A Compton Spectrometer Experiment in Support of the NOνA Experiment Calibration Effort

Eric L. Flumerfelt

Department of Physics, University of Tennessee, Knoxville, TN 37996

Abstract

The NOνA experiment is part of the next generation of accelerator neutrino experiments. Liquid scintillators like those used in NOνA suffer from several effects which result in nonlinear response. NOνA uses in-situ muons to calibrate the detector, but the response can be suppressed by up to 15% for electrons, positrons, and gammas by these effects. There is an ongoing effort at the University of Tennessee to measure the non-linear response of the NOνA liquid scintillator. We measure both Birks coefficient and the UV re-emission properties of the scintillator (The UV re-emission measurements were a separate experiment performed by UT graduate student Philip Mason). These results will then be used in simulations to predict the response of the liquid scintillator to electromagnetic particles at incident energies up to several GeV.

Keywords:
NOνA Experiment, Compton spectrometer, scintillation counters, liquid scintillators

1. Introduction

Liquid scintillators such as those used in the NOνA Experiment [1] suffer from quenching of the signal and Cherenkov re-emission effects [2]. The quenching follows an empirical relationship first characterized by Birks (Equation 1 [3]), and is proportional to $\frac{dE}{dx}$. While Birks quenching tends to reduce the light seen for a given particle in the detector, Cherenkov re-emission has the opposite effect, increasing it. The Cherenkov light absorbed by the flours in the scintillator and re-emitted in the absorption range of the Wavelength-Shifting (WLS) fibers used in the NOνA cells. A series of experiments have been performed in order to precisely measure the response versus energy curve for the NOνA LS and the Cherenkov re-emission properties of the NOνA LS. These measurements were then integrated into the NOνA simulations and calibration, allowing for the energy of electromagnetic showers to be correctly simulated and reconstructed.

$$L = L_0 \ast \frac{dE}{dx} \left(1 + \beta \frac{dE}{dx}\right)$$

(1)
2. Theory

Cherenkov light is produced by a particle traveling faster than the local speed of light. Cherenkov light is produced in a cone whose opening angle is determined by the particle’s velocity and the optical properties of the medium (Equation 2).

\[ \cos \theta_C = \frac{1}{\eta \beta} \]  

We see from this equation that Cherenkov light emission only occurs for wavelengths where \( \beta \eta \) is greater than 1 \((\eta \text{ itself is a function of } \lambda)\). The number of Cherenkov photons produced is proportional to the velocity of the particle and the optical properties of the material, and is given by Equation 3.

\[ dN = \int_0^{\lambda_{\text{max}}} \left[ \frac{2\pi \alpha z^2}{A^2} \left( 1 - \frac{1}{\beta^2 n^2(\lambda)} \right) \right] d\lambda \]  

Where \( z \) is the charge of the particle and \( \alpha \) is the fine structure constant, equal to \( \frac{1}{137} \).

The quenching of the signal is due to the molecules in the scintillator reaching maximum excitation. Additional ionizing radiation starts to break down the scintillating components at this point, and no additional light is produced \([3]\). These effects are significantly different for muons (which have much lower \( \frac{dE}{dx} \), Figure 1), and the Compton Spectrometer measurement allows for the translation of in-situ calibration efforts (which are done using cosmic-ray induced muons) to absolute scale compatible with precision measurement of electron neutrino energy with the NO\( \nu \)A detectors through the reconstruction of electromagnetic showers. The light output of the scintillator is therefore given by Equation 4; it is proportional to the Cherenkov light plus the scintillation light from the energy deposited in the scintillator, corrected by Birk’s formula \((f(R, N_{\text{Cherenkov}}) \text{ denotes the UV re-emission of the scintillator, and is an empirically-measured quantity})\).

\[ L_{\text{total}} = L_{\text{Birks}} + f(R, N_{\text{Cherenkov}}) \]  

3. Compton Measurement

3.1. Overview

The Compton Spectrometer is a device used to test the response of a detector to electrons of known energy \([4]\). This is accomplished using a highly collimated \( ^{22}\text{Na} \) source and a coincidence detector that can be rotated about the center of the test detector (Figure 2). Requiring coincidence “selects” an electron
energy in the test detector determined by the initial gamma energy (for $^{22}$Na, either 511 keV or 1275 keV) and the angle between the beam-line and the coincidence detector (Eqn. 5).

$$E_{\text{kinetic}}^e = \frac{E_\gamma^2(1 - \cos \theta)}{m_e c^2 + E_\gamma(1 - \cos \theta)}$$

(5)

3.2. Upgrades

The Compton Spectrometer was first run at UT for the KamLAND experiment [2]. The Compton Spectrometer has since been upgraded with a Germanium detector in place of a NaI scintillator as the coincidence detector. Because of the different properties of semiconductor detectors, the DAQ chain for the coincidence detector had to be separated from the test detector (Figure 3), and software logic put into place to synchronize the two ADC units. The LabVIEW-based DAQ system was completely rewritten and multiple performance and organizational improvements were made, allowing the DAQ system to operate the detectors in an un-triggered calibration mode as well as the experiment’s coincidence mode.

4. Geant4 Model

The experiment was simulated using Geant4 (Figure 4). This simulation is used in conjunction with the results of a UV Monochromator experiment [2] to determine Birks quenching constant and UV re-emission coefficient in the NOvA scintillator. The full experiment is simulated in the Monte Carlo, and the Birks’ coefficient in the simulation is adjusted to match the data (Figure 5). As in neutrino experiments like NOvA, the Monte Carlo simulation informs the data analysis, in this case explaining a feature present in the data. Early versions of the Geant4 simulation used the Cherenkov re-emission and Birks coefficients found for KamLAND scintillator, as they have similar composition.

The Geant4 model has been configured to write its data files in the same format as the LabVIEW DAQ for the Compton spectrometer, so that a single analysis package can be run over both data and Monte Carlo simulations.

Once the simulation has been tuned to reproduce the data from the Compton Experiment, it will be run with those parameters for positrons and photons, allowing for histograms of observed energy versus true energy to be made for all of the constituents of an electromagnetic shower. This information will then be
integrated into the NOvA Monte Carlo, and corrections from this can be applied to data during E-M shower reconstruction in order to accurately reconstruct the energy of electron neutrinos in the detector.

5. Results and Analysis

The Compton Spectrometer has been run once through the full angular spectrum (0-120 degrees). The data from the LabVIEW DAQ was run through ROOT analysis scripts (Figure 6), and this result forms the initial sample for refining analysis techniques and as a sanity check on the Geant4 model. The primary features we expected to see are the triangle-shaped area denoting the full visible energy of the photon, and a deviation to high reconstructed energy for higher true energies, due to the Cherenkov re-emission. The UV monochromator experiment is still ongoing, but once it is complete, it will allow for accurate subtraction of these effects.

Because Compton scattering can be approximated as an elastic scattering event, we know that the energy of the recoil electron in the scintillator is simply the initial gamma energy minus the final energy we measure in the coincidence detector. Because the germanium detector has a very high spectral resolution, we can determine the electron’s “true” energy with very high precision. Therefore, for each energy level from the $^{22}$Na source, a new histogram can be created relating “true” energy to “observed” energy, based on a calibration of the scintillator performed with gamma sources. The nonlinear effects are then simply read off of this graph, as the full energy of the photon will lead to a “triangle” shape, with the Cherenkov re-emission effects causing a deviation to higher observed energy at low true energy.

The final variable in this experiment is the Birks quenching parameter, measured by deviations from unity of the reconstructed energy over the true energy for each point, after Cherenkov subtraction. A second run of the Compton Spectrometer is in progress, to increase the sample size and providing more data on the calibration of the liquid scintillator and translation between ADC units, deposited energy and the number of scintillation photons (for use in Equation 4).

6. Acknowledgments

I would like to thank my advisors Dr. Yuri Kamysshkov and Dr. Thomas Handler, the undergraduate students who have worked on this experiment, Cameron Erickson and Laura Gunderson, and Dr. Yuri Efremenko and the Physics Division of ORNL for providing the Germanium detector used as the coincidence detector. The UV Monochromator experiment was run by graduate student Philip Mason. This work was funded by the DOE Office of Science, through a grant to the University of Tennessee Department of Physics.
Fig. 5: Simulation results from the Geant4 model of the Compton Spectrometer

(a) Result of the model with Birks and Cherenkov effects turned off.

(b) Result of the model with Birks and Cherenkov effects turned on.

(c) True energy (from the PADC, assuming 511 keV line) versus reconstructed energy. (Geant4 Simulation)

(d) True energy (from the PADC, assuming 1275 keV line) versus reconstructed energy. (Geant4 Simulation)

Fig. 6: Analyzed data from the first run of the Compton Spectrometer

(a) Calibrated data, with the QDC on the horizontal axis and the PADC on the vertical.

(b) True energy (from the PADC, assuming 511 keV line) versus reconstructed energy.

(c) True energy (from the PADC, assuming 1275 keV line) versus reconstructed energy.
References

[1] Technical design report, Tech. rep., NOvA Collaboration.
URL http://www-nova.fnal.gov/nova_cd2_review/tdr_oct_23/tdr.htm

[2] O. Perevozchikov, Search for electron anti-neutrinos from the sun with kamland detector, Ph.D. dissertation, University of Tennessee (2009).

[3] G. Knoll, Radiation Detection and Measurement, 3rd Edition, Wiley, 2000.

[4] J. D. Valentine, B. D. Rooney, Design of a compton spectrometer experiment for studying scintillator non-linearity and intrinsic energy resolution, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 353 (13) (1994) 37 – 40. doi:http://dx.doi.org/10.1016/0168-9002(94)91597-0.
URL http://www.sciencedirect.com/science/article/pii/0168900294915970