintillating fibers rather than sheets or bars, however, and could only be used to proof-of-concept test. Information about the samples is given in Table 1.

Sample	PT	Gd ₂ O ₃	bis-MSB
0	0%	0%	0%
1	1%	0%	0.01%
2	1%	3%	0.01%
3	1%	5%	0.01%
4	0%	0%	0.01%
5	0%	0%	0.01%
6	1%	0%	0.01%
7	1%	0.5%	0.01%
8	1%	1%	0.01%
9	1%	2%	0.01%

Table 1: Each sample was made using polystyrene (PS) with varying levels of bis-MSB (p-bis-(o-methylstyryl)-benzene), gadolinium oxide (Gd₂O₃), and p-t-butylstyrene (PT).

For the testing of each scintillator, data was taken with up to 5000 incident cosmic ray MIPs through the triple coincidence paddles. The plots in Figure 6 show the results once the pedestal was subtracted for each sample.

Figure 6: The results of using cosmic rays to test the different doped scintillator in Table 1 . Samples 4 and 5 were not tested because they gave no response at all.

In Figure 6, Samples 1 and 6, which do not have Gd_2O_3 , have well defined peaks. The lack of peaks for the Gd_2O_3 doped scintillators is due to the opaqueness introduced by the doping, making the samples less efficient at transporting light. However, as seen in Figure 6e, sample 7 has a defined peak, meaning for low concentrations of Gd_2O_3 , a useable signal is recovered.

Scintillator Casting

Throughout the history of this project several methods for casting scintillator tiles have been undertaken. Some methods included in-house production and the acquisition of industry produced scintillators [2]. In devising a method to produce quality scintillator doped with Gd_2O_3 , two major difficulties had to be overcome. The first of these difficulties was to make sure that the Gd_2O_3 particles, which are not soluble in polar liquids, maintained colloidal suspension during the casting process; otherwise the particles would settle and there would not be a homogeneous distribution of Gd_2O_3 within the scintillator. The second problem was making sure that the Gd_2O_3 did not clump together forming larger than nano-sized particles.

Nano-scale Gd_2O_3 particles are necessary since they will allow for the most homogeneous distribution of neutron absorbing material throughout the scintillator and contribute significantly to degrading the optical path in the scintillator. The nano-scale particles will also allow Brownian motion to become a significant factor in maintaining the suspension.

A four-step method was developed to keep the Gd_2O_3 in suspension [5].

1. The Gd_2O_3 aggregate must be processed in order to reduce its size to a level such that Brownian motion becomes a significant factor in maintaining the colloidal suspension. This was done by sonicating the Gd_2O_3 powder alone at 55°C for three hours per gram. The sonication helps break up the agglomerates into the smaller nano-scale Gd_2O_3 particles.

Figure 7: This figure shows that the minimum size of the Gd_2O_3 nanoparticles is 1.5 microns before sonication.

2. The second step is the first polymerization of the suspension. A small quantity of monomer solution—approximately 30g—is created using 1.5% and 1.0% by weight of the primary scintillator (2,5-Diphenyloxazole -- PPO) and initiator (Dibenzoyl peroxide) respectively. A large amount of processed Gd_2O_3 should be added to the monomer solution at this point; on the order of 10% of the monomer solution by weight. This step should have a larger concentration of Gd_2O_3 than is ultimately desired. The suspension is then sonicated for six hours at 55°C . We used small glass vials with airtight caps as containers for the sonication. The solution is sonicated to not only disperse the insoluble Gd_2O_3 particles but also to allow any dissolved gases to come out of the solution. This polymerization could take anywhere between 24 hours to 5 days depending on the volume of the solution. The first polymerization will show some settling of the Gd_2O_3 particles.

Figure 8: The minimum size of the Gd_2O_3 nanoparticles is about 0.1 microns after sonication.

3. The next step is to pulverize the scintillator ingot; the addition of large amounts of Gd_2O_3 makes the polymer very brittle and allows us to pulverize the material by hand. The pulverized ingot is then ground to a fine powder.
4. The final step is the second polymerization of the material. The pulverized material is

diluted using liquid monomer to achieve the desired dopant concentration. The small polymer particles from the pulverization process will easily dissolve while maintaining the initial dispersion of Gd_2O_3 particles. The thin film of polymer that was created around each Gd_2O_3 particle will help the particles stay in suspension. Appropriately selecting the desired solid fraction concentration will give a high viscosity solution that will prevent settling in the final sonication process. This polymerization should occur in a mold that will give the desired shape of the scintillator tile [5].

Figure X. a) Aluminum mold. b) Tile doped with 0.5% Gd_2O_3 after the four step method.

Although it happened late in the project, this two-step casting process was a **major breakthrough**, and remains the primary intellectual achievement of the project. Using this method we plan to create several sets of tiles with varying levels of Gd_2O_3 to find out which level is best for neutron detection in a hadronic calorimeter module.

Future Research

In the past few years various groups at Louisiana Tech University have been working on high altitude ballooning. It has been proposed that Gd_2O_3 doped scintillator be sent up into the atmosphere to test the capabilities of the SiPMs. A senior design team is currently developing a balloon payload, using scintillator cast during this project.

Summary

Louisiana Tech University has made great strides in its development of gadolinium-doped scintillator tiles. These tiles will eventually be used in the construction of a calorimeter capable of improving the detection of neutrons during hadronic showers. Thus far we have been able to perform simulation studies of showers, test scintillator tiles and equipment using two testing platforms. From our examinations of the Fermilab samples we have been able to show that for small levels of Gd_2O_3 (0.5%) a recoverable signal can be found. We have additionally **created our own method for the polymerization of scintillator tiles with Gd_2O_3** . Unfortunately due to the time required to cast such tiles, and the depletion of funds, we do not yet have a completed calorimeter module. Louisiana Tech University is still deeply interested in the field of neutron-enhanced detectors and will continue its research into this area.

References

Along with background information dealing with calorimetry research many of the senior research papers stemming from the project have been added as supplementary information.

- [1] Geant4. Retrieved May 12, 2006, from <http://geant4.web.cern.ch/geant4/>
- [2] Abbott, Matthew. *Enhancing Neutron Calorimetry by using Gadolinium Oxide Doped Scintillator*. Louisiana Tech University. College of Engineering and Science.
- [3] Abbott M. *Neutron Calorimeter(NECH)*. Spring 2007. Louisiana Tech University. College of Engineering and Science.
- [4] Fabjan C W . Rep. Prog. Phys. 52 (1989). *Energy measurement of elementary particles*. CERN, Geneva, Switzerland. Johnson, Christian.
- [5] Johnson, Christian. *A Casting Method for Producing Organic Scintillator with Metal Oxide Nanoparticle Dopants*. Louisiana Tech University. College of Engineering and Science. May 2011.
- [6] Sawyer, Lee. *Neutron-Enhanced Calorimetry for Hadrons (NECH)*. Dec 2005. DoE grant #: DE-FG02-99ER41117.
- [7] Toler, Benjamin. *Operation Manual for Cosmic DAQ*.
- [8] Toler Benjamin. *Data Acquisition for Neutron Enhanced Calorimetry for Hadron Particles*. Louisiana Tech University. College of Engineering and Science. May, 2009.