CAPTURE-GATED NEUTRON SPECTROSCOPY WITH A NOVEL LITHIUM-GLASS-POLYMER COMPOSITE SCINTILLATION DETECTOR

A Thesis in
Nuclear Engineering
by
Jason T. Nattress

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Submitted in Partial Fulfillment of the Requirements for the Degree of Master of Science

December 2015
The thesis of Jason T. Nattress was reviewed and approved* by the following:

Igor Jovanovic  
Professor of Nuclear Engineering  
Thesis Advisor

Arthur T. Motta  
Professor of Nuclear Engineering and Materials Science and Engineering  
Chair of Nuclear Engineering

Marek Flaska  
Assistant Professor of Nuclear Engineering

*Signatures are on file in the Graduate School.
Abstract

The shortage of $^3$He, a gas widely used in neutron detectors, has stimulated the development of neutron detection technologies based on alternative materials. Although one type of detector may not be able to perform as excellent as $^3$He in every metric, a detector with modest absolute neutron detection efficiency combined with additional capabilities, such as spectroscopy, could potentially fill some of the need left from the dwindling supply. The key concerns in addressing this current need are speed, accuracy, and precision in detecting and measuring the properties of neutron sources. A major challenge facing the nuclear security community is the detection and characterization of special nuclear material for safeguards applications. Special nuclear material (SNM) emits both neutron and gamma radiation, but at a low rate. Gamma rays emitted by SNM can be readily shielded by high-Z materials. In contrast, fast neutrons can be more penetrating through high-Z materials, providing an opportunity for detection of SNM. Furthermore, the ability to measure neutron energy could enhance the ability to identify the presence of SNM, especially if neutron energy can be measured on an event-by-event basis.

In this work, the development of a fast neutron detector that can potentially provide direct energy measurement of the incident neutron on a single-event basis is discussed. A capture-gated technique is used to identify thermalization events of incident neutrons, which are representative of incident neutron energy. Specifically, spectroscopic measurements conducted with a glass-polymer composite neutron detector are examined and light yield as a function of incident neutron energy is characterized. The neutron scintillator constructed utilizes both pulse height and pulse shape discrimination to achieve outstanding gamma rejection, with one of
every $10^8$ gamma events misidentified as a neutron. Monte Carlo simulations were conducted to define capture gating timing acceptance windows and to substantiate the correlation of the total light output produced in neutron thermalization to the incident neutron energy. Other simulations were performed to show the relative capture efficiency at various neutron energies. The cylindrical detector used in this work is 5.08 cm in diameter and 5.05 cm in height and was fabricated using 1-mm square lithium glass rods and scintillating polyvinyl toluene. The light output produced when the detector was exposed to fast monoenergetic neutron sources has been measured using capture-gated coincidence techniques. The results of the simulations and experiments are discussed and the measurement potential of the detector is assessed.
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Acknowledgments

I would like to thank my advisor, Professor Igor Jovanovic, for his guidance and support in assisting me in my research and challenging me to do the best work possible. I would like to thank the Nuclear Material Science Group at the Pennsylvania State University, consisting of Albert Foster, Amira Meddeb, Cory Trivelpiece, and Zoubeida Ounaies, for fabricating the detector prototype and continuous input that aided to the success of this research. I also want to thank Tan Shi, a graduate student at the Pennsylvania State University, who assisted me with data fitting and Pieter Mumm, staff physicist at the National Institute of Standards and Technology, for his assistance with the measurements.

I would like to extend a special appreciation to my mentor and postdoctoral scholar working with me on the project, Michael Mayer, for his continuous guidance during my first few years as a graduate student and assistance with Geant4 and experimental analysis code development, without which this work would not have been possible.

I would like to acknowledge the United States Department of Energy, National Nuclear Security Administration, whose support funded this research under my appointment to the Nuclear Nonproliferation International Safeguards Graduate Fellowship sponsored by the National Nuclear Security Administration’s Next Generation Safeguards Initiative (NGSI). Lastly, I wanted to acknowledge the support by the National Science Foundation under Grant No. ECCS-1348366 and ECCS-1348328 and by the U.S. Department of Homeland Security under Grant Award Number 2014-DN-077-ARI079-02 and 2014-DN-077-ARI078-02, under which the collaborative project is funded.
Chapter 1  
Background and Modeling

1.1 Introduction

The neutron was discovered by James Chadwick in 1932 through a neutron-nucleus scattering interaction [1]. The nature of this experiment raised an opportunity to measure neutron energy, opening avenues for neutron spectroscopy. The measurement techniques and nuclear reactions that lead to the discovery of the neutron are still used to detect and measure neutron energy today.

Rapid and accurate identification and characterization of sources of fast neutrons is essential for nuclear counterterrorism, safeguards, and nonproliferation, as well as for basic research. Neutrons are highly penetrating through high-Z shielding and provide a powerful method for material interdiction, which is complementary to detection of gamma rays. Since the neutron spectra vary depending on their source, neutron spectroscopy can help distinguish among various spontaneous fission sources and the \((\alpha,\text{n})\) neutron sources. Further, by providing a direct energy measurement of the incident neutron spectrum, improved quantification and identification of nuclear material can be achieved and applied to a variety of problems in nuclear safeguards, such as compliance verification of arms control treaties and other agreements regarding the control, production, and processing of nuclear material [2].

The *de facto* standard for neutron detection has been the pressurized \(^3\text{He}\) tube due to its high efficiency, simplicity, and excellent gamma rejection. With the worldwide shortage of \(^3\text{He}\), the neutron detection community has an urgent need for alternative detection technologies that exhibit similar performance characteristics,
but are more readily available and inexpensive. This is especially of interest in many nuclear security applications, including detection of SNM, nuclear safeguards, and other nonproliferation scenarios, where the spectroscopic capability and neutron counting of $^3$He detectors have proved invaluable. Furthermore, the need for innovative detectors capable of high-fidelity particle identification, where size and shape of the detector are readily customizable and scalable exists in other areas of research and industry. Fast neutron detectors based on pulse shape discrimination in liquid scintillators and, more recently, plastics have also been demonstrated [3,4].

In this work, spectroscopic measurements of fast neutrons with a small, recently developed prototype composite scintillation detector based on a combination of lithium-doped scintillating glass and scintillating polyvinyltoluene (PVT) are presented. The design, fabrication, and characterization of the detector using a spontaneous fission source have been previously described in Ref. [5]. In the past, doped scintillators have been hindered with unexceptional gamma/neutron separation, which has limited their application as a substitute for $^3$He detectors [6]. The prototype detector used in this work is not a doped scintillator, but it builds on the advantages of a homogenous doped scintillator, such as its sensitivity to a wide range of neutron energies and high neutron reaction cross sections. Due to heterogenous composition of the composite scintillator, it is possible to overcome the usual limitation of poor gamma/neutron separation, providing an attractive technology that can at least partially address the $^3$He shortage.

1.2 Capture-Gated Detection

Scintillation detectors rely on the measurement of light produced in the interaction of particles with the detector material. The incident particles first interact in the scintillation medium, where all or a part of their kinetic energy is converted into scintillation light, typically in a range of 150 to 800 nm. The light is then directed towards a photodetector, undergoing reflection, absorption, and scattering along its path. The scintillation light that reaches the photodetector is converted into an electrical signal with a finite efficiency, after which this electrical signal is analyzed.

The capture-gated technique is based on the measurement of two consecutive signals that originate from the same neutron, where the second signal originates from neutron capture. In our detector, the first pulse is produced primarily by the
scattering of the neutron on hydrogen and carbon nuclei in the PVT scintillator. The collisions cause the neutron to slow down and approach the thermal energy region, where the cross section for neutron capture in the neutron sensitive material is significantly higher. The origin of the second pulse in our detector is the capture of the neutron in the Li-doped glass scintillator. Figure 1.1 shows two typical signals measured using the detector used in this work, where the pulse produced by neutron thermalization in PVT is shown in blue, while the second pulse in red, is produced by neutron capture on $^6\text{Li}$ in Li-doped glass. The time between the two pulses corresponds to diffusion of a neutron slowed down to near thermal energy. For the pulses in Fig. 1.1, the time difference was approximately 12 $\mu$s.

![Figure 1.1](image)

**Figure 1.1.** Two pulses that originate from the same neutron separated by approximately 12 $\mu$s. Each sample number corresponds to 2 ns, the time step of the CAEN DT-5730 digitizer used in the experiments. The first pulse in time is the result of neutron elastic scattering (in blue) and is followed by the second pulse, which is the result of neutron capture (in red). The scintillation decay times of pulses indicate the materials in which the majority of the energy depositions occurred. The pulses that are created in the PVT have fast decay times compared to the slower decay time in the Li-glass.

The thermalization (scattering) pulse, when associated with capture pulse by their inter-event time, can be correlated to the incident neutron energy and used to measure the incident neutron spectrum [7]. This unique signal comprising two consecutive pulses (thermalization and capture) is further identified by requiring a particular energy of the neutron capture event. The initial scatters of the fast
neutron in the detector happen in rapid succession, on order of a few tens of ns, producing a single scintillation pulse that carries information of the total energy deposited (the sum of nuclear recoils) and is related to the incident neutron energy. Although a nuclear recoil of carbon is possible, elastic neutron scattering on hydrogen (proton) at few-MeV energies is the most probable and results in largest average energy transfer [8].

The composite detector is comprised of both organic and inorganic materials. The light yield from identical charged particle interactions varies for each material. The light yield associated with the organic material, PVT, is of primary interest for spectroscopic measurements. The response of plastic scintillators is linear for electrons with energies greater than 125 keV, but nonlinear for heavy charged particles. The specific light output for a heavy charged particle, such as a proton, is always lower than that for an electron [9]. The absolute light yield is quantified in the units MeV electron equivalent (MeVee), where 1 MeVee is the amount of light produced by a 1 MeV electron. Full energy deposition of a 1 MeV proton produces significantly lower light output than 1 MeVee.

The response to charged particles in an organic scintillator can be described by

$$\frac{dL}{dx} = \frac{S}{1 + kB} \frac{dE}{dx}, \quad (1.1)$$

where $S$ is normal scintillation efficiency, $dL/dx$ is the fluorescent energy emitted per unit path length, $kB$ is an adjustable parameter, and $dE/dx$ is the specific energy loss for a specific charged particle. The relationship assumes that quenching occurs along the particle’s track due to the presence of a high ionization density, damaging molecules leading to a lower scintillation efficiency. Equation (1.1) is generally referred to as the Birk’s formula, where $kB$ can be fit to experimental data and is specific to the scintillation medium [8,9].

Neutron capture occurs with high probability only when the neutron is fully or nearly thermalized; as a result, restricting the neutron detection events to those that produce a capture pulse limits the events to those in which the thermalization pulse is due to complete deposition of the neutron kinetic energy in the scintillator. This complete energy deposition, however, does not generate an ideal peak in the differential spectrum of the produced scintillation light even when the incident neutrons are monoenergetic, which is primarily due to the nonlinearity of the...
scintillator and different collision histories of each neutron prior to capture.

1.3 The Composite Neutron Scintillator

Our lithium-loaded plastic detector is an extension of a neutron detector previously fabricated at Lawrence Livermore National Laboratory. In the preliminary work, an inorganic lithium-gadolinium-borate (LGB) scintillating crystals were embedded in a scintillating and non-scintillating plastic matrix. Fast neutrons incident on the composite scintillator have been first thermalized and then captured by high cross section nuclides, such as Li, Gd, or B. This demonstrated that two materials that do not intrinsically possess neutron–gamma discrimination can be combined and achieve a high degree of neutron–gamma separation through analysis of their pulse shape [10].

Alternatives to LGB were considered for a second prototype based on limited availability of depleted gadolinium; as a result, a lithium glass 5.08 cm by 7.62 cm detector was developed. It displayed pulse shape discrimination properties and achieved an efficiency of $5 \times 10^{-3}$. The detector was not optimized for neutron detection efficiency or spectroscopy, but it demonstrated the feasibility of a composite detector using enriched lithium glass and scintillating plastic [11].

The composite scintillator used in this experiment uses 1-mm square-aperture, 50.8-mm long GS20 Li-doped glass rods suspended in scintillating PVT (Eljen EJ-290). The glass constitutes a 6% mass fraction of the detector. The heterogeneous design and geometry of the composite material enables pulse shape discrimination of neutron captures from gamma-induced events and neutron recoils, since the two types of energy depositions occur preferentially in glass and PVT components of the detector, respectively. Since the scintillation decay times of GS20 glass and EJ-290 scintillator are different, the material in which the energy deposition takes place can be identified using the pulse shape. The slower scintillation decay time of the Li-glass results in an increased tail region of the pulse compared to a faster decaying pulse in the PVT. As a result, the ratio of the tail integral to the full integral for a neutron event occurring in the glass results can be easily identified.

Neutron-induced events are further discriminated from gamma events by the requirement for neutron capture. Once the neutron reaches thermal energies, the mean free path of a neutron in the Li-glass is approximately 230 $\mu$m, which is
smaller than the dimensions of the glass rod, resulting in high capture probability. The resulting heavy charged particles (HCPs) have ranges on the order of tens of µm, making the full energy deposition of HCP kinetic energy in the glass highly probable [12, 13].

The neutron sensitive material used in this composite is $^6$Li. The neutron capture reaction that takes place in our detector occurs on $^6$Li:

$$^6\text{Li} + n \rightarrow ^3\text{H} (2.05 \text{ MeV}) + ^4\text{He} (2.73 \text{ MeV}). \quad (1.2)$$

The choice of $^6$Li provides a high Q-value for the neutron capture reaction, producing high scintillation light yield in Li-doped glass scintillator, which uniquely identifies a neutron event simultaneously through pulse height and pulse shape. Furthermore, $^6$Li has a large thermal neutron cross section of approximately 940 b, making it an attractive choice for use as a capture agent.

A typical range of an energetic electron produced by interaction of a gamma ray with the composite detector greatly exceeds the transverse dimensions of the lithium glass rod. For example, a 1 MeV electron in a typical plastic scintillator (polyvinyltoluene based) is on order of a few mm [14]. Since the glass constitutes a relatively small fraction of the detector mass, the electrons deposit their energy primarily in the PVT material. Additionally, they can be readily distinguished by their pulse shape and the absence of the subsequent neutron capture pulse. Similar to gamma rays, the neutron recoils deposit their energy primarily in the PVT, but the requirement for a subsequent neutron capture pulse allows their discrimination from gamma rays.

Although many advances have been made in capture-gated neutron spectrometry, complex unfolding techniques are still heavily relied upon to measure the neutron spectra. This thesis discusses the measurement of neutron energy on an event-by-event basis without spectral unfolding in a mixed radiation field with a unique composite detector. The composite detector shows promise not only as a potential substitute for $^3$He detectors, but also for use in a fast neutron spectrometer.
1.4 Monte Carlo Simulations

Monte Carlo simulations of the detector were performed using the Geant4.10.0.p1 framework [15]. The exact composition and geometrical configuration of the fabricated detector was adopted from Ref. [5] and the response to 2.45 MeV and 14.1 MeV monoenergetic neutrons was studied. Simulations were used to calculate the neutron capture efficiency, time to neutron capture, and the neutron energy at capture. The ratio of neutron energy lost to thermalization prior to capture and the incident neutron energy was examined to help interpret the neutron spectroscopic measurements.

For calculating the capture efficiency, a fan beam of monoenergetic neutrons was directed towards the side of the composite detector, and the number of neutron captures was tallied. The calculated efficiencies were $2.1 \times 10^{-3}$ for 2.45 MeV neutrons (based on $10^6$ simulated neutrons) and $3.7 \times 10^{-4}$ for 14.1 MeV neutrons (based on $5 \times 10^7$ simulated neutrons). Figure 1.2 shows the simulated detector geometry and neutron particle source (referred at the neutron particle gun in the Geant4 framework) directed to the side of the cylindrical detector. 14.1 MeV neutron trajectories are shown in red.

Figure 1.2. Geant4 Monte Carlo simulation of composite detector of dimensions matching that of the fabricated prototype detector. The 14.1 MeV neutron trajectories are represented in red. The neutron particle source is directed towards the side of the detector. Neutrons scatters are readily observable in the figure.

Figure 1.3 shows the energy-dependent neutron capture cross section on $^6$Li,
exhibiting a characteristic $1/v$ behavior. Although a neutron can undergo capture on $^6$Li at any energy, the probability of capture decreases rapidly with energy (the cross section for neutron at thermal energies is on the order of $10^3$ b and drops to be on the order of $10^{-1}$ b at 2 MeV) [16]. This dependence of the capture cross section on neutron energy results in a strong correlation of the total scintillation light yield produced by neutron thermalization in the PVT to the incident neutron energy. In Figure 1.4, the simulated neutron energy spectrum at the time of neutron capture is shown. The neutron resonance in $^6$Li centered at 0.25 MeV increases the probability of neutron absorption and is visible in the spectrum, but constitutes a small fraction (<1%) of the events. A large majority of neutrons undergo nearly complete thermalization prior to capture; the simulation shows that 76% of the neutrons that are captured deposit >99% of their original energy. The simulation results have also been analyzed for 14.1 MeV neutrons, arriving with a nearly identical result. Figure 1.5 further illustrates the fact that a capture is likely only after a neutron has deposited nearly all of its kinetic energy in the detector. For a sequence of interactions that end in neutron capture, the ratio of thermalization energy and the incident neutron energy approaches unity, and therefore the total

![Figure 1.3. $^6$Li capture cross section as a function of incident neutron energy. A resonance is present at approximately 250 keV [16].](image)
Figure 1.4. Simulated energy of a neutron at the time of capture in the composite detector. The incident neutron energy is 14.1 MeV. The majority of capture events occur at low energies.

scintillation light output of the thermalization pulse is representative of complete energy deposition of the neutron. The simulated time distribution between the

Figure 1.5. Simulated ratio of neutron thermalization energy to incident neutron energy in the composite detector (50×10⁶ 14.1 MeV neutron events).

first scatter of a neutron and its capture for incident neutron energies of 2.45 MeV and 14.1 MeV is shown in Fig. 1.6. For both energies, the mean time to capture calculated from the simulation results is approximately 2.6 µs. A time acceptance window for correlated (thermalization followed by capture) event in the data analysis
was set to 40 µs, which includes >99% of all thermalization events that lead to neutron capture.

Figure 1.6. Simulated distribution of the time to capture for (a) 2.45 MeV and (b) 14.1 MeV neutron incident on the detector.
Chapter 2  
Experiment

2.1 Experimental Site
All measurements were performed at the National Institute of Standards and Technology Californium Neutron Irradiation Facility located in Bethesda, Maryland. The room where the measurements were conducted had a footprint of approximately 5 m × 5 m × 5.9 m. The room was located underground at a 10 meter water equivalent depth and lined with anhydrous borax on the floor, ceiling, and all walls to reduce the potential neutron room scatter during the experiments. The combined effect of both the overburden and boron lining provide an ideal environment for neutron spectroscopic measurements [17].

2.2 Neutron Sources
Monoenergetic neutrons were produced from DD and DT fusion reactions at energies of 2.45 MeV and 14.1 MeV, respectively. The DD generator used was Thermo Electron Model P-325 and it was operated at a current of 100 μA and voltage of 100 kV, producing approximately 10^6 neutrons/s. The DT generator used was a Thermo Scientific Model P-38 and was operated at a current of 50 μA and a voltage of 50 kV, producing a neutrons at a rate on the order of 10^8. The DT and DD generators emit a nearly isotropic neutron flux; no shielding or collimation was used in the experiment so that the neutron spectrum incident on the detector is not perturbed.
2.3 The Neutron Detector

The dimensions of the composite cylindrical detector fabricated for testing are 5.05 cm by 5.08 cm for height and diameter, respectively. The neutron sensitive material used is in the form of GS20, which is lithium-doped glass enriched to approximately 95% in $^6$Li. The lithium glass is in a square rod geometrical form with a $1 \times 1$ mm$^2$ size, with length equal to the height of the detector. The material surrounding the rods is EJ-290, a scintillating PVT plastic, providing moderation and enabling the spectroscopic measurements. If simple neutron counting is the only performance concern, non-scintillating PVT could be utilized to sustain higher count rates, as well as improved neutron/gamma discrimination. The ratio of lithium glass to PVT is 6% by weight, with the rods placed in a pseudo-square array.

Optical transparency was achieved by choosing materials with particular, similar optical properties, specifically the index of refraction. The indices of refraction of the two materials match within 1% at 1.56 and 1.58 for the Li-glass and PVT, respectively. Materials and methods were chosen for detector fabrication to be relatively economical, straightforward, and rapid.

The fabrication of the solid–state, lithium glass–PVT composite uses a fabricated plastic mold for structural support, consisting of a glass wall and 3D-printed base and lid. The 3D printed mold is made with a heat resistant material and of suitable composition to withstand the harsh chemical environment created by the toluene used in the polymer mixing kit. Figure 2.1 shows the mold with the top and bottom plates. The plates are printed with a mirrored hole pattern on the top and bottom for rod placement and alignment. Figure 2.2 further shows the latter stage with the placement of the glass rods prior to addition of PVT. The fabrication process of the GS20–PVT composite begins by dissolving the catalyst into the solvent/monomer solution in a separate container than the mold. This process was completed in accordance with instructions provided by Eljen Technologies, the manufacturer of the product. Once the solution is thoroughly mixed, it is degassed overnight under vacuum to remove excessive air bubbles that may have been introduced during the mixing process. The solution is then poured into the mold where the GS20 rods are secured in the plastic top and bottom plates.

Prior to curing, further degassing is performed to remove any remaining bubbles to achieve optical transparency. The sample is then cured at 65 °C and post-cured
Figure 2.1. Empty mold before adding the PVT, showing the top and bottom plates used to secure the lithium glass rods [5].

Figure 2.2. Glass mold provides the structural support prior to adding of PVT [5].
at 80 °C under nitrogen. Following the curing process, the sample is cured again for an additional 8 hours and then polished. Figure 2.3 cured composite prior to cutting and polishing. Figure 2.4 shows a top view of the fabricated detector exposed to an ultraviolet lamp.

**Figure 2.3.** Illustration of the curing process [5].

**Figure 2.4.** Fabricated composite neutron scintillator. Blue scintillation is observed under ultraviolet illumination. [5].
2.4 Experimental Setup

The detector was placed on a metal stand 220 cm above the ground and positioned in the room as depicted in Fig. 2.5. The DD generator was positioned directly above the detector, approximately 110 cm from the circular face opposite of the PMT. The detector position remained unchanged for the DT measurements. The DT generator was located in the corner of the room, with the shortest distance to the side of the detector of 200 cm. Figures 2.6 and 2.7 are photographs taken of the experimental setups for the DD and DT measurements.

DT measurements were conducted for a total time of 14.1 hours in four separate data runs. One DT data run was conducted overnight. The DD experimental time totaled 9.36 hours with nine individual data runs all completed under continuous observation. For both neutron sources, the individual data files were combined in the analysis to provide adequate statistical support for the results. A control station was located approximately 10 meters from the location of the borax-lined room, where the neutron generators and data acquisition systems were remotely operated. A camera was available to monitor the digital electronics for proper operation.

Figure 2.5. Illustration of the placement of the detector (Det), DD generator, and DT generator in the experiment. Illustrations are not drawn to scale. a) Horizontal positioning of detector with respect to the DT generator. The DT generator was placed on the floor of the room.
2.5 Calibration

The detector was calibrated in accordance with the methodology outlined in Ref. [18]. Due to the low atomic number of the constituents of the PVT, the photopeak is rarely observed. A gamma typically undergoes one Compton scatter prior to exiting the detector, resulting in a Compton edge with a broad and asymmetric structure. PVT-based detectors are thus calibrated using the Compton edge region through implementation of an algorithm outlined in Ref. [18], and which is based on the ratio of the Compton maximum and Compton edge positions.

The Compton edge is associated with the maximum energy transfer of an incident photon to an electron in a single Compton scatter. The maximum energy transfer occurs at an angle equal to $\pi$, and the energy observed in the detector is
calculated as follows:

\[
E_c = h\nu - E_e = \frac{h\nu}{1 + 2h\nu/m_0c^2},
\]

where \(h\nu\) is the energy of the incident photon and \(m_0c^2\) is the rest mass equivalent energy of an electron. The two gamma sources used for calibration were \(^{137}\)Cs and \(^{60}\)Co, with Compton edge energies at 477 keV for \(^{137}\)Cs and a median value of 1040 keV for \(^{60}\)Co. The electron equivalent energies as measured by the scintillation light output were identified and used to develop a linear calibration fit. The calibration fit was applied to measured neutron spectra to express them in units of electron equivalent energy. Figures 2.8 and 2.9 show the calibrated full energy spectra of \(^{137}\)Cs and \(^{60}\)Co, respectively. The Compton maxima are observed above
the Compton edges of 477 keVee and 963 keVee for their respective spectra.

**Figure 2.8.** Light output spectrum of $^{137}$Cs used for calibration at Compton edge equivalent energy of 477 keVee.

**Figure 2.9.** Light output spectrum of $^{60}$Co used for calibration at Compton edge equivalent energies of 963 keVee.
2.6 Electronics and Data Acquisition System

The fabricated composite scintillator was coupled to a Hamamatsu R6231-100 photomultiplier tube (PMT) with optical grease and wrapped with Tyvek to provide optimal reflection. Tyvek was chosen based on its high reflectivity at wavelengths near 400 nm, matching the scintillation spectrum of the composite detector. Figure 2.10 shows the reflectivity of some common materials used in constructing scintillation detectors. An layer of black Tedlar was used to isolate the detector from external light. The PMT was connected to a CAEN DT5533 desktop high voltage power supply and a CAEN DT5730 14-bit 500 MS/s digitizer for data acquisition (DAQ). Full waveform data were collected with the acquisition time set to 400 ns. A pre-trigger of 80 ns was used to determine the waveform baseline. The digitizer used the standard CAEN firmware package and a ROOT-based graphical interface for DAQ [20]. The DAQ was externally triggered at 0.0633 Hz, with the external clock reset at the beginning of each new external trigger signal. Timing information for each event was saved as well as a total running clock for the experiment. Pulses were processed using a custom analysis code.

![Figure 2.10. Reflectivity of commonly used reflectors [19]](image_url)

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Chapter 3  
Data Analysis

3.1 Pulse Shape Analysis

Pulses were analyzed on an event by event basis. The pulse shape parameter ($PSP$) was defined by

$$PSP = \frac{Q_{\text{tail}}}{Q_{\text{full}}},$$  \hspace{1cm} (3.1)

where total pulse area, $Q_{\text{full}}$, was calculated by integrating the pulse starting at 20 ns prior to the pulse peak and up to the end of the entire record length (400 ns). $Q_{\text{tail}}$ was calculated by performing a partial integration starting 16 ns after the pulse peak to the remainder of the event and up to the end of the entire record length (400 ns). Figure 3.1 shows a typical pulse measured with the composite detector. The start integration limits are identified for the full integral and tail integral at $t_0$ and $t_1$, respectively. The integration window is terminated at $t_2$ for both the full and the tail integral.

Particle identification relies on the localization of the event in the $PSP$ – Energy space. The scintillation properties of two different components of the detector (PVT and Li-doped glass) coupled with the preference for energy deposition of different particles in different detector components results in a greater tail integral for neutrons, therefore producing a higher $PSP$ value in neutron events. The capture reaction of a neutron on $^6$Li also produces a unique energy deposition value and provides an additional means to discriminate between the particle types.
3.2 Analysis Cuts

The waveform data were processed using a custom analysis code to calculate and subtract the waveform baseline and subsequently determine the pulse height, pulse peak position, and the $PSP$ value. Baseline was calculated and subtracted on an event by event basis using the first 30 ns of the waveform, which corresponds to pre-trigger component of the record.

Several cuts were applied in the analysis to ensure the data quality. The first is the pulse peak position cut, verifying the correct operation of the DAQ trigger such that the entire pulse is captured within the length of the individual waveform. A Gaussian distribution was fitted to the distribution of all peak pulse locations, and a $3\sigma$ cut was applied; all pulses with a peak position falling outside of this $3\sigma$ cut were rejected. A mean value of the peak position was found at a sample number of approximately 72 with $\sigma = 3.2$. Figure 3.2 shows the Gaussian fit (red) to all events for an individual DD data run of approximately one hour duration. The horizontal axis in this plot is in the units of sample number, with one sample number being equal to the timing resolution of the digitizer used in the measurements (2 ns).

The timing cut was applied next to remove the majority of uncorrelated events. The time acceptance window of 40 µs was selected to include 99% of all thermalization pulses prior to capture, as predicted by Monte Carlo simulation.

In Fig. 3.3, the result of the analysis from a fraction of the measurements...
Figure 3.2. Peak position of all pulses recorded during a DD experiment of approximately 1 hour. The horizontal axis unit is the sample number, where one sample number corresponds to 2 ns. A Gaussian distribution is fit to the data (red). The mean of the pulse peak position is 72 with $\sigma = 3.237$.

counted with 14.1 MeV neutrons is shown. The neutron capture events are localized at a mean $PSP \approx 0.6$ and mean $E \approx 0.47$ MeVee. A double Gaussian was fitted to the neutron region and a $3\sigma$ cut applied. Only events that remain after this cut are identified as accepted as neutron captures. The preceding 40 $\mu$s is scanned for thermalization events and they are accepted if present.

The events that have been preselected through the trigger event and inter-event time cuts are subsequently classified by their $PSP$ and light output. The region in Fig. 3.3 at $0.1 < PSP < 0.2$ is attributed to events that occur in the PVT component of the scintillator, while the region at $0.4 < PSP < 0.5$ and $0.5$ MeVee<Light Output$<0.6$ MeVee is attributed to neutron captures in the GS20 glass component of the scintillator. A double Gaussian was fitted to the neutron region and a single Gaussian to the PVT region. Figure 3.4 shows the Gaussian fit in red for the events occurring in the PVT region, where the $PSP$ value was tallied focused on the lower light output band. The Gaussian fits are applied to those two characteristic regions in the data to separate the neutron captures from events depositing energy primarily in PVT (nuclear and electronic recoils from neutron scatters and gamma interactions, respectively). The results of the fit are reported in Table 3.1.

The events within $3\sigma$ of the cuts defined in this manner are accepted. It is also verified that two consecutive events are not both identified as neutron captures;
Figure 3.3. Experimental results of a fraction of the measurement conducted with 14.1 MeV neutrons prior to $PSP$ and energy cuts. The neutron captures are approximately centered at a light output of 0.5 MeVee and a $PSP$ value of 0.6. Since neutron recoil and gammas primarily interact in the PVT, their associated events both populate the same lower $PSP$ band centered at 0.16.

Figure 3.4. Experimental results of a subset of the measurement conducted with 14.1 MeV. The events are approximately centered at a lower $PSP$ band centered at 0.16. A Gaussian distribution is shown in red.
Table 3.1. Event cuts

<table>
<thead>
<tr>
<th>Event Type</th>
<th>$\langle PSP \rangle$</th>
<th>$\sigma_{PSP}$</th>
<th>$\langle E \rangle$ (MeVee)</th>
<th>$\sigma_E$ (keVee)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Captures (GS20)</td>
<td>0.606</td>
<td>0.034</td>
<td>0.469</td>
<td>0.028</td>
</tr>
<tr>
<td>Recoils (PVT)</td>
<td>0.161</td>
<td>0.026</td>
<td>–</td>
<td>$\infty$</td>
</tr>
</tbody>
</table>

in such case the later event is rejected. In addition, it was possible for accidental coincident events to occur in the time acceptance window. This occurrence was accounted for by selecting the spectra for the time window from 40 $\mu$s to 80 $\mu$s and subtracting the associated calibrated thermalization energy spectrum to remove uncorrelated background events.

Figure 3.5 show the results of DD and DT measurements after all analysis cuts. The figure shows both the thermalization and capture events. The DD results are filtered to 24368 events, which is 0.06% of the number of events in the raw data. The DT experiment yielded 19568 events after application of all cuts, approximately 0.07% of the number of all collected raw data.

In Fig. 3.5, the extension of the Light Output axis in units of MeVee is made to better visualize the neutron capture island. The thermalization events for the 14.1 MeV neutrons extend out past 10 MeVee and are shown in Fig. 3.6.
Figure 3.5. Final \textit{PSP} results after implementation of all data cuts. a) 2.45 MeV and (b) 14.1 MeV neutrons.
Figure 3.6. Thermalization events after all data cuts from the DT source. Thermalization spectrum extends to much higher energies in comparison to that measured using the DD source.
Chapter 4  |  Results

4.1 Gamma-Neutron Separation Performance

The capture gated detection scheme utilized in these measurements relies on the identification of a neutron event to initiate the analysis. Misinterpretation of a gamma event as a neutron thermalization event could affect the resulting capture gated spectra, making the discrimination between events taking place in PVT (gamma-induced electron recoils and neutron-induced proton recoils) and Li-doped glass (neutron captures) a critical performance measure of the detector. The degree of separation of those two classes of events is quantified by a figure of merit (FOM), defined as

\[
FOM = \frac{d}{FWHM_{\text{recoil}} + FWHM_{\text{capture}}},
\]

where \(d\) is the distance between the recoil and capture region centroids and \(FWHM\) is the full-width-half-maximum of the two fitted Gaussian distributions of the two independent regions, shown in red in Fig. 4.1 [21]. The FWHM for a Gaussian distribution is defined as \(2.35\sigma\), where \(\sigma\) is the standard deviation of the distribution. Thus, the measure of the ability to distinguish between gamma and neutron events is related to the ability to distinguish between thermalization and capture events occurring in the PVT and lithium glass, respectively. The Gaussian fit was applied to the PVT event region \(0.06 < PSP < 0.3\), with a mean value of 0.16 and \(\sigma = 0.026\). The neutron capture region’s Gaussian fit was applied in the range of \(0.52 < PSP < 0.68\), resulting in a mean value of 0.6 and \(\sigma = 0.035\).

The calculated FOM for the detector is 3.03. Table 4.1 shows FOMs for some existing neutron detectors compared to the composite detector used in the
Figure 4.1. Gaussian fits to the thermalization and capture regions are shown in red. The fit to the thermalization region spans from $PSP$ values of 0.06 to 0.3 with a mean value of 0.16 and $\sigma = 0.026$. The capture region fit is applied to the range of $PSP$ values from 0.52 to 0.68, resulting in a mean value of 0.6 and $\sigma = 0.035$. The inset displays the magnified neutron region where the fit was performed.

measurements discussed. Table 4.1 is not an inclusive list, but it still allows a comparison of gamma-neutron separation performance to be made with some common detectors, including capture-gated and non-capture-gated.

Table 4.1. Comparison of calculated FOM with selected literature [22–24]. $^a$ FOM calculation places a lower cut in light output at 100 keVee.

<table>
<thead>
<tr>
<th>Work</th>
<th>Detector Type</th>
<th>FOM</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>Li-PVT Composite</td>
<td>3.03</td>
</tr>
<tr>
<td>Pawelczak et al. (2014)</td>
<td>Boron loaded plastic</td>
<td>1.4</td>
</tr>
<tr>
<td>Nyibule et al.</td>
<td>EJ-299-33 Plastic</td>
<td>0.8$^a$</td>
</tr>
<tr>
<td>Pawelczak et al. (2013)</td>
<td>EJ-309</td>
<td>1.32</td>
</tr>
</tbody>
</table>
4.2 Inter-event Timing

The random time distribution between consecutive events behaves as a Poisson statistical process. The time interval distribution function of uncorrelated events is defined by

\[ I_0(t)dt = r \exp(-rt)dt, \quad (4.2) \]

where \( t \) is the length of the time interval and \( r \) is the average rate of event occurrence [9]. Monte Carlo simulation predicts that for >99% of all neutron events that lead to capture, the capture happens within 40 \( \mu \)s of the beginning of the first neutron scatter. A plateau in the experimental inter-event time distribution is observed after after 40 \( \mu \)s due to the uncorrelated events. The exponential fit defined in Equation (4.2) was made based on the range of data between 40 \( \mu \)s and 80 \( \mu \)s of the experimental inter-event time distribution and extrapolated to the range of between 0 \( \mu \)s and 40 \( \mu \)s for uncorrelated event subtraction. The fit is shown in red in Fig. 4.2 for a fraction of the DT measured data.

\[ \text{Counts} \]
\[ \log \text{Counts} \]
\[ \text{Time(\mu s)} \]

Figure 4.2. An exponential function was fit to the distribution between 40 \( \mu \)s to 80 \( \mu \)s. The function was extrapolated to the region between 0 \( \mu \)s and 40 \( \mu \)s for subtraction of the accidental coincidences.

Figure 4.3 (blue) shows the time-to-capture distribution of a subset of the DT experimental data. The distribution shown in blue is the time difference between a capture reaction and a correlated thermalization event following all data.
cuts, except the correction for uncorrelated events. The accidental coincidence event rate of adjacent pulses is evident. Overlaid in Fig. 4.3 (red) is the time-to-capture distribution after the fit to the accidental rate, as shown in Fig. 4.2, is subtracted. Figure 4.4 shows the experimental inter-event time distribution

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure4_3}
\caption{Measured time-to-capture for 14.1 MeV neutrons. Blue – no accidental correction; red – accidental events subtracted.}
\end{figure}

(after the correction for accidental rate), along with the Monte Carlo calculated time-to-capture distribution for comparison. Monte Carlo results were obtained by simulating \(5 \times 10^7\) 14.1 MeV neutrons. Each distribution is normalized to the integral of the distribution ranging from 0.2 \(\mu\)s to 250 \(\mu\)s. The start point of integration, 0.4 \(\mu\)s, is required due to the length of the record length of the DAQ chosen for the measurements. Figure 4.4 shows good agreement between simulation and experimental results. A good agreement between experimental and simulation results is present in the 2.45 MeV (DD) results as well.

### 4.3 Neutron Energy and Light Output

The reconstructed capture gated spectra for 2.45 MeV and 14.1 MeV neutrons are shown in Fig. 4.5. Both spectra have been obtained with background subtracted and all cuts applied. Distinct peaks are apparent in both capture gated spectra, corresponding to two neutron energies used in the experiment. Gaussian fits have
been applied to the two peaks, resulting in the electron-equivalent light yield of 0.62 MeVee and 8.97 MeVee for 2.45 MeV and 14.1 MeV neutrons, respectively. The fits were performed in the energy range between 0.5 MeV and 0.6 MeV for the DT neutrons and between 8.5 MeV and 9.7 MeV for DD neutrons. A nonlinear response of the EJ-290 scintillator to deposited neutron energy is apparent from the measured light yield at those two discrete neutron energies.

A first-order fit of the Birk’s formula was performed using the two points obtained in Fig. 4.5. Numeric integration for step sizes of 0.1 keV were carried out for the fit with total stopping powers, $dE/dx$, for PVT obtained from the NIST P-Star database [14]. The fitting parameter, $kB$, was found to be 0.02 g/MeV cm$^2$ and the scintillation light efficiency, $S$, equal to 1.2 MeVee/MeV. The results of the fit are shown in Fig. 4.6, where the correlation between the light emitted per unit length is defined by

$$\frac{dL}{dx} = \frac{1.2}{1 + 0.02} \frac{dE/dx}{dE/dx}.$$  \hspace{1cm} (4.3)

The $kB$ fitting parameter obtained is in good agreement with values reported in literature, shown in Table 4.2 [25].
Figure 4.5. Capture gated thermalization spectra of (a) 2.45 MeV and (b) 14.1 MeV neutrons. Gaussian fits are shown in red.

Table 4.2. Comparison of first-order fit of Birk’s constant from experimental data and literature [25].

<table>
<thead>
<tr>
<th>Work</th>
<th>Energy (MeV)</th>
<th>$kB$ (g/MeV cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>This work</td>
<td>2.45-14.1</td>
<td>0.02</td>
</tr>
<tr>
<td>Torrisi</td>
<td>5-62</td>
<td>0.0207</td>
</tr>
<tr>
<td>Craun and Smith</td>
<td>0.35-15</td>
<td>0.0131</td>
</tr>
<tr>
<td>Gooding et al.</td>
<td>28-148</td>
<td>0.0132</td>
</tr>
<tr>
<td>Badhwar et al.</td>
<td>36-220</td>
<td>0.0126</td>
</tr>
</tbody>
</table>
Figure 4.6. Light output in units of MeVee as a function of neutron energy. The two points are the mean values of the Gaussian distributions fitted in Fig. 4.5. A function is fit to the experimental data with the adjustable fitting parameter, $k_B$, equal to 0.022 g/MeV cm$^2$. 
Chapter 5  |  Summary and Outlook

In this work, neutrons of two discrete energies were measured with a composite detector comprised of enriched lithium-doped scintillating glass and scintillating PVT. Monte Carlo simulations were performed to assess the time correlation between thermalization and capture pulses, enabling spectroscopic measurements using this composite detector. As a result of the different scintillation decay times of the two materials used in the detector, the capture events in lithium-doped glass scintillator and the preceding thermalization events are accurately identified. The thermalization spectrum shows distinct neutron peaks for both 2.45 MeV and 14.1 MeV neutrons with electron recoil-equivalent light output of 0.62 and 8.97 MeVee, respectively. The broadening of the peaks in the energy spectra at 2.45 MeV and 14.1 MeV is partially caused by the variation in collision history that an incident neutron can incur. Monte Carlo simulation assists in understanding the most probable collision history and specific light output associated with particular histories. A nonlinearity in the scintillation light output as a function of deposited neutron energy has been observed and a relationship established through experimental fitting of the Birk’s constant, $k_B$. Additional measurements at intermediate neutron energies could help to more accurately characterize this nonlinearity. Furthermore, time of flight measurements using radioisotope sources could be used to characterize the light response to a range energies below 2 MeV. Given the consistency of light output for a given neutron energy, a promising application of this detector could be event-by-event reconstruction of the neutron energy and spectrum, without the use of spectral unfolding methods that are needed in recoil-based detectors. If scaled to larger volumes, the increased intrinsic neutron efficiency combined with spectroscopic capability would make the composite detector discussed a more
attractive alternative to $^3$He neutron counters for specific applications in nuclear safeguards.
Bibliography


Appendix A
Geant4 Analysis Code

//This program is to calculate the number of capture events where an
alpha or a triton is produced in a Geant4 simulation..... written by:
J. Nattress
#define delayedneutron_cxx
#include "delayedneutron.h"
#include <iostream>
#include <fstream>
#include <TROOT.h>
#include <TStyle.h>
#include <TRint.h>
#include <TApplication.h>
#include <TFormula.h>
#include <TChain.h>
#include <TString.h>
#include <TF1.h>
#include <TH1.h>
#include <TH2.h>
#include <TH3.h>
#include <TFile.h>
#include <TMath.h>
#include <TCanvas.h>
#include <TString.h>
#include <TGraphErrors.h>
#include <TVector3.h>
#include <TLorentzVector.h>
#include <TDirectory.h>
#include <TLine.h>
#include <algorithm>
#include <vector>
using namespace std;

int ncounts=0;
int capturecounts=0;
int alphacounts=0;
int Tcounts=0;
int ratiocounts=0;
int eventcheck=0;
bool tnflag=true; //is there a thermal neutron event already this event
bool capflag=true; //is there a capture in this event already in this event
bool Tflag=true;
bool alphaflag=true;
bool ratioflag=true;
double nen;
bool nen_flag;

int main(int argc, char** argv)
{
    //set style and color scheme for root
    gROOT->SetStyle("Plain");
gStyle->SetPalette(1);
delayedneutron pass1;
cout="Starting to perform analysis"
"<<endl;
//pass0.Loop();
pass1.Loop();
cout="Analysis has finished"
"<<endl;
}

void delayedneutron::Loop()
{
number 12
In a ROOT session, you can do:

```c
Root > .L delayedneutron.C
Root > delayedneutron t
Root > t.GetEntry(12); // Fill t data members with entry
```

// // // //
//
//
// Note that the argument to GetEntry must be:
Root > t.Show();
Root > t.Show(16);
Root > t.Loop();
// Show values of entry 12
// Read and show values of entry 16
// Loop on all entries
This is the loop skeleton where:
jentry is the global entry number in the chain
ientry is the entry number in the current Tree
//
//
//
// METHOD1:
// fChain->SetBranchStatus("*",0); // disable all branches
// fChain->SetBranchStatus("branchname",1); // activate branchname
// METHOD2: replace line
// fChain->GetEntry(jentry); //read all branches
//by b_branchname->GetEntry(ientry); //read only this branch
if (fChain == 0) return;
```
//The Set-up code goes here
Long64_t nentries = fChain->GetEntriesFast();
Long64_t nbytes = 0, nb = 0;

jentry for TChain::GetEntry
iencey for TTree::GetEntry and TBranch::GetEntry
To read only selected branches, Insert statements like:
for (Long64_t jentry=0; jentry<nentries;jentry++) {
    Long64_t ientry = LoadTree(jentry);
    if (ientry < 0) break;
    nb = fChain->GetEntry(jentry); nbytes += nb;
    // if (Cut(ientry) < 0) continue;
    //The Loop code goes here
    if(eventID!=eventcheck){
        //this is stuff to clear after each event (i.e., a
        new neutron fired)
        eventcheck=eventID;
        tnflag=true;
        capflag=true;
        alphaflag=true;
        Tflag=true;
        nen_flag=true;
        ratioflag=true;
        nen=999999.;
    }
    if(pdgNum==2112&&nen_flag){
        nen=kineticE;
    }
    if(pdgNum==2112&&kineticE<=0.000025&&tnflag){//in keV
        cout<<kineticE*1000.<<endl;
        ncounts++;
        cout<<nen<<endl;
        tnflag=false;
    }
    if(pdgNum==1000020040&&alphaflag&&volumeName[1]=='L'){//
alphacounts++;
if(nen<122.5){
   ratiocounts++;
}
   //cout<<kineticE/1000."<<nen*1000."<<endl;
   alphaflag=false;
}
if(pdgNum==1000010030&&Tflag&&volumeName[1]=='L'){ //
   Tcounts++;
   Tflag=false;
}
if(!alphaflag&&!Tflag&&capflag){//if there is an alpha and triton and no captured yet
   capturecounts++;
   capflag=false;
}
/*if(pdgNum==2122&&kineticE<=24.5&&ratioflag){ //if (pdgNum==1000010030){
   ratiocounts++;
   ratioflag=false;
} */
//} }*/

   //The wrap-up code goes here
   cout<<"You have "<<ncounts<<" thermal neutrons in this run."<<endl;
   cout<<"You have "<<capturecounts<<" capture events in this run."<<endl;
   cout<<"You have "<<alphacounts<<" alpha capture events in this run."<<endl;
   cout<<"You have "<<Tcounts<<" T capture events in this run."<<endl;
   cout<<"you have "<<ratiocounts<<" ratio counts"<<endl;
#define analyzer_cxx
#include "analyzer.h"
#include <TStyle.h>
#include <TRint.h>
#include <TApplication.h>
#include <TF1.h>
#include <TH1.h>
#include <TH2.h>
#include <TH3.h>
#include <TFile.h>
#include <TMath.h>
#include <TCanvas.h>
#include <TString.h>
#include <TGraphErrors.h>
#include <TVector3.h>
#include <TLorentzVector.h>
#include <TDirectory.h>
#include <TLine.h>
#include <TKey.h>
```cpp
#include <TSystem.h>
#include <TError.h>
#include <iostream>
#include <fstream>
#include <vector>
#include <string>
#include <sstream>
#include <iostream>
#include <fstream>
using namespace std;

TGraph *graph;
char gname[256];
vector<int> x;
vector<int> y;

int main(int argc, char **argv){
  analyzer t;
  t.Loop();
  return 0;
}

void analyzer::Loop()
{
  cout<<"Please input the filename that you want to output:";
  TFile *ROOTFile;
  string OutFileName;
  cin>>OutFileName;
  //OutFileName="out.root";
  ROOTFile = new TFile(OutFileName.c_str(),"RECREATE");
  ROOTFile->SetCompressionSettings(3);
  TTree *otree;
  otree = new TTree("TC","ROOT tree");
  TH1F *timetest = new TH1F("timetest","time of pulses;time;counts",
   1000,0,100);
  TH2F *psd_all = new TH2F("psd_all","psd;Energy (ADC);PSP",
   45,0,45,100,0,1000000000);
```
1000,0,30000,200,-0.2,0.8);
TH2F *psd_all_MeV = new TH2F("psd_all_MeV","psd;Energy (ADC);PSP",
20000,0,20,200,-0.2,0.8);
//TH2F *psd_cuts = new TH2F("psd_cuts","psd;Energy (ADC);PSP",
10000,0,30000,200,-0.2,0.8);
TH2F *psd_cuts_MeV = new TH2F("psd_cuts_MeV","psd;Energy (ADC);PSP",
20000,0,20,200,-0.2,0.8);
TH2F *psd_back_MeV = new TH2F("psd_back_MeV","psd;Energy (ADC);PSP",
20000,0,20,200,-0.2,0.8);
TH2F *psd_all_h = new TH2F("psd_all_h","psd;Energy (ADC);PSP",
1000,0,30000,200,-0.2,0.8);
TH2F *psd_n = new TH2F("psd_n","psd;Energy (ADC);PSP",
1000,0,30000,200,-0.2,0.8);
TH2F *psd_thermalization = new TH2F("psd_thermalization","psd;Energy (ADC);PSP",
1000,0,30000,200,-0.2,0.8);
//TH2F *psd_thermalization_allcuts = new
TH2F("psd_thermalization_allcuts","psd;Energy (ADC);PSP",
1000,0,30000,200,-0.2,0.8);
TH1F *height_thermalizaton = new TH1F("height_thermalizaton","Pulse Height;ADC;Counts",16500,0,16500);
TH2F *cap_thermpulse = new TH2F("cap_thermpulse","Capture Time vs. Thermalization Energy;Pulse Area;Capture Time",
10000,0,1000000,2500,0.,250.);
TH1F *capture_time = new TH1F("capture_time","Time;Time(#mus);Counts",
1000,0,1000);
TH1F *full_capture_time = new
TH1F("full_capture_time","Time;Time(#mus);Counts",2500,0.,250.);
TH1F *full_capture_time_normal = new
TH1F("full_capture_time_normal","Time;Time(#mus);Counts",
2500,0.,250.);
TH1F *full_capture_time_normal_cuts = new
TH1F("full_capture_time_normal_cuts","Time;Time(#mus);Counts",
2500,0.,250.);
TH1F *histo_event_time = new
TH1F("histo_event_time","Time;Time(#mus);Counts",2500,0,250);
TH1F *full_spec = new TH1F("full_spec",";Energy (ADC);Counts",1000,0,30000);
TH1F *full_spec_MeV = new TH1F("full_spec_MeV",";Energy (ADC);Counts",10000,0,20);
TH1F *fom_integral = new TH1F("fom_integral","psp;Counts",200,-0.2,0.8);
TH1F *fom_height = new TH1F("fom_height","psp;Counts",300,0,100);
TH1F *n_full_spec_MeV = new TH1F("n_full_spec_MeV",";Energy (MeV);Counts",10000,0,20);
TH1F *halfpercent_n_full_spec_MeV = new TH1F("halfpercent_n_full_spec_MeV",";Energy (MeV);Counts",10000,0,20);
//for DT
//TH1F *n_full_spec_MeV_allcuts = new TH1F("n_full_spec_MeV_allcuts",";Energy (MeV);Counts",250,0,20);
//TH1F *n_full_spec_MeV_back = new TH1F("n_full_spec_MeV_back",";Energy (MeV);Counts",250,0,20);
//for DD
TH1F *n_full_spec_MeV_allcuts = new TH1F("n_full_spec_MeV_allcuts",";Energy (MeV);Counts",20000,0,20);
TH1F *n_full_spec_MeV_back = new TH1F("n_full_spec_MeV_back",";Energy (MeV);Counts",20000,0,20);
TH1F *ne_spec = new TH1F("ne_spec",";Energy (ADC);Counts",10000,0,300000); //10E6 for DT and 10k size bin
TH1F *pulseheight = new TH1F("pulseheight",";Energy (ADC);Counts",10000,0,300000);
TH1F *full_ne_spec = new TH1F("full_ne_spec",";Energy (ADC);Counts",10000,0,300000);
TH1F *baseline = new TH1F("baseline","Baseline;ADC;Counts",1000,15500,16500);
TH1F *peak_n = new TH1F("peak_n","Peak;Position;Counts",500,0,500);
TH1F *height_n = new TH1F("height_n","Pulse Height;ADC;Counts",16500,0,16500);
TH2F *height_total_therm = new TH2F("height_total_therm","total/height

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vs full integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
TH2F *pspcut3 = new TH2F("pspcut3","total/height vs full
integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
TH2F *pspcut4 = new TH2F("pspcut4","total/height vs full
integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
//TH2F *height_total_therm_gammacut = new
TH2F("height_total_therm_gammacut","total/height vs full
integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
TH2F *height_total_n = new TH2F("height_total_n","total/height vs full
integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
TH2F *height_total_full = new TH2F("height_total_full","total/height
vs full integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
TH2F *height_total_full_peakcuts = new
TH2F("height_total_full_peakcuts","total/height vs full
integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
TH2F *height_total_timing_back_sub = new
TH2F("height_total_timing_back","total/height vs full integral;Energy
(ADC);pulse height",1000,0.,30000,300,0,100);
TH2F *height_thermalizaton_allcuts = new
TH2F("height_thermalizaton_allcuts","total/height vs full
integral;Energy (ADC);pulse height",1000,0.,30000,300,0,100);
TCanvas *c1 = new TCanvas("c1","",200,10,600,400);
// In a ROOT session, you can do:
// Root > .L analyzer.C
// Root > analyzer t
// Root > t.GetEntry(12); // Fill t data members with entry
// number 12
// / / / / / / / /
//
//
// Note that the argument to GetEntry must be:
Root > t.Show();
Root > t.Show(16);
Root > t.Loop();
// Show values of entry 12
// Read and show values of entry 16
// Loop on all entries
This is the loop skeleton where:
jentry is the global entry number in the chain
ientry is the entry number in the current Tree
//
//
//
// METHOD1:
// fChain->SetBranchStatus("*",0); // disable all branches
// fChain->SetBranchStatus("branchname",1); // activate branchname
// METHOD2: replace line
// fChain->GetEntry(jentry);       // read all branches
// by b_branchname->GetEntry(ientry); // read only this branch
  double radius;
  double c_peak = 6828.;//6801;//
  double c_sigma = 439;//393.2;//
  double p_peak=0.6063;//29.22;://
  double p_sigma=0.03389;//1.848;//
  double psp;
  double hi_ratio;
  bool neutron=false;

jentry for TChain::GetEntry
ientry for TTree::GetEntry and TBranch::GetEntry
To read only selected branches, Insert statements like:
  bool prevpart=false;
  //bool pprevpart=false;
  double prevtime=0;
  double prevtime0=0;
  //double prevtime1=0;
  //double prevtime2=0;
```cpp
//double prevtime3=0;
double totaltime=0;
//double prevtotaltime=0;
double prevtotal=0.;
double prev_psp=0.;
double prevheight=0;
double prevhi_ratio=0;
double prevpeakpos=0;
int firsttime=0;
//int firsttime1=0;
//int firsttime2=0;
//int firsttime3=0;
int counter=0;
//double delay=0;
double eventtime=0;
char gname[256];
vector<int> x;
vector<int> y;
//ofstream ofile;
//ofile.open("out.xls");
if (fChain == 0) return;
Long64_t nentries = fChain->GetEntriesFast();
Long64_t nbytes = 0, nb = 0;
for (Long64_t jentry=0; jentry<nentries;jentry++) {
  Long64_t ientry = LoadTree(jentry);
  if (ientry < 0) break;
  nb = fChain->GetEntry(jentry); nbytes += nb;
  // if (Cut(ientry) < 0) continue;
  //cout<<100*(float)(jentry+1)/(float)nentries<<endl;
  threshold
  //if(DataCh0_PulseHeight<100) continue; //internal hard
  if(DataCh0_PSDTotalIntegral<1) continue;
```
//converted_E=DataCh0_PSDTotalIntegral*7E-5-0.007;
//cout<<converted_E<<endl;
neutron=false;
hi_ratio=DataCh0_PSDTotalIntegral/DataCh0_PulseHeight;
psp=DataCh0_PSDTailIntegral/DataCh0_PSDTotalIntegral;
full_spec->Fill(DataCh0_PSDTotalIntegral);
full_spec_MeV->Fill(DataCh0_PSDTotalIntegral*7E-5-0.007);
if(jentry==0) firsttime=DataCh0_TimeStamp;
//firsttime1=DataCh1_TimeStamp;
//firsttime2=DataCh2_TimeStamp;
//firsttime3=DataCh3_TimeStamp;
height_total_full->Fill(DataCh0_PSDTotalIntegral,DataCh0_PSDTotalIntegral/DataCh0_PulseHeight);
pulseheight->Fill(DataCh0_PulseHeight);
//pulseheight_Cal->Fill(DataCh0_PulseHeight);
peak_n->Fill(DataCh0_PeakPosition);
radius =
   //pow(DataCh0_PSDTotalIntegral-c_peak,2.0)/
pow(3.*c_sigma,2.0)+pow(DataCh0_PSDTotalIntegral/DataCh0_PulseHeight-p_peak,2.0)/pow(3.*p_sigma,2.0);
pow(DataCh0_PSDTotalIntegral-c_peak,2.0)/
pow(3.*c_sigma,2.0)+pow(psp-p_peak,2.0)/pow(3.*p_sigma,2.0);//equation for an ellipse... tells me it is a neutron hi_ratio psp
psd_all->Fill(DataCh0_PSDTotalIntegral,psp);
psd_all_MeV->Fill(DataCh0_PSDTotalIntegral*7E-5-0.007,psp);
psd_all_h->Fill(DataCh0_PulseHeight,psp);
fom_integral->Fill(psp);
fom_height->Fill(DataCh0_PSDTotalIntegral/DataCh0_PulseHeight);
//peak position cuts histograms
if(DataCh0_PeakPosition<=84.&&DataCh0_PeakPosition>=66.){
   height_total_full_peakcuts->Fill(DataCh0_PSDTotalIntegral,DataCh0_PSDTotalIntegral/
DataCh0_PulseHeight);
}
    //if(psp>0.19&&DataCh0_PSDTotalIntegral>3000)
    if(radius<1&&DataCh0_PeakPosition<=84.&DataCh0_PeakPosition>=66.){
        neutron=true;
        //cout<<"a neutron"<<endl;
        baseline->Fill(DataCh0_Baseline);
        height_n->Fill(DataCh0_PulseHeight);
        psd_n->Fill(DataCh0_PSDTotalIntegral,psp);
        height_total_n->Fill(DataCh0_PSDTotalIntegral,DataCh0_PSDTotalIntegral/
DataCh0_PulseHeight);
    }

    //if(DataCh0_PeakPosition<=84.&DataCh0_PeakPosition>=66.)
    eventtime=DataCh0_TimeStamp*8.*1E-3;
    //cout<<"the time is now "<<eventtime-prevtime<<endl;
    if(eventtime-prevtime>0){
        histo_event_time->Fill(eventtime-prevtime);
    }
    timetest->Fill((DataCh0_TimeStamp-prevtime0)*8);
    //cout<<"DataCh0= "<<DataCh0_TimeStamp<<endl;
    //cout<<"the time is now "<<DataCh0_TimeStamp-
prevtime0<<endl;
    totaltime=eventtime/1000000+16.*DataCh0_TMultiplier;
    //cout<<"the time is now "<<totaltime<<endl;
    if(neutron&&(eventtime-prevtime)<=40&&(eventtime-
prevtime)>0&&!
prevpart&&DataCh0_PeakPosition<=84.&DataCh0_PeakPosition>=66.){
        neutron&& &&!prevpart
prevheight);
    psd_thermalization->Fill(prevtotal,prev_psp);
    height_thermalization->Fill(prevheight);
    capture_time->Fill(eventtime-prevtime);
    ne_spec->Fill(prevtotal);
height_total_therm->Fill(prevtotal,prevtotal/n_full_spec_MeV->Fill(prevtotal*7E-5-0.007);
   halfpercent_n_full_spec_MeV->Fill(prevtotal*6E-5+0.0288);
   pspscut3->Fill(prevtotal,prevhi_ratio);
   pspscut3->Fill(DataCh0_PSDTotalIntegral,hi_ratio);
   //cout<<"the time is now "<<eventtime-
   prevtime<<endl;
 }

//all cuts
if(neutron&&(eventtime-prevtime)<=40&&(eventtime-
   prevtime)>0&&!prevpart&&!prevhi_ratio<10.632&&!prevhi_ratio>7.9605&&DataCh0_PeakPosition<=84.&&DataCh0_PeakPosition>=66.){
   height_thermalizaton_allcuts->Fill(prevtotal,prevhi_ratio);
   height_thermalizaton_allcuts->Fill(DataCh0_PSDTotalIntegral,DataCh0_PSDTotalIntegral/
   DataCh0_PulseHeight);
   n_full_spec_MeV_allcuts->Fill(prevtotal*7E-5-0.007);
   pspscut4->Fill(prevtotal,prevhi_ratio);
   pspscut4->Fill(DataCh0_PSDTotalIntegral,hi_ratio);
   psd_cuts_MeV->Fill(DataCh0_PSDTotalIntegral*7E-5-0.007,psp);
   psd_cuts_MeV->Fill(prevtotal*7E-5-0.007,prev_psp);
 }

if(neutron&&(eventtime-prevtime)>=40&&(eventtime-
   prevtime)<=80&&(eventtime-prevtime)>0&&!
   prev_psp<0.24004&&!prev_psp>0.08217&&DataCh0_PeakPosition<=84.&&DataCh0_PeakPosition>=66.){
   height_total_timing_back_sub->Fill(prevtotal,prevhi_ratio);
   height_total_timing_back_sub->Fill(DataCh0_PSDTotalIntegral,hi_ratio);
   n_full_spec_MeV_back->Fill(prevtotal*7E-5-0.007);
psd_back_MeV->Fill(prevtotal*7E-5-0.007,prev_psp);
psd_back_MeV->Fill(DataCh0_PSDTotalIntegral*7E-5-0.007,psp);
}

if(neutron&&(eventtime-prevtime)>0&&!prevpart&&prev_psp<0.24004&&prev_psp>0.08217&&DataCh0_PeakPosition<=84.0&&DataCh0_PeakPosition>=66.0){
    full_capture_time_normal_cuts->Fill(eventtime-prevtime);
}
if(neutron&&(eventtime-prevtime)>0&&!prevpart){//neutron&& &&!prevpart
    prevtime);
    prevtime<<endl;
}
full_capture_time->Fill(eventtime-prevtime);
full_capture_time_normal->Fill(eventtime-prevtime);
full_ne_spec->Fill(prevtotal);
cap_thermpulse->Fill(prevtotal,(eventtime-
    //cout""the time is now "<<eventtime-
    //if(!neutron&&(eventtime-prevtime)<=200&&!prevpart){//neutron && !prevpart
        notpsd_thermalization->Fill(prevtotal,prev_psp);
        notheight_thermalizaton->Fill(prevheight);
        notcapture_time->Fill(eventtime-prevtime);
    
    y
    >end(),y.begin());
y.clear();
if(jentry==0){
    for(int a=0;a<(Waveform0->size());a++){
        x.push_back(a);
    }
}
y.resize(Waveform0->size());//looks for the size of
    copy(Waveform0->begin(),Waveform0-
notne_spec->Fill(prevtotal);
cout<<"the time is now "<<eventtime-prevtime<<endl;
}
delete graph;

graph = new TGraph(Waveform0->size(),&x[0],&y[0]);/& forces vector to be an array pushes x and y there
command
sprintf(gname,"graph%lld",jentry);//sprintf is a C command
graph->SetName(gname);
if(jentry<100){
}
// delete graph;
/* y.clear();
graph->SetMinimum(15000);
graph->SetMaximum(16000);
graph->Write();
//graph->SetMinimum(15500);
//graph->SetMaximum(16000);
//c1->SaveAs("waves.root");
counter++;
if(jentry==0){
    for(int a=0;a<(Waveform0->size());a++){
        x.push_back(a);
    }
    y.resize(Waveform0->size());
copy(Waveform0->begin(),Waveform0->end(),y.begin());
graph = new TGraph(Waveform0->size(),&x[0],&y[0]);/& forces vector to be an array
sprintf(gname,"graph%lld",jentry);//sprintf is a C command
}
graph->SetName(gname);
    graph->Draw();
if(psp>0.55&&psp<0.69&&DataCh0_PSDTotalIntegral>2000&&DataCh0_PSDTotal
Integral<5500&&counter<101){
counter++;
}*/

// ofile<<jentry<<"t"<<neutron<<"t"<<DataCh0_PSDTotalIntegral<<"t"<<ps
p<<"t"<<DataCh0_TimeStamp<<"t"<<DataCh0_TMultiplier<<"t"<<((DataCh0
_TimeStamp*8.)+(16000000000.*DataCh0_TMultiplier))/1000000000.<<endl;
prevpart=neutron;
prevtotal=DataCh0_PSDTotalIntegral;
prevtime=eventtime;
prev_psp=psp;
prevheight=DataCh0_PulseHeight;
prevhi_ratio=hi_ratio;
prevpeakpos=DataCh0_PeakPosition;
//prevtotaltime=totaltime;
//prevtime0=DataCh0_TimeStamp;
//prevtime1=DataCh1_TimeStamp;
//prevtime2=DataCh2_TimeStamp;
//prevtime3=DataCh3_TimeStamp;
}

if (full_capture_time_normal->Integral()!=0){
    full_capture_time_normal->Scale(1/
full_capture_time_normal->Integral());
}

ROOTFile->Write();
ROOTFile->Close();
//ofile.close();
cout<<"the total time in seconds is "<<totaltime<<endl;